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# A Research Strategy for Electric and Magnetic Fields: Research Needs and Priorities

## Review Draft

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**This document is a preliminary draft. It has not been formally released by the U.S. Environmental Protection Agency and should not at this stage be construed to represent Agency policy. It is being circulated for comment on its technical accuracy and policy implications.**

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Office of Research and Development
U.S. Environmental Protection Agency
Washington, D.C.

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# A RESEARCH STRATEGY FOR ELECTRIC AND MAGNETIC FIELDS: RESEARCH NEEDS AND PRIORITIES

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## EXECUTIVE SUMMARY

Recently, widespread media attention has been focused on whether adverse human health effects could result from exposure to electric and magnetic fields (EMF). Public and private concerns are based on research reports of a statistical association between EMF exposure to human populations and some forms of cancer, as well as measurable biological effects in laboratory animals, tissues, and cells. Although the existing evidence is insufficient for discerning a cause-effect relationship for EMF exposure and human disease or injury, it does suggest the need for further research to allow for a realistic assessment of the possibility of health risks and their magnitude.

The goal of this document is to describe a strategic framework which identifies the major research topics and their relative priorities. It is meant to be a "research strategy" and not a "research plan." That is to say the focus is on general EMF research needs and relative priorities within the context of the EMF question; not on development of specific research plans for each area of potential interest. The prioritization is based on a determination of which research topics are most likely to provide near-term results that will improve and/or strengthen our assessment of EMF health risks.

The discussion is devoted exclusively to EMF in the range of 0 to 500,000 Hertz (Hz). Sources emitting EMF in this spectrum include electric power lines (e.g., transmission and distribution lines, electric circuits in the home), electrically powered devices in the home and office (e.g., electric blankets, televisions, hair dryers, video display terminals, fluorescent lights), industrial equipment (e.g., arc welding machines, lathes, induction furnaces), civilian and military communication systems (e.g., LORAN, OMEGA, GWEN), and medical devices (e.g., magnetic resonance imagers). Although EMF at frequencies above 500,000 Hz may also have potential health effects, the lower range is emphasized because of the concern about EMF from power lines and commonly used electric devices in the home and workplace.

The strategy evaluates research needs in four major areas:

- Animal and human studies to determine if adverse health effects (cancer and reproductive, nervous, and immune system effects) might result from EMF exposure.

- Investigation of biophysical mechanisms, including both physical and biological interactions, that underlie any effects which may occur from exposure to EMF

- Improved assessment of human exposure to EMF, including source identification and characterization, instrumentation development, exposure measurement and modeling, EMF coupling to biological objects, and laboratory exposure systems.

- Determining what type of control technology, if any, may be needed to prevent and reduce human exposure to EMF.

High priority research areas are those determining possible carcinogenic health effects, biophysical mechanisms, and human exposure assessment. The possible effects on reproductive and nervous systems were assigned a medium research priority. A low priority rank was given to immune system effects and control technology investigation. Research recommendations are summarized in the conclusions (Chapter VI) and listed by topic in Appendix A.

Although the research needs and relative priorities are based primarily on consideration of health risk assessment issues, the research to be accomplished is not specific to any particular public or private organization.

# CHAPTER I

## INTRODUCTION

The high standard of living in the United States is due in large measure to the use of electricity. Our technological society developed electric power generation, distribution, and utilization with little expectation that exposure to the resultant electric and magnetic fields (EMF) might possibly be harmful beyond the obvious hazards of electric shocks and burns, for which protective measures were instituted. Today, the widespread use of electric energy is clearly evident by the number of electric power lines and the myriad of electrically energized devices in the home, workplace, medical arena, and outside environment.

Because of the extensive use of electric power, everyone in the United States today is exposed to a wide range of EMF not present in the pre-technological world. Recent research reports describe an association between exposure to EMF and health effects in human populations, biological effects in laboratory animals, and biological effects in cells and tissues derived from human beings and laboratory animals. Although the evidence is insufficient to relate human health effects to specific exposure levels of EMF or to prove a cause-and-effect relation between EMF exposure and human disease, the potential for health effects is a concern because of the huge population exposed to EMF. More than 100,000,000 people -- virtually all those born in the United States since 1940 -- have been exposed throughout their lives to technology-generated electric and magnetic fields.

This document addresses sources of EMF that emit electric and magnetic fields at frequencies of 0 to 500,000 Hertz (Hz). Such sources include electric power lines, including transmission and distribution lines as well as electric circuits within homes, offices, and industrial facilities, electric grounding systems, and electrically powered devices such as home appliances, office and industrial equipment, civilian and military communication and navigation systems, and medical devices. Specific examples of the above include electric blankets, electrically heated water beds, electric razors, hair dryers, video display terminals (VDTs), photocopiers, printers, facsimile machines, lathes, drill presses, fluorescent lights, light dimmers, televisions, arc welding machines, induction furnaces, magnetic resonance imaging equipment, navigational and communication systems such as LORAN, OMEGA, and GWEN; and electric trains, cars and other mass transit systems. Although exposure to EMF at frequencies above 500,000 Hz is also a health concern, the lower range is emphasized because of the heightened concern for possible health effects from exposure to 60 Hz EMF from power lines and to commonly used devices in the home and workplace that emit EMF below 500,000 Hz. An EPA report entitled "Biological Effects of Radiofrequency Radiation" (EPA 600/8-83-026F), published in 1984 is a critical and comprehensive review of the literature on frequencies above 500,000 Hz.

This report describes a research strategy to address the concern that exposure to EMF, aside from electric shocks and burns, might have significant human health effects. The goal of this document is to identify needs and specify priorities for research to determine the possible health effects of EMF exposure, define exposure conditions, and determine what type of control technologies might be needed to mitigate EMF exposure in the home, workplace, and outside environment. The recommendations in this report describe research needs for (1) human health effects that specifically address cancer, reproduction and development, the nervous system, and the immune system; (2) biophysical mechanisms; (3) exposure assessment; and (4) possible control technologies. Examples are used for each of these categories to illustrate the types of important research needs.

The report format consists of two parts. First, an overview of the current state of knowledge for each of the four subject areas is presented; the overview identifies research gaps and explains the rationale for the recommendations. Second, research recommendations are given for important unresolved issues and emerging technologies. The discussion of research needs and priorities is based on literature reviews and other reports listed on page R-1. The literature is not reviewed in detail and original research articles are not cited.

Important questions considered in this report are:

- What, if any, are the health effects in human populations exposed to EMF?
- What, if any, are the other biological effects of EMF exposure?
- What are the biophysical mechanisms that underlie interactions between EMF and biological systems?
- What electric and magnetic fields exist in the home, workplace, and the outdoor environment?
- What are the sources of the fields?
- If necessary, how can exposure be mitigated?

The document is written for scientists and engineers, managers, regulators, and policy makers who are interested in the research issues associated with EMF. It is meant to identify important research needs and to prioritize those needs based on their relevance for future decisions about the likelihood and magnitude of human health effects resulting from EMF exposure. The research strategy outlined here is envisioned as a framework from which mission-oriented research programs can be derived. It was developed without consideration for which organizations might perform the necessary research.

Concerns about potential health effects associated with EMF were the stimulus for recent interest by Federal agencies in the associated research questions. The EPA critically reviewed the literature on cancer in "Evaluation of the Potential Carcinogenicity of Electromagnetic Fields" (External Review Draft, EPA/600-6-90/005B, October 1990). They concluded that the data are insufficient to determine whether a cause-and-effect relation exists between EMF exposure and cancer; clearly highlighting the need for further research. The Food and Drug Administration briefed (11/14/90) an advisory committee on EMF exposure levels and possible human health effects associated with use of electric blankets. The National Institute for Occupational Safety and Health sponsored a workshop on the Health Effects of Electromagnetic Radiation on Workers (1/30-31/91) to identify research that would close the knowledge gaps and permit reliable recommendations for protecting workers. The National Institute of Health held a workshop on Recent Developments in the Health Consequences and Clinical Applications of Low Frequency Electromagnetic Fields (2/11/91) to brief members of a research grant panel on the current state of knowledge of EMF.

In addition to Federal agencies, a wide range of national and international groups, industrial associations, and state agencies have recognized the importance of EMF research. A sampling of comments is given below.

> With advances in technology and the ever greater need for electric energy, human exposure to 50/60 Hz electric and magnetic fields has increased to the point that valid questions are raised concerning safe limits of such exposure...From a review of the scientific literature, it is apparent that gaps exist in our knowledge, and more data need to be collected to answer unresolved questions concerning biological effects of exposure to these fields. (International Radiation Protection Association, Health Physics, vol. 58, pp. 113-114, 1990)

> Further study is needed on the influence of electric and magnetic fields on cellular and animal systems, particularly in the areas of the nervous system and the reproductive system...Emphasis should be given to validating recent findings that suggest an association between cancer and exposure to ELF [extremely low frequency] fields...Because the lack of exposure data is the greatest source of uncertainty in investigations of human health effects, increased effort is needed to improve exposure assessment techniques for future human studies. (World Health Organization, Nonionizing Radiation Protection, Second Edition, pp. 223-224, 1989)

> Research results available raise important scientific questions in the areas of developmental biology, neural function, dosimetry, and mechanism. To answer these questions and to assess their implications for potential health hazards will require high quality research, fastidious reporting, and independent replication of experiments. (Nonthermal Effects of Nonionizing Radiation, Final Report, National Academy of Sciences, National Research Council, pp. 5-6, 1986)

> Although too little is known about field effects on cells and effects in the whole animal to conclude that there is a causal connection between ELF [extremely low frequency] fields and disease, there is also too much evidence for effects of weak fields on important biological functions to ignore the possibility that harmful health effects may occur. More research is needed to decide if the biological interactions with ELF fields are only interesting laboratory phenomena or are the signature of a widespread environmental health problem. (Potential Health Effects of Electric and Magnetic Fields From Electric Power Lines, Report to the California State Legislature, September 15, 1989, p. 100)

The possibility of EMF playing a role in carcinogenesis cannot be ruled out, but much work remains to be done in identifying a carcinogenic mechanism, if any, and in providing an accurate assessment of human risk...However, much additional research needs to be done on the issue. Exposure standards and reliable estimates of human risk cannot be ascertained without such necessary research. (Extremely Low Frequency Electric and Magnetic Fields and Cancer: A Literature Review, Electric Power Research Institute, EPRI EN-6674, December 1989, see Report Summary)

A critical need, at present, is significant increases in federal funding for research on interaction mechanisms and animal studies, while maintaining efforts in epidemiology but with greater emphasis on confounding factors and co-carcinogens and agents with known carcinogenicity. Moreover, a measurement program to identify and characterize sources of electric and magnetic fields would be essential before procedures for exposure mitigation could be implemented, if needed. (Statement to the Subcommittee on Natural Resources, Agriculture Research, and Environment Committee on Science, Space, and Technology, U.S. House of Representatives, James C. Lin, Chairman, Committee on Man and Radiation, Institute of Electrical and Electronic Engineers, July 25, 1990)

Recent years have seen dramatic developments in the science which have prompted many observers to conclude that the issue of possible 60 Hz health risks should be taken seriously... Already concerns have prompted vigorous public intervention and litigation which has significantly impeded the ability of private and public utilities to construct new power transmission facilities. Such protests will probably grow and its seems likely that similar concerns about fields will soon be raised at other levels. Without adequate science on which to base answers, the resulting contention could go on for many years and have costs significantly greater than the costs of the needed research. (Biological Effects of Power Frequency Electric and Magnetic Fields-Background Paper, U.S. Congress, Office of Technology Assessment, OTA-BP-E-53, May 1989, pp. 80-81)

# CHAPTER II

# HEALTH EFFECTS

Many epidemiological studies report an association between EMF exposure and health effects. The most frequently reported health effect is cancer. In particular, EMF exposure has been reported to be associated with elevated risks of leukemia, lymphoma, and nervous system cancers in children. Occupational studies of adults describe an association between EMF exposure and leukemia, lymphoma, nervous system cancer, and other cancers. Although there have been more than 40 epidemiological studies of children and adults conducted, uncertainties remain in our understanding of the potential health effects of EMF. For example, uncertainties surrounding exposure assessment are significant. Few epidemiological studies contain measured exposure levels. In some studies, exposure levels have been estimated by surrogate measures such as job title, broad occupational groupings, or the configuration of electric power lines outside the home. In addition to cancer, other health concerns are associated with the reproductive, nervous, and immune systems. Further research is needed to clarify these reported associations.

