Proceedings of the Scientific Workshop on the Health Effects of Electric and Magnetic Fields on Workers

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PREFACE

The possibility of adverse health effects from exposure to electric and magnetic fields (EMF) has generated a heated controversy in recent years, "debated" before the public through the national broadcast and print media. The American worker would justifiably be concerned and deserves a clear message on this issue. It is usually the case with environmental exposures that workers are exposed "first and worst," as potentially hazardous chemicals, materials, and agents are introduced first for industrial purposes, and used in ways that expose workers to much higher concentrations than would generally occur in the community. This is true for EMF among certain occupations in utilities and other industries where frequent, persistent, or high exposures may occur.

The National Institute for Occupational Safety and Health (NIOSH) is the federal research agency charged with "assuring safe and healthful working conditions" for all workers. Towards this end, it is the responsibility of NIOSH to lead in the development of national scientific priorities. In January 1991, NIOSH convened a scientific workshop to develop a research agenda on the health effects of EMF and methods for reducing exposures.

At the workshop, we brought together leading scientists to discuss the relevant aspects of a research agenda and prevention strategies. We endeavored to clarify what is known, and to identify what is not known so as to plan a research agenda that will fill gaps in our current knowledge. In this way, we intend to push forward the availability of knowledge necessary for the protection of workers. We hope this coalescing of expertise will assist the progress of all partners in this field. We need to focus our efforts in evaluating the potential hazards of EMF until we understand the nature and extent of any effects and how to prevent them. Then, we will bring our findings to occupational safety and health professionals, employers, and employees.

This year, NIOSH marks its 20th anniversary. I am delighted that we started this anniversary year with this workshop. It is in the best tradition of the Institute. I hope you will find these Proceedings useful. For those who attended the workshop, this document will serve as a record of the excellent plenary papers presented. For those who were not able to attend, and for others wishing to gain insight into EMF research needs, we trust this text will serve as an excellent reference.

Finally, I wish to thank the Chair and Co-Chair of this workshop, Mr. Philip Bierbaum and Dr. John Peters. Dr. Peters was instrumental in the selection of presenters and the program content; Mr. Bierbaum was responsible for organizing it all. Of course, each of the individual plenary paper presenters, panel moderators and rapporteurs, and panel members made possible this text. I applaud all of these efforts in making the workshop the great success that it was.

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In addition to the plenary paper presenters, panel moderators and rapporteurs, and panel members, we wish to thank the following NIOSH employees for their diligent effort in the conduct of this workshop and the preparation of this document: Rosalynd J. Kendall, who served as our administrative coordinator for the workshop and who "did it all"; Maggie A. Ivory and Heather K. Houston, who served as Ms. Kendall's assistants; Theodore F. Schoenborn, who served as the coordinator for the preparation of this document; Vivian K. Morgan, Janice M. Huy, Charlene B. Maloney, Shirley M. Carr and Thomas E. Zeigler, who served as team members for our printing and publication activities; and Heinz W. Ahlers, Rodger L. Tatken, Jerry W. Newman, Ronald L. Schuler and Rebecca W. Spry, who served as team members in developing the bibliography that was used for the workshop.

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

The National Institute for Occupational Safety and Health (NIOSH) convened a group of scientists on January 30-31, 1991, in Cincinnati, Ohio, to develop a national research strategy on the health effects of electromagnetic radiation on workers. The purpose of the workshop was to review current data and new findings regarding electric and magnetic fields which may have relevance for occupational exposures; to identify knowledge gaps that might be filled by directed research; and to recommend a national research agenda which, if implemented, would close the gaps and permit reliable recommendations for protecting workers. The workshop emphasized electric and magnetic fields at frequencies up to 1000 Hz, excluding static fields; and carcinogenic, reproductive, and neurologic health effects. Approximately 300 individuals attended the workshop, including 120 from governmental agencies, 35 from academia, 20 consultants, 25 from the health care field, 40 from general industry, 30 from utility companies, and 30 from research laboratories.

Five plenary papers were presented, each addressing a specific aspect of potential health effects from exposure to electric and magnetic fields, exposure assessments, or controls as they relate to workers. The five presentations covered:

- *In Vitro*/Cellular Mechanism Studies
- *In Vivo* Studies
- Epidemiologic Studies
- Exposure Assessments, and
- Methods for Reducing Exposures.

Panels of scientific experts in the five areas, using the information presented in the plenary papers, focused on the development of the national research agenda.

These Proceedings, then, serve as a report to the Nation based on the interaction and discussions that occurred during the workshop. Dr. J. Donald Millar indicated in his introductory remarks at the workshop, that this document would provide a lasting record of the excellent plenary papers that were presented, and would focus research on the needs that were identified for worker protection. These Proceedings provide the reader with the following information:

- An executive summary which highlights the findings from the workshop.
- The five plenary papers which served as the basis for the panel discussions.
- The research recommendations which resulted from the panel deliberations.
- A glossary of terms that is useful for familiarizing the reader with the terminology that is used in this scientific field.
- Details on how to obtain a copy of the NIOSH bibliography that was provided to the participants of the workshop.

It should be noted that the initial terminology used to characterize the workshop (i.e., "electromagnetic radiation") is more correctly referred to as "electric and magnetic fields (EMF)." Therefore, the title of these Proceedings and the terminology used in the section on Research Recommendations have been modified accordingly.

GENERAL FINDINGS

- **The frequency range initially identified (i.e., up to 1000 Hz, excluding static fields) is appropriate for a research agenda dealing with the workplace.**

- **There is uncertainty about the relationship between exposures to electric and magnetic fields and health outcomes.**

- **The health end points that were initially identified as most important (i.e., carcinogenic, reproductive and neurologic) remained so.** Other health end points that were discussed, but with less emphasis, dealt with immunologic and endocrine changes and cardiovascular effects. Specific subsets of the health end points are discussed in more detail in the section on Research Recommendations.

- **The scientific leadership role for protecting workers in the EMF arena is a NIOSH responsibility which goes beyond the conduct of the workshop.** NIOSH was charged with fulfilling this mandate by initiating the appropriate research within its own mission and by continuing to influence and interact with all involved parties (i.e., other Federal agencies, state and local agencies, industry, labor and academia). Of importance was the identified need to interact and coordinate activities with the Department of Energy, Environmental Protection Agency, Department of Defense, Food and Drug Administration, National Institute of Environmental Health Sciences and National Cancer Institute. These interactions should include an immediate and continuing translation of current knowledge to the occupational and environmental health community via NIOSH's dissemination mechanisms.

- **The need to transfer the results of research to occupational safety and health professionals, employers and workers through training and education programs is paramount to an overall prevention strategy.**

HIGHEST PRIORITY RESEARCH NEEDS

It was recognized that the identified research needs were not unusual for the occupational/environmental health field. However, for the specific EMF hazards under discussion (i.e., lower frequency fields), we are in the infancy of a research agenda when compared to other occupational/environmental hazards. Also, it was acknowledged that the research needs in the five areas that were compartmentalized for the purposes of the workshop are dependent and overlapping. But, there was a very clear consensus of what the highest priorities are for the research agenda. The highest priority research issue is to determine whether occupational exposure to electric and/or magnetic fields produces untoward health effects, and, if so, to determine not only the type(s) and level of exposure that will produce them but also ways to reduce exposure. In order to do this we need to accomplish the following:

- Determine the number of workers exposed; the industries and occupations where the exposures take place; and the extent and type of exposures (including identification and characterization of EMF sources, magnitude of the fields as a function of frequency, phase and duration).
- Establish standardized assessment protocols, including measurement techniques and performance criteria for instruments and dosimeters, plus standardized approaches for experimental and epidemiologic studies.
- Conduct experimental and epidemiologic studies directed at hypotheses-testing for *specific* health end points of interest, testing models, mechanism questions, and occupational groups to be studied. Standardized protocols and procedures, including specific quality assurance approaches, also must be developed for the experimental and epidemiologic studies.
- Conduct more long-term, definitive control technology research for reducing the identified exposures to acceptable levels .

This summary does not mean that the various components of experimental and epidemiologic research on "health effects" have to be conducted in sequence. However, it should be noted that without better exposure assessment tools for estimating dose and without better knowledge about workplace exposure levels and types of exposure, there will be limitations in the ability to interpret the health effects data. Also, the scenario presented here should not preclude implementing exposure reduction strategies that are now available and feasible.

SUMMARY OF RESEARCH NEEDS

The major research needs in each of the five program areas that were discussed at the workshop are highlighted below.

In Vitro/Cellular Mechanism Studies

- **Correlation of Exposure Parameters for *In Vitro* Studies with Potentially Harmful Exposures found in the Workplace**

  A detailed occupational exposure assessment must be conducted by qualified individuals in order to provide EMF parameters for *In Vitro*/Cellular Mechanism Studies.

- **Development of Methods for Occupational Dosimetry which Reflect Exposures at the Cellular Level**

  Appropriate methods for theoretical and experimental dosimetry should be developed and applied to permit accurate extrapolation of EMF exposure levels found in the workplace to exposure levels used in cellular studies.

- **Theoretical Studies and Models**

  Theoretical studies and models are necessary because of the multitude of possible experimental exposures and parameters and other conditions which need to be defined prior to conducting definitive *In Vitro*/Cellular mechanism studies.

- **Development of Reference Criteria for Experimental Design and EMF Field Characterization**

  To reduce ambiguity and uncertainty in progressing toward a unified understanding of the biological actions of EMF, standardized criteria for conducting and reporting the results of *in vitro* studies must be encouraged.

- **Research Priorities for Health End Points**

  The highest priority should be assigned to *in vitro* studies which help to define the nature of carcinogenic effects. Other targets for EMF occupationally induced adverse effects that should be investigated using *in vitro* methods include: the male and female reproductive systems, endocrine and neuroendocrine systems, alterations in fetal development, and non-cancer related aspects of immune system function. Regardless of the disease or system being investigated, the focus of *in vitro* research should be on:

  (a) mechanisms of interaction of EMF with biological systems
  (b) the consequences of those interactions, and
  (c) relationship to EMF-related diseases.

In Vivo Studies

- **Conduct Studies with Scientific Rigor**

  Reproducing the results of current research on *in vivo* effects has been difficult. Therefore, the first priority should be to improve the reproducibility and credibility of current and future research.

- **Characterize EMF Exposures**

  There are many variables (e.g., exposure systems, EMF parameters, and exposures in relation to biological rhythms) that can be manipulated or controlled in *in vivo* experiments, and these must be well characterized and documented.

- **Characterize Critical Effects of EMF**

  Establishment of critical effects on which to focus *in vivo* research is essential. This requires using scientifically accepted methods; stressing quality assurance procedures, etc; properly formulating and testing hypotheses; replicating key findings; exploring relationships between exposure and dose; and elucidating the mechanisms by which biological effects occur.

- **Neuroendocrine Dysfunction Produced by EMF**

  Specific recommendations include characterizing neural, endocrine, and neuroendocrine responses; and studying behavioral effects, central nervous changes, sleep disturbances, and mood changes.

- **Definitive Studies of the Role of EMF in Carcinogenesis**

  Specific recommendations include conducting *in vivo* tests of tumor initiation, promotion and progression with emphasis on leukemia, brain, and hormone-dependent tumors.

- **Reproductive and Developmental Effects of EMF**

  Specific recommendations include studying shifts in patterns of development, maturation and degeneration of animal systems such as the nervous, reproductive and immune systems.

- **Cardiovascular Effects of EMF**

  Specific recommendations include conducting confirmatory studies in both humans and other animal species with emphasis on such phenomena as calcium ions and neurotransmitters.

Epidemiologic Studies

- **Characterization of Exposure**

  Researchers should consider conducting exposure assessments or surveys of selected occupational groups/jobs in order to characterize their potential for exposure to EMF prior to the selection of these worker populations for epidemiologic studies. New epidemiologic studies should include a characterization of exposure.

- **Health Effects/Responses of Interest**

  The priorities were defined as cancer, reproductive effects, health effects resulting from hormonal changes (e.g. sleep disorders, behavioral changes, motor neuron diseases, immunologic changes), and non-disease end points and biomarkers (e.g. melatonin).

- **Methodological Issues**

  Common protocols should be developed for both exposure assessments/characterization as well as the epidemiologic analyses; multi-center studies should be considered; the use of existing databases should be explored; hypotheses need to be well formulated based on previous epidemiologic studies or on laboratory findings; potential confounders need to be identified and analytical techniques need to be improved to evaluate these confounders; and hypothesis generating studies, such as PMR studies based on union or company death benefit records should continue to be pursued.

◆ **Potential Worker Populations to Study**

Populations to be considered included "high" exposure groups, with significant variation in EMF exposure and no other confounding exposures; women workers (for reproductive and breast cancer studies); groups exposed to extremely low frequencies other than the "power" frequencies of 50 and 60 Hz; health care workers; welders; aluminum reduction potroom workers; electric railroad workers; and electric machinery/motor workers.

Exposure Assessment Studies

◆ **Measurement Guidelines**

Standardized measurement protocols are required and training programs are needed for health and safety professionals in assessing exposure to EMF.

◆ **Exposure Metrics**

Accurate and uniform exposure metrics need to be developed for epidemiologic studies.

◆ **Measurement Instrumentation**

Independent assessments are needed to evaluate instrument performance, and standardized quality assurance programs should be established. Personal dosimeters are needed that will measure transient magnetic fields and their time rate of change. Also, contact current meters need to be developed and evaluated.

- **EMF Dosimetry**

  Dosimetric modeling techniques are needed that will estimate the distribution of induced currents throughout the body and provide a basis for specifying a dose measure.

- **Non-Utility Sources of Exposure**

  Recommendations in this area are essentially identical to those developed by the Panel on Epidemiologic Studies.

- **Worker Communication**

  Ways of effectively communicating the concepts of EMF exposure assessment to workers must be developed and validated.

Methods for Reducing Exposures

- **Identify EMF Sources**

  The identification and characterization of EMF sources are important to any control strategy. Attention should be paid to the magnitude of EMF as a function of frequency and phase.

- **Review and Recommend Electrical Code Changes**

  Important items to consider for potential code changes include use of safe installation practices and computer modeling of EMF.

- **Continue Research on Field Cancellation Techniques**

  Important items to consider in improving cancellation techniques include computer modeling of EMF, and examining the wiring and circuit design of industrial equipment, power tools and office appliances.

- **Materials Research**

  Research is needed to develop better materials for shielding from magnetic fields.

- **Work Practices**

  Work task redesign and workstation design methods should be developed.

- **Substitution**

  Substitutes should be designed to eliminate appliances that generate high EMF.

- **Transient Suppression**

  A study of generic approaches to reducing transient fields should be conducted.

- **Personal Protective Equipment**

  Material research is needed to develop light weight, practical materials which can be fashioned into functional garments for the worker

- **Training and Education**

  Education of professionals and workers in the concerns associated with exposure to EMF will help as a control mechanism for reducing future EMF exposures.

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PLENARY PAPERS

IN VITRO STUDIES: LOW FREQUENCY ELECTROMAGNETIC FIELDS

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IN VITRO STUDIES: LOW FREQUENCY ELECTROMAGNETIC FIELDS

INTRODUCTION

In vitro studies of effects of low-frequency (LF) electromagnetic (EM) fields have revealed a variety of sensitive cell-physiologic endpoints. Effects have been reported on: (1) DNA, RNA and protein synthesis; (2) cell proliferation; (3) cation fluxes and binding; (4) immune responses; and (5) membrane signal transduction (i.e. hormones, enzymes, and neurotransmitters). Typically such effects occurred as a result of short-term exposure of cells to EM at frequencies of 100 Hz or less and at low field intensities. The dependency on frequency or modulation, as well as the apparent weak cellular interaction of these LF EM fields, lacks theoretic explanation. It has not been determined whether effects are induced by electric or magnetic fields.

Confounding the interpretation of the results of such studies are associated phenomena such as: (1) transient or time-delayed responses; (2) modulation- and intensity-specific effects, referred to as modulation or intensity "windows"; and (3) general lack of dose-(or dose-rate) response data or EM field thresholds. Consequently, although it is well-established that LF EM fields affect biological systems *in vitro* use of these data to assess human health effects is limited.

Purpose

The purpose of this plenary paper is to review selected representative published reports of LF EM fields on *in vitro* systems. This is not intended to be an exhaustive review. *In vitro* studies that did not detect EM field effects were not reviewed in detail since they provide no guidance for the direction of future research. This does not imply that ment of effects of EM fields on *in vitro* systems. However, the limited number of published reports of EM field effects, be they positive or negative, precludes the generation of a consensus view at this time.

To the extent possible, relevance of the findings to occupational exposures will be assessed. Principally, this will be attempted by considering the consistency of *in vitro* and *in vivo* EM exposure effects and comparison of EM field intensities that affect *in vitro* systems with occupational EM exposure intensities. Finally, suggestions will be made for the direction of future *in vitro* research of direct pertinence to potential occupational exposure problems.

Definitions

In the context of this article *in vitro* studies are defined as experimental or theoretical studies of the effects of low frequency (i.e. frequencies less than 1000 Hz) electromagnetic (EM) fields on individual cells or explanted tissue, exposed and assayed outside of human or animal bodies. *In vitro* studies may involve: (a) normal mammalian cells or tissue, such as lymphocytes or other blood cells, obtained from donors prior to exposure, or (b) transformed mammalian cells that are maintained indefinitely in culture. Type (a) cells, derived from a specific donor in limited quantities, have a finite lifespan of up to a week or so. Type (b) cells, on the other hand, may be propagated indefinitely in large numbers and exposed to EM radiation, or other agents, for extended periods of time in various laboratories. Cells of either type can be maintained under controlled conditions in defined composition culture media supplemented with various growth factors and antibiotics.

Advantages and Limitations

The primary advantages of *in vitro* studies include: 1) the potential for the precise control of experimental variables such as electric or magnetic field strength, temperature, culture medium composition, etc., 2) accurate and detailed dosimetric and densitometric information, 3) exposure replication (essentially unlimited replication for type (b) cells), 4) relatively simple cell geometry, amenable to theoretical modeling of electric and/or magnetic field interactions with cells or cell constituents, such as the plasma membrane, 5) significant reduction in cost relative to *in vivo* studies. Taken as a whole, *in vitro* studies afford the opportunity to determine basic mechanisms of interaction of EM fields with living systems. This distinction, relative to *in vivo* systems, is attributed to the complex nature of EM field interactions and induced field distributions within the body of experimental animals or humans which impede the establishment of precise dose-effect relationships. The advantages of *in vitro* systems may be exploited in investigations of co-factor interactions of EM fields with other physical or chemical agents. Such studies should prove of value in screening for potentially adverse interactions of EM fields with other agents in the workplace.