The proposed research described below first addresses methodologic and study design issues important to epidemiological studies. Following are discussions of research for both human and laboratory animal studies for four major types of health effects: cancer, alterations in reproduction and development, changes in nervous system function, and effects on the immune system.

## A. METHODOLOGIC ISSUES FOR EPIDEMIOLOGY

Human exposure to EMF results from: (1) ambient exposure to fields from sources outside the home and workplace; (2) residential exposure to fields from sources inside the home, and (3) occupational exposure to fields from equipment or facilities. These exposure environments can vary greatly with respect to intensity, duration, frequency, direction of the fields, and modulation, including the number of on/off cycles. To assess the effect of EMF on human beings, a variety of characteristics of the exposure field have to be considered. Attention should focus on resolving apparent discrepancies between magnetic field measurements and surrogates of exposure, e.g., wiring configurations, so that the relevant exposure parameter(s) can be identified. Accurate exposure data will decrease misclassification in epidemiological studies, improve the ability to develop exposure-response relationships, and provide more reliable risk estimates.

RECOMMENDATION: **EMF exposure in the home, workplace, and outside environment should be more fully characterized to identify common and special exposure situations. Exposure data are needed for statistically valid population estimates and to help identify the field parameters that may be biologically active. The development and validation of personal**

**external dosimetry methods to document and evaluate the exposure of human beings to EMF should continue. Epidemiological research and exposure assessment research must be integrated.**

A major concern with the epidemiological data is the paucity of information on factors which may distort the measure of risk associated with EMF exposure. This concern is not unique to studies of EMF. Such distortions, if undetected, could seriously affect the interpretation of the results. The concern for these factors in EMF studies is due in part to our generally poor understanding of what causes cancer and to relatively poor exposure assessment of all types of EMF environments. For the latter, many studies were not designed to characterize total exposure. Some studies of childhood cancer tried to address these other factors through extensive questionnaires used to interview parents. Recent occupational studies have made some advances in identifying exposure to agents other than EMF, but more rigorous investigation is needed. Factors deserving examination include, but are not limited to, smoking history, chemical exposures, health status, occupational information in studies of residential exposure, and residential information in studies of occupational exposure.

RECOMMENDATION: **Epidemiological studies on the effect of EMF should be designed to identify and evaluate other factors which may distort the measure of association with EMF exposure. Studies of humans in controlled laboratory settings, animal studies, and in vitro studies should be evaluated for exposure parameters and other information that would improve the design of epidemiological studies on EMF.**

In general, epidemiological studies have chiefly examined exposure to EMF associated with electric power use in the home and workplace, and studies of people exposed to frequencies other than 60 Hz are neglected. The greatest attention has focused on so-called "electrical workers" even though other kinds of workers have been identified as possibly at risk from EMF exposure. On the other hand, the term "electrical worker" is very broad and EMF exposure can be to a mix of frequencies. Examples of specialized exposed populations available for study include VDT operators, medical personnel, aluminum smelter workers, and induction heater operators. Most occupational studies are of men, but reports of increased miscarriages and increased malformations suggest that women and children potentially exposed to EMF may be at special risk. Emerging information about a possible link between EMF exposure and breast cancer points to a need for more cancer studies of women; breast cancer is the most common cancer in women and thus of significant health concern.

RECOMMENDATION: **Epidemiological studies should be conducted on populations exposed to EMF other than electric power frequency fields. Important populations to examine are women and highly exposed groups. Three major health effects to investigate are cancer, reproductive effects, and nervous system changes.**

## B. CANCER

### B.1. HUMAN

Information on time-dependent factors that affect carcinogenesis is insufficient. The length of time a person lived in a residential setting has not been adequately addressed in residential studies. The length of residency in a particular EMF environment may be an important component of exposure characterization and could provide important information relevant to exposure-response relations. In a few childhood cancer studies, the risk of cancer was substantially increased for children who had the same "birth" address as the "diagnosis" or "death" address, compared to those children who had moved sometime between birth and diagnosis. The influence of latency and induction time have also not been rigorously examined in most epidemiological studies. Different types of cancer have different latent periods. For example, lymphoma, leukemia, and brain cancer have different latent periods that also differ depending on cell type and whether the patients are children or adults. Researchers may have been unable to determine the true risks of cancer, especially the risk for specific types of cancer, because they did not consider the duration and timing of EMF exposure.

RECOMMENDATION: **Epidemiological studies on EMF and cancer should assess the influence of time-dependent factors such as length of residency, duration of exposure, and latency on the risk of specific types of cancer to (1) identify exposure-response relations with length of residency as a surrogate for exposure and to (2) validate whether or not specific cancer types have satisfied known latency and temporal requirements for causality.**

Another major problem with some epidemiological studies is the grouping of cancers into broad categories. In some childhood cancer studies, the strongest associations are between EMF exposure and all cancers combined. The specific cancers associated with EMF exposure are leukemia, lymphoma, and nervous system cancer. Yet, each of these categories contain separate and distinct disease subtypes. Many reports do not distinguish between different subtypes of cancer. For example, the risk of acute lymphatic leukemia, chiefly a childhood cancer, may not have been considered separately from other acute and chronic nonlymphatic leukemias that more typically affect adults. Lymphatic and non-lymphatic leukemia are different diseases that may involve different mechanisms. Nervous system cancer is a generic term that includes a number of histologically defined structures with different etiologies, and lymphomas may constitute a class of different cancers with different causes or processes. Often, studies group diseases because a low incidence of different types of cancer is found in the study population. However, specific cancers associated with EMF may be missed in studies that group cancers into broad categories.

RECOMMENDATION: **Epidemiological cancer studies should emphasize identification of distinct cancer types in populations exposed to EMF because the reporting of cancer by general class may mask elevated risk for specific cancer types.**

The reported association between EMF exposure and cancer suggests the need for clinical research based on effects in biological models. Magnetic field exposure of cells derived from human tissue is reported to increase the rate of DNA synthesis and change the proliferative capacity of cancer cells. Human lymphoma cells exposed to 60 Hz fields showed an increase in the activity of ornithine decarboxylase, an enzyme considered to be essential for the growth of normal as well as cancer cells. Carcinogenic chemicals can also increase the activity of ornithine decarboxylase. Breast cancer is believed to be mediated by oncogenes and alterations in oncogenes and tumor-suppressor genes are believed to be important in the development of colon cancer. Since these biological changes are associated with the carcinogenic process, they are candidate biomarkers for the disease.

RECOMMENDATION: **Human clinical studies should try to identify possible biomarkers of EMF exposure in the carcinogenic process, including alterations in the pattern of DNA synthesis, ornithine decarboxylase activity, and oncogene activation.**

## B.2. ANIMAL

Studies in animals and other biological test systems are needed to examine the associations reported in human studies between cancer and exposure to EMF. Laboratory studies provide an opportunity to discover cause-and-effect relations between well-characterized biological systems and defined, controlled exposures to EMF. Such definitive information cannot be obtained from human studies.

The EPA document on the potential carcinogenicity of EMF concluded that several biological phenomena related to carcinogenesis are affected by these fields. EMF exposures are reported to enhance DNA synthesis, alter transcription of information from DNA into messenger RNA, alter normal patterns of protein synthesis, delay the mitotic cell cycle, induce chromosome aberrations, induce enzymes normally active during cell proliferation, inhibit differentiation and stimulate the growth of carcinoma cell lines, and mimic the effect of phorbol esters, a class of cancer-promoting chemicals.

The biological phenomena mentioned above are related to postulated mechanisms of carcinogenesis; however, reports of EMF-induced changes in biological systems do not prove that the fields are carcinogenic by themselves or that exposure to them are risk factors for human cancer. Furthermore, the relevance of these findings is questionable because many occur at field strengths and conditions (e.g., pulsing fields) different from the time-averaged ambient levels experienced by human populations. Although a wide array of biological systems have been investigated under a broad range of exposure conditions, independent confirmation of specific experiments remains important.

RECOMMENDATION: **The potential role of EMF in carcinogenesis should be studied in the laboratory (both in vitro and in whole animals) to discover the basic nature of the field-dependence of effects. Gene expression, growth of transformed cells, and intracellular reactions associated with chemical signalling are areas of special interest.**

Epidemiological studies have suggested that exposure to ambient power frequency magnetic fields may correlate with development of cancer. At this time, the carcinogenicity of EMF has not been tested in animals under well-defined laboratory exposure conditions, although some studies concerned with the ability of EMF to promote cancer are now in progress.

RECOMMENDATION: **Studies with laboratory animals are needed to examine whether exposure to power frequency magnetic fields induces a carcinogenic response.**

## C. REPRODUCTIVE AND DEVELOPMENTAL EFFECTS

### C.1. HUMAN

Environmental agents that cause reproductive and developmental effects are important because they may directly influence health, lifespan, propagation, and functional and productive capacity of our children. EMF exposure encompasses the entire reproductive and developmental periods of life, including pre-conceptional germ cell development in parents, the period from conception to birth, the postpartum growth and development stage, and the reproductive ages.

Epidemiological studies have reported reproductive and developmental effects from exposure to EMF generated by devices in the workplace and home. Investigations of women and the outcome of their pregnancies have included operators of VDTs and users of specific home appliances (electric blankets, heated water beds, and ceiling electric heat). The reports of increased miscarriages and increased malformations suggest that maternal EMF exposure may be associated with adverse effects. In addition, other studies have reported an increased incidence of nervous system cancer in children whose fathers had occupations with potential EMF exposure. However, many studies have used surrogate measures of exposure, have determined exposure at a time other than the one that is biologically relevant to the health effect, and have examined in a limited fashion, if at all, other factors that could distort the findings reported in EMF studies. Thus, the human data are not adequate to support a definitive conclusion that EMF exposure has reproductive and developmental effects.

RECOMMENDATION: **Epidemiological studies are needed to confirm reported reproductive and developmental effects of EMF. Studies should be designed to include EMF exposure assessment, identify factors other than EMF that may affect the study conclusions, identify relevant exposure periods, and be guided by our understanding of reproductive and developmental effects in laboratory animals.**

### C.2. ANIMAL

Studies of reproduction in laboratory animals include measures of sexual behavior, capacity to fertilize, reproductive efficiency, sex organ morphology and function, and synthesis of sex steroids. Although EMF exposure of the parent before conception has been reported to affect several reproductive measures, including sexual behavior and maturation, as well as male fertility, these results have not been independently confirmed.

Laboratory mammals have been used also to study the potential consequences of in utero exposure to EMF. A wide range of effects have been reported for rats and mice exposed to such fields and their offspring. The effects include increased embryonic death, decreased body weight, shifts in weights of hormonally-responsive organs (including gonads and organs sensitive to steroid levels), changes in levels of chemicals in serum and cells, and altered behavioral patterns. Most of the effects reported in laboratory animals have not been independently confirmed.

There is evidence to indicate that magnetic fields may influence embryonic development in laboratory animals. The most frequently used animal model for demonstrating the effects of EMF is the chicken embryo. In 17 reports on the chicken embryo exposed to various EMF, 36 of 103 individual experiments showed a statistically significant increase in abnormal embryos, while 67 did not.

**RECOMMENDATION: Research should attempt to confirm independently reported reproductive effects in mammals. Developmental studies with standard laboratory models should employ exposure conditions reported to be effective in nonmammalian systems. The relevance of developmental effects in nonmammalian embryo models to permanent changes in mammals should be explored because of the significance to epidemiological findings.**

**RECOMMENDATION: The reported association of increased cancer rates in human offspring, or an association of any effect in offspring, to paternal exposure requires a mechanistic link via paternal germ cell changes. A link to effects from paternal exposure, as reported in epidemiological studies, needs to be studied in laboratory animals.**

## D. NERVOUS SYSTEM EFFECTS

### D.1. HUMAN

Neurotransmitters and neurohormones are substances involved in communication both within the nervous system and in the transmission of signals from the nervous system to other body organs. These regulatory chemicals transmit information and regulate or modulate various bodily functions that range from the learning of new skills to the control of heart rate and blood pressure. Neuroregulatory chemicals are released in pulses with a distinct daily or circadian pattern. Serotonin, melatonin, dopamine, and noradrenaline have been the focus of much attention in the brain sciences. Aberrant levels of these neurochemicals accompany clinical disorders like depression and many of the drugs used to treat these diseases interact with these neurochemicals. Their metabolites can be monitored in easily accessible body fluids and provide information about the role of neuromodulators in disturbed nervous system function.

Data of this type from exposed human subjects are not available but relevant animal experiments report that neurotransmitter metabolite levels are lowered in primates and that circadian patterns of neurotransmitters and their metabolites are desynchronized in rodents exposed to EMF. The few studies in which human subjects have been exposed to EMF in controlled laboratory settings describe the following effects: changes in brain evoked-potential indicative of possibly slowed information processing, slowed reaction time and altered behavioral performance in which ability to gauge the passage of time was a pivotal component, and altered cardiovascular function including slowed heart rate and pulse that may indicate direct action on the heart or the neurochemicals controlling cardiac function. Results also indicated specific combinations of electric and magnetic fields may be necessary before alterations are observed.

Melatonin, a hormone released by the pineal gland during the dark period of the daily cycle, may be an important marker for certain health effects of EMF. Alterations in the circadian pattern of melatonin accompany depression, "jet lag," and "shift lag," which can occur from rotating shift work schedules. Disruption of physiological functions, such as sleep, that are synchronized with melatonin secretion are symptoms for all three conditions. Body temperature is also synchronized with melatonin rhythms. When humans isolated from external time cues are exposed to electric fields their sleep-wake periods and core temperature patterns reportedly shift. Manipulation of the light-dark cycle is used to treat depression, and "jet lag" symptoms are ameliorated after treatment with light or melatonin. Night-time pineal melatonin levels are reported to be suppressed in rats exposed to electric fields and intermittent magnetic fields. EMF may also suppress nocturnally high levels of melatonin in human beings. In one study, the use of electric blankets configured to allow frequent on/off switching of the magnetic field that was 50% greater than that associated with a conventional electric blanket, was shown to reduce the nighttime urinary excretion of melatonin's major metabolite. A possible link between EMF-induced alteration in melatonin synthesis and cancer has been hypothesized. Studies with rats show that EMF can suppress the melatonin level in the dark phase of the daily cycle. This action of reducing melatonin may possibly increase the potential for cancer because melatonin is known to inhibit the growth of some cancers.

RECOMMENDATION: **Work should continue with human subjects in controlled laboratory settings where exposure to real and sham fields occur under double- blind conditions. Physiological and behavioral endpoints previously reported to be sensitive, as well as those reported in animal studies, should be monitored before, during, and after exposure to EMF. Because of the suspected role of altered melatonin rhythms in clinical disorders and in cancer, other studies should determine if EMF can alter the circadian pattern of melatonin and its metabolites in body fluids. Particular attention should be directed to whether the rate of activation and deactivation of the field (intermittent exposure) has a more marked effect than continuous application.**

## D.2. ANIMAL

Studies examining the related areas of behavior, circadian rhythms, and neurochemistry have been the focus of laboratory animal research concerned with EMF and the nervous system. Behavior is the integrated output of the nervous system and alterations in circadian patterns or neurochemical levels are often reflected in behavioral changes. Physiological and biochemical processes have a synchronized daily cycle or circadian rhythm and aberrant rhythms have been linked to a variety of disorders. Such disorders range from altered sensitivity to drugs and toxins to sleep, performance, and psychiatric disorders, including chronic depression.

The performance of both spontaneous and learned behaviors is affected by EMF. Studies of spontaneous behavior have provided data on the threshold and possible mechanism of perception of 60 Hz electric fields. Although detection thresholds vary according to species, it is generally believed that fields are detected by mammals with fur or hair, including humans, because hair vibration caused by the oscillating electric field activates sensory mechanisms in the skin. No perception mechanism for magnetic fields is known except for the visual effect in humans known as magnetophosphenes or phosphenes (light flashes) caused by high intensity magnetic fields. This phenomenon, which exhibits a threshold and is highly frequency-dependent (maximum response in the 20 to 30 Hz range), is apparently caused by induced electric fields in the eye that stimulate the retina. Thus, a pulsed magnetic stimulus is interpreted as flashes of light by the brain.

The performance of several learned behaviors in animals is reported to be affected by EMF. The reaction time of non-human primates is compromised by exposure to electric fields. Rats trained to respond with a certain pattern and rate of behavior to earn rewards are less efficient when exposed to EMF. Magnetic fields decrease the sensitivity of mice to the pain-relieving action of drugs such as morphine and other opiates. Sixty-Hertz magnetic fields also reduce the number of seizures induced in rats by an epileptogenic drug. The latter studies indicate that research incorporating a drug challenge may help to identify the interaction of EMF with the nervous system.

Research results also suggest that circadian rhythms can be altered by EMF. In nonhuman primates, patterns of food and oxygen consumption were affected by field intensity; for some monkeys, these altered biological rhythms persisted after the cessation of exposure. Other work shows that 60 Hz electric fields produced phase delays in activity and metabolism rhythms in mice. In addition, exposure to electric fields has been shown to affect the circadian rhythm of serotonin, noradrenaline, and dopamine in rats. As mentioned previously, alterations in the level and rhythm of neurochemicals with respect to the natural daily light-dark cycle may have implications for sleep and mood disorders, including chronic depression.

One of the most consistent neurochemical findings is that the circadian pattern of melatonin synthesis in the rat can be altered by EMF. Melatonin levels vary with the daily light/dark cycle and are higher in the dark phase. The finding that EMF can suppress the higher melatonin level in the dark phase may possibly be related to purported carcinogenic effects of EMF because melatonin inhibits the growth of some cancers. A possible link between EMF-induced alteration in melatonin synthesis and cancer development requires study.

**RECOMMENDATION: Studies of EMF effects on behavior of laboratory animals should emphasize learned tasks and drug interactions. Other work should determine whether the effects of EMF on circadian rhythms and neurochemical levels are significant in related areas such as behavior and cancer. The consistent finding that EMF affects melatonin synthesis should be the focus of studies to determine the sites and mechanisms of interaction. A primary goal of research on EMF and the nervous system is to define causative exposure conditions; particular attention should be given to the possible differential effects of electric versus magnetic fields.**

## E. IMMUNE SYSTEM EFFECTS

### E.1. HUMAN

The immune system defends against cancer and other diseases. Environmental agents that compromise the effectiveness of the immune system could potentially increase the incidence of cancer and other diseases. No research recommendation is given for the human studies category because of the lack of data on immune system effects in human beings and the preliminary state of knowledge of such effects in both in vitro and in vivo laboratory studies (see below).

### E.2. ANIMAL

A series of comprehensive investigations in the United States on the effect of 60 Hz electric fields on the immune system of laboratory animals found no effect of chronic exposure of rats and mice. Thus, it was concluded that power frequencies have small or no effects on the immune systems of exposed animals. However, the role of magnetic fields was not investigated.

In vitro tests have also been used to investigate the effect of EMF on the immune system. The results suggest that the magnetic field alone or in combination with an electric field can affect immune function. Magnetic fields have been reported to inhibit the proliferation of immune cells, inhibit killing of abnormal cells by the immune system, and to change the proliferative capacity of cancer cells. Independent confirmation of the in vitro immune results would open a promising research approach to investigate the possible link between exposure to EMF and cancer. In addition, these tests would help to define effective exposure parameters because some immune effects are reported to be frequency-specific and to have a nonlinear exposure-response relation. Also, work with modulated high-frequency radiation indicates that the low frequency of modulation is the biologically effective frequency.

**RECOMMENDATION: Research is needed to confirm independently the reported in vitro immune effects. In addition, immune responses in laboratory animals exposed chronically to magnetic fields warrants investigation.**

# CHAPTER III

# BIOPHYSICAL MECHANISMS

Studies of biophysical mechanisms are important because the research examines both stages of the interaction process: (1) the nature of the initial physical/chemical interaction of EMF with biological systems and (2) the expression of the physical/chemical change as a biological response. This information is needed to identify field parameters and biological responses important for health research.

There is a substantial body of literature upon which the investigation of biophysical mechanisms can be based. It is apparent from this literature that EMF should not be considered a single entity, but rather a generic class of physical agents, similar to classes of chemicals. Because of the infinite number of potential combinations of exposure parameters, such as frequency, intensity, modulation, etc., it is possible that more than one mechanism may account for the variety of EMF effects. Examples of reported biological responses to electric and magnetic fields include: (1) alteration of melatonin synthesis in the pineal gland, (2) response of brain tissue, e.g., ion flux changes and behavioral changes, (3) intervention in biochemical signalling across the plasma membrane, including second-messenger systems and protein-kinase action pathways that are important in hormone-induced responses, (4) alterations in circadian rhythms, (5) effects on developmental and immune processes, (6) bone fracture healing, and (7) alterations in gene regulation that are implicated in tumor production.