In vitro systems thus provide a versatile means of investigating direct EM cellular interactions or co-factor interactions. However, there are limitations on their use in developing guidelines or standards for occupational exposure to EM fields due to the complex interactive nature of integrated physiological systems comprising an organism which preclude direct extrapolation of *in vitro* data to *in vivo* responses. *In vitro* data, including EM cellular effects thresholds and dose-response relationships can, however, provide the basis for the design of *in vivo* studies by defining critical physiological end-points, and EM field parameters. Understanding basic cellular-level interaction mechanisms will provide a general basis for extrapolation of *in vitro* to *in vivo* exposure effects, as well as inter-species exposure effects of EM effects on mammalian systems.

IN VITRO EFFECTS OF LF EM FIELDS

Biomolecular Synthesis

Low intensity LF electric and magnetic fields affect rates of synthesis of DNA, RNA and proteins *in vitro*. Liboff et al. (1984), for example, reported increased DNA synthesis in human fibroblasts exposed to low intensity sinusoidal magnetic fields (15 to 4000 Hz). Weak ELF electric or magnetic fields affected collagen and/or glycosaminoglycan synthesis in fibroblasts (Fitton-Jackson and Bassett, 1980; Kamrin, 1974; Farndale and Murray, 1985; Cleary et al., 1988). ELF electric fields increased DNA (Rodan et al., 1978) and glycosaminoglycan (Lee et al., 1982) synthesis in chondrocytes. Binderman et al. (1985) reported cell-specific bi-phasic stimulation of cyclic AMP levels and DNA synthesis in skeletal-derived cell cultures exposed to 3 Hz electric fields.

Goodman et al. (1987), detected increased rate of messenger RNA synthesis (transcription) in dipteran salivary gland cells exposed to pulse-modulated magnetic fields at frequencies of 15 to 72 Hz. Transcriptional activity was also increased following exposure to 72 Hz sinusoidal magnetic fields for periods of up to 45 min. The maximum induced magnetic and electric field strengths were less than approximately 4 mT (milliTesla) (40 Gauss) and 10 mV/m respectively. Although all of the magnetic fields affected transcriptional activity, there were quantitative and possible qualitative differences in the effects of the different magnetic field wave forms. Analysis of the X-chromosome transcription patterns indicated that pulsed magnetic fields augmented activation of pre-existing (normally active) chromosomal loci and activated inactive genes or gene sets. Subsequent studies demonstrated similar effects of LF modulated magnetic fields (including 60 Hz fields) on RNA transcription and protein synthesis in other cell types (Goodman et al., 1989) and in cell-free systems (Goodman, unpublished observations). The mechanism(s) for magnetic field effects on transcription are unclear. However, since this effect occurred in cell-free, as well as cell systems, possible direct genomic interaction is suggested. This is of interest since most other *in vitro* cellular effects of LF electric or magnetic fields have been associated with interactions with the cell membrane, although here again mechanisms are uncertain.

Whereas ELF electric and/or magnetic fields of various intensities, frequencies and modulation affect cell biosynthetic processes, attempts to detect chromosomal alterations such as rearrangements, single strand breaks, point mutations, or sister chromatid exchange have proven negative (Cohen et al., 1986; Livingston, 1986; Benz, 1987; Reese et al., 1988).

Membrane Calcium Fluxes and Binding

The most extensively investigated and replicated *in vitro* effect of LF EM fields is altered calcium ion (Ca^{2+}) binding to chick brain tissue. These studies revealed tissue sensitivity to extremely low intensity LF electric and magnetic fields characterized by multiple modulation- and intensity-specific responses, referred to as modulation and intensity "windows", respectively. Multiple response windows, which have proven difficult to explain theoretically, present potentially perplexing problems with respect to the development of occupational exposure guidelines since they violate traditional dose-effect and threshold response concepts. To date there is limited *in vitro* data suggesting windowed responses for other cell end points such as cell proliferation (Cleary et al., 1988; Ross, 1990) or fibroblast protein synthesis (McLeod et al., 1987). This limitation may well be attributed to the small number of studies designed to detect windows.

Bawin et al., (1975, 1976) first reported modulation windows for Ca^{+2} efflux from chick brain exposed to 147 MHz radio frequency (RF) electromagnetic radiation, amplitude modulated (AM) at specific frequencies between 6 and 20 Hz. Blackman and co-workers, (1979, 1980a) reported intensity (power-density) windows for this phenomenon and subsequently found similar responses using modulated 50 MHz RF radiation (Blackman et al., 1980b). Sheppard et al. (1979)

also observed a Ca^{+2} efflux intensity window for modulated RF radiation. Dutta et al. (1984; 1989) reported multiple intensity windows for Ca^{+2} efflux from neuroblastoma cells in culture exposed to 915- or 147 MHz RF radiation amplitude modulated at 16 Hz.

Sinusoidal ELF fields induced intensity- and modulation-dependent windowed effects on Ca^{+2} efflux from chick brain tissue *in vitro* (Blackman, 1985a). Whereas a 16 Hz sinusoidal field enhanced Ca^{+2} efflux at 6 and 40 V/m, 1- or 30 Hz fields were ineffective, as was a 42 Hz field at 30-, 40-, 50- or 60 V/m. A 45 Hz field enhanced efflux at 40 V/m, of similar magnitude to the 16 Hz field. Field strengths between 45- and 50 V/m increased efflux at 45 Hz, whereas at 60 Hz, 35- and 40 V/m were effective intensities. Holding the field strength constant at 42.5 V/m and varying the frequency revealed Ca^{+2} efflux enhancement in a region around 15 Hz and another from 45 to 105 Hz (Blackman et al., 1985a).

Blackman et al. (1985b) observed that the local DC magnetic field at the site of ELF-exposed samples determined which electric and magnetic field frequencies were effective in inducing Ca^{+2} release from chicken-brain tissue *in vitro*. In this study the DC magnetic field was perpendicular to the plane containing oscillating electric and magnetic field components. In a subsequent study Blackman et al. (1990) observed that Ca^{+2} efflux occurred when the DC-magnetic field was perpendicular to the alternating magnetic field component of a 314 Hz, 15 V/m, 61 nT (nanoTesla) EM field, but not when the magnetic fields were in parallel alignment. They noted that this result is consistent with a magnetic resonance-like transduction mechanism for the conversion of EM energy into a physicochemical change, such as enhanced ion transport through helical membrane channels. It was also noted that the magnetic field alignment dependence was in direct contrast to the results of Smith et al. (1987), who demonstrated a resonance-like effect of an alternating ELF magnetic field on the mobility of diatoms.

Diatom mobility depends upon transmembrane transport of Ca^{+2}. Smith et al. (1987) exposed diatoms to combined DC and alternating magnetic fields they predicted would enhance Ca^{+2} transport on the basis of an ion cyclotron resonance theory advanced by Liboff (1985) and McLeod and Liboff (1986) (discussed below). In agreement with theory, a mobility maximum occurred at 16 Hz when the diatoms were exposed to a DC magnetic field of 20.9 μT and an AC field of 20.9 μT, when the static and AC magnetic fields were in parallel alignment. Perpendicular magnetic field alignment had no effect on diatom mobility. As noted by Blackman et al. (1990), the diatom experiments of Smith et al. (1987) and chick brain experiments were conducted under different conditions. Smith et al. (1987) exposed diatoms to a 1000-fold greater magnetic flux density than Blackman et al. (1985) and with different magnetic field alignment.

The results of Blackman et al. (1985a,b; 1990) and Smith et al. (1987), as well as observations of Thomas et al. (1986) on the effects of LF AC magnetic fields on rat behavior, provide evidence of intensity- and frequency-dependent responses having common features such as: (a) multiple windows at frequencies less than 1000 Hz; (b) intensity windows in a range of intensities well below levels at which cellular alterations can be accounted for by conventional, well understood physicochemical interaction mechanisms and (c) dependence on orientation of geomagnetic and applied EM field components.

In view of these complexities, and the limited number of studies that have been conducted, it is not surprising that the physiological significance of EM-induced alterations in membrane cation binding or transport has not been ascertained. The central role of Ca^{+2} fluxes in neural processes is well known. Effects of low-intensity LF EM fields on Ca^{+2} binding to brain tissue *in vitro*, reported by Bawin et al. (1975; 1976) and Blackman et al. (1979; 1980a,b; 1985a,b), suggest that such fields may affect the mammalian central nervous system (CNS) *in vivo*. The results of Thomas et al. (1986), and behavioral changes in monkeys induced by exposure to LF EM fields reported by Gavalas-Medici and Day-Magdaleno (1976) do, in fact, implicate this phenomenon in EM-induced effects on the mammalian CNS. Further evidence derives from the observation that low-amplitude LF AM electromagnetic radiation induced Ca^{+2} release from the brain of a live cat (Adey et al. 1982). The potential physiological significance of LF EM field exposure has been reviewed in detail by Adey (1981).

Cell Proliferation

The most extensive body of information concerning cellular effects of LF EM radiation derives from studies of cell proliferation *in vitro*. Interest in effects on cell proliferation has been stimulated by clinical applications of such fields for the treatment of connective tissue disorders, such as bone nonunions (Bassett et al., 1981, 1982), fresh fractures (Wahlstrom, 1984) and tendinitis (Binder et al. 1985), as well as reported association of LF EM field exposure and cancer. Attempts to more fully characterize and quantitate *in vivo* responses, and to establish mechanisms, have led to a series of *in vitro* studies, many of which employed pulsed magnetic fields of the type reported to be clinically effective. The results of such *in vitro* studies of effects on nerve, muscle, fibroblasts, neural crest cells, and epithelial cells, reviewed by Robinson (1985), document effects of LF electric and/or magnetic fields on proliferation, intercellular communication and development.

In addition to effects of LF pulsed magnetic fields, the results of Liboff et al. (1984) indicated that sinusoidally varying magnetic fields at frequencies in the range 15 Hz to 20 kHz induced proliferative changes in human embryonic foreskin fibroblasts *in vitro*. Exposure to a 76 ± 4 Hz magnetic field, at an intensity of 1.6×10^{-5} T_{rms} (Tesla root-mean-square), induced statistically significant time dependent increases in DNA synthesis during exposures of up to 96 hours. In this series of experiments the maximum increase in proliferation, which occurred after 96 hours of exposure, was approximately 60%. Compared to sham-exposed cells, DNA synthesis in fibroblasts exposed to ten different LF EM frequency and amplitude combinations exhibited a time dependent maximum after 20 hours of exposure. Liboff et al. (1984) noted that this exposure duration corresponded to the midpoint of the S-phase of the fibroblast cell cycle, suggesting that EM exposure effects may be related to specific cell cycle alterations. Cell proliferation data for various combinations of magnetic field intensity and frequency provided a means of testing the hypothesis that cell proliferation was directly stimulated by eddy currents induced by sinusoidal magnetic fields. According to Faraday's law the magnitude of the eddy currents, or induced electric fields, is proportional to the product of the magnetic field frequency and intensity. The data did not support this hypothesis, leading Liboff et al. (1984) to conclude that either the magnetic field effect on fibroblast proliferation was not due to induced eddy currents or that the effect was a saturable phenomenon, such as a self-limiting shift in the onset of S-phase. The threshold for sinusoidal magnetic field effects on fibroblast proliferation was in the range 5 to 25 μT/s (microTeslas per second). Liboff et al. (1984) noted that this value was similar in magnitude to the value of approximately 10 μT/s reported to interfere with development of chick embryos (Delgardo et al., 1982).

Liboff et al. (1984) also noted that threshold magnetic field magnitudes in their study were on the order of ambient 60 Hz fields in the vicinity of devices such as fluorescent lights, fans, or electric motors. Consequently, ambient fields must be measured and controlled to ensure against artifacts in *in vitro* studies.

Ross (1990) investigated the effect of 48 hour exposure of rabbit ligament fibroblasts *in vitro* to 16, 75, or 100 Hz sinusoidal magnetic fields. Variation of AC magnetic field amplitude, frequency, and vertical DC magnetic field strength resulted in either stimulation or inhibition of proliferation. Proliferation was inhibited at all three frequencies when the amplitude of the AC and DC magnetic fields corresponded to cyclotron resonance conditions. The bi-phasic nature of the effect of sinusoidal magnetic fields on proliferation was demonstrated by varying the amplitude of a 100 Hz signal from 0.1 to 1 mT (milliTesla), holding the DC magnetic field constant at 0.13 mT. Proliferation was inhibited at amplitudes of 0.5 mT or less but enhanced when the magnetic field intensity was increased to 0.7 mT or greater, up to a maximum at 1 mT, the largest amplitude reported. By varying the amplitude of the DC field from 0.1 to 0.3 mT and the AC field from 0.5 to 1 mT, while holding the frequency of the AC field at 100 Hz, Ross (1990) detected a significant interaction between DC and AC magnetic fields and fibroblast proliferation. These data support the hypothesis of a cyclotron resonance-like phenomenon being associated with inhibition or stimulation of fibroblast proliferation.

Ross (1990) commented on the bi-phasic (stimulation/suppression) proliferative effect of varying the AC magnetic field intensity. He noted that cell proliferation is triggered synergistically by several biomolecular pathways (O'Keefe and Pledger, 1983; Roger et al., 1987; Van der Burg et al., 1988) which may be differentially affected by magnetic fields at different intensities. It was also noted that the AC magnetic field intensities used in this study were on the order of those encountered occupationally (Miller, 1974).

Evidence that in addition to effects of magnetic fields, electric fields per se affect cell proliferation was reported by Noda et al. (1987). DNA synthesis was increased 20% in rat osteosarcoma cells exposed for 34 hours to 60 Hz electric fields at current densities of 0.3 to $3A_{rms}$ per m^2. Higher or low current densities were ineffective, indicating a current density "window". The results of this study are of interest since the electric field effect depended upon a number of variables including: (a) concentration of fetal calf serum (FCS); (b) cell seeding density; (c) "stage" or age of the cell population at the time of seeding. In general these data indicate that the 60 Hz electric field effect on proliferation depended upon the mitotic status of the cell population during exposure. This finding is potentially significant since it suggests specific interaction of LF EM fields with the mammalian cell cycle. The dependence of the proliferative effect of EM fields on factors such as (a) – (c), if not taken into account in the design of *in vitro* studies, could result in highly variable or contradictory results.

Further evidence that electric fields *per se*, of a different wave form than used by Liboff et al. (1984), Noda et al. (1987) or Ross (1990), affected cell proliferation was provided by Cleary et al. (1988) who exposed normal chicken tendon explants *in vitro* to low amplitude, unipolar, square wave pulsed electric fields. An electrical field parameter set consisting of 1 Hz, 1 millisecond duration pulses, having a time averaged current density of 7 mA/m^2 (maximum current density 7 A/m^2) induced a highly statistically significant 32% increase in fibroblast proliferation in tendon explants exposed for 96 hours. Exposure to the same pulsed field at a time averaged current density of 1.8 mA/m^2 did not affect fibroblast proliferation. Exposure to current densities of greater than 10 mA/m^2, on the other hand suppressed both proliferation and collagen synthesis, without affecting non-collagen protein synthesis.

The effect of the 1 Hz pulsed electric field on fibroblast proliferation was also dependent upon orientation of the explant with respect to the electric field. Fibroplasia was enhanced when the explant longitudinal axis was oriented parallel to applied E-fields having current densities of 3.5 or 7 mA/m^2. For perpendicular orientation there was no effect on proliferation. Fibroblast proliferation and collagen synthesis were inversely proportional to donor age for the 3 to 16 week old chickens used in this study. However, there was no interaction between donor age and the effect of ELF pulsed field exposure on these dependent variables. Subsequent studies revealed that the effect of pulsed electric fields on proliferation of explants from chickens aged 8 – 16 weeks depended upon extra-cellular Ca^{+2} and FCS concentration. This was not true for explants from chickens less than 3 weeks of age (Cleary, unpublished results).

It may be concluded that low intensity LF EM fields modulate proliferation of normal as well as transformed mammalian connective tissue cells *in vitro*. Intensity (current density) windows resulted from exposure to magnetic as well as unipolar or bipolar (AC) electric fields. The magnitude of the proliferative response was dependent upon EM field intensity, exposure duration, and cellular and extracellular factors.

Cell Surface Effects

Phillips et al. (1986a) investigated the effect of 60 Hz EM fields on the expression of the transferrin receptor on human colon carcinoma cells *in vitro*. Cells were exposed for 24 hours to either a 300 mA_{rms}/m^2 electric field; a 10^{-4} T_{rms} magnetic field; or combined E and H-fields at these intensities. The rationale for this study was the association of the transferrin receptor with the receptor of natural killer cells (cytotoxic lymphocytes), and the fact that expression of this receptor is correlated with proliferation of normal and malignant cells. Phillips et al. (1986b) reported that exposure of colon cancer cells *in vitro* to 60 Hz EM fields significantly increased colony formation in soft agar and increased the expression of tumor associated antigens.

Phillips et al. (1986a) reported a 24-fold increase in colony formation in colon cancer cells exposed to both E and H-fields; a 14-fold increase in magnetic field exposed cells; and an increase of 1.7 times in cells exposed to the 60 Hz E-field. The increased clonogenic capacity persisted for the 8 month study duration. The expression of transferrin receptors in cells exposed to the combined fields, or to the magnetic field alone, was maintained at maximal levels and was not under the normal cell density regulatory influence. The change in transferrin receptor expression was maintained in cells up to 8 months after EM exposure. Based on these data, Phillips et al. (1986a) suggested that EM exposure may affect normal cell proliferation control processes.

Luben et al. (1982) exposed osteoblast-like mouse bone cells to either a continuous pulse train magnetic field having a pulse burst repetition rate of 72 Hz or recurrent bursts modulated at 15 Hz. These fields induced extra-cellular electric field strengths of 0.1 V/m or less and current densities on the order of 10 mA/m^2 or less. Exposure to either EM signal for up to 90 hours significantly reduced the normal ability of bone cells to produce cyclic adenosine monophosphate (cAMP) in response to parathyroid hormone (PTH). There was no EM field effect on adenylate cyclase activity. EM field exposure blocked the inhibitory effects of PTH on collagen synthesis. However, inhibition of collagen synthesis by 1,25-dihydroxyvitamin D_3 was not affected. PTH acts at the site of the plasma membrane, in contrast to 1,25-dihydroxyvitamin D_3, which acts primarily in the cell nucleus. Luben et al. (1982) concluded that their data supported the hypothesis that EM field effects are mediated primarily in the plasma membrane of osteoblasts, either by interfering with hormone receptor interactions or by blocking receptor cyclase coupling in the membrane. Support for hypothesized cell surface alterations induced by EM fields was provided by Marron et al. (1988) who used a chromatographic technique to demonstrate that both 60 Hz electric and magnetic fields altered the physical characteristics (surface charge, hydrophobicity) of the surface of the amoebae *Physarum*. The E and H-fields acted independently and in different ways. A 60 Hz, 1 V/m electric field exposure for 24 hours increased net negative surface charge, whereas magnetic field exposure at 0.1 mT decreased surface hydrophobicity.