The biological effects of EMF can be best understood by a three-step paradigm: transduction, amplification, and expression. In the first step, energy in electric or magnetic fields must be converted, or transduced, into a biochemical or biophysical change to affect a biological system. The EMF intensities reported to cause effects and the photon energy of frequencies in the 0 to 500,000 Hz range are very small. Even if the transduction step were 100% efficient, there is insufficient energy to break chemical bonds. The second step, amplification, is needed to boost the initial biophysical changes triggered by the field. Amplification would then lead to the third step, expression of the effect as an observable entity in the laboratory; expression could occur through a constellation of both intra- and extra-cellular biological changes.

Advances in understanding the principles of physical interaction of EMF with biochemicals and living cells will further define both transduction and amplification. Well-known biochemical amplification systems are probably also important to study in the context of EMF. Expression appears to be primarily caused by the interplay of various biological and biochemical systems. The following discussion of biophysical mechanisms is presented in two parts: physical interactions and biological interactions.

## A. PHYSICAL INTERACTIONS

In the past, characterization of the physical interactions of EMF with biological materials emphasized electric field interactions. Recently, this focus has changed because data from epidemiological studies suggest that the magnetic component may be the active agent. Thus, interest has shifted to the biological consequences of the induced current resulting from a changing magnetic field. The biological influence of these magnetically induced currents has not been well characterized. Magnetic fields may also affect biological objects by acting directly through naturally occurring magnetic dipoles in the body.

RECOMMENDATION: **The interaction of magnetic fields with biological systems needs to be explored to test the hypothesis that induced currents from oscillating magnetic fields are causative. It is also important to establish whether the effects of currents induced by electric fields differ categorically from those produced by magnetic fields. These two issues, in addition to the evidence that magnetic fields also interact with biological systems via magnetic dipoles (e.g., magnetic resonance imaging), need to be developed and examined for physiological significance and risk implications.**

Other physical parameters establish and define the electric and magnetic conditions that cause biological changes. The field frequency can influence the reaction sites and processes that are affected. The biological response as a function of frequency can be used to identify the number and character of response sites. The intensity of the field is equally important, because it can provide information about kinetics of the response, which leads to specific biological processes. Furthermore, signal shape and temporal dynamics, including high peak-intensity single or multiple pulses, can have a substantial effect. In more limited situations, the presence of a static magnetic field and its orientation with regard to alternating electric and magnetic components has been shown to be an important feature of exposure.

RECOMMENDATION: **Principles established in ultraviolet radiation biology, which examines biological responses as functions of field intensity, frequency and time, should form the basis for the investigation of the biological effects of EMF. Adjunct studies should include examination of frequency bandwidth, signal shape and modulation, and the involvement of the earth's magnetic field with frequency-specific effects. Furthermore, the interaction of combined electric and magnetic fields in biological systems should be examined.**

Models of the interaction of EMF with biological objects can identify the critical physical aspects of the exposure situation that should be tested. Models that successfully predict effects can provide a basis for extrapolating exposure outcomes to other situations and to focus research planning. To utilize modeling capabilities, measurements and analyses must be performed at various levels of biochemical and biological organization. These range from measurements of the dielectric constant and magnetic susceptibility, and analysis of the thermodynamic models of chemical reactions, to analyses incorporating complex reactions in non-equilibrium systems. The emphasis of such models should be on intensities of EMF that would provide a basis to understand ambient exposure levels in terms of risk identification and assessment.

RECOMMENDATION: **Models of possible mechanisms of action are needed. Such models could be molecular, thermodynamic, or non-equilibrium in nature. Some of the models developed for the study of EMF at frequencies above 500,000 Hz should be examined for relevance to lower frequencies. New models may also be required.**

## B. BIOLOGICAL INTERACTIONS

The health effects of EMF are described in general terms in Chapter II. This chapter emphasizes those biological effects and models important to guide research on mechanisms of interaction.

Changing magnetic fields, because they are more penetrating than electric fields, can induce electric fields and currents throughout biological systems. At the cellular level, several sites of interaction and biochemical processes have been identified as likely targets. Both models and experimental results indicate that membrane interfaces are a primary site of transduction of field energy to biochemical change. The principal membrane involved is thought to be the plasma membrane because of its role in the transfer of biochemical information between the exterior and interior of the cell. Potential sites of action in the membrane include membrane lipids and membrane/protein interfaces such as ion channels, gap junctions, and hormone receptors. Biochemical transmembrane signal-transduction processes are reported to be involved in EMF effects. In addition to possible membrane interactions, magnetic fields have been reported to affect gene regulation, presumably at the nucleic acid level. This interaction may occur through alteration of intermediate complexes of DNA and repressor/inducer or polymerase molecules. Thus, electric and magnetic fields could differentially influence various cellular components and processes.

RECOMMENDATION: **Research is needed to identify and characterize the influence of EMF on plasma membrane sites such as ion channels, gap junctions, and transmembrane signal-transduction processes. Reports of altered gene expression should be independently confirmed, and where warranted, models should be developed to establish the exposure conditions necessary to cause changes.**

Response dynamics of cellular or biochemical systems can provide critical insight into mechanisms of action. Linear or monotonic exposure-response kinetics have been observed in some experiments but nonlinear exposure responses also have been reported in cells and tissues capable of excitation. In the latter studies, only certain ranges of frequencies and intensities produce effects, whereas other ranges have no effect. These nonlinear "windowed" results may reflect the involvement of a resonant or a dynamic system. Such results could provide the basis for amplification to account for changes at ambient exposure conditions that more classical analyses can not address.

RECOMMENDATION: **Research should continue to examine the "windows" of intensity, frequency, and pulse repetition rate that cause responses. These conditions need to be incorporated into a coherent physical and biochemical interaction scheme in order to establish mechanisms of action.**

Another way to view biological interactions of EMF is at the tissue/ organism level, particularly in tissues with cells in electrical contact with one another. The fact that electrical currents normally occur in bone during growth and fracture repair, in soft tissue during healing and nerve regeneration, and in tissues during development and differentiation suggest that exogenous or external currents might alter biological systems. For example, magnetic fields have been used in over 50,000 human cases to enhance reunion of fractured bones. Understanding critical field parameters and mechanisms involved in the healing process allow potential benefits to be optimized and potential adverse effects to be assessed.

**RECOMMENDATION: Research on mechanisms should include studies of EMF exposure characteristics reported to have therapeutic action in biological systems.**

This discussion of biophysical mechanisms deals primarily with cellular and subcellular levels of organization. Whole animal studies also provide the opportunity to examine mechanisms of action, particularly between interacting tissue systems. Research needs involving whole animals in the areas of cancer, reproduction and development, the nervous system, and the immune system are described in Chapter II.

# CHAPTER IV

# EXPOSURE ASSESSMENT

This chapter describes engineering and physical science research needed to reduce uncertainties in the exposure assessment of EMF. Although exposure assessment is the most verifiable, least controversial, and best supported area of EMF research, the following six areas require study: (1) source identification and characterization, (2) instrumentation and calibration; (3) environmental measurements and documentation; (4) exposure modeling; (5) EMF coupling to biological objects; and (6) laboratory exposure systems.

## A. SOURCE IDENTIFICATION AND CHARACTERIZATION

Electric and magnetic fields at the power frequency of 60 Hz are generated by the production, delivery, and use of electric power. Sources of exposure include power transmission and distribution lines, electric circuits in homes, offices, and industrial facilities; electric grounding systems, electric appliances (e.g., hair dryers, electric blankets, and electric razors); office equipment (e.g., facsimile machines, photocopiers, and printers); and industrial power equipment (e.g., lathes and drill presses). Higher frequency fields as well as 60 Hz fields are generated by switching transients and by devices such as fluorescent lights, light dimmers, televisions, VDTs, arc welding machines, and induction furnaces. A number of civilian and military navigational and communication transmitters generate fields at frequencies below 500,000 Hz. Existing electrically powered transportation systems such as mass transit systems or electric trains and proposed systems such as magnetically levitated trains and electric automobiles may generate strong magnetic fields at frequencies above and below 60 Hz.

Although many EMF sources in our environment have been identified, in general, the electric and magnetic fields associated with these sources have not been well-characterized. An exception is high voltage transmission lines. Less effort has been expended on the characterization of fields associated with distribution lines which, in comparison to transmission lines, are much more extensive and are a much more common source of exposure in residential areas. Even less effort has been devoted to field characterization in the home, office, and workplace where people live and work in close proximity to electric circuits in buildings, appliances, and office and industrial equipment. Thus, a program on exposure assessment of EMF should include characterization of sources in the home, office, and workplace as well as distribution and transmission lines in the outside environment.

RECOMMENDATION: **The identification of sources of electric and magnetic field exposure should be an explicit part of a program of exposure assessment. The identification process requires some preliminary effort in source characterization involving exploratory measurement and/or basic physical understanding of field sources. Logging of activities and location during personal exposure monitoring studies can assist in source identification. Maintenance of a source inventory or data base should be a continuing effort.**

## B. INSTRUMENTATION AND CALIBRATION

Instrument development in the private sector as well as in the government has been responsive to perceived needs for field measurements. In particular, a number of survey instruments that measure electric and magnetic fields that vary with time are now available, and miniaturized pocket-size recording instruments have been developed recently. Also available are instruments for measuring static electric and magnetic fields. In addition to the purpose for which they were developed, these instruments can be used as a development base to assemble devices that measure and record a wide range of field parameters as the need arises. Important measurement issues include the definition of appropriate meter characteristics and the routine availability of calibration services. The question of what field parameter(s) to measure requires the collaborative interaction of specialists in engineering, the physical sciences and the biological sciences.

RECOMMENDATION: **Specifications and calibration procedures for instrumentation should be developed to provide appropriate measurements of fields for health effects studies. This can be accomplished by a continuing series of workshops to evaluate and update the methodology.**

## C. ENVIRONMENTAL MEASUREMENT AND DOCUMENTATION

Electric and magnetic fields have been measured in residences and occupational settings to help resolve uncertainties in the interpretation of epidemiological results. Although state and local governments, utilities, private firms, and individuals are currently measuring EMF, these measurements are often conducted without adequate supervision and expertise. In general, measurements have not been appropriate for determining population or occupational exposures. Moreover, no central data base on EMF measurements exists.

RECOMMENDATION: **EMF measurement training must be emphasized for individuals responsible for field measurements and efforts to develop protocols for electric and magnetic field measurements should continue to be supported. A program to sample exposure of the general population and high exposure subgroups should be initiated with emphasis on monitoring exposure during daily activities and in specific environments such as schools and residences. Occupational measurements should focus initially on those job categories that epidemiological studies have reported to be associated with a health risk. Additional occupational measurements are needed to assess environments in which workers are exposed continuously to strong electric and magnetic fields. Concurrently, an effort should be initiated to develop a central file of measurement data by collecting and indexing available information. Development of a certification program for field measurements is not recommended at this time because of the difficulty of defining field parameters associated with health effects.**

## D. EXPOSURE MODELING

Mathematical models to estimate EMF exposure have been developed because measurement of fields at all locations and under all conditions of interest is not practical. Two types of models, theoretical and statistical, are described here. The application of theoretical models usually involves a numerical solution in which field parameters are determined as a function of current or voltage on electrical conductors. The frequency of interest has a wavelength that is large compared to the dimensions of the exposed object and thus models, such as "quasi-static" models, can be applied to a range of frequencies. For example, the same model used to calculate 60 Hz fields near a power line may be used to determine higher frequency transient fields generated by the power line.

Theoretical models can only be developed for well-documented configurations of electric conductors and field-perturbing materials. Thus, most theoretical modeling of 60 Hz fields has been applied to power transmission lines because such models can be constructed easily. Home environments with a number of sources have not been modeled, although some models have been made of ground currents in water pipes. Individual appliances in which the primary sources are transformers, motors, or heating elements have not been modeled except for electric blankets. However, computer programs are being developed to estimate fields in the home.

Statistical modeling makes use of magnetic field measurements of appliances at non-standardized distances within homes. These models are used to develop statistical estimates of average exposure. Statistical modeling does not predict individual exposures, but provides estimates for groups of the population, e.g., school children, homemakers, and workers. This approach could benefit from characterization of important microenvironments where exposures occur, such as schools, homes, offices, and factories. Although microenvironmental modeling is a relatively new concept, it is readily adaptable to EMF exposure modeling.

A combination of statistical and theoretical approximations of measurement data could be used to develop specific source, microenvironmental, and general environmental models to estimate EMF exposure. For example, in the general environment, application of Geographic Information System (GIS) technology could be used to analyze and display EMF levels measured outdoors from sources such as power lines as well as comparative EMF levels measured indoors (microenvironmental measurements), and to calculate the distribution of exposed populations. A measurement and source data base could be used to create exposure models to estimate human exposure to EMF sources and to evaluate the effectiveness of control technologies.

RECOMMENDATION: **Research on exposure modeling is needed to develop more refined models to estimate exposures resulting from sources in the home, workplace, and the outside environment. Modeling data are needed to complement EMF measurement programs and to support quality control programs.**

## E. EMF COUPLING TO BIOLOGICAL OBJECTS

The previous sections in this chapter have dealt strictly with determining the unperturbed electric and magnetic field in the absence of a human body. In the presence of a body, the electric field immediately outside the body is strongly perturbed and the intensity of the field may differ greatly from that of the unperturbed field. In contrast to the electric field, the magnetic field that penetrates the body is essentially unchanged. Both external electric and magnetic fields that vary with time induce electric fields internally and electric current inside the body is proportional to the induced internal electric field.

It is a common assumption that biological effects are related to the induced currents. However, it is not known whether low-level effects are caused by the internal electric fields and associated currents, by the magnetic field acting directly on magnetic dipoles or on moving electric charges, or by other exposure parameters. If effects are due only to the magnetic field acting directly, then further study of inductive field coupling would not be a priority. If the effects are at least in part due to induced electric fields and currents, then field coupling research is critical. Internal electric fields depend strongly on the size and shape of the exposed body or system. Thus, EMF coupling analysis is necessary when scaling internal electric fields or currents from animal and in vitro exposures to human exposures.

Much of the work on EMF coupling analysis has involved a model in which the sample is assumed to be electrically uniform and linear. The internal field values obtained under these assumptions may be misleading. At lower frequencies, for example, it is likely that currents flow principally around and not through cells. Therefore, extracellular current density may be much greater than the average current density calculated over a mass of tissue. Even if the details of a model seem complete from a physical perspective, caution needs to be exercised in extrapolating the results to a living organism because of the complexity of biological systems. The reports that weak electric and magnetic fields cause biological effects implies that processes such as amplification and frequency and intensity selectivity can occur. The latter includes "windowed" responses, that is, discrete bands of frequency and intensity that produce effects separated by bands that have no effect.

**RECOMMENDATION: Exploratory research is needed to develop models to explain how electric and magnetic fields interact with cells and tissue to produce the reported biological effects. Efforts in progress to develop better cellular and anatomical models of the electric characteristics of human beings, laboratory animals, and in vitro samples need additional support. Work on implantable probes for macroscopic and microscopic measurement of internal currents, voltages, and other field parameters in living systems should continue. A long-term goal is the development of a standard formula and unit of "dose" that is dependent on external exposure fields and is proportional to biological effect and/or human health risk.**

## F. LABORATORY EXPOSURE SYSTEMS

If the process by which biological effects occur were simple and relatively straightforward, then minor variations in EMF exposure conditions or other parameters might not affect the results significantly. If such were the case, independent confirmation of experimental results should be a relatively simple matter of repeating the experiment. If, however, effects are a complex function of several exposure conditions that may not be well controlled, then confirmation becomes problematic. The history of EMF research implies that careful control of important experimental variables is needed.

It is important that laboratory exposure systems allow potentially critical exposure variables to be controlled. For example, the steady magnetic field of the earth has been implicated as an important exposure variable. This implies that the earth's geomagnetic field in the exposure system needs to be controlled or at least measured and reported. Also, exposure can easily be correlated with vibrations, switching noises, and possibly heat from the EMF source. Thus, experimental procedures must ensure that the treatment of exposed samples is identical to control samples except for the intended EMF exposure. Incidental EMF in the laboratory must be considered also. For example, steady magnetic fields are produced by magnetized tools and magnetic door latches, whereas time-varying magnetic fields are produced by magnetic stirrers and incubator heating coils.

Basic biological research aimed at testing specific theoretical models requires relatively simple field configurations that can be varied in a controlled manner. However, environmental exposure to EMF is far more complex than exposure regimens typically used in the laboratory. This complexity may be an important factor in determining the risk of a given exposure. Once biological responses are established as markers of risk, they can be used to test the effectiveness of simulated EMF environments.

RECOMMENDATION: **Exposure systems for health research should be designed and constructed to allow electric and magnetic fields, including time-varying and steady fields, to be controlled and monitored. Facilities for chronic and lifetime exposure of laboratory animals to electric and magnetic fields will be needed. A need may develop for exposure systems that simulate ambient EMF environments.**

# CHAPTER V

# CONTROL TECHNOLOGY

For purposes of this research strategy document, the issue of EMF control technology is almost entirely dependent upon the results of health effects and biophysical research programs discussed earlier. Clearly, if the scientific research finds no relationship between EMF exposure and adverse health effects, there is no rationale or need, from a human health standpoint, to develop exposure controls for EMF. Research on control technology for EMF exposure is, therefore, a low priority research area within the overall EMF research strategy discussed in this document. Despite the lack of demonstrated need for control technologies at present, identifying and characterizing EMF sources by measurement or modeling is important. This procedure defines the framework for possible future research on control technologies, by surveying the current state-of-the-science for EMF control technology.

The major source of environmental exposure to EMF is the electric power system, which includes transmission lines, the distribution system (substations, lines, and transformers), residential and commercial wiring, and appliances and machinery. Although considerable effort has been focused on the control of EMF from electric utility systems, little work has been done on controlling fields generated by electrically powered appliances and tools, industrial equipment, and clinical devices. (Note: this text is not intended to apply to the purposeful exposure of patients to EMF.)

Concurrent with the increase in concern for the possible health effects of EMF exposure has been the development and widespread use of devices like the VDT and magnetic resonance imager. These devices, along with emerging technologies, such as electric automobiles and magnetically levitated transportation systems, offer the important advantages of convenience, economy, or clinical and diagnostic power. Nevertheless, the EMF they emit may be significantly different than that emitted by transmission or distribution lines. Furthermore, unlike transmission and distribution facilities, these technologies are not generally controlled by one segment of the electric industry. Control technologies may, therefore, need to be developed so as to be available to producers of products that emit EMF, should a need to control EMF be demonstrated.

In most circumstances, the strength of low-frequency EMF decreases with distance from the source. One simple mitigation approach is therefore to increase separation distance (e.g., increase the right-of-way for a transmission line). At low frequencies, such as 60 Hz, the electric and magnetic components of EMF are essentially uncoupled and each field component must be considered separately by control technologies. Thus, techniques that reduce electric fields may or may not reduce magnetic fields, and vice versa. Three mitigation methods are known to be effective regardless of frequency: shielding; proper design, location, and choice of components; and filtering. These methods are described in more detail below.

Shielding: One of the most important components of EMF control technology is shielding. The shielding effectiveness of a given material is a measure of the reduction in field intensity. Magnetic fields cannot be effectively shielded with readily available and inexpensive materials, especially at 60 Hz, because most materials are essentially transparent to magnetic fields. Effective magnetic shielding requires a special class of metals called ferromagnetic or MU metals. On the other hand, low frequency electric fields including 60 Hz fields can be shielded by readily available and inexpensive metals. Thus, electric fields can be effectively shielded by metal enclosures, but the equivalent magnetic enclosure is not as practical or effective.

Design, Location, and Component Choice: After shielding, proper grounding of power distribution systems in buildings is of utmost importance to reduce EMF, especially magnetic fields. Improper grounding, in addition to increasing exposure per se, can reduce shielding effectiveness. Ground currents result when a structure, such as a house, has multiple grounds such as water pipes, ducts, anchors, etc., in addition to the ground at the electrical service panel. In an electric conductor, the magnetic field is proportional to the current in the wire. Thus, strong ground currents produce strong magnetic fields. To avoid ground current loops, only one grounding connection should be made.

Another important consideration for the mitigation of EMF exposure is the location of electric conductors. For example, consider two wires in close proximity to one another. One wire supplies the current and the other wire conducts the return current back to the source (required to complete the circuit). Since the supply and return currents are in opposite directions, they produce equal but opposite magnetic fields that cancel each other. This illustrates a very important principle: for every supply current there is an equal and opposite return current. The location of the return current is the most crucial determinant of the strength of the magnetic field. Thus, when wires are closely spaced and the currents are fairly well balanced (no ground loops), the magnetic fields will be small. For this reason twisted-pair wiring and coaxial cables produce little or no external magnetic fields.

Filtering: Transformers and motors may produce EMF with harmonic content, that is, frequencies that are multiples of the primary frequency, which is usually 60 Hz. Secondary distribution lines, grounding circuits, and appliances might have harmonic frequencies up to the 11 to 17th harmonic (660 to 1020 Hz). Solid-state electronic devices can also produce high-frequency emissions. Capacitors can be installed at appropriate locations on circuits and electrical equipment to filter or reduce the harmonic or high-frequency waveforms. Transmission lines and primary distribution lines have little or no harmonic content.

## A. TRANSMISSION AND DISTRIBUTION LINES

Control technology for transmission and distribution lines has been developed and could be applied if warranted. These techniques focus on compaction and shielding of transmission conductors. Compaction is based on the principle that for three-phase, balanced, conductor systems, the net field, electric or magnetic, of the three phases is zero. A disadvantage of compaction is that it results in an increase in electrical arcing, which affects system reliability. For situations in which compaction was an ineffective control technology, shielding techniques have been developed that reduce the electric field at the edge of the right-of-way by approximately tenfold. Compaction techniques and super-compaction techniques (cable technology) that have been developed include gas-insulated transmission lines, super-conducting cables, and direct-current cable technologies. In cable or gas-insulated transmission technologies, conductors are inside a metallic sheath in which the electric field exists only between the conductors and the sheath; electric fields external to cable sheaths are essentially zero. Super-compaction or cable circuits significantly reduce magnetic fields because the magnetic fields from the phase conductors are self-canceling.