Cancer Promotion

Membrane mediated alterations, induced by 60 Hz electric fields, have been implicated in cancer promotion. Byus and co-workers (1987) reported altered activity of ornithine decarboxylase (ODC), an enzyme intimately involved in induction of proliferation of normal and tumor cells. A 1 hour exposure to a 60 Hz 1 V/m electric field induced a 500 percent increase in ODC activity in human lymphoma cells and a 200 to 300 percent increase in mouse myeloma cells *in vitro*. The magnitude and duration of ODC activation depended upon cell type, E-field strength, and exposure duration. For example, a 1 hour exposure of hepatoma cells to a 60 Hz field strength of 10 mV/m induced a 30 percent increase in ODC. Exposure for 2 hours at 1 V/m had no effect, whereas a 3 hour exposure decreased enzyme activity. Based on a comparison of the effect of EM fields and the tumor promoting phorbol ester TPA on cellular ODC activity, Byus et al. (1987) indicated that 60 Hz EM fields may function as a tumor promoting stimulus. They noted, however, that there were significant differences in the magnitude of the effects of TPA and the EM fields used in their study, on cellular ODC activity and that tumor promotion by TPA is highly dependent on the dosage time schedule. Thus direct comparisons of the tumor promoting potential of EM fields and TPA were not possible.

In addition to the possibility that LF EM fields may act as a tumor promoter, as suggested by Byus et al. (1987), there is *in vitro* evidence of an alternative, but not mutually exclusive mechanism to relate EM exposure to cancer, namely effects on immune surveillance. Lyle and co-workers (1988) detected a statistically significant 25 percent inhibition of allogeneic cytotoxicity of B-lymphoma target cells by murine cytotoxic T-lymphocytes that were exposed for 48 hours to a 1 V/m_{rms} 60 Hz sinusoidal electric field. The magnitude of cytotoxic inhibition was dependent upon E-field strength. Exposure of T-lymphocytes to 0.1 – 0.01 V/m resulted in 19 and 7 percent reductions in cytotoxicity, respectively. When the 4 hour cytotoxicity assay was conducted in the presence of a 1 V/m 60 Hz E-field, using previously unexposed T-lymphocytes there was a statistically nonsignificant 5 percent reduction in cytotoxicity. These results suggest that the EM field effect depended upon exposure duration and field strength. Lyle et al. (1988) indicated that the threshold for inhibition of cytotoxicity in clonal T-lymphocytes by exposure *in vitro* to a 60 Hz sinusoidal electric field is between 0.01 and 0.1 V/m.

Theoretical Studies

A theory that adequately accounts for the reported *in vitro* and *in vivo* effects of LF EM fields must address three major issues:

(1) How effects are induced by EM fields at intensities well below those known to induce recognized physical or physicochemical alterations in living systems;
(2) Why effects occur only in specific intensity ranges (i.e. intensity or power density windows);
(3) Why effects occur only at specific frequencies or modulations (i.e. frequency or modulation windows).

Whereas theories that partially explain LF EM field effects have been advanced, none provide an adequate quantitative basis encompassing these three issues. Failure to develop an adequate theoretical basis for low intensity LF EM field effects may be, in a general sense, attributed to the uniqueness of non-equilibrium living systems which render them not directly amenable to descriptions based on classical physical or biochemical principles. The need to consider living systems from different perspectives was discussed by Fröhlich (1984) Kaiser (1985), and others.

The general concept of cooperative and/or coherent interactions between elements in living systems, such as membrane constituents, has been invoked to explain effects involving weak coupling of EM fields. Theoretical models incorporating such concepts were described, for example, by Adey (1988a,b). Blackman et al. (1989) discussed specific implications of such theories with respect to the Ca^{+2} efflux from brain tissue *in vitro.*

Bawin et al. (1976), Blackman et al. (1989), and Smith et al. (1987) observed frequency windows in the efflux or transport of Ca^{+2} at or near 16 Hz. The observation that the position of the Ca^{+2} frequency window was dependent upon the magnitude and direction of the static geomagnetic field led Liboff (1985), and McLeod and Liboff (1986), to advance a theory that LF AC and DC magnetic fields coupled energy to cations, such as Ca^{+2} or Li^{+}, via a cyclotron resonance phenomenon. Whereas this theory predicted the observed occurrence of fundamental and harmonic frequency windows, unanswered questions remain about the cyclotron resonance phenomenon as applied to enhanced cation transport in biomembrane channels. Halle (1988), for example, questioned physical aspects of the model on the basis of classical mechanics, and indicated that fluid friction would preclude significant magnetic field effects on ion transport. The cyclotron resonance model also was criticized on the basis of predicting an inconsistently large ion radius of gyration and longer ionic collision damping times than predicted from physical principles (Sandweiss; 1990).

Weaver and Astumian (1990) developed physicochemical models to explain the coupling of weak periodic electric fields to cells. They modelled effects of applied electric fields on transmembrane potential under various assumptions, comparing the magnitude of induced alterations to thermally induced fluctuations. For large elongated cells with membranes having informational processing sensitivities limited to specific extrinsic low frequency EM field band widths of 10 or 100 Hz, minimal detectable electric fields (i.e. transmembrane induced signals at least as great as thermal fluctuations) of 8×10^{-4} and 3×10^{-3} V/m, respectively were predicted. Phenomena such as cell membrane signal averaging and electroconformational coupling of applied electric fields to membrane macromolecules, such as enzymes, were also considered with respect to cellular effects of LF EM fields (see also Astumian et al., 1990). Weaver and Astumian (1990) concluded that their estimates are consistent with experimental observations that low intensity EM fields affect living systems via non-thermal interaction mechanisms.

In summary, theoretical models have not adequately described LF EM field effects on ion binding or membrane transport, or other low intensity field effects. It may be anticipated that ever increasing knowledge of the unique nature of biological systems that has rendered them refractory to straight forward description by the application of physicochemical principles may advance theoretic understanding of phenomena such as LF EM effects on living systems. Obviously, a more extensive *in vitro* data base, including dose responses and thresholds, will facilitate the development of theoretical models of the interactions and effects of LF EM fields.

SUMMARY AND CONCLUSIONS

In vitro studies provide direct evidence that LF EM fields induce physiologically significant alterations in normal and transformed human and other mammalian cells. The weight of experimental and theoretical evidence indicates that the outer surface of the cell membrane is the primary locus for EM field induced cellular alterations.

In a general sense, the type and magnitude of EM field effects on cells *in vitro* are not inconsistent with purported effects on humans or experimental animals, principally effects on cancer incidence, behavior, and development. However, the limited extent and nature of *in vitro* data preclude drawing conclusions about the specific relevance to *in vivo* exposure effects. Although there are uncertainties in EM exposure levels in *in vitro* as well as *in vivo* systems, it may be concluded that EM field induced alterations in *in vitro* systems occur at approximately the same levels encountered in occupational settings.

In vitro data indicates that effects such as altered biosynthesis or proliferation occur from exposure to extrinsic LF EM fields that induce cellular level fields of the same approximate magnitude and frequency as endogenously generated fields (Cleary et al., 1988; Robinson, 1985). This suggest that instead of inducing unique physiological alterations, EM fields may perturb normal cell functions by mimicking endogenous fields. Mechanisms for EM field effects may thus be sought by contrasting endogenous and exogenous field characteristics, such as band width, wave form, etc.

Major impediments to utilization of extant *in vitro* data relate to: (a) the dearth of dose response relationships and/or effects thresholds; (b) dosimetric and densitometric uncertainties, especially in the case of magnetic field exposure, that result in imprecise knowledge of cellular level induced EM field magnitudes; and (c) the lack of an adequate theory to account for LF EM field effects characterized by: (1) extremely low interaction energies, (2) intensity and modulation windows, and (3) apparently complex temporal dependency.

In view of the unique and essential contributions of *in vitro* studies to defining and understanding occupational health effects of LF EM field exposure, future efforts must be directed toward removing these impediments.

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BIOLOGICAL EFFECTS OF EXTREMELY LOW-FREQUENCY ELECTROMAGNETIC FIELDS: *IN VIVO* STUDIES

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INTRODUCTION

Until the last few decades, the natural background levels of atmospheric electric and magnetic fields were extremely low; however, they have since dramatically increased. The industrialization and the electrification of society have resulted in the exposure of people, animals and plants to a complex milieu of elevated electromagnetic (EM) fields that span all frequency ranges. One of the most significant contributions to this changing electrical environment has been the technological advances associated with the growth of electrical power generation and transmission systems. In addition, EM field-generating devices have proliferated in industrial plants, office buildings, public transportation systems, homes and elsewhere.

EM fields, which may extend far beyond their sources, are mostly imperceptible to people. In the past, there was considerable controversy as to whether fields in the extremely-low-frequency (ELF) portion of the electromagnetic spectrum could even cause significant biological effects, let alone pose a hazard to health. However, research and clinical experience have shown that biological effects from such fields are not precluded simply because they are not perceived. Recent data confirm some of the earlier reports that ELF fields do cause changes in certain biological systems. Thus, it is both reasonable and timely to evaluate the interactions between the modern EM environment and living organisms and to investigate whether such interactions are beneficial or detrimental, transient or permanent.

In the past two decades, research programs throughout the world have greatly expanded in scope and depth to address such issues. Significant progress has been achieved, both in defining the ways living organisms interact with ELF fields and in describing biological effects, both real and potential, from such fields. Much of this effort has been directed toward electric fields of power frequencies. However, frequencies other than 50 and 60 Hz have also been examined, and research has been expanded to include magnetic as well as electric fields. Although it is now clear that ELF EM fields do cause biological effects, the basis for those effects and the underlying mechanisms of interaction remain largely unknown, and the health implications for humans and animals have yet to be fully determined.

As in other areas of scientific investigation, the research being conducted on ELF bio-effects has been performed at several levels: human studies (primarily epidemiological), animal experiments, and cellular (mechanistic) studies.

Some of the earliest efforts to examine health-related issues of ELF fields were focused on the impacts of such fields in humans. Despite the obvious desirability of obtaining such data, they are the most complex and least complete. Additionally, often experimental questions cannot be investigated in humans. Therefore, many areas of biological investigation are more appropriately and efficiently conducted with animal models.

This paper specifically examines the biological effects of exposure to ELF EM fields observed in *in vivo* (animal) studies. An attempt is made to evaluate experimental results and, insofar as possible, interpret them with respect to potential health implications. An overview of current concepts and possible mechanisms is given, and possible future directions of research are discussed.

PHYSICAL CONSIDERATIONS FOR COMPARING EXTREMELY LOW-FREQUENCY EXPOSURE BETWEEN SPECIES

Physical Parameters of Exposure

ELF fields (less than 300 Hz) are quantified in terms of the electric field strength E (volts per meter) and the magnetic field strength H (amperes per meter) or the magnetic flux density B (tesla). Natural environmental ELF fields are normally very low, but with widespread and increasing use of electrical energy, the potential for exposure has increased considerably. Exposure from man-made sources generally ranges up to 100 V/m and from 0.1 μT to 30 μT; the higher exposures occur for short time durations. The highest occupational exposures may be on the order of tens of kilovolts per meter and tens of milliteslas. Typically, however, occupational exposures are 10 to 100 times lower than these high levels.

ELF fields are used in a variety of therapeutic and diagnostic applications, including healing of nonunion bone fractures, promotion of nerve regeneration, and acceleration of wound healing. These applications involve partial-body exposures in the range of 1 to 30 mT. Exposures to time-varying electric and magnetic fields also result from medical use of magnetic resonance devices.

Whole-body exposure to ELF electric fields may involve effects related to stimulation of sensory receptors at the body surface (hair vibration, or possible direct neural stimulation) and effects within the body caused by the flow of current. Magnetic fields would appear to interact predominantly by the induction of internal current flow.

Internal current flow is described in terms of current density in tissue J (amperes per meter squared). Ohm's law permits an equivalent expression of current density in terms of internal electric field strength E (volts per meter). It is not known whether J or E is the more useful and relevant physical quantity for an understanding of the mechanisms of biological effects. Internal current densities produced by exposure to external E or B fields at practical levels (up to approximately 100 kV/m and 1 mT) are far lower than the current densities produced by contact with electrical conductors that produce various electric shock effects.

Data on neuromuscular stimulation (including respiratory tetanus and cardiac fibrillation) indicate that current densities higher than about 0.1 A/m^2 can be dangerous. Current densities near 0.01 A/m^2, particularly with long-term exposures, may cause biological effects that are important to health. At lower levels a variety of biological effects may occur; however, the health implications of exposure at such levels are not clear.

The magnitude of the internal current density is in direct proportion to the frequency for sinusoidal external E and B fields. For pulsed or other wave forms the rate of change of the field is relevant. The duration of current flow is also important. It is practical to relate observed effects to internal current density and the inducing external fields. Accurate relationships of external field and internal current density are functions of frequency, orientation of the body in the field, body size and shape, and tissue composition. Thus, from these fundamentals of interactions, possible mechanisms can be proposed and defined in terms of external unperturbed E and B field strengths, frequencies, and durations.

Dosimetry of Field/Animal Interaction

Electric-field coupling to living organisms has been investigated, both from a theoretical and an experimental perspective. Theoretical treatments, which are addressed in other plenary papers, have been extensively reviewed (Kaune 1985; Kaune and Phillips 1985; Polk and Postow 1986) and will not be discussed here. Experimental modeling is briefly reviewed because it provides important scaling/ dosimetric information for extrapolating data from animals to humans. A more detailed treatment of the subject can be found in reviews by Kaune and Forsythe (1985) and Tenforde and Kaune (1987).

In animals or models exposed to an electric field, an easily determined electrical parameter is the short-circuit current induced in the grounded subject. Although most of the data collected to date were obtained at only one frequency and body weight, currents at other frequencies (f) and body weights (W) can be determined using an $fW^{2/3}$ dependence (Kaune, 1981). The total short-circuit currents in humans and various animals have been compared during exposure to a constant vertical ELF electric field .

Table 1

Short Circuit Currents Induced in Grounded Humans and Animals by Vertical Extremely Low Frequency Electric Fields.*

Species	Short-Circuit Current $I \times 10^8/fw^{2/3}E_o$* (µA)
Human	15.0
Horse	8.5
Cow	8.6
Pig	7.7
Guinea Pig	4.2
Rat	4.0

* Taken from TS Tenforde and WT Kaune 1987

** I = current (A), f = frequency (Hz), W = weight (g), and E_0 = electric field intensity (V/m).

Another method of comparison, is a simple relationship described by Deno (1977), in which the external electric fields acting on the surface of a body are measured. Kaune and Phillips (1980) used such measures to compare surface electric fields and induced-current distributions in grounded models of rats and pigs. Current densities were estimated from the induced current data. By combining data derived from Deno's human measurements and Kaune's animal data, researchers have determined peak surface electric fields and current densities have been determined (Figure 1). All three models shown in this figure were exposed to an identical 60-Hz electric field of 10 kV/m. An evaluation of the data shows that, despite comparable exposure, the doses of electric fields received by the three models are quite different. If dose is represented by either the induced axial (along the long axis of the body) current density or the peak surface electric field, the values are considerably larger in the human than in the animal models. Therefore, if one wishes to extrapolate biological data from one species to another, adjustments must be made to scale the exposure parameters. Since exposures are usually given as unperturbed field levels (that is, fields with no bodies present), a scaling factor must be used to equalize differences between species. A complicating element is that the value of the scaling factor depends upon the internal or external quantity that is being scaled. For example, at the top of the body the surface fields (180, 67, and 37 kV/m for human, pig, and rat respectively) require scaling factors of approximately 1:3:5 for these respective species. If, on the other hand, axial current density in the neck is the desired comparison, the scaling factors are about 1:14:20 for the three species. These values

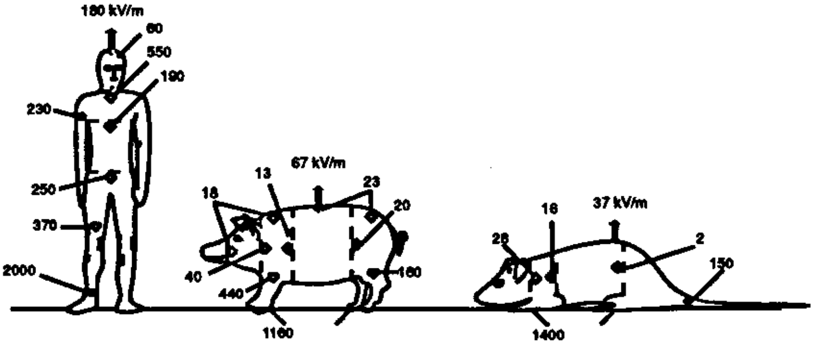

Figure 1. Electric field intensity (kV/m)comparisons are made for the highest point on the surface of a grounded man, pig, and rat exposed to a 10 kV/m, 60-Hz electric field. Estimated average axial current densities (nA/cm2) are also compared for the same species through the body sections as shown. Also given for man and pig are current densities calculated as being perpendicular to the body surface. Relative body sizes are not to scale (adapted from Kaune and Phillips 1980).

change to 1:12.5:125, respectively, for current densities through the lower abdomen. Although the general principle of scaling is applicable and necessary, precise, quantitative extrapolation of data across species requires additional knowledge about the specific site of action for a particular biological end point.

More precise current-density data have recently been obtained by measuring more than one component of the total internal current-density vector. Representative data for a human model exposed to a vertical, 10 kV/m electric field is shown in Figure 2 (Kaune and Forsythe 1985). Similar data have been obtained for animal models as well (Kaune and Forsythe 1988). Methods have also been developed to extrapolate data obtained with grounded subjects to the ungrounded condition (Kaune et al. 1987).

Coupling of humans or animals to ELF magnetic fields is different from the electric field coupling discussed previously. Although biological organisms do not perturb an incident ELF magnetic field, they serve as a conductive pathway in which eddy currents are induced. These circulating currents lie in planes perpendicular to the direction of the incident magnetic field (Tenforde 1986). The magnitude of an electric field induced by an external magnetic field depends mainly on the loop size of the induced current. Equivalent doses for subjects exposed to a magnetic field can be obtained by using a scaling factor based roughly on the size of the animal or human in question.

As described in a paper by Tenforde and Kaune (1987), if the relative magnitudes of the electric field induced in a human by electric (10 kV/m) and magnetic (30×10^{-4} T) fields (simulating the fields close to a high-voltage power transmission line) are compared, the internal fields induced by the electric field are roughly an order of magnitude larger than those induced by the magnetic field. That much of the ELF bio-effects research has been focused on electric field exposure can be partially explained by this large difference in induced internal electric fields.