Distribution circuits, unlike transmission circuits, rarely contain three-phase balanced conductor systems. There is usually a net current flow and, if this net current does not return in the cable sheath or in an immediately adjacent neutral circuit, then large current loops exist between the cable circuit and the actual return path of the net current. Therefore, distribution cable circuits can produce fields that are similar to that of overhead transmission lines, even though voltage and current levels are much smaller.

Two states have developed programs related to EMF control technology for transmission and distribution lines. One program will identify and characterize sources of magnetic fields and investigate means of reducing magnetic field levels associated with power delivery and use. The other program requires the utility industry to allocate funds for research on management of magnetic fields from transmission and distribution lines. One goal is to develop design options for the reduction of ground level EMF from power lines.

RECOMMENDATION: **Control technology research in this area is supported or conducted by organizations with long-standing interest in the design and development of transmission and distribution facilities; this effort should continue. A future strategy for the reduction of public exposure to EMF from transmission lines might include generation of electricity at the site of use by new technologies (photovoltaic systems and fuel cells) as they become available and competitive.**

## B. RESIDENCES AND WORKPLACES

Residences: EMF inside the home can be emitted from appliances, the wiring system, including the grounding, underground and overhead distribution lines, and transmission lines. Most mitigation research has focused on the magnetic field because electric fields are fairly easy to shield. As stated earlier, the characterization (measurement/calculation) and control of EMF are intimately related, consequently any mitigation program should be accompanied by a characterization effort.

The power frequency magnetic fields in the home have been characterized in a limited fashion. In most of these studies, fields were measured at unstandardized distances from appliances, and frequencies other than 60 Hz, in addition to field transients and other field parameters, were largely ignored. Therefore, exposure to EMF in the home has not been well characterized.

The magnetic fields emitted by some appliances have been measured as a function of distance from the appliance, although such data may not be particularly useful in developing magnetic field control strategies. The devices that produce strong magnetic fields have been identified, but how the field is produced has not been well characterized. A few appliances, especially electric blankets and heated water beds, have been identified as important sources of magnetic field exposure because of their close proximity to the body for long periods of time. Electric blanket and waterbed heater manufacturers have responded by developing low magnetic field appliances. Procedures for making the measurements and therefore for determining the effectiveness of the control technology have not been standardized.

It is important to standardize measuring procedures in the home environment. These measurements should take into account use of electric appliances and living habits. Actual exposure of different parts of the body should be determined. Research volunteers, wearing dosimetric devices on various parts of the body, could be used to determine the exposure characteristics of different home environments. For magnetic field control in the home, a standardized measurement strategy that can be adjusted to account for appliance usage is required. This should be accompanied by an effort to create models that can predict magnetic field exposure on the basis of home design and appliance installation. In such models, emphasis could be placed on the devices that produce the strongest fields, on chronic exposure, on strong transient fields, or on other exposure conditions deemed important. If the field characteristics of an appliance were well documented, then simple engineering principles such as twisted-pair wiring or control of circular current loops might be sufficient to control the magnetic fields. Localized shielding techniques may be effective on small volume devices.

Workplaces: Little is known about occupational exposure. The utility industry has conducted a series of studies of personnel with nominally high exposure, such as transmission and distribution line maintenance workers. These studies have shown that the average exposure for these personnel is not necessarily greater than that of the general workforce. Occupations that have not been examined in an organized manner include workers in heavy industrial environments: operators of lathes, drill presses, and induction furnaces; workers near arc furnaces; and operators of demagnetizing equipment. A standardized measurement/mitigation procedure is needed, much like that discussed for the home but applied to different types of work environments.

**RECOMMENDATION: Source Characterization/Mitigation. To characterize the EMF from residential appliances and industrial equipment, three-dimensional field maps should be generated by measurement or calculation. These fields should be given as magnitudes as a function of frequency for steady-state operation. Magnitude and frequency changes, as a function of duty cycle, as well as transient fields, should also be documented. Once the field sources have been identified and characterized, the development of control techniques can be addressed.**

Mapping living and working environments requires a methodical way to accommodate the time and space variability of fields that are produced by randomly positioned current paths. These current paths exist in electric devices, the leads supplying the devices, the internal and external electric power supply lines, and stray ground return paths. Thus, measurement protocols are required that will realistically assess exposure levels for complicated EMF environments.

RECOMMENDATION: Grounding Practice Review. National and local electric safety codes have specific requirements for electric service grounding to control the hazard of shock. Yet, these current paths, intentionally created, contribute significantly to magnetic field exposure. The advantages in terms of magnetic field management versus disadvantages from interference, reliability, and safety should be carefully evaluated for delta (ungrounded), single-point grounded, and multi-grounded circuits. From the point of consumer interface and in the consumer (residential, commercial, or industrial) environment, single-point grounding, ground potential shift, and interference with ground-fault interrupt circuits need to be carefully evaluated. Effects on co-located utility (e.g., communication cables on power poles) grounding practices will have to be evaluated to maintain service reliability and worker safety.

RECOMMENDATION: Shielding. Research should be devoted to the development of new materials to shield magnetic fields, e.g., a malleable high permeability material. Concurrently extending the range of permeability as a function of low magnetic field strength could be very useful if the purported health effects of magnetic field exposures identified in epidemiological studies are confirmed. Research into magnetically modified polymers may be fruitful, since both fabrication and field strength problems may be solved by one material.

Active magnetic shielding approaches should be investigated. In this approach, magnetic fields are purposely generated to cancel other magnetic fields.

Also, robotic technology could be evaluated for some work environments as an alternative to human exposure to EMF.

## C. SPECIAL CONSIDERATIONS

Existing mass transit systems (subways and electric trains) and emerging technologies such as magnetically levitated trains, electric automobiles, and superconducting magnetic energy storage devices require special consideration. These systems can produce magnetic fields over large areas at different frequencies. Passengers on magnetically levitated trains will be exposed to static fields and to frequencies up to about 1,000 Hz. Existing engineering control technologies may not be sufficient to significantly reduce exposure, if mitigation is needed.

Another device that merits special concern is the VDT. In addition to being energized by 60 Hz power, VDTs can produce EMF at frequencies of up to 250,000 Hz. This higher-frequency EMF is generated by the deflection yoke that controls the horizontal deflection system and produces images on the VDT screen. VDT manufacturers, however, have begun to reduce fields by shielding techniques. Metal enclosures are used to shield electric fields, while active magnetic shielding techniques are used to reduce magnetic fields. In the latter case, purposely generated magnetic fields act to cancel the magnetic field produced by the deflection yoke in VDTs.

**RECOMMENDATION: Both research on field characterization and shielding technologies may be required for special devices. Recently developed magnetic field monitoring equipment may need to be adapted to measure the unique magnitude-frequency-time course characteristics of these fields.**

# CHAPTER VI

## SUMMARY AND CONCLUSIONS

International and national organizations, industrial associations, federal and state agencies, Congress, and the public have expressed concern about the potential health effects of exposure to EMF. This document describes a research strategy to determine the possible health effects of EMF; to define exposure conditions in the home, workplace, and outside environment; and to determine what types of control technologies may be necessary to mitigate EMF exposure. EMF in the frequency range of 0 to 500,000 Hz is the focus of the proposed research because this range includes EMF emitted from power lines and from commonly used devices, such as video display terminals. Research recommendations are presented for (1) health effects that specifically address cancer, reproduction and development, the nervous system, and the immune system; (2) biophysical mechanisms; (3) exposure assessment; and (4) possible control technology.

The literature on EMF is substantial but considerably diverse because of the variety of biological systems tested and the complex nature of the physical agent. Rather than a single entity, EMF is more appropriately considered a generic class of physical agents, similar to classes of chemicals. Because of the complexity of EMF exposure conditions, most studies of biological effects have been hypothesis-generating studies rather than hypothesis-testing research and many of the reported effects have not been independently confirmed. Confirmation of key findings in biological studies is a major research issue.

The relative priorities for EMF research are summarized below. Highest priority was assigned to those issues where it was felt targeted research over 3-5 years could potentially provide decision makers with better information upon which to base decisions about the likelihood and magnitude of potential health effects from EMF exposure.

TABLE 1. RELATIVE PRIORITIES FOR EMF RESEARCH

| RESEARCH AREAS | RELATIVE PRIORITY |
|---|---|
| HEALTH EFFECTS | |
| Cancer | High |
| Reproductive and Developmental Effects | Medium |
| Nervous System Effects | Medium |
| Immune System Effects | Low |
| BIOPHYSICAL MECHANISMS | High |
| EXPOSURE ASSESSMENT | High |
| CONTROL TECHNOLOGY | Low |

High-priority research areas are cancer, exposure assessment, and biophysical mechanisms of action. Cancer research is a top priority because there are more than 40 human studies on this subject and it is most important to independently confirm key human cancer studies with improved protocols and exposure assessments. A major concern with the epidemiological data is the dearth of information on factors that may confound the estimate of risk; therefore, human studies should address this issue. Epidemiological studies should assess the influence of time-dependent factors such as length of residency, duration of exposure, and latency on the risk of specific types of cancer to (1) identify exposure-response relations with length of residency as a surrogate for exposure and (2) to validate whether or not specific cancer types have satisfied known latency and temporal requirements for causality. In addition, a continuing examination of the potential role of EMF in carcinogenesis should be conducted in laboratory studies of animals and in cells and tissues to discover the basic nature of the exposure-response relation and the effective exposure conditions.

Exposure assessment research is also high priority because it is essential to the successful interpretation of the biological response and is critically important for risk assessment. In all types of biological studies, exposure data are needed to define exposure-response relations and to establish cause-and-effect relations. In particular, cancer research, both in human populations and in laboratory studies, requires definitive exposure data to judge the validity of the suggested causal link between EMF exposure and cancer. The agenda for exposure assessment identifies research needs in the following areas: source identification and characterization; instrumentation and calibration; EMF coupling to biological objects; and laboratory exposure systems. In addition, research needs for environmental measurements and exposure modeling reflect the fact that exposure to EMF in the home and workplace has not been well characterized. Measurement and modeling efforts are needed to define exposure to EMF from appliances, wiring systems including transmission and distribution lines, grounding systems, medical devices, and office and industrial equipment. These data are also needed to define the direction for control technology research.

Another high priority research area is biophysical mechanisms. An understanding of how EMF interacts with biological systems is needed to minimize uncertainty in extrapolating laboratory data to human exposure situations and to identify effective exposure parameters. In particular, mechanistic research is needed to test hypotheses that (1) the cell membrane is the primary site of interaction with EMF and (2) the magnetic field, not the electric field, is the critical exposure parameter in cancer development. A number of biological effects, including those reported to have therapeutic potential, offer promising avenues for research on mechanisms of interaction of electric and magnetic fields.

Research on human reproductive effects should emphasize the independent confirmation of isolated reports of increased miscarriages and increased malformations, and reports of increased incidence of nervous system cancer in children whose fathers had occupations with potential EMF exposure. The results of laboratory studies of non-mammalian models that exhibit developmental effects from exposure to EMF should be used to design studies with mammals. Research on reproductive and developmental effects is a medium priority, but confirmation of developmental effects in human beings or in laboratory mammals would elevate the priority.

Research on the nervous system should further examine physiological, neurochemical, and behavioral endpoints in human subjects reported to be sensitive to EMF. Laboratory studies on the effect of EMF on the behavior of laboratory animals should emphasize learned tasks and drug interactions. A primary goal is the identification of effective exposure conditions, such as possible differential effects of electric and magnetic fields. The consistent finding that EMF affects melatonin synthesis in the pineal gland should be further investigated. Research on the nervous system is a medium priority because the reported biological effects in both human studies and laboratory experiments may be generally regarded as hypothesis-generating.

Research on the immune system is a low priority because reported effects occur primarily in isolated cellular systems. The research recommendation for immunology emphasizes independent confirmation of the cellular effects and screening studies of laboratory animals exposed to magnetic fields. The need for this research is related to the important role of the immune system in cancer prevention.

The potential need for future controls to reduce risks from exposure to EMF is the rationale for control technology research. This research is a low priority because no cause-and-effect relation between human health risk and EMF exposure has been established. However, products from the control technology research recommended in this report may ultimately be needed to mitigate EMF exposure in the home, workplace, and outside environment. The research strategy addresses electric grounding issues important to public health and recommends that the ongoing effort to develop control technology for transmission and distribution systems be continued. Similarly, other control technology research should be done in concert with health and exposure assessment research so that mitigation procedures and devices will be available if warranted by future health risk assessments of EMF exposure.

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## GLOSSARY

**Ambient.** Encompassing or surrounding area.

**Behavior.** Action that can be observed directly and studied in relation to antecedent conditions. In animals, a distinction can be made between learned and spontaneous behaviors. Learning is a long-lasting change that results from experience with environmental events and includes actions such as solving a maze for food. Spontaneous behaviors are actions that do not result from a response to direct stimulation and include behaviors like locomotor activity.

**Biomarker.** An indicator of variation in cellular or physiological components or processes, structures, or functions that are measurable in a biological system or sample.

**Biophysical mechanisms.** Physical and/or chemical interactions of electric and magnetic fields with biological systems.

**Capacitor.** A device made of two electrically conducting surfaces, separated by an insulator that stores electric charge.

**Carcinogen.** A chemical, biological, or physical agent capable of producing tumor growth.

**Carcinogenic process.** A series of stages at the cellular level culminating in the development of cancer.

**Chromosome.** A very long molecule of DNA, complexed with protein, containing genetic information.

**Circadian rhythms.** Biological processes that have synchronized daily cycles of approximately one day (24 hours).

**Circuit.** A closed conducting path for the flow of electric current.

**Conductor.** A material that allows the flow of electric charge, e.g., wires on transmission lines.

**Control technology.** The application of engineering approaches to manage or mitigate exposure to environmental agents, e.g., electric and magnetic fields.

**Current.** The flow of electric charge.

**Cytotoxicity.** Toxic effects in cells.

**DNA.** Deoxyribonucleic acid. The nucleic acid molecule in chromosomes that contains the genetic information.

**Developmental effects.** Effects in the developing offspring due to exposure before conception (either parent), prenatally, or postnatally to the time of sexual maturation. Developmental effects may be expressed at any time in the life span of the organism. Developmental effects are a subset of reproductive effects.

**Electric dipole.** Two separated electric charges; a molecule (or other structure) having the effective centers of positive and negative charges separated.

**Electric field.** A field describing the electrical force on a unit charge in space. Electrical charges are a source of electric fields. The electric field from a power line is an alternating, 60 Hz field.

**Electric and magnetic fields (EMF).** Energy in the form of electric and magnetic fields. In this report, the frequency range of interest for EMF is 0 to 500,000 Hz.

**Embryo.** The early stages in the developing organism in which organs and organ systems are developing. For humans, this stage lasts between the second through eighth weeks after conception.

**EMF.** See Electric and magnetic fields.

**Endpoint.** An observable or measurable biological, chemical, or functional event used as an index of the effect of a chemical, physical, or biological agent on a cell, tissue, organ, organism, etc.

**Epidemiology.** The study of the occurrence and distribution of a disease or physiological condition in human populations and of the factors that influence this distribution.

**Exposure.** The joint occurrence in space and time of an organism and the agent of concern, expressed in terms of the environmental level of the agent.

**Exposure assessment.** Measurement or estimation of the magnitude, frequency, duration, and route of exposure of an organism to environmental agents. The exposure assessment also describes the nature of exposure and the size and nature of the exposed populations, and is one of four steps in risk assessment.

**Exposure-response relation.** A relationship between exposure and the effect produced by the exposure. Response can be expressed either as the severity of injury or proportion of exposed subjects affected.

**Extrapolation.** An estimate of response or quantity at a point outside the range of the experimental data. Also refers to the estimation of a measured response in a different species or by a different route than that used in the experimental study of interest (i.e., species-to-species, route-to-route, acute-to-chronic, high-to-low).

**Field.** Any physical quantity that takes on different values at different points in space.

**Frequency.** The number of complete cycles of a periodic waveform per unit time. Frequency is expressed in Hertz (Hz), which is equivalent to one cycle per second.

**Gene.** The simplest complete functional unit in a DNA molecule. A linear sequence of nucleotides in DNA that is needed to synthesize a protein and/or regulate cell function.

**Geomagnetic field.** The earth's natural magnetic field.

**Germ cell.** A cell capable of developing into a gamete (ovum [egg] or sperm).

**Grounding.** The connection of a conductor to something that will accept excess electrical charge, for example, the earth.

**Hertz (Hz).** One cycle per second.

**Hormone.** A chemical substance, formed in one organ or part of the body and carried in the blood to another organ or part where it alters the functional activity, and sometimes the structure, of one or more organs in a specific manner.

**Immune system.** The body's primary defense against abnormal growth of cells (i.e., tumors) and infectious agents such as bacteria, viruses, and parasites.

**Insulator.** A nonconductor of electrical charges.

**In utero.** In the uterus; unborn.

**In vitro.** Isolated from the living organism and artificially maintained, as in a test tube or culture dish.

**In vivo.** Occurring within the whole living body.

**Ion efflux.** The movement of ions, charged atoms or molecules, from a sample into a surrounding solution.

**Latency.** The time between exposure to an injurious agent and the manifestation of a response.

**Learned behavior.** See behavior.

**Leukemia.** A progressive, malignant disease of the blood-forming tissues, marked by an excessive number of white blood cells and their precursors.

**Lymphoma.** Any abnormal growth (neoplasm) of the lymphoid tissues. Lymphoma usually refers to a malignant growth and thus is a cancer.

**Magnetic dipole.** Two separated magnetic poles; an object such as a permanent magnet, particle, or current loop, that gives rise to a magnetic field. The object acts as if it consists of two magnetic poles of opposite sign separated by a small distance.

**Magnetic field.** A field describing the force experienced by magnetic objects or moving electrical charges in space.

**Malformation.** A permanent structural change in a developing organism that may adversely affect survival, development, or function.

**Mechanisms.** See Biophysical mechanisms.

**Messenger RNA.** See RNA.

**Metabolism.** The biochemical reactions by which energy is made available for the use of an organism from the time a nutrient substance enters, until it has been utilized and the waste products eliminated.

**Microenvironment.** The immediate local environment of an organism.
**Mitosis.** Cellular and nuclear division that involves duplication of the chromosomes of a parent cell and formation of two daughter cells.

**Model.** (1) Mathematical model. A mathematical representation of a natural system intended to mimic the behavior of the real system, allowing description of empirical data, and predictions about untested states of the system. (2) Biological model. A condition or disease in animals similar to the condition or disease in human beings.

**Modulation.** The process of varying the amplitude, frequency, or phase of EMF.

**Neurotransmitter.** A chemical substance that transmits nerve impulses across the space between nerve endings called the synapse.

**Oncogene.** A mutation of a naturally occurring gene involved in growth regulation that results in uncontrolled growth. Oncogenes are associated with the development of some forms of cancer.

**Photon.** A particle of electromagnetic energy.

**Plasma membrane.** The membrane surrounding plant and animal cells.

**Power.** The time rate at which work is done. Electrical power is proportional to the product of current and voltage.

**Proliferation.** Production of new cells through the process of cell division.

**Promotion.** The second hypothesized stage in a multistage process of cancer development. The conversion of initiated cells into tumorigenic cells.

**Reproductive effects.** Effects on reproduction which may include, but not be limited to, alterations in sexual behavior, onset of puberty, fertility, gestation, parturition, lactation, pregnancy outcomes, premature reproductive senescence, or modifications in other functions that are dependent on the integrity of the reproductive system. Developmental effects are a subset of reproductive effects.

**Risk assessment.** The scientific activity of evaluating the toxic properties of an environmental agent and the conditions of human exposure to it in order to ascertain the likelihood that exposed humans will be adversely affected, and to characterize the nature of the effects they may experience. May contain some or all of the following four steps:

> **Hazard identification** - The determination of whether a particular agent is or is not causally linked to particular health effect(s).
>
> **Dose-response assessment** - The determination of the relation between the magnitude of exposure and the probability of occurrence of the health effects in question.
>
> **Exposure assessment** - The determination of the extent of human exposure.
>
> **Risk characterization** - The description of the nature and often the magnitude of human risk, including attendant uncertainty.

**RNA.** Ribonucleic acid. Messenger RNA, the nucleic acid in cells that is the template for the sequential ordering of amino acids during protein synthesis, is synthesized in the nucleus of the cell during the process of transcription.

**Spontaneous behavior.** See behavior.

**Static fields.** Electric and magnetic fields that do not vary in intensity or strength with time.

**Survey instrument.** A portable instrument capable of measuring the strength of electric and magnetic fields.

**Time-varying fields.** Electric and magnetic fields that change in intensity or strength with time. Examples include 60 Hz, modulated, and transient fields.

**Transcription.** The cellular process in which messenger RNA is synthesized, i.e., the process in which the genetic information in DNA is transcribed in the form of a single molecule of messenger RNA.

**"Windowed" responses.** Effects found within bands or ranges of frequency or intensity separated by bands or ranges without effect; nonlinear exposure-response relations.

# APPENDIX A: RESEARCH RECOMMENDATIONS

## I. HEALTH EFFECTS

### A. METHODOLOGIC ISSUES FOR EPIDEMIOLOGY

RECOMMENDATION: EMF exposure in the home, workplace, and outside environment should be more fully characterized to identify common and special exposure situations. Exposure data are needed for statistically valid population estimates and to help identify the field parameters that may be biologically active. The development and validation of personal external dosimetry methods to document and evaluate the exposure of human beings to EMF should continue. Epidemiological research and exposure assessment research must be integrated.

RECOMMENDATION: Epidemiological studies on the effect of EMF should be designed to identify and evaluate other factors which may distort the measure of association with EMF exposure. Studies of humans in controlled laboratory settings, animal studies, and in vitro studies should be evaluated for exposure parameters and other information that would improve the design of epidemiological studies on EMF.

RECOMMENDATION: Epidemiological studies should be conducted on populations exposed to EMF other than electric power frequency fields. Important populations to examine are women and highly exposed groups. Major health effects to investigate are cancer, reproductive effects, and nervous system changes.