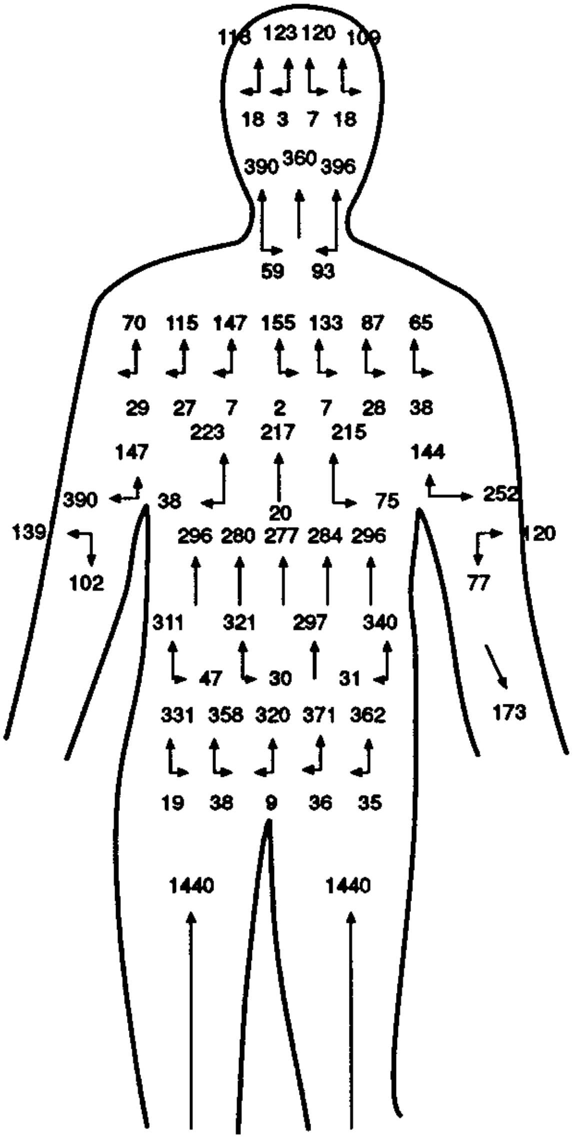

Figure 1. Induced current densities measured in a saline model of a man exposed to a 10 kV/m, 60-Hz electric field. Axial and radial components of the induced densities are represented by the vertical and horizontal arrows respectively with length of the arrows roughly comparable to the intensity value of the current (from Tenforde and Kaune 1987).

REVIEW OF ANIMAL STUDIES

Although the interaction of humans with electric and magnetic fields is of prime importance and concern, many areas of biological investigation are more efficiently and appropriately conducted using various other animal species. Animals provide an integrated system that can be used in prospective studies, in contrast to the retrospective studies usually done with humans. A major challenge of using data from animal studies is the question of extrapolation to human exposure conditions as discussed previously.

By far the largest body of information on biological effects of ELF fields has been obtained in experimental research on animals exposed to electric fields. Experiments have been performed primarily on rodents (rats and mice), but a wide variety of other subjects have also been used, including insects, birds, cats, dogs, swine, and nonhuman primates. A broad range of exposure levels has been employed and an equally large number of biological end points have been examined for evidence of possible electric and/or magnetic field effects. These multitudinous studies have been reviewed several times (Sheppard and Eisenbud, 1977; WHO, 1984; Anderson and Phillips, 1985; Graves, 1985). Summaries of the important findings are presented here, arranged according to the biological systems that appear to be principally involved: neural and neuroendocrine systems (including behavior), reproductive systems (including fertility, growth and development), and other functions (including cardiovascular and blood chemistry, bone growth and repair, and cellular and membrane properties). A separate section addresses the issue of carconogenesis and mutagenesis.

Biological research conducted at power-frequency electric fields of 50 to 60 Hz has produced the preponderance of experimental data. More limited work has been conducted at lower frequencies (15 to 35 Hz); very few studies have been performed at frequencies between 100 and 300 Hz. Only relatively recently have investigators begun to focus on the effects of ELF magnetic field exposures on biological systems.

Neural and Neuroendocrine Systems

Many of the biological effects observed in animals exposed to ELF fields appear to be directly or indirectly associated with the nervous system. This apparent relationship might be anticipated, since the nervous system is composed of tissues and processes that are unusually responsive to electrical signals. In addition, both the structure and function of this system are fundamentally involved in the interaction of an animal with its environment. The major features of this interaction; transmittal of sensory input from external stimuli, central processing of such information, and subsequent efferent innervation of tissues and organs, may provide the basis for explaining possible links between ELF exposure and observed biological consequences.

In early experimental studies, nervous system parameters were measured only occasionally, although many of the observed effects, primarily behavioral, were related to nervous system function. Before the late 1970s, studies on ELF exposure relating to nervous system function could generally be classified in three categories: assessments of activity or startle-response behavior, evaluations of stress-related hormones (such as corticosteroids), and general measurements of central nervous system responses (such as EEGs and interresponse times). Results were often contradictory, with claims of both effects and non-effects from ELF electric field exposure. However, because of the possible and suggested sensitivity of the nervous system to ELF fields, subsequent studies included a broader range of neurological assessments. Specific nervous system responses, in addition to behavior, began to be sought in experiments. This effort was mounted to determine the extent of ELF interaction with tissue and/or organ systems and also to investigate the mechanisms underlying the observed biological effects.

Behavior

Among the most sensitive measures of perturbations in a biological system are tests that determine modifications in the behavioral patterns of animals. This sensitivity is especially valuable in studying environmental agents of relatively low toxicity.

Behavioral studies in several species provide evidence of field perception and of the possibility that EM fields may directly alter behavior. The threshold of detection reported by Stern et al. (1983) is between 4 and 10 kV/m in rats. Human volunteers were able to detect a 9 kV/m 60 Hz field in certain postures (Graham et al., 1987). Thresholds for perception of the field have been reported in the 25 to 35 kV/m range in other animal species, including mice (Moos, 1964; Rosenberg et al., 1983), pigs (Kaune et al., 1978), and pigeons and chickens (Graves et al., 1978 a,b). It appears that a change in other environmental factors, such as relative humidity has the potential to alter perception threshold values (Weigel and Lundstrom, 1987). Cutaneous sensory receptors that respond to a 60 Hz electric field have been identified in the cat paw (Weigel et al., 1987). Whether such receptors exist in human skin is unknown.

An evaluation of the preference/avoidance behavior of animals for remaining in or out of the E-field has been conducted at several field strengths for 60 Hz electric fields. At 100 V/m, no effect of exposure, either in preference behavior or temporal discrimination, was evident in monkeys (deLorge, 1974). At 25 kV/m, rats preferred to spend their inactive period in the field, whereas at 75-100 kV/m they avoided exposure (Hjeresen et al., 1980). Swine (Hjeresen et al., 1982) remained out of the field (30 kV/m) at night but demonstrated few other observable behavioral changes. Alterations in activity have also been reported in animals exposed to ELF fields, including a transitory, increased activity response on initial exposure of rats or mice at 25 to 35 kV/m (Hjeresen et al., 1980; Rosenberg et al., 1983).

Much of the behavioral work with nonhuman primates has been performed at very low field strengths (7 to 100 V/m), where essentially no effects of exposure were reported (summarized in NAS, 1977). Gavalas et al. (1970) and Gavalas-Medici and Day-Magdaleno (1976) observed changes in interresponse time of monkeys during exposure, but no other effects. At much higher field strengths (30 kV/m), Rogers et al. (1987) reported minor behavioral changes in exposed baboons that appear related to the animals' perception of the field. The observed effects do not seem to be permanent or deleterious.

In studies examining the effect of ELF magnetic fields on behavior, many of the investigations carried out at low field intensities have shown behavioral alterations, primarily activity changes (Persinger, 1969; Persinger and Foster, 1970; Smith and Justesen, 1977). In contrast, studies conducted at higher field intensities have shown no evidence of a field-associated effect on animal behavior (Creim et al., 1985; Davis et al., 1984).

In the experimental studies that have been conducted to determine whether ELF fields cause behavioral alterations, remarkably few robust effects have been demonstrated (Lovely, 1988). Effects that have been observed, usually arousal or activity responses, are probably due to the animal's detection and possible perception of the electric field.

Biological rhythms

Far from being static, living organisms exhibit marked dynamics in metabolism and function. Major elements of such dynamics are the endogenous rhythms of varying frequencies (such as ultradian, circadian, and infradian). These biological rhythms, which respond to exogenous environmental cues, are normally a complex mix of phase-locked rhythms and have significant impacts on the physiological and psychological well-being of the organism. Biochemical processes, cellular communications, and functional systems are all intimately associated with endogenous rhythms, as is overall systemic response to the environment. Dysfunctions in these underlying rhythms can profoundly affect the organism and lead to a variety of biological effects.

A number of investigations have been conducted to examine the effects of ELF electromagnetic fields on natural biological rhythms. Following Wever's significant findings (1971) on the influence of electromagnetic fields on humans, several studies have been performed. Dowse (1982) claimed that a 10 Hz, 150 V/m field affected the locomotor rhythm of individual fruit flies. Researchers in Ehret's laboratory (Duffy and Ehret, 1982; Rosenberg et al., 1983) used metabolic indicators to examine both circadian and ultradian rhythms in rats and mice exposed to 60 Hz electric fields. They observed no effects of exposure in rats, but they reported that the activity and rhythms of oxidative metabolism in male mice could be phase shifted by exposure.

Wilson et al. (1981, 1983) directly examined another aspect of circadian activity in rats by measuring the cyclical pineal production of indolamines and enzymes. A significant reduction in the normal nighttime rise of melatonin and biosynthetic enzymes in the pineal gland was observed in rats exposed to either 1.5 or 40 kV/m. Furthermore, the change in pineal indole response occurred only after at least 3 weeks of chronic exposure (Wilson et al., 1986). There was also a suggestion of phase-shifting in young rats exposed to 60 Hz fields (Reiter et al. 1988). In other studies, nocturnal pineal components in mice and rats have been shown to be sensitive to rotated magnetic fields (Welker et al., 1983; Kavaliers et al., 1984; Lerchl et al., 1990). Recent evidence suggests that retinal sensors may be involved in the pineal response to EM fields (Olcese et al., 1985; Reuss and Olcese, 1986).

Sulzman and Murrish (1987) investigated the effects of ELF fields on circadian function in squirrel monkeys. In an examination of exposure to a range of electric field intensities (2.6, 26, and 39 kV/m), accompanied by a 100 μT magnetic field, they reported apparent intensity-related effects. None of the monkeys exposed to 2.6 kV/m showed any change in activity or feeding after 2 weeks of exposure. However, 33% of the monkeys exposed to 26 kV/m and 75% of those exposed to 39 kV/m had significant changes in their circadian cycles.

Although firm conclusions cannot yet be made regarding potential health impacts from ELF effects on circadian or biological rhythms, it is apparent that EM fields can alter the circadian timing mechanisms in mammals. Much work remains to be accomplished before the observed effects and their biological consequences are clearly understood. It seems probable that ELF effects on rhythms, particularly those mediated by neuroendocrine systems, could play an important role in other areas of observed bio-effects, such as behavior and development.

Neurochemistry/Neurophysiology

The relationship between the neurotransmitters norepinephrine and epinephrine and the physiological responses of stress and arousal is well established. As researchers began to look for potential biological effects of ELF electric fields, measuring these transmitters became one of the assessments used to examine the nervous system for evidence of a stress response in animals. This approach, which benefited from the ease of measuring these chemicals in serum, urine, or brain tissue, specifically addressed reports that ELF fields act as mild stressors (Dumansky et al., 1977; Marino and Becker, 1977). Unfortunately, potential methodological problems raised serious questions about the validity of the results from early studies (Michaelson, 1979). Experimental design and methodology problems have also contributed to contradictory results in some of the more recent studies.

Groza et al. (1978) measured catecholamines in both urine and blood after exposure of rats to 100 kV/m, 60 Hz fields. They reported significant increases in epinephrine levels in both blood and urine after acute (6-hour to 3-day) exposures but no changes in norepinephrine or epinephrine with longer-term (12-day) exposures.

A report of increased norepinephrine in serum of rats exposed to 50 Hz (50 V/m and 5.3 kV/m) is found in the work of Mose (1978). A companion paper by Fischer et al. (1978) examined norepinephrine content in brain tissue of rats exposed to 5.3 kV/m for 21 days; after 15 minutes of exposure the levels increased rapidly. However, after 10 days of exposure, levels were significantly lower than in a control group. Portet and Cabanes (1988) reported no changes in adrenal epinephrine or norepinephrine in 2-month-old rats exposed to a 50 kV/M, 50 Hz field for 8 hours a day. In contrast, Wolpaw et al, (1987) reported decreases in cerebrospinal fluid concentrations of the major metabolites of dopamine and serotonin, homovanillic acid, and 5-hydroxindoleacetic acid in macaques exposed to electric and magnetic fields. In addition to possible species-specific response differences, some of the discrepancies between results of various laboratories may be explained in light of results described by Vasquez et al.

(1988). Because of circadian fluctuations in levels of neurotransmitters, the time of sampling may be critical in determining whether an ELF effect is observed. Vasquez et al. reported significant changes in diurnal patterns of several biogenic amines when rats were exposed to 60 Hz electric fields for 4 weeks.

Examining another neurochemical parameter, Kozyarin (1981) measured the acetylcholinesterase (AChE) enzyme levels in rats exposed to 50 Hz electric fields. He reported that serum AChE activity was approximately 25 times baseline levels in both young and old animals exposed to 15 kV/m for 60 days, 30 minutes a day. Brain levels of AChE decreased in exposed animals, although not by such large percentages. Further important measurements were made to estimate the course of recovery from the observed effects. All values had returned to normal 1 month after cessation of exposure. The author concluded that electric fields can cause changes in the functional condition of the central nervous system, although the changes appear to be temporary.

Measurements of corticosteroids in animals exposed to electric fields have resulted in a somewhat confusing picture, perhaps because of the quick response to stimuli of these adrenal steroids (Michaelson, 1979). Studies at Pennsylvania State University examined the hypothesis that 60 Hz electric fields act as a biological stressor (Hackman and Graves, 1981). In that study an acute, transient increase in plasma corticosterone levels occurred in mice exposed to 25 or 50 kV/m. Serum levels of the steroid returned to normal within 1 day. In some studies conducted in the Soviet Union, Dumansky et al. (1976) showed an increase in corticosteroids in rats exposed for 1, 3, or 4 months at 5 kV/m.

In a study conducted by Marino et al. (1977), serum corticosteriod levels were decreased in animals exposed to 15 kV/m for 30 days. This study, however, used pooled, grouped samples of serum. It also had several other technical problems: cages varied, and in four experiments exposed rats were individually housed, whereas control rats were housed in groups.

Results that appear to contradict Marino's and Dumansky's data have been described by Free et al. (1981) and Portet and Cabanes (1988), who exposed rats or rabbits to 100 and 50 kV/m, respectively, for 30 days or 120 days. No differences in corticosterone levels were observed between exposed and control animals. Providing additional support for these data was a study by Gann (1976) in which dogs exposed to 15 kV/m showed no effects of E-field exposure on corticosterone secretion. Quinlan et al. (1985) collected blood samples from rats via carotid artery cannulas during exposure or sham exposure to an 80 kV/m, 60 Hz electric field. No statistically significant differences in corticosterone levels were noted.

In general, neurochemical data provide relatively weak evidence that exposure to electric fields in the power-frequency range may cause slight changes in nervous system function. The number of experiments is not large, and there are significant questions about the validity of several of the studies. Nevertheless, the findings support the hypothesis that ELF exposure alters internal rhythms, increases arousal in animals, and is transient in its effect.

Several laboratories have examined the morphology of brain tissue from animals exposed to ELF electric fields. Carter and Graves (1975) and Bankoske et al. (1976) exposed chicks to 40 kV/m E fields and saw no effects on central nervous system morphology. This finding was supported by those of Phillips et al. (1978), who examined rats exposed to 100 kV/m for 30 days. Again, no morphological evidence of an electric field effect was observed. In a study in Sweden (Hansson 1981a,b), dramatic changes in cell structure were reported in the cerebella of rabbits exposed to a 14 kV/m E field. Exposed animals showed disintegration of Nissl bodies and the three-dimensional endoplasmic reticulum structure, as well as the abnormal presence of many lamellar bodies, particularly in the Purkinje cells of the cerebellum. Reduced numbers of mitochondria, reduced arborization of the dendritic branches, and an absence of hypolemmal cisterns were also evident in these cells. However, these reported changes must be interpreted with caution. The animals were exposed outdoors and showed evidence of significant health deficits (whether resulting from the electric field, other environmental conditions, or some combinations of these factors is not clear). Furthermore, results from these studies are in conflict with experiments conducted by Portet and Cabanes (1988), in which no ultra-structural changes occurred in the cerebella of young rabbits exposed to 50 kV/m. These questions concerning neuroanatomical changes have yet to be resolved. However, the lack of obvious, significant functional deficits in the central nervous systems of thousands of animals exposed to date suggests that the dramatic morphological alterations in exposed rabbits may result from conditions unrelated to electric field exposure. The possibility of synergistic effects from the E field and a stressful environment cannot be ruled out.

Because the nervous system is by nature electrically sensitive, it has been assumed to be particularly sensitive to influence by external ELF fields. To some degree this assumption has been borne out by experimental results, although in the area of neurophysiology a confusing array of studies have claimed both effects and no effects of ELF field exposure. A case in point is the commonly used measure of general central nervous system activity, the EEG. When chicks were exposed for 3 weeks to 60 Hz E fields of up to 80 kV/m, Graves et al, (1978b) noted no changes in EEGs recorded via electrodes implanted after exposure. Similarly, no effects were observed in the EEGs of cats exposed to 80 kV/m at 50 Hz (Silney, 1981). Earlier, Blanchi et al. (1973) reported significant changes in EEG activity when guinea pigs were exposed for 1/2 hour to a 100 kV/m, 50 Hz field. Takashima et al, (1979) examined EEGs from rabbits exposed to 1 to 10 MHz, modulated at 15 Hz. Before exposure, these animals had silver electrodes implanted in their skulls for recording the EEG. After 2 to 3 weeks of exposure, abnormal responses were observed in the EEGs, although it was subsequently determined that the EEG returned to normal when the electrodes were removed during exposure. The investigators thus concluded that the effect on the EEG was due to the local fields created by the presence of the electrodes in the cranial cavity. Gavalas et al. (1970) noted that 7 and 10 Hz E fields of only 7 V/m affected EEGs recorded from monkeys via implanted electrodes. The significance of these results is unclear, since they may be due to an artifact caused by the implanted electrodes as noted previously.

EEGs from cats exposed to 50 Hz magnetic fields (8 hours a day at 20 mT) showed short-term decreases in power density spectra (Silney, 1979). This response was observed only for a short time after the magnetic field was switched on.

In an assessment of a more specific electric "fingerprint" of the brain, the visual evoked response (VER), no effects of exposure were observed in adult or developing rats. Jaffe et al. (1983) assessed the VER in 114 rats exposed *in utero* through 20 days post partum. The dams, fetuses, and subsequent pups were exposed to a 65 kV/m, 60 Hz electric field. No consistent, statistically significant effects of exposure were observed. Wolpaw and associates (1987) examined evoked potentials in pig-tailed macaques exposed to combined electric and magnetic fields. As in Jaffe's studies, the VER and the auditory evoked potential showed no changes caused by exposure. However, an attenuation of the late components of the somatosensory evoked potentials was demonstrated in exposed animals. The authors suggest that these abnormalities may have been due to a particularly large number of stimuli giving rise to a change in the mechanisms of attention.

Two other neurophysiological studies have had clear, replicable results. Jaffe et al. (1980) examined synaptic junctions from chronically exposed rats (60 Hz and 100 kV/m for 30 days). In these studies, presynaptic fibers were stimulated with a pair of above-threshold pulses. The height ratio of the resultant action potentials, observed as a function of the interspike interval, demonstrated an enhanced neuronal excitability in nerves from exposed animals. However, many other parameters tested in these nerves showed no changes in exposed animals. In a second experiment Jaffe et al. (1981) examined a wide range of physiological parameters of the peripheral nervous system and neuromuscular function. The only effect observed was slightly faster recovery from fatigue after chronic stimulation in one class of muscle; the soleus, slow-twitch muscle.

In summary, numerous studies have been initiated to determine how greatly an electrical environment containing electric or magnetic fields of ELF affects the nervous system. Many of the experiments have not confirmed any neuropathological effects, even after prolonged exposures to high-strength (100 kV/m) electric fields and high-intensity (5 mT) magnetic fields (Tenforde, 1985). As discussed previously, nervous system effects that have been observed include altered neuronal excitability, altered circadian levels of pineal hormones, and behavioral aversion to or preference for the field. In addition, in several instances where unconfirmed or controversial data exist, observed effects may or may not be real. Examples are changes in serum catecholamines or corticosteroids, morphology of brain tissue, and EEG wave forms. Possibly these and other putative effects are due to a direct interaction of the electric field with tissue or to an indirect interaction, such as a physiological response owing to detection or stimulation of sensory receptors by the field. The nature of the physical mechanisms involved in field-induced effects is obscure, and elucidating them is one of the urgent goals of current research.

The behavioral tests that most frequently showed an effect of exposure were those relating to detection of the field or to activity responses. Most other behaviors did not change with ELF field exposure. It should also be noted that influences of the nervous system on other biological systems are often mediated indirectly through neuroendocrine or endocrine responses.

Reproduction and Development

Developing organisms, including prenatal and postnatal mammals, are generally considered more sensitive to physical or chemical agents than are adult animals (Mahlum et al., 1978). This greater sensitivity, when it occurs, is thought to originate in subtle effects on the increased number and activity of processes and controls that guide the developing cellular interactions. A number of studies have examined the effects of ELF exposure on reproduction and development of both mammalian and non-mammalian species. These studies have been assessed in detail by other reviewers (Chernoff, 1985; Sikov, 1985) and are briefly summarized here.

Most of the non-mammalian studies have been performed on chickens or pigeons. Many studies have indicated that electric field exposure of chicks at several field strengths, before and after hatching, did not significantly affect viability, morphology, behavior, or growth (Krueger et al., 1972; Reed and Graves 1984; Veicsteinas et al., 1987). However, in one series of experiments chicks exposed to 40 or 80 kV/m on days 1 to 22 after hatching showed significantly less motor activity during the week after removal from the field (Graves et al., 1978b).

Few studies have examined the effects of ELF magnetic fields on growth and development of birds. Krueger et al. (1972) exposed chicks from hatching through 28 days of age to a nonuniform, 45 Hz, 1.4 x 10^{-4} T field. Growth rates were depressed, but no other parameters were affected. Great interest has been shown in the reports of Delgado et al, (1982), who observed a marked increase in malformation rate in chick eggs exposed to low levels of pulsed magnetic fields (0.12 or 12 x 10^{-6} T). It was subsequently reported that an important determinant of the results was the wave shape of the pulse (Ubeda et al., 1983). Several research groups have cooperated in a multi-laboratory replication of the Delgado experiments. Results described in a combined report (Berman et al., 1990) indicated that significant malformation increases were suggested in 5 of 6 laboratories with statistically significant differences observed in two of the laboratories.

Unreplicated studies have given some indications that exposure of prenatal mammals to electric fields produces deleterious effects on postnatal growth and survival (Knikerbocker et al., 1967; Marino et al., 1976, 1980; Hansson, 1981b; Sikov et al., 1987). These results are countered by others in which rats, rabbits, or mice were exposed to 20, 50, 100, 200, or 240 kV/m and no effects on reproduction, survival, or growth and development were demonstrated (Cerretelli et al., 1979; Fam, 1980; Sikov et al., 1984; Pafkova, 1985; Rommereim et al., 1987; Portet and Cabanes, 1988).

In an evaluation of reproductive and developmental toxicology in swine, Sikov et al. (1987) observed no increased terata in progeny from the first breeding of swing exposed during preganancy to a 60 Hz electric field. After 18 months of continued exposure the dams were rebred and their litters were examined at 100 days of gestation. At that time, malformation incidence in litters of exposed animals was significantly greater than in comparable sham-exposed litters. Similar results were obtained in litters of second generation gilts that were born in the field and bred after 18 months of exposure.

This study was followed by one of similar design (but much greater statistical power) in which rats were the experimental model. No significant differences in growth and development were observed in litters of rats exposed to 10, 65, and 130 kV/m when compared with sham-exposed controls (Rommereim et al., 1988). In similar experiments using 60-Hz magnetic fields, no significant changes were demonstrated in exposed animals (Rommereim et al., 1990; Brinkman et al., 1988).

In other studies a rotating magnetic field (0.5 to 15 x 10^{-4}T) was used to expose pregnant rats during various stages of gestation. Some differences were noted between exposed and sham-exposed offspring, including increased thyroid and testis weights in exposed pups. Also, the exposed offspring were more responsive when tested in a suppressed response paradigm (Ossenkopp et al., 1972; Persinger and Pear, 1972). As indicated previously, conflict remains over results of studies investigating the potential for ELF electric or magnetic field exposure to affect reproduction and development. This confusion over results indicates the need for carefully designed, statistically sound experiments that will help clarify this important area of investigation.

Other Biological Functions

Bone growth and repair

One report of animals exposed to 60 Hz electric fields (McClanahan and Phillips, 1983) indicated that bone growth per se was not affected by exposure to 100 kV/m. However, this study, as well as an additional report (Marino et al., 1979), suggested that bone fracture repair was retarded in rats and mice exposed to 5 or 100 kV/m, 60 Hz fields but not to very low (1 kV/m) field strengths. McClanahan and Phillips (1983) suggest that exposure affects the rate of healing but not the strength of the healed bone.

In contrast to the experiments with sinusoidal 60 Hz fields, research studies and clinical trials (discussed previously) have been performed in which magnetic fields were used to treat bone fractures and arthroses in humans. The weak electrical currents induced in bone tissue by magnetic field pulses may enhance fracture repair by altering intracellular concentrations of calcium ions, thus modifying cellular metabolism and stimulating growth of the osteoblasts and chondrocytes (Luben et al., 1982; Bassett, 1978). Why 60 Hz sinusoidal electric fields cause a retardation of fracture repair, whereas pulsed magnetic fields facilitate repair, is unclear.

Cardiovascular system

Cardiovascular function has been assessed by measuring blood pressure and heart rate and performing electrocardiographic measurements. Early studies indicated as possible effects a decrease in heart rate and cardiac output in dogs exposed to 15 kV/m (Gann, 1976) and increased heart rates in chickens exposed to 80 kV/m (Carter and Graves, 1975). A more recent and comprehensive study in rats exposed to 100 kV/m showed no such effects of exposure, even when the animals were subjected to cold stress (Hilton and Phillips, 1980). Cerretelli and Malaguti (1976) reported transient increases in blood pressure in dogs exposed to 50 Hz E fields greater than 10 kV/m. Hilton and Phillips (1980) were unable to confirm a report by Blanchi et al. (1973) of electrocardiographic changes in animals exposed to 100 kV/m.

Magnetic field exposure of dogs (50 Hz, 2 T) caused a stimulation of the heart in the diastolic phase, with salvos of ectopic beats appearing in the recordings (Sliney, 1985). Humans exposed to combined electric and magnetic fields (9 kV/m, 20 µT) have demonstrated a longer cardiac interbeat interval than sham-exposed subjects (Graham et al., 1987).

Serum chemistry appears to be relatively unaffected by exposure to either ELF electric or magnetic fields (Marino and Becker, 1977; Mathewson et al., 1977; Ragan et al., 1979, 1983). Hematological data, however, present a more confusing picture. With electric field exposure, white blood cell count was often elevated in populations of mice and rats (Graves et al., 1979; Ragan et al., 1983). With the exception of one report by Tarakhovsky et al. (1971), all the published studies on hematological effects of magnetic field exposure have shown no field-associated effects (Beischer et al., 1973; de Lorge, 1974; Fam, 1981; Sander et al., 1982). The occasional positive or negative effects on the hematopoietic system must be carefully evaluated. Apparent sporadic effects may not be biologically or statistically significant; particularly when appropriate multi-variate analyses are used to evaluate the wide range of hematological and serum chemistry parameters.

Immunology

There is some indication that exposure of animals to electric fields does not markedly affect the immune system. In a comprehensive investigation of the humoral and cellular aspects of the immune system, Morris et al. (1979, 1982, 1983) observed no effects of exposure at very low field strengths (150 to 250 V/m) in mice or rats. In subsequent experiments at higher field exposures (100 kV/m), no effects were seen in immune system response. However, Lyle et al. (1983) reported significant decrements in the cytolytic capacity of lymphocytes exposed to radio frequency fields modulated at 60 Hz. Further work with 60 Hz electric fields alone also resulted in a suppression of T-lymphocyte cytotoxicity (Lyle et al., 1988). A significant difference between the work reported from these two laboratories is that Morris measured lymphocyte responses from exposed animals, whereas Lyle exposed lymphocytes in culture.

In contrast to the apparent lack of strong or consistent electric field influences on the immune system, immunoresponse to mitogens and antigens appears to be significantly susceptible to ELF magnetic fields (Odintsov, 1965; Mizushima et al., 1975; Conti et al., 1983).

Carcinogenesis and Mutagenesis

No effects suggesting a direct effect of electric field exposure on mutagenesis or carcinogenesis have been observed (Mittler, 1972; Frazier et al., 1987). However, there is considerable research interest on this question due to an increasing number of epidemiological studies that suggest a possible association between ELF magnetic field exposure and cancer. As yet, only a few published laboratory studies, conducted in animals, bear directly on this question and there is an urgent need for such studies.

No studies to date have been reported in which spontaneous tumor development was followed in normal animals exposed to ELF fields. Another possible approach would be a cocarcinogenesis system in which EM exposure is used as a promoter following an initiating event (chemical or ionizing radiation).

In a preliminary report, Leung et al., (1988) describes an experiment wherein animals were exposed to 60 Hz electric fields for extended periods (approximately 180 days). The exposed and sham-exposed animals were treated with a single dose of the potent mammary tumor initiator dimethylbenz(a)- anthracene at 55 days of age. No increases were reported in the number of rats developing tumors. However, they did observed an increase in the number of tumors per tumor-bearing animal.

Tumor growth was inhibited in a few experimental animal models when pulsed magnetic fields were used to expose the animals (Bellossi et al., 1986). However, sinusoidal 60 Hz fields, did not exhibit growth altering action (Thomson et al., 1988).

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HEALTH EFFECTS OF ELECTROMAGNETIC RADIATION ON WORKERS: EPIDEMIOLOGIC STUDIES

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HEALTH EFFECTS OF ELECTROMAGNETIC RADIATION ON WORKERS: EPIDEMIOLOGIC STUDIES

This paper was prepared for a plenary session of the NIOSH scientific workshop on the health effects of electromagnetic radiation on workers. It reviews the epidemiological evidence on cancer, reproduction, and neuropsychological effects with respect to the risk resulting from occupational exposure to 60/50 Hz electromagnetic fields (EMF). Childhood and adult cancers resulting from residential exposure to EMF are not included in this review, nor are studies dealing with direct current energy. With a few exceptions, this review is limited to published studies in peer reviewed journals.

CANCER

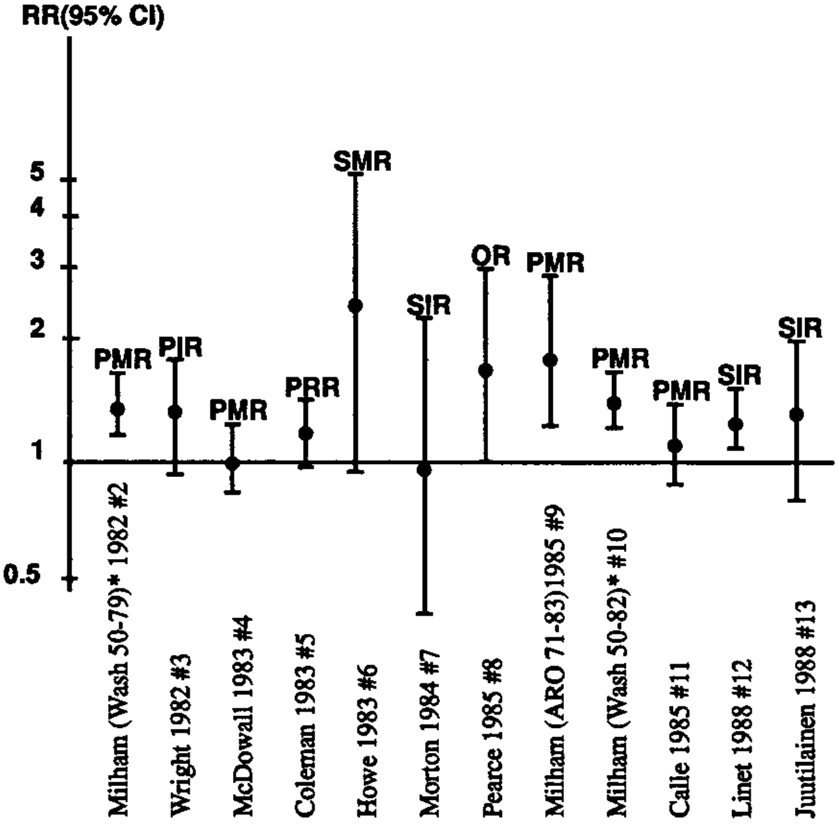
Cancer was first associated epidemiologically with exposure to EMF in 1979, when Wertheimer and Leeper (1) reported that children dying from cancer resided more often in homes with high current configuration than did healthy control children. Wire configuration around houses was used as a surrogate for EMF exposure.

Soon after this study, epidemiologists from many countries looking at occupational cohorts, reported what seemed to be a confirmation of the putative association, EMF - cancer, as proposed by Wertheimer.

Since 1982, scores of occupational epidemiologic studies have been published. To discuss the evolution of knowledge gained through those studies, it is convenient to regroup them under subtitles: (1) cancer hypotheses generating studies, (2) leukemia case control studies, (3) brain cancer case control studies, (4) cohort studies of electrical workers, (5) skin melanoma case control studies, (6) welding and exposure to EMF, (7) male breast cancer.

Cancer hypotheses generating studies

To test Wertheimer's hypothesis, occupational epidemiologists first examined existing mortality and morbidity registries of several countries. Within six years, from 1982 to 1988, no less than 12 communications had been published, most of them as short papers or letters to editors. As seen from figure 1, the majority of these reports observed an excess of leukemia among broadly defined "electrical occupations" and this excess seemed to be higher for acute myleoid leukemia (Figure 2). Pooled analyses of these results have established a significant excess of all leukemias with a risk estimate of 1.18 (1.09 - 1.29) and a significant excess of acute myeloid leukemia with risk estimate of 1.46 (1.27 - 1.65) (14). Results presented in figures



* some overlapping

Figure 1. Leukemia Risks among Electrical Workers—All Leukemia

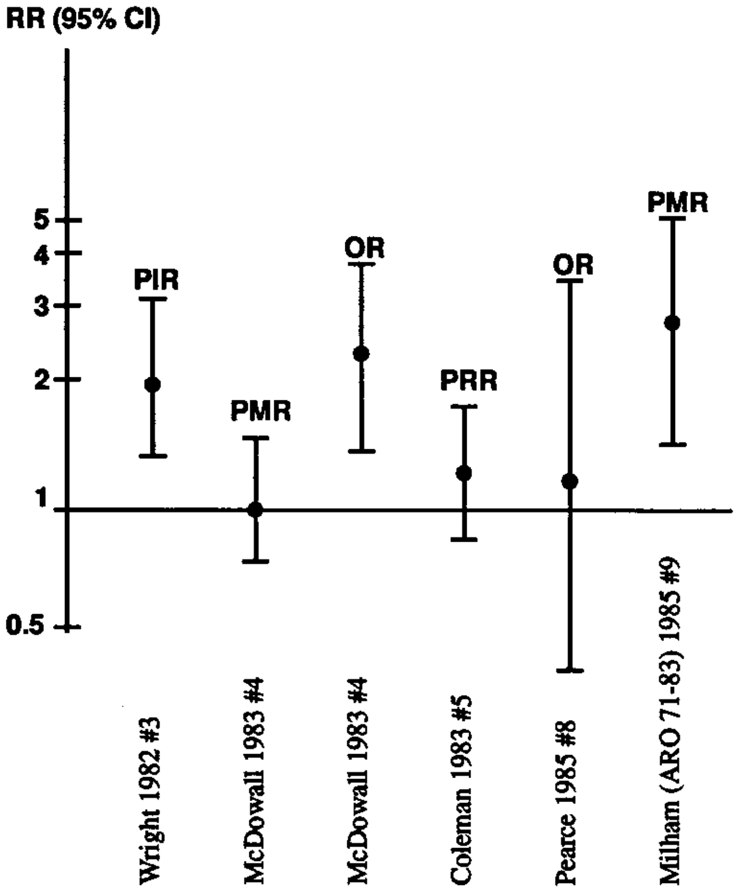


Figure 2. Leukemia Risks among Electrical Workers—Acute Myeloid Leukemia

1 and 2 are for all leukemias and for all workers. More spectacular excesses were noted for specific leukemia types and/or specific occupational groups but these excesses varied between studies and no consistent finding can be pinpointed.

Everybody, including the authors, have recognized that these exploratory studies were gross, that numbers were small, that exposure was ill defined, that statistical analyses very often were weak, that there may exist at the workplace carcinogenic agents other than EMF responsible for the excesses observed, that no confounders have been controlled for and consequently that the results can only be indicative and need to be reassessed by more powerful and better designed studies

Leukemia case control studies

Five case control studies bearing on the issue of leukemia among workers occupationally exposed to EMF have been published since 1985 (see Table 1). These studies are impressive: they are well

Table 1

LEUKEMIA AMONG WORKERS OCCUPATIONALLY EXPOSED TO EMF

	CASES / CONTROLS	EXPOSURE ASSESSMENT		OR (CONF. INT.)
Gilman#15	underground coal miners	time spent	all L	2.53*
1985	40 leukemia deaths	\underground	acute L	2.85
	160 non cancer deaths		chronic L	8.22*
			CLL	6.33*
			Myelogenous L	4.74*
			AML	3.80
Stern#16	naval shipyard workers	job histories	for electricians	
1986	53 leukemia deaths		+ years of employment	
all L	3.00 (1.29 - 6.98)			
	212 members of cohort		ML	2.33 (0.77 - 7.06)
	alive at dx of cases		LL	6.00 (1.47 - 24.45)
			for welders	
			all L	2.25 (0.92 - 5.53)
			ML	3.83 (1.28 - 11.46)
			LL	0 (----)
Flodin#17	population based search	postal	for electrical workers (elec.	
1986	for association with gamma	questionnaire	technicians, elec. welders,	
	rad in houses		computer telephone mechanics)	
	59 AML alive		AML	3.8 (1.5 - 9.5)
	354 general population controls			
Coggon#18	male cancers in	occupational hist.	AML a cluster of 5 electrical	
1986	3 UK counties	through postal	workers in these 29 cases	
	29 acute myeloid leukemia	questionnaires		
	2913 other cancers			
Pearce#19	New Zealand cancer	occupation on	for all electical workers	
1989	reg. 80 - 84	registry forms	all L	1.62 (1.04 - 2.52)
	534 male leukemia		acute L	1.25 (0.62 - 2.54)
	all other cancers		chronic L	2.12 (1.19 - 3.76)
			ML	1.22 (0.60 - 2.48)
			LL	1.73 (0.89 - 3.37)
			AML	1.16 (0.48 - 2.84)

* $p < 0.05$

designed, with reasonably large numbers of leukemia cases. On two occasions, the association of leukemia with EMF was an incidental observation by authors whose objective was to test a different hypothesis. Odd ratios are higher than

those observed in the exploratory studies. In general, excesses are seen for all leukemias and acute myeloid leukemia; chronic lymphoid leukemia is also reported with elevated odds ratios. These five studies, however, are plagued with one weakness: exposure assessment. Exposure is estimated based usually on occupational history secured through postal questionnaire or transcribed from registration forms. Gilman (15) used time spent underground as a surrogate of EMF exposure for coal miners.

These case control studies seem to support and even strengthen the possible association between leukemia and working in 'electrical occupations,' but because of the gross estimates of exposure, they say little about its association with EMF.

Brain cancer case control studies

Brain is the second cancer site that has caught the attention of occupational epidemiologists. Since 1985, at least seven case control studies of brain cancer and occupational exposure to EMF have been published (Table 2).

Most of these studies have shown elevated odd ratios for electrical related occupations. Some odd ratios were high (Speers (22) observed an OR of 13.10 among Texas utility employees). At least 3 studies indicated the presence of a dose response relationship between EMF exposure and brain cancer.

As with the leukemia studies, these case control studies of brain cancer are impressive. There are reasonably large numbers of cases among exposed workers. Many elevated odd ratios are statistically significant and dose response relationships were observed more than once. However exposure has been estimated based on remote information, usually through occupations reported on registry files or secured through postal questionnaires.

Table 2

BRAIN CANCER AMONG WORKERS OCCUPATIONALLY EXPOSED TO EMF

	CASES / CONTROLS	EXPOSURE ASSESSMENT	OR (CONF. INT.)	
Lin#20				
1985	Maryland residents	occupation on	EMF exposure determined	
	519 glioma/	death certif.	from occupation	
	astrocytoma deaths	panel rating	A (definite)	2.15 (1.1 - 4.1)
	519 rand. non cancer	based on	B (probable)	1.95 (0.9 - 3.9)
	deaths	occupations	C (possible)	1.44 (1.1 - 2.0)
			D (no)	1.00 (- - - -)
Coggon#18				
1986	male cancer in	occupational	elec. eng.	1.9 (0.4 - 5.6)
	3 UK counties	hist. through	elec. & electron.	
	97 brain cancers	postal quest.	workers	2.0 (0.8 - 4.1)
	2845 other cancers			
Thomas#21				
1987	Louisiana, N. Jersey,	occupational	MW/RF rad.	1.6 (1.0 - 2.4)
	Penn. residents	history from	MW/RF manf.	
	435 brain cancer	next of kin	repair of elec.	
	deaths	panel rating	equipment	2.3 (1.3 - 4.2)
	386 non-brain cancer	based on occ.	electron. wkr	3.9 (1.6 - 9.9)
Speers#22				
1988	East Texas res.	occ. hist. on	utility emp.	13.10 (1.3-128.9)
	202 glioma deaths	death certif.	elec. occ.	2.11 (0.8 - 5.8)
	238 ran. non-brain			
	tumor deaths			
Pearce#19				
1989	New Zealand cancer	occ. on	all elec.	
	Registry 80 - 84	reg. forms	workers	1.01 (0.56 - 1.82)
	452 male brain can.		elec. eng.	4.74 (1.65-13.63)
	all other cancers		electric.	1.91 (0.84 - 4.33)
Savitz#23				
1989	1095 brain cancer		elec. wrkrs	1.5 (1.01 - 2.1)
	deaths in 16 US states			
			elec. & electron.	
			technicians	3.1
			electric power	
			repairmen	2.4
Brownson#24				
1990	Missouri Cancer	occ. frm	communication	
	Registry 84 - 88	hosp. rcrd	workers	1.4 (0.5 - 4.1)
	312 wh male brain	(usl or lngst)	utilities & sanitary	
	cancers		services	0.5 (0.1 - 1.7)
	1248 other cancers			

Cohort studies of electrical workers

In a search for further clues on the possible association of cancer with occupational exposure to EMF, studies of cohorts of workers exposed to EMF are worth looking into. Such studies should provide us with additional information on the risks for leukemia and brain cancer as well as other cancer types.

Several cohort studies of electrical workers exist in the literature. The occupational cohorts that have been studied are: telephone operators, electronic industry workers, electrical engineers, telecommunications industry workers, linemen, station operators, electricians, amateur radio operators, telephone company workers, electrical utility workers, and radiomen. In most of them, sample sizes are large and observation periods extend over many years.

Two trends are noticeable (see Table 3). Up until 1990, although several risk ratios for leukemia and brain cancer were over 1.0, few excesses were statistically significant. Only one study observed a significant excess of acute myeloid leukemia (AML) (31), and only one, an excess of all leukemias (35). No brain cancers were significantly in excess. Since 1990, care has been given to defining exposed groups with more homogeneity. As a consequence, more significant excesses for leukemia and brain cancer have been observed.

Since exposure in large cohort studies is usually 'diluted,' the observation made concerning leukemia and brain cancer in these cohorts supports the possibility of an association between these cancers and exposure to EMF (as suggested by case control studies). Moreover, while cohort studies have not been very powerful in showing an excess of leukemia and brain cancer among exposed workers, they have revealed a fairly constant excess of skin melanoma(skin melanoma is in excess in 5/7 cohorts).

Table 3

COHORT STUDIES OF ELECTRICAL WORKERS

	all cancer	skin melanoma	brain	leukemia	acute myeloid leukemia
Wiklund 1981, RR #25					
Telephone operators	NR	NR	NR	1.03 (12)	NR
Vagero 1983, RR #26					
Electronics industry	1.15* (1855)	1.35* (59)	< 1.0	< 1.0	< 1.0
Olin 1985, SMR #27					
Electrical engineers	0.5* (24)	3.2 (3)	1.0 (2)	0.9 (2)	0
Vagero 1985, SMR #28					
Telecommunication industry	1.03 (102)	2.5* (8)	1.0 (5)	0	0
Tornqvist 1986, RR #29					
Linemen	1.10 (236)	NR	1.5 (13)	1.3 (10)	NR
Station operators	1.00 (463)	NR	1.0 (17)	1.0 (16)	NR
McLaughlin 1987, SIR #30					
Electricians		NR	NR	0.8 (42)	NR
NR					
Powerline workers	NR	NR	1.0 (13)	NR	NR
Telecommunications	NR	NR	1.1 (13)	NR	NR
Milham 1988, SMR #31					
Amateur radio operators	0.89* (741)	NR	1.39 (29)	1.24(36)	1.76*(15)
Guberan 1989, SMR #32					
Electricians	1.14 (52)	0.91 (1)+	1.54 (2)	1.43 (2)	0
De Guire 1988, SIR #33					
Telecommunication industry	NR	2.7* (10)	NR	NR	NR
Lin 1989, SMR #34					
Telecommunication industry	1.01 (129)	NR	2.4 (5)	NR	NR
Matanoski 1989, SIR #35					
all telephone employees	0.81* (391)	NR	1.0 (13)	0.77 (12)	0.85 (7)
all line workers	0.83* (265)	NR	0.7 (6)	0.88 (9)	0.74 (4)
cable splicers	1.81* (40)	NR	1.79 (2)	7.00*(3)	2.31 (1)
Koifman 1989, PMR #36					
Electrical utility workers	1.60* (347)	0.82 (1)	1.44 (8)	0.89 (4)	NR

Table 3 cont'd

	all cancer	skin melanoma	brain	leukemia	acute myeloid leukemia
Garland 1990, SIR #37 Young males in navy					
electrician's mate	NR	NR	NR	2.4* (7)	NR
electronics technician	NR	NR	NR	1.1 (5)	NR
radioman	NR	NR	NR	1.1 (4)	NR
Juutilainen 1990, SIR #13					
probably exposed to EMF	NR	NR	1.31 (13)	1.85* (10)	1.47 (3)
possibly exposed to EMF	NR	NR	1.29*(149)	1.42* (94)	1.37(34)
electricians (indoor installers)	NR	NR	0.75 (10)	0.95 (7)	0.74 (2)
telephone installers & repairmen	NR	NR	2.37 (9)	1.43 (3)	1.23 (1)
linemen and cable jointers	NR	NR	0.91 (2)	3.08 (4)	2.08 (1)
Vagero 1990, PRR/SRR #38					
electrical, electronic	NR	0.98 (63)	NR	NR	NR
	NR	1.18 (16)	NR	NR	NR
telephone operators	NR	12.03* (2)	NR	NR	NR
electrical engineers	NR	6.92 (2)	NR	NR	NR

\+ all skin
* statistically significant
NR not reported
Numbers in parentheses indicate the number of cases for each cause.

Skin melanoma case control studies

Two case control studies of eye melanoma with mention of electrical workers, were traced (see table 4). In 1983, Swerdlow (39), observed elevated odd ratios of eye melanoma for electrical and electronics workers. However, in another case control study of eye melanoma in 4 Canadian western provinces, Gallagher (40) did not find an excess of electrical or electronics workers among his cases.

So reports of excess of skin (and eye) melanoma among electrical and electronics workers should not be overlooked. It is however, commonly argued that the excess of skin melanoma in this group of workers reflects more the higher socio-economic status of these people rather than the consequence of exposure to EMF. This deserves further attention.

Table 4

EYE MELANOMA AMONG WORKERS OCCUPATIONALLY EXPOSED TO EMF

	CASE / CONTROLS	EXPOSURE ASSESSMENT	OR (PRR)
Swerdlow 1983(#39)	England and Wales Cancer registry 2159 m. incident cases 2125 f. incident cases other registrants	occupation in registry	for electrical and electronics workers 1968 - 78 1.26 1971 1.67 1972 7.14* 1973 2.63 1974 4.44* 1975 5.71*
Gallagher 1985 (#40)	Cancer registry of 4 provinces in west Canada (79 - 81) age 20 - 79 65 ocular melanoma 65 random controls	occupation secured through interviews	no elevated risk found for electrical or electronics workers

* $p < 0.05$
PRR = Proportional Registration Ratios

Welding and EMF

Welders are exposed to intense electric and magnetic fields. Theoretically, they are among the workers most exposed to EMF. In 1987, Stern (41) included an extensive review of 15 cancer studies in welders (Table 5). He observed that excess lung cancer was reported in most studies but not leukemia. He proposed that this observation goes against the hypothesis of an association of EMF - leukemia. However, at approximately the same time, in a case control study of chronic myeloid leukemia, Preston-Martin (42) reported a highly elevated odd ratio (OR adjusted 25.4 (22) 2.78-232.54) for welders. This last finding is remarkable in view of the negative studies previously cited.

Male breast cancer

In a recent study of telephone workers, Matanowski (35) found an elevated risk of male breast cancer among central office technicians. This is an extremely rare disease. Two cases were found among the 9,561 workers; ordinarily, none would be expected. The work environment of central office technicians is typified by a pattern of "spikes" in magnetic field intensity.

Table 5

STUDIES OF LEUKEMIA INCIDENCE IN WELDING POPULATIONS (FROM STERN #41):

	ALL LEUKEMIA		ACUTE LEUKEMIA		LUNG CANCER	
	O	RR	O	RR	O	RR
1)	6	0.96	4(m)	1.71		
2)	—	—	0(1)	—		
3)	20	0.83	13(a)	1.04		
4)	7	2.25				
5)			—(m)	(3.8)		
6)	19	0.89	6(a)	0.67		
7)	0	—			6	0.95
8)	0	—			17	1.5
9)	4	4.2			10	2.2
10)	4	0.35			50	1.32
11)	1	2.5			7	1.38
12)			6(a)	1.81	27	0.99
13)	43	0.99			193	1.42
14)	15	1.14			12	1.60
15)	27	0.85	7(m)	0.76	381	1.46
			4(1)	0.63	305	1.27
Pooled data RR	146	0.92	40	0.92	1008	1.34

(m)acute myeloid
(l)acute lymphoid
(a)all acute leukemia
—number not given

To test Matanowski's hypothesis, Demers (43) carried out a case control study of 227 male breast cancers drawn from 10 registries from the Surveillance Epidemiology and End Results (SEER) program of the National Cancer Institute. Controls were selected (300) through random digit dialing or from medicare eligibility lists. Exposure was based on work history. An elevated risk was found for any exposed job (OR = 1.8, CI 1.0 - 3.2) and was highest among electricians, telephone linemen, and electric power workers (OR = 6.0, CI 1.7 - 21.5), and radio or communication workers (OR = 2.9, CI 0.8 - 10.2).

The observation of an excess of male breast cancer among exposed workers may carry a particular significance in view of the proposed mechanism by which EMF could cause cancer through interfering with the melatonin hormonal system.

Conclusions on cancer evidence

Even if epidemiologic studies, so far, have raised more questions than they have answered and have yielded little convincing evidence, they should not be over looked. They were blamed to be plagued with methodologic weaknesses and above all, with crude estimates of exposure. Even with such weaknesses and estimates of exposure, they nevertheless, have observed increased risks which may mean methodologic improvements and more accurate measurements of exposure may confirm previous findings. It is disappointing to realize that since 1979, not much progress has been made. Things go at a snail's pace. Much hope is being put on the "mega research" projects that are now being conducted in several places in the world.

REPRODUCTION

Reproductive health is a concept that encompasses many concerns including genotoxicity, teratogenicity, infertility, effects on the child to be born or even cancer at a young age. Few studies have addressed these questions in the context of exposure to EMF.

It is convenient to regroup the traced studies under headings such as (1) outcomes of pregnancy and use of electric blanket, (2) outcomes of pregnancy in wives of exposed workers, (3) infertility of exposed male workers, (4) central nervous system cancer in children of exposed fathers, (5) childhood cancer and prenatal exposure to electric appliances.

Outcomes of pregnancy and use of electric blanket

Use of electric blanket and heated waterbed is probably the most intense domestic exposure to EMF that one can get. This may carry some impact on pregnancy outcomes by acting either directly on the fetus or on the gametes through some genotoxicity. Surprisingly, only two studies so far have addressed this question and they are both from the same authors, Wertheimer and Leeper (44,45) (see Table 6).

Table 6

OUTCOMES OF PREGNANCY AND USE OF ELECTRIC BLANKETS

		prolonged gestation period	low birth weight	congenital malform.	early fetal loss
Wertheimer 1986 #44					
Population:	1784 Colorado births 102 fetal losses				
Exposure:	electric blankets heated waterbeds (determined by telephone)	+	+	N/A	+
Outcome:	extracted from birth records				
Wertheimer 1989 #45					
Population:	1879 Oregon births 142 fetal losses				
Exposure:	cable ceiling heating electric blankets heated waterbeds (determined from gov't records)	N/A	N/A	N/A	+
Outcome:	< 20 weeks gestation from birth records of sibling				

-	negative results
+	positive results
N/A	not applicable

In their first study, based on 1,784 Colorado births and 102 fetal losses, the authors observed a seasonal variation in prolonged gestational periods among users of electric blankets and heated waterbeds. They show that this variation paralleled the use of these electrical devices at the time of conception (Figure 3). Similarly, they observed an association between abortion rates and use of electrically heated beds (Figure 4). Even low birth weights were associated with the use of electrical devices, although this association existed only in combination with prolonged gestational periods in what the authors call "slow growing" infants.

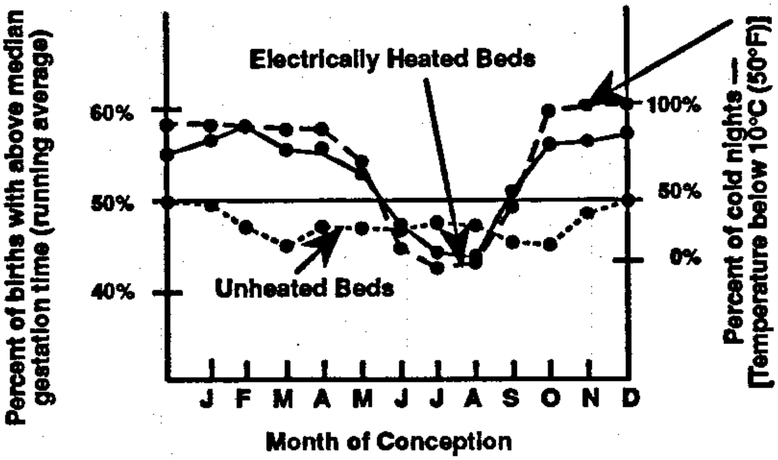


Figure 3. Seasonal pattern of cold nights (Denver, 1976-1982) and of gestation period, for users and nonusers of electrically heated beds. Gestation periods were generally longer for infants of users of electrically heated beds when those infants were conceived in the season when the need for electrical bed heating is greatest.
Based on Wertheimer (44)

In their second study, the authors examined the relationship between early fetal losses and exposure to heating cables in private houses (as well as use of electric blankets and heated waterbeds). They observed a monthly variation in the ratio of abortions occurring among those exposed to EMF over the abortions occurring in unexposed controls. These variations paralleled the changes in heating degree days (Figure 5). Based on these two studies, the authors pposed that an association may exist between EMF exposure and unfavorable outcomes of pregnancy.

Outcomes of pregnancy in wives of exposed workers

Only one study has addressed this question. In 1983, Nordstrom (46) tried to assess the impact of fathers' exposure at work on the outcome of their wives' pregnancies (Table 7). Exposure was assessed based on the occupational history reported in questionnaires distributed to active and former employees of a Swedish electrical plant (Table 7).

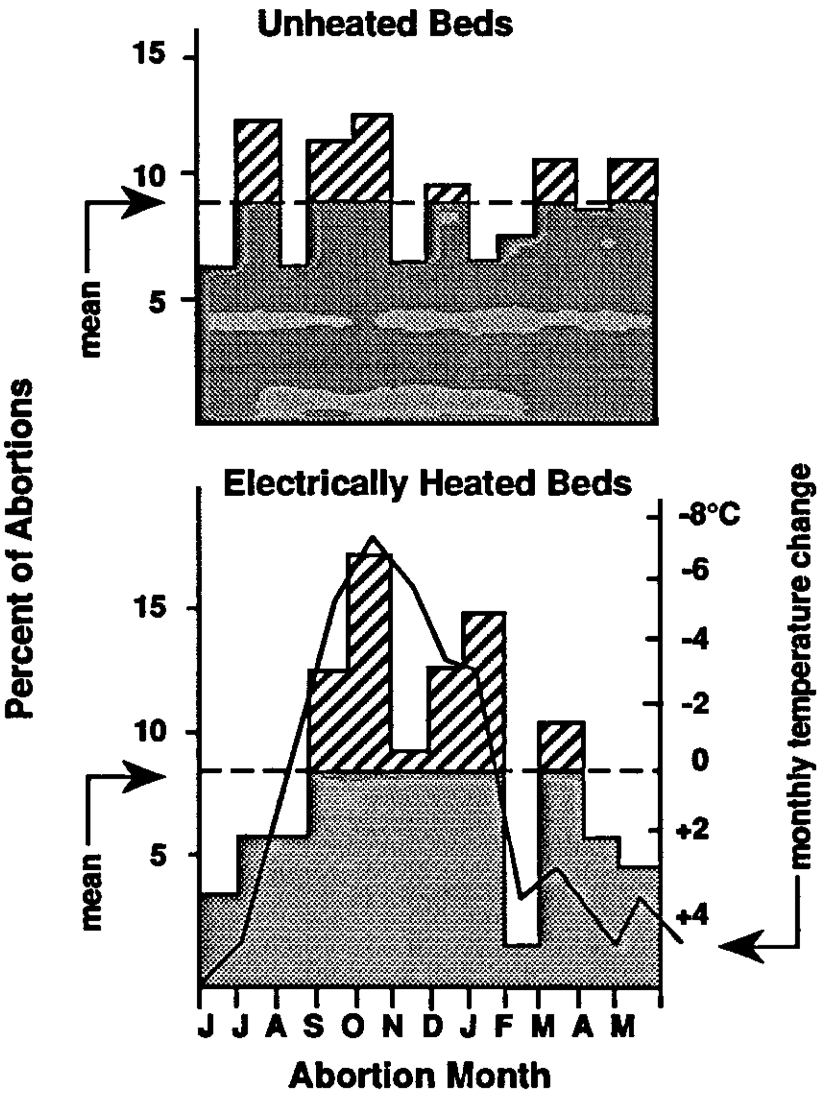


Figure 4. Season of abortion related to monthly changes in mean minimum temperature (Denver, 1976-1982). For users of electrically heated beds, an excess of reported abortions occurs in the winter months, especially in those months when the mean minimum temperature is colder than it was during the preceding month.

Based on Wertheimer (44)

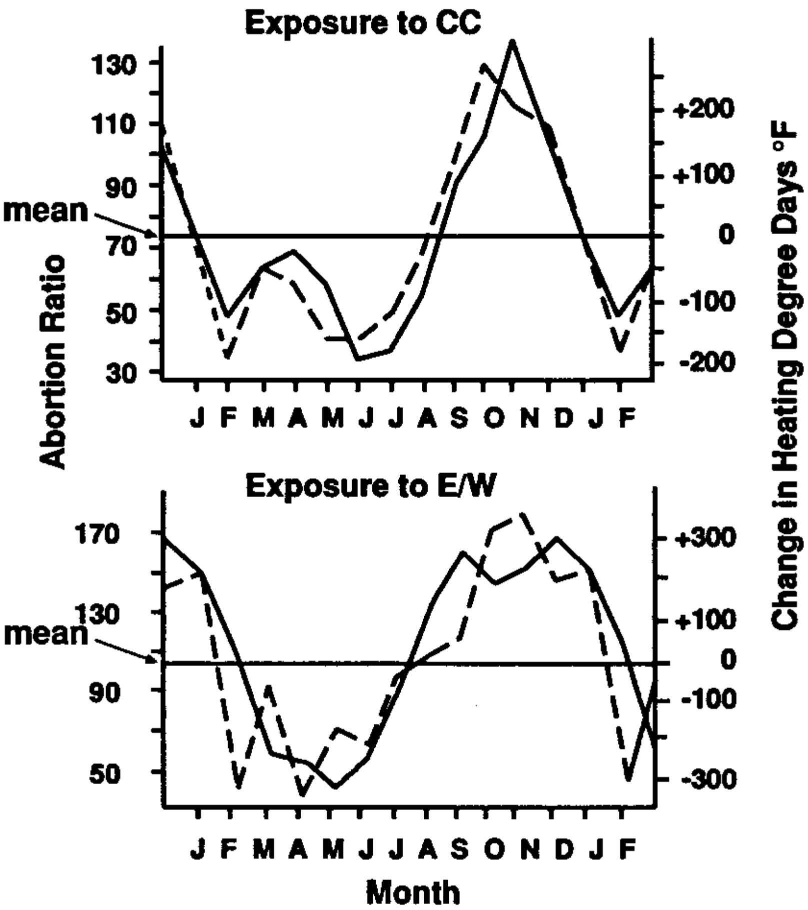


Figure 5. Abortions related to change in temperature. A monthly running ratio of abortions occurring among those exposed to electromagnetic field sources, divided by abortions occurring in unexposed controls, is represented by the solid line. The monthly change in heating degree days (compared with the preceding month) is represented by the broken line. (Note: heating degree days F can be converted to heating degree days C by multiplying by 0.55.) In the top graph, the source of electromagnetic fields is ceiling cable electric heat (CC); in the bottom graph, the exposure source is electric blankets and heated waterbeds (E/W). Increased abortion in each exposed group is highly correlated with months when cold weather is increasing (with a consequent increase of electromagnetic field exposure in the exposed group). *Based on Wertheimer (44)*

Table 7

OUTCOMES OF PREGNANCY IN WIVES OF EXPOSED WORKERS

		low birth weight	spontaneous abortion	perinatal death	congenital malform.
Nordstrom 1983 #46					
Population:	483 electrical utility employees 880 pregnancies				
Exposure:	male employment (determined through questionnaire)	-	-	-	+
Outcome:	answers to questionnaire checked against hospital records				

- negative results
+ positive results

Pregnancy outcomes were checked against hospital records. The outcomes studied were: spontaneous abortions, perinatal deaths, stillbirths and congenital malformations. The authors reported an excess of abnormal pregnancies due mainly to an increase in congenital malformations among couples whose male partner worked in high voltage switch yards . No effects were observed for the other outcomes that were studied.

Infertility of exposed male workers

To look into the potential influence of occupational EMF exposure on workers' fertility, authors have studied several end points such as: number of children, children's sex ratios male/female, difficulty in attaining pregnancy, and azoo and oligo spermia.

Number of children and their sex ratios

In an unpublished report, Roberge (47) reported that in a group of 56 utility workers exposed to 735 kV transmission lines, the children's sex ratio male/female was 1.1 (27/25) before starting work and changed to a ratio of 5.7 (17/3) 4.5 years later (Table 8). In 1979, Knave (48) observed that 53 substations (400 kV) workers had fewer children (mostly boys) than a group of non exposed utility workers, but he attributed this difference to confounding due to higher education

Table 8

INFERTILITY OF EXPOSED MALE WORKERS

Roberge 1976 #47	children sex ratio modified by exposure	
	before	1.1 (27/25)
	after	5.7 (17/3)
Knave 1979 #48	less children among exposed workers (mostly boys)	
Nordstrom 1983 #46	children sex ratio varies somewhat with exposure	
	exposed	0.92 (67/73)
	moderately exposed	1.23 (190/154)
	non exposed	1.16 (167/144)
	exposed workers had more difficulty attaining pregnancy	
Buiatti 1984 #50	azoospermia / oligospermia	
	for radio electric workers	OR 5.89(5) 0.86 - 40.18
Baronocelli 1986 #49	no trend in number of children by exposure categories	

of the exposed men. In 1983, Nordstrom (46) reported that the children's sex ratio male / female in 3 groups of utility workers was as follows: switchyard workers 0.92 (67/73), other exposed workers 1.23 (190/154), non exposed workers 1.16 (167/144). In 1986, Baroncelli (49) studied the number of children among several exposure categories of utility workers and did not observe any difference.

These issues of number of children among exposed utility workers and the sex ratio male/female of these children, have been rather controversial and have contributed little to the question of infertility among exposed workers.

Difficulty in attaining pregnancy

In his study of reproductive hazards among workers at high voltage substations in Sweden, Nordstrom (46) attempted to estimate male infertility by inquiring about the difficulty in attaining pregnancy in couples where the male was exposed during the fertility age. The reported rates of difficulty were as follows: 400 kV switchyard workers 20% (32/164), 380-220 V transmission line workers 19% (12/62), and those exposed to a maximum of 130 kV 6% (2/33). In further analyses, the difficulties in the first group were concentrated among high voltage switchyard workers.

Azoo spermia/oligo spermia

In 1984, in a well structured case control study, Buiatti (50) reported an elevated although not significant azoo spermia and oligo spermia odd ratio of 5.89 (5) CI = 0.86 - 40.18, for radio electric workers. The authors considered this observation very unusual and recommended further investigations. In general, it is reasonable to say that male infertility remains an issue that has not been sufficiently studied so far and should be pursued.

CNS cancers and paternal occupational exposure before birth

Paternal exposure before birth on the development of brain cancer in childhood has been addressed in at least 4 population based case control studies, 2 from Texas by the same research team, 1 from New York State and 1 from Philadelphia (Table 9).

Table 9

CNS CANCER IN CHILDREN AND PARENTAL OCCUPATIONAL EXPOSURE TO EMF / CASE-CONTROL STUDIES

	CASES / CONTROLS	EXPOSURE ASSESSMENT		OR (CASES) CONF. INT.
Spitz, 1985 #51 157 neuroblastoma, < age 15, 1964-78 314 rand. controls from general population Texas	father's occupation on birth certificate	group I: electricians electric & electronics workers, linemen, utility employees, welders		2.14 (13) 0.95-4.82
	elec. equipment salesmen	group II: group I +		2.13 (17) 1.05-4.35
	and repairmen electron. wrkrs			11.75 (6) 1.40-98.55
Nasca, 1988 #52 338 CNS primry cancers < age 15, 1968-77 678 rand. cntrls from gen. population NY state	father's occ. at birth and dx/mother's interview	group I: elec., electron. wrkrs,	brth	1.70 (15) 0.80-3.59
		linemen, welders	dx	1.28 (11) 0.56-2.91
		group II: group I + electric equipment	birth	1.61 (19) 0.83-3.11
		repairmen, utility workers	dx	1.14 (12) 0.53-2.46

Table 9—CNS cancer and parental occupational exposure to EMF / case-control(cont'd)

	CASES / CONTROLS	EXPOSURE ASSESSMENT	OR (CASES) CONF. INT.
Johnson, 1989 #53 499 CNS cancers <age 15, 1964-80 998 rand. cntrls frm gen. population Texas	father's occ. on birth certificate	all ind. with potential EMF exposure	1.64 (25) 0.96-2.82
		- electron. manuf.	3.56 (7) 1.04-12.24
		- elec. and electron.s apparatus manuf.	1.42 (7) 0.54-3.77
		- telephone comm. industry	1.22 (3) 0.29-5.14
		radio & TV ind.	0.68 (1) 0.07-6.54
		- elec. utilities	2.71 (4) 0.60-12.18
		- elec. repair servcs	1.63 (4) 0.44-6.10
		- comp. & off. mach. manufacturing	4.07 (4) 0.74-22.32
		- elec., electron. engineers	0.50 (1) 0.06-4.51
		- radio operators	2.01 (2) 0.28-14.32
		- electrical, electronic apparatus assemblers and mechanics	2.01 (4) 0.50-8.08
		- electron. apparatus assmblrs & mechanics	3.01 (3) 0.50-18.11
		- elec. & electron. assmblrs, installers & mechanics	1.34 (10) 0.60-3.01
		- electricians	3.52 (7) 1.02-12.08
		- const. elec.	10.05 (5) 1.17-86.29
Bunin 1990 #54 104 neuroblastoma 104 random controls	occupation history of both parents telephone interview	group I: as Spitz	1.3 (-) 0.4-4.1
		group II: as Spitz	1.0 (-) 0.4-2.3
		electrical and electronics	
		products workers	1.6 (-) 0.5-6.2
		products assemblers	4.0 (-) 0.4-195.0
		elec. and electron. prod. assmbly wrkrs (both mother & father exposures)	6 cases / 1 control

The number of cases in these studies was fairly large (from 157 to 499); the children were from 0 to 14 years of age. Fathers' occupations were assessed from birth certificates in two studies and from interviews with the mother or father in the other two. Exposure was estimated from fathers' occupation and no direct measurements were carried out.

Most odd ratios in these studies are elevated, several of them reaching statistical significance. The most striking results concern occupations that involve use, repair or manufacture of electrical and electronics equipment; electronics workers; and electricians.

In view of previous studies that have observed an excess of brain cancer among workers exposed to EMF, these studies of the potential relationship between childhood brain cancer and paternal exposure at birth deserve to be repeated and this issue needs to be investigated further.

Childhood cancer and use of electric appliances

Alongside the study of the association between residential exposure and childhood cancer, Savitz (23) interviewed mothers of children about their use of electric appliances before and after the child's birth. His results were published in 1990 (Table 10). After adjustment for income, prenatal electric blanket exposure was associated with a small increase in the incidence of childhood cancer (OR 1.3, CI 0.7 - 2.2) that was more pronounced for leukemia (OR 1.7, CI 0.8 - 3.6) and brain cancer (OR 2.5, CI 1.1 - 5.5).

Table 10

CHILDHOOD CANCER AND PRENATAL EXPOSURE TO ELECTRIC APPLIANCES

		all cancers	leukemia	brain
Savitz 1990 #23				
252 cancers aged 0-14 222 random controls				
exposure by questionnaire	electric blankets	1.3 (0.7-2.2)*	1.7 (0.8-3.6)*	2.5 (1.1-5.5)*
	water beds	0.7 (0.4-1.4)	0.3 (0.1-1.2)	0.5 (0.2-2.0)
multiple controlled analysis	electric clocks	0.8 (0.5-1.2)	0.9 (0.5-1.6)	0.8 (0.4-1.7)
	heating pads	1.1 (0.6-1.9)	0.9 (0.4-2.2)	0.9 (0.4-2.7)

* after adjustment for income

Conclusions on reproduction

The findings on reproduction can be summarized as follows: association between EMF exposure from electric blanket or through exposed spouse on pregnancy outcomes (prolonged gestation period, low birth weight, congenital malformation, spontaneous abortion) has been proposed by some authors, but so few studies have been conducted that this concern remains to be explored further. With regard to male infertility, studies on the number of children and sex ratio of children of exposed workers are probably not worth pursuing. Four studies have addressed this concern and they are either contradictory or totally negative. The issue of difficulty in attaining pregnancy among couples whose men are switchyard workers and the issue of azoo spermia/aligo spermia among workers exposed to elevated fields may be worth pursuing in the context of observations made by Nordstrom (46) and Buiatti (50). The most worrisome observation and the one that deserves careful scrutiny is brain cancer in children of exposed workers or/and children whose parents used electric blankets anteceding their birth.

NEUROPSYCHOLOGICAL EFFECTS

Several epidemiological studies have tried to test the hypothesis raised many years ago by Russian authors of a potential effect of EMF exposure on the nervous system. Most of them are cross sectional studies of workers or residents working or living near and away from electrical sources.

Numerous effects, symptoms and performances in psychological tests have been investigated. Neurasthenic and depressive symptoms, schizophrenic diseases, psychological tests including reaction time, memory, manual dexterity, perceptual speed, medical visits, medicinal consumption, headache, etc. are but a few examples of this myriad of end points observed. A schematic summary of the most important studies is given in Tables 11a and 11b.

Table 11a

PSYCHOLOGICAL AND NEUROLOGICAL EFFECTS OF EXPOSURE TO EMF

			psychological tests											
	medical consultations	medicinal use	reaction time	memory test	manual dexterity	tapping	perceptual speed	overall	headaches	anxiety	obsession	depression	cognitive failure	personality problems
Strumza #55	—	—												
Knave #48			—	—	—	—	—	—						
Broadbent #56	—	—							—	—	—	—	—	—
Baroncelli #49		—								—				
Perry #57												+		+

— negative results
\+ positive results

Except for depression and personality abnormalities among high rise building dwellers reported in one study (57), no differences in psychiatric diseases or psychological abnormalities were observed between exposed and non exposed people. Results are remarkably negative. Knave (48) even reported that performance to psychological tests was better among exposed than non exposed workers, attributing these differences to higher socio-economic and educational levels of men working in high voltage substations. It is

Table 11b

PSYCHOLOGICAL AND NEUROLOGICAL EFFECTS OF EXPOSURE TO EMF

		psychological tests							
	neurasthenic symptoms	reaction time	memory	manual dexterity	perceptual speed	overall	medical visits	medicine use	headaches
Strumza 1970 #55 267 persons living or working within 25 meters of high tension power lines 258 p. liv. or work. > 125 meters of high tension power lines	N/A	N/A	N/A	N/A	N/A	N/A	no	no	N/A
Knave 1979 #48 volunteer workers, cross sectional 53 exposed to 400 kV substations - 53 non exposed from same co.	no	no	better	better	no	better	N/A	N/A	N/A
Broadbent 1985 #56 questionnaire to 390 electric utility workers	no	N/A	N/A	N/A	N/A	N/A	no	no	no
Baroncelli 1986 #49 railway high voltage substation workers / cross sectional exp. # 0 133 1 117 10 153 20 224	no	no	N/A	N/A	no	no	N/A	N/A	N/A
Perry 1988 #57 high rise building dwelling 75 cases (37 near, 38 distant)	yes (depression)								

surprising however, to realize that no study has investigated alteration in sleep patterns among EMF exposed workers. Knowing that EMF may alter the circadian rhythm and may interact with the secretion of melatonine (58), it would seem reasonable to conduct studies on the relationship between sleep pattern and exposure to EMF.

One concern related to the nervous system that has been studied with more attention was suicide (Table 12). Reichmanis (59) examined the association between the act of suicide and estimated EMF field exposure arising from 50 hertz overhead high voltage transmission lines at the residence of 598 suicide victims and controls in the Midlands, England. The addresses of cases and controls were plotted on planemetric maps together with transmission lines. The total electric and magnetic fields attributable to electric lines were estimated from this information for each case and control. There were differences in exposure between cases and controls but no clear association with intensity of exposure.

Table 12

SUICIDE AND EXPOSURE TO EMF

		Exposure Assessment	RR		
Reichmanis 1979 #59	598 suicides (69-76) 598 rand. cntrls stratified by map areas West Midlands, UK	MF est. from maps of electrical equipment	suicide victims more exposed no clear association with MF intensity		
Perry 1981 #60	second analysis of same material	MF measured at 0.5 meter from front door of the residence	cases exp.	305/590	$p < .05$
			controls exp.	257/594	
			cases X	0.087 μT	$p < .05$
			controls X	0.071 μT	
McDowall 1986 #61	8000 prsns residing within 30 mf of source in 1971 followed up to 1983	exp. est. from maps	SMR 75 (8)		
Baris 1990 #62	British occ. mortality data	elec. occ.	for radio/radar mechanics PMR 1.53 (19) .92-2.39		
			for telegraph/radio operators PMR 2.56 (10) 1.23-4.71		

Later, Perry (60), conducted a similar study on the same 598 cases and controls. Measurements of magnetic fields (MF) were carried out at suicide and control addresses. More suicide than control measurements were above the median (278 suicides, 232 controls, $p < 0.01$) and the mean value of measured MF for the suicide address (0.087 μT) was significantly higher than that of the controls (0.071 μT) ($p < 0.05$). Socio-economic factors did not seem to account for this difference.

McDowall (61) followed up 8000 persons in England who were living within 30 meters of electric transmission facilities in 1971. The subjects were traced to 1983 and death certificates were obtained from national records. He found an SMR of 75 (8 observed, CI 32-147) for suicide (5) and "undetermined" deaths (3) combined. For those cases residing within 15 meters of the lines, the SMR was 143 (2 observed, CI 16-516). This study does not provide support for an association between EMF and suicide.

Baris (62) examined mortality from suicide in men with occupations likely to have resulted in exposure to electric and magnetic fields, using the British occupational mortality data from 2 independent decennial supplements (1970-72 and 1979-83). Except for an excessive PMR of 256 (CI 123-471) for telegraph radio operators and 153 (CI 92-239) for radio and radar mechanics in the 1970-72 supplement, no other excess was noted in potentially exposed occupations, even the most exposed ones.

In summary, the evidence linking suicide to EMF exposure is thin. It stems mostly from Reichmanis (59) and Perry's (60) studies. However, the counter evidence from McDowall (61) and Baris (62) is not convincing either. In light of recent experimental studies supporting a plausible biological mechanism through hormonal (melatonine) system, depression and suicide resulting from exposure to EMF remain timely issues.

CONCLUSIONS

With regard to health consequences from exposure to EMF in the working environment, three concerns have been addressed with some consistency by epidemiologists: cancer, reproduction and neuropsychological effects. Of the three, cancer is the one that has raised the most interest. Leukemia, brain cancer and recently breast cancer are three sites where excess risks have been reported among workers engaged in "electrical occupations." Skin melanoma has also been in excess but it is believed to be reflective of a higher socio-economic status of electrical workers. Almost all "electrical occupations" have shown excesses of one cancer or another but no consistent observation has allowed firm conclusions. The size of the excess risk noted so far may seem small but it is to be regarded seriously in view of the poor estimates of exposure used. The real agent responsible for the excesses of cancer observed in "electrical occupations" may be something other than EMF (referred to as confounders by many authors), such as chemical exposures, but this has yet to be demonstrated.

Suspicion was raised of a potential effect of EMF on reproduction. Myriads of end points have been looked at. They encompassed outcomes of pregnancy, male infertility, and childhood cancer resulting from parental exposure. Many observations have yielded positive results. Unfortunately, they stemmed from few and most often from a unique observation and they still need to be confirmed. One of the most disturbing observation is a potential excess of brain cancer among children of parents exposed to EMF during pregnancy.

No neuropsychological effects have been reported among exposed workers. It even was observed that electrical workers performed better on psychological tests. The issues of depression and suicide remain open to more investigation. Sleep pattern should be studied in relation to EMF exposure.

In his critical review of the evidence on low frequency electromagnetic fields and leukemia, Cartwright (63) has referred to it as the "saga so far" and has predicted that the whole issue of adverse health effects of EMF with respect to leukemia, will end, after "many more years of speculation" as having been a dreadful scarecrow. He may be right, with respect to EMF being the causal agent of the cancer excess noted, but one cannot help from recognizing that the evidence points toward the existence of one carcinogenic factor in "electrical occupations and/or environment."

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Occupational Exposure Assessment for Electric and Magnetic Fields in the 10-1000 Hz Frequency Range

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OCCUPATIONAL EXPOSURE ASSESSMENT FOR ELECTRIC AND MAGNETIC FIELDS IN THE 10-1000 Hz FREQUENCY RANGE

INTRODUCTION

Exposure assessment is the determination or estimate of the magnitude, frequency of occurrence and rate of exposure for an individual or group to an agent in the environment. The agents of interest in this case are electric and magnetic fields (EMF) in the extremely low frequency (ELF) range of 10-1000 Hz. There is increasing concern that exposure to ELF electric and magnetic fields may be associated with biologic and health effects. This concern has prompted numerous measurement projects and the development of instrumentation, methodologies, and exposure models: all directed at exposure assessment for EMF. The purpose of this paper is to review the status of EMF exposure assessment research and to identify remaining issues as they relate to occupational exposures. During this period of active research on EMF exposures it is difficult to keep abreast of the results and ramifications of all ongoing and recently completed projects. Rather than serve as a comprehensive catalog of research and results, this paper draws on past and recent results to emphasize the unique aspects of EMF exposures and to highlight research needs.

Characteristics of EMF

Power frequency electric and magnetic fields (EMF) are present wherever electricity is being generated, transmitted or used. Electric fields are related to the voltage (potential difference between two points) on the electric conductors, while magnetic fields are produced by currents (movement of charges in the conductors). Fields are vector quantities characterized by a magnitude, direction, and frequency. The frequency of the fields is determined by the frequency of the source. Electric systems operate such that the magnitude and direction of both voltage and current alternate over time. The power systems in the U.S., Canada and Mexico operate at 60 Hz (cycles per second), while 50 Hz is used elsewhere, including Europe. Fields at other frequencies arise when other power frequencies are used in special equipment or when nonlinear characteristics in electrical devices generate harmonics.

The magnitude of the electric field is directly related to the voltage of the source. Since voltages on field sources remain relatively constant, electric field levels vary from location to location in a predictable manner, but remain essentially constant over time. Electric fields are measured in units of volts/meter (V/m) or kilovolts/meter (kV/m).

Currents within an electrical system or used by equipment vary widely and frequently experience instantaneous, hourly, daily or seasonal variability. Magnetic fields, which are directly related to current levels, are highly variable not only from location to location but also over time at the same location. Magnetic fields are commonly expressed in units of tesla (T) or microtesla (μT). A common unit for magnetic field that has been used historically is the gauss (G) or milligauss (mG) where 1 G is 10^{-4}T or 1 mG = 0.1 μT. (Technically, the magnetic field or H-field is expressed in units of ampere/m (A/m) and the magnetic flux density or B-field is given in terms of tesla (T). For purposes of this paper, the term "magnetic field" refers to the B-field or magnetic flux density and is expressed in gauss or milligauss.)

Special Considerations for EMF Exposure Assessment

Although there is a systematic approach to exposure assessment (1), each environmental agent can present unique problems and ELF fields are no exception. There are numerous factors that make exposure assessment for ELF electric and magnetic fields complex and difficult.

ELF fields are not detectable by humans at levels found in most environments, making indirect assessments of exposure through questionnaires, or other means problematic.

EMF exposure situations are not memorable with the exception of electric blanket use and certain occupational settings. High exposure situations are generally fleeting and localized with little or no recognition of the event by the exposed party.

The lack of accepted definitions of *exposure* and *dose* for EMF leads to uncertainty in what to measure. Defining dose requires an understanding of the mechanism by which the agent interacts with the human body. For EMF, there is no widely accepted, demonstrable mechanism for this interaction. Consequently there is no accepted definition of dose for EMF. Even characterization of physical exposure is difficult. Without a known mechanism there is no guidance as to what attribute of the field should be measured: magnitude, frequency, variation, maximum, etc.

Unlike most other environmental agents, everyone is exposed to EMF to some degree. The presence of these fields in all environments where electric power is used makes exposure pervasive and compounds the difficulty of defining unexposed subjects.

Variety in the extent and magnitude of fields from different sources produces large spatial variations in field levels. For example, in occupational settings, magnetic fields can range from levels above 100 mG near electrical equipment to less than 1 mG in adjacent office areas. Such variation dictates caution in the selection of monitoring location and in the use of measurements to characterize EMF fields in a space.

Perturbation and shielding of the fields make consistent and meaningful measurements of electric field exposure difficult.

Magnetic fields can have substantial temporal variability as a function of power use in and around the environment under study. Equipment may be operated intermittently during the work day. There may be weekly, monthly or other seasonal patterns of use as well as long term changes associated with altered work practices and technologies. This variation of fields over time complicates the assignment and measurement of exposure.

The nature of many jobs requires workers to spend time near one or more pieces of electrical equipment on a sporadic basis. Consequently, the uncertainty introduced by source variation is compounded by subject movement and activity.

All of these factors make the assignment of contemporary, let alone retrospective, EMF exposure even more difficult than for many other environmental agents.

STATE OF KNOWLEDGE

Exposure assessments for ELF fields have utilized point-in-time and long term measurements, in specific locations, personal exposure measurements and surrogates. With the exception of electric utility environments, many of the electric and magnetic field measurements have been anecdotal. Exposure data that are now becoming available indicate that EMF exposures, even within an occupation, are diverse and that measurements made at only a few locations or with a few individuals will not be sufficient to accurately characterize the exposure of a group. The paucity of extensive data at power frequencies in occupations other than those associated with utilities and at other frequencies for all occupations can be attributed to the relatively recent interest in ELF fields as an environmental agent and also to the lack of any clearly demonstrable health effects.

Initial interest in ELF exposures centered on electric fields at power frequencies because of the relatively high levels of these fields near electric transmission facilities and because there are perceivable short term effects from electric fields. However, interest now has shifted to magnetic field exposures at power and other frequencies because of laboratory and epidemiology studies that have suggested possible health effects.

Electric Fields

Characterization of electric fields in the work environment has been mainly limited to the utility industry. Except for those relatively few occupations where high voltage sources are prevalent, electric fields encountered in the workplace have been shown to be similar to residential and non-work exposures.

Environment and Source Characterization

ITT Research (2) measured electric fields in 14 commercial and retail locations in rural Wisconsin and Michigan. The average electric field was 4.8 V/m with a standard deviation of 4.3 V/m. Median electric field was about 3.4 V/m. These values are about one third the values in residences reported in the same study. Power-frequency electric fields near video display terminals (VDT) are about 10 V/m, similar to other appliances (3). However, fields near VDTs are very dependent on the manufacturer and are being reduced in response to increasing public concerns and regulations in Sweden and elsewhere.

Electric fields in areas of occupational exposure near high voltage power transmission facilities have been thoroughly investigated. Levels of unperturbed electric field depend on the voltage class of the equipment, proximity to energized conductors, the presence of conducting objects, and distance above the ground. Typical maximum values for various installations at different system voltages are given in Table 1 and indicate the maximum 60-Hz electric fields in an occupational setting. The levels reported in a survey of utilities in 21 countries are consistent with measurements in U.S. facilities (4, 5). The range of fields in a high-voltage substation or similar facility is very great and a simple exposure metric cannot characterize the fields. For example, in a substation, the electric fields in most areas are considerably reduced from the maximum levels shown in Table 1.

Other occupations besides utility workers that are associated with the proximity to electrical equipment have been assigned electric and magnetic field exposure in various epidemiologic studies. However, until recently there has been a paucity of actual field or exposure measurements for these so-called "electrical worker" categories (6,

7) Bowman et al. performed electric and magnetic field measurements at 114 work sites corresponding to the "electrical worker" occupations that have been presumed to have elevated electric and magnetic field exposures in epidemiologic studies. In this study one or two measurements were taken near the worker and arithmetically averaged to produce a field value for each site. The geometric mean field measured for 67 "electrical worker" environments was 4.6 V/m while measurements in the work areas of four secretaries indicated fields in the range of 2 to 5 V/m. Certain environments related to electrical work did exhibit higher electric field levels: overhead lines for power line workers (n=2), 160 V/m; transmission (n=3) and distribution (n=3) substations for power station operators, 298 V/m and 72 V/m, respectively; and repair shops for radio and TV repairers (n=11), 45 V/m. Electric fields associated with other "electrical worker" environments were found to be comparable with office or residential levels.

Table 1

Range of Maximum Electric Fields Near High Voltage Facilities

	System Voltage (kV)	Transmission Lines (kV/m)	Substations (kV/m)
a) Worldwide (4) Gary et al, 1986			
	330	5	7.5 - 10
	400	3.0 - 11.5	11.0 - 22.5
	500	6.5 - 10	8.5 - 15
	750	8.0 - 15	9.0 - 25
b) US (5) Deno and Zaffanella, 1982			
	23	0.01 - 0.05	
	115	0.1 - 2.0	
	345	2.3 - 5.6	7.5
	500	8	8.5
	765	10	9

Stuchly and Lecuyer (8) measured 60 Hz electric fields near arc welders and found them to be very low (<1 V/m) in most cases. The highest electric field at an operator location was 300 V/m for one device. All others produced fields less than 100 V/m with most less than 1 V/m.

Personal measurements of electric field exposure during the Electric Power Research Institute's (EPRI) EMDEX Project Occupational Study were collected in eight work and three non-work environments and can be considered as indicative of the area where they were recorded subject to limitations discussed below (9). The results are shown in Table 2. The measurements in each environment were analyzed in two ways: first as individual measurements aggregated over all periods in each environment, and second as "partition" means, defined as the arithmetic average of all measurements during a contiguous period in the environment. For example, for the transmission line environment there were 296,892 individual measurements of electric field recorded during 364 partitions or periods in that environment. As expected the transmission line, distribution line and substation environments have the highest measured electric fields with measurements in the office and shop work environments characterized by lower fields. The electric field measurements used to characterize the environments were collected with personal exposure meters and are limited in their interpretation as discussed in a subsequent section. As with other measurements made during the EMDEX Project, the distribution of electric field measurements within the environments is highly skewed and not adequately described by any single statistical descriptor.

Because of different methodologies, it is not possible to compare the area measurements of Bowman et al. (7) for a relatively small number of sites with the environmental characterizations provided by the personal exposure measurements of the EMDEX Project. However, the two investigations are consistent in confirming those environments where high electric fields are present and in indicating a large disparity in fields between these environments and other work environments.

Table 2

Electric Field Distribution for Environments in kV/m: a) by partition mean; b) by all measurements

a) by Partition Mean

Electric Partition Means by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	geo mean
Generation	729	0.001	0.002	0.003	0.005	0.008	0.021	0.595	0.009	0.006
Transmission	364	0.001	0.003	0.006	0.026	0.173	1.897	11.534	0.410	0.035
Distribution	736	0.001	0.002	0.004	0.008	0.032	0.437	2.761	0.076	0.014
Substation	1325	0.001	0.002	0.007	0.020	0.066	0.351	10.261	0.098	0.023
Office	1571	0.001	0.002	0.003	0.004	0.007	0.015	0.064	0.006	0.005
Shop	1052	0.001	0.001	0.003	0.004	0.007	0.015	0.146	0.006	0.005
Travel	3687	0.001	0.001	0.003	0.004	0.007	0.018	0.473	0.007	0.005
Other	1057	0.001	0.001	0.003	0.005	0.008	0.024	0.791	0.010	0.005
Home	1395	0.001	0.002	0.004	0.007	0.011	0.022	0.183	0.009	0.007
Travel (nonwork)	2067	0.001	0.001	0.003	0.004	0.006	0.013	0.319	0.005	0.004
Other (nonwork)	653	0.001	0.001	0.003	0.004	0.008	0.022	1.872	0.015	0.005

b) by 10-Second Measurement distributions

Electric 10-Second Measurements by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	geo mean
Generation	998092	0.001	0.001	0.001	0.003	0.005	0.018	29.174	0.008	0.004
Transmission	296892	0.001	0.001	0.003	0.005	0.029	1.718	78.524	0.444	0.011
Distribution	552040	0.001	0.001	0.003	0.003	0.012	0.272	29.854	0.074	0.006
Substation	1069854	0.001	0.001	0.003	0.005	0.016	0.335	45.186	0.115	0.007
Office	1091882	0.001	0.001	0.003	0.003	0.005	0.016	3.350	0.006	0.003
Shop	629312	0.001	0.001	0.001	0.003	0.005	0.018	2.723	0.006	0.004
Travel	1056530	0.001	0.001	0.001	0.003	0.005	0.018	7.674	0.007	0.003
Other	418614	0.001	0.001	0.003	0.003	0.008	0.025	10.351	0.012	0.004
Home	1371725	0.001	0.001	0.003	0.005	0.010	0.027	3.199	0.009	0.005
Travel (nonwork)	523377	0.001	0.001	0.001	0.003	0.005	0.014	3.428	0.006	0.003
Other (nonwork)	333143	0.001	0.001	0.001	0.003	0.008	0.018	4.842	0.007	0.004

Bracken, 1990 (9)

Personal Exposure Measurements

Measurements made with a conducting vest as a sensor for a personal exposure meter yielded average equivalent fields of 3.7 and 5.7 V/m for grocery or other stores and shopping malls, respectively (10). Electric field exposures for farming near transmission lines were also investigated using the vest (10). Although large electric fields are expected on the right-of-way, the actual time spent in such fields is small. For example, Silva estimated that a 345-kV line with a maximum field of 4.3 kV/m contributes approximately 80 hours per year of exposure in fields above domestic levels (50 V/m). In other words, farmers can experience the peak levels found under transmission lines, but do so only a very small proportion of the time. Modern mechanized equipment with enclosed cabs can also reduce electric field exposures substantially.

Exposure measurements made on high-voltage utility workers in several studies indicate that very little time is spent in fields above 1 kV/m. Bracken (11) found that the median time above 0.4 kV/m was only 13 minutes per day for Bonneville Power Administration workers near 500-kV equipment. For lower voltages, the median time above this threshold field was reduced correspondingly. In this study 295 utility employees wore a small exposure meter and generated 3098 days of exposure data. Measured exposures of 47 electrical workers over 319 days in the United Kingdom showed that the median time spent in fields greater than 0.4 kV/m was about 6 minutes per day or less for all job categories except linemen, who spent a median time of about 9 minutes per day above 0.4 kV/m (12). On average for these workers, 2.1 minutes per day or less was spent in fields greater than 4.5 kV/m. The two studies were consistent in their measurements of overall exposure, in associating higher fields with higher voltages and in emphasizing the relatively small amount of time spent in the maximum fields cited in Table 1. However, even with this small portion of time spent in higher fields, the electric fields that high-voltage workers encounter are definitely discernible from those encountered in an office environment: Time-integrated exposures for the high-voltage workers in the BPA study were two to three orders of magnitude greater than in a control group working inside an office (11).

Using a small 60-Hz dosimeter, Deadman et al. (13) measured occupational exposures over a one week period for 20 utility workers and 16 office workers. The geometric mean of the time integrated weekly exposures during work for the 20 utility workers was 48.3 V/m compared to 4.9 V/m for the office workers. The transmission