### B. CANCER

#### 1. HUMAN STUDIES

RECOMMENDATION: Epidemiological studies on EMF and cancer should assess the influence of time-dependent factors such as length of residency, duration of exposure, and latency on the risk of specific types of cancer to (1) identify exposure-response relations with length of residency as a surrogate for exposure and to (2) validate whether or not specific cancer types have satisfied known latency and temporal requirements for causality.

RECOMMENDATION: Epidemiological cancer studies should emphasize identification of distinct cancer types in populations exposed to EMF because the reporting of cancer by general class may mask elevated risk for specific cancer types.

RECOMMENDATION: Human clinical studies should try to identify possible biomarkers of EMF exposure in the carcinogenic process, including alterations in the pattern of DNA synthesis, ornithine decarboxylase activity, and oncogene activation.

### 2. ANIMAL STUDIES

RECOMMENDATION: The potential role of EMF in carcinogenesis should be studied in the laboratory (both in vitro and in whole animals) to discover the basic nature of the field-dependence of effects. Gene expression, growth of transformed cells, and intracellular reactions associated with chemical signalling are areas of special interest.

RECOMMENDATION: Studies with laboratory animals are needed to examine whether exposure to power frequency magnetic fields induces a carcinogenic response.

## C. REPRODUCTIVE AND DEVELOPMENTAL EFFECTS

### 1. HUMAN STUDIES

RECOMMENDATION: Epidemiological studies are needed to confirm reported reproductive and developmental effects of EMF. Studies should be designed to include EMF exposure assessment, identify factors other than EMF that may affect the study conclusions, identify relevant exposure periods, and be guided by our understanding of reproductive and developmental effects in laboratory animals.

### 2. ANIMAL STUDIES

RECOMMENDATION: Research should attempt to confirm independently reported reproductive effects in mammals. Developmental studies with standard laboratory models should employ exposure conditions reported to be effective in nonmammalian systems. The relevance of developmental effects in nonmammalian embryo models to permanent changes in mammals should be explored because of the significance to epidemiological findings.

RECOMMENDATION: The reported association of increased cancer rates in human offspring, or an association of any effect in offspring, to paternal exposure requires a mechanistic link via paternal germ cell changes. A link to effects from paternal exposure, as reported in epidemiological studies, needs to be studied in laboratory animals.

## D. NERVOUS SYSTEM EFFECTS

### 1. HUMAN STUDIES

RECOMMENDATION: Work should continue with human subjects in controlled laboratory settings where exposure to real and sham fields occur under double-blind conditions. Physiological and behavioral endpoints previously reported to be sensitive, as well as those reported in animal studies, should be monitored before, during, and after exposure to EMF. Because of the suspected role of altered melatonin rhythms in clinical disorders and in cancer, other studies should determine if EMF can alter the circadian pattern of melatonin and its metabolites in body fluids. Particular attention should be directed to whether the rate of activation and deactivation of the field (intermittent exposure) has a more marked effect than continuous application.

#### 2. ANIMAL STUDIES

RECOMMENDATION: Studies of EMF effects on behavior of laboratory animals should emphasize learned tasks and drug interactions. Other work should determine whether the effects of EMF on circadian rhythms and neurochemical levels are significant in related areas such as behavior and cancer. The consistent finding that EMF affects melatonin synthesis should be the focus of studies to determine the sites and mechanisms of interaction. A primary goal of research on EMF and the nervous system is to define causative exposure conditions; particular attention should be given to the possible differential effects of electric versus magnetic fields.

### E. IMMUNE SYSTEM EFFECTS

#### 1. HUMAN STUDIES

RECOMMENDATION: No research recommendation is given for this category because of the lack of data on immune system effects in human beings and the preliminary state of knowledge of such effects in both in vitro and in vivo laboratory animal studies.

#### 2. ANIMAL STUDIES

RECOMMENDATION: Research is needed to confirm independently the reported in vitro immune effects. In addition, immune responses in laboratory animals exposed chronically to magnetic fields warrants investigation.

## II. BIOPHYSICAL MECHANISMS

### A. PHYSICAL INTERACTIONS

RECOMMENDATION: The interaction of magnetic fields with biological systems needs to be explored to test the hypothesis that induced currents from oscillating magnetic fields are causative. It is also important to establish whether the effects of currents induced by electric fields differ categorically from those produced by magnetic fields. These two issues, in addition to the evidence that magnetic fields also interact with biological systems via magnetic dipoles (e.g., magnetic resonance imaging), need to be developed and examined for physiological significance and risk implications.

RECOMMENDATION: Principles established in ultraviolet radiation biology, which examines biological responses as functions of field intensity, frequency and time, should form the basis for the investigation of the biological effects of EMF. Adjunct studies should include examination of frequency bandwidth, signal shape and modulation, and the involvement of the earth's magnetic field with frequency-specific effects. Furthermore, the interaction of combined electric and magnetic fields in biological systems should be examined.

RECOMMENDATION: Models of possible mechanisms of action are needed. Such models could be molecular, thermodynamic, or non-equilibrium in nature. Some of the models developed for the study of EMF at frequencies above 500,000 Hz should be examined for relevance to lower frequencies. New models may also be required.

### B. BIOLOGICAL INTERACTIONS

RECOMMENDATION: Research is needed to identify and characterize the influence of EMF on plasma membrane sites such as ion channels, gap junctions, and transmembrane signal-transduction processes. Reports of altered gene expression should be independently confirmed, and where warranted, models should be developed to establish the exposure conditions necessary to cause changes.

RECOMMENDATION: Research should continue to examine the "windows" of intensity, frequency, and pulse repetition rate that cause responses. These conditions need to be incorporated into a coherent physical and biochemical interaction scheme in order to establish mechanisms of action.

RECOMMENDATION: Research on mechanisms should include studies of EMF exposure characteristics reported to have therapeutic action in biological systems.

## III. EXPOSURE ASSESSMENT

### A. SOURCE IDENTIFICATION AND CHARACTERIZATION

RECOMMENDATION: The identification of sources of electric and magnetic field exposure should be an explicit part of a program of exposure assessment. The identification process requires some preliminary effort in source characterization involving exploratory measurement and/or basic physical understanding of field sources. Logging of activities and location during personal exposure monitoring studies can assist in source identification. Maintenance of a source inventory or data base should be a continuing effort.

### B. INSTRUMENTATION AND CALIBRATION

RECOMMENDATION: Specifications and calibration procedures for instrumentation should be developed to provide appropriate measurements of fields for health effects studies. This can be accomplished by a continuing series of workshops to evaluate and update the methodology.

## C. ENVIRONMENTAL MEASUREMENT AND DOCUMENTATION

RECOMMENDATION: EMF measurement training must be emphasized for individuals responsible for field measurements and efforts to develop protocols for electric and magnetic field measurements should continue to be supported. A program to sample exposure of the general population and high exposure subgroups should be initiated with emphasis on monitoring exposure during daily activities and in specific environments such as schools and residences. Occupational measurements should focus initially on those job categories that epidemiological studies have reported to be associated with a health risk. Additional occupational measurements are needed to assess environments in which workers are exposed continuously to strong electric and magnetic fields. Concurrently, an effort should be initiated to develop a central file of measurement data by collecting and indexing available information. Development of a certification program for field measurements is not recommended at this time because of the difficulty of defining field parameters associated with health effects.

## D. EXPOSURE MODELING

RECOMMENDATION: Research on exposure modeling is needed to develop more refined models to estimate exposures resulting from sources in the home, workplace, and the outside environment. Modeling data are needed to complement EMF measurement programs and to support quality control programs.

## E. EMF COUPLING TO BIOLOGICAL OBJECTS

RECOMMENDATION: Exploratory research is needed to develop models to explain how electric and magnetic fields interact with cells and tissue to produce the reported biological effects. Efforts in progress to develop better cellular and anatomical models of the electric characteristics of human beings, laboratory animals, and in vitro samples need additional support. Work on implantable probes for macroscopic and microscopic measurement of internal currents, voltages, and other field parameters in living systems should continue. A long-term goal is the development of a standard formula and unit of "dose" that is dependent on external exposure fields and is proportional to biological effect and/or human health risk.

## F. LABORATORY EXPOSURE SYSTEMS

RECOMMENDATION: Exposure systems for health research should be designed and constructed to allow electric and magnetic fields, including time-varying and steady fields, to be controlled and monitored. Facilities for chronic and lifetime exposure of laboratory animals to electric and magnetic fields will be needed. A need may develop for exposure systems that simulate ambient EMF environments.

# IV. CONTROL TECHNOLOGY

## A. TRANSMISSION AND DISTRIBUTION LINES

RECOMMENDATION: Control technology research in this area is supported or conducted by organizations with long-standing interest in the design and development of transmission and distribution facilities; this effort should continue. A future strategy for the reduction of public exposure to EMF from transmission lines might include generation of electricity at the site of use by new technologies (photovoltaic systems and fuel cells) as they become available and competitive.

## B. RESIDENCES AND WORKPLACES

RECOMMENDATION: Source Characterization/Mitigation. To characterize the EMF from residential appliances and industrial equipment, three-dimensional field maps should be generated by measurement or calculation. These fields should be given as magnitudes as a function of frequency for steady-state operation. Magnitude and frequency changes, as a function of duty cycle, as well as transient fields, should also be documented. Once the field sources have been identified and characterized, the development of control techniques can be addressed.

Mapping living and working environments requires a methodical way to accommodate the time and space variability of fields that are produced by randomly positioned current paths. These current paths exist in electric devices, the leads supplying the devices, the internal and external electric power supply lines, and stray ground return paths. Thus, measurement protocols are required that will realistically assess exposure levels for complicated EMF environments.

RECOMMENDATION: Grounding Practice Review. National and local electric safety codes have specific requirements for electric service grounding to control the hazard of shock. Yet, these current paths, intentionally created, contribute significantly to magnetic field exposure. The advantages in terms of magnetic field management versus disadvantages from interference, reliability, and safety should be carefully evaluated for delta (ungrounded), single-point grounded, and multi-grounded circuits. From the point of consumer interface and in the consumer (residential, commercial, or industrial) environment, single-point grounding, ground potential shift, and interference with ground-fault interrupt circuits need to be carefully evaluated. Effects on co-located utility (e.g., communication cables on power poles) grounding practices will have to be evaluated to maintain service reliability and worker safety.

RECOMMENDATION: Shielding. Research should be devoted to the development of new materials to shield magnetic fields, e.g., a malleable high permeability material. Concurrently extending the range of permeability as a function of low magnetic field strength could be very useful if the purported health effects of magnetic field exposures identified in epidemiological studies are confirmed. Research into magnetically modified polymers may be fruitful, since both fabrication and field strength problems may be solved by one material.

Active magnetic shielding approaches should be investigated. In this approach, magnetic fields are purposely generated to cancel other magnetic fields.

Also, robotic technology could be evaluated for some work environments as an alternative to human exposure to EMF.

## C. SPECIAL CONSIDERATIONS

RECOMMENDATION: Both research on field characterization and shielding technologies may be required for special devices. Recently developed magnetic field monitoring equipment may need to be adapted to measure the unique magnitude-frequency-time course characteristics of these fields.

# APPENDIX B:
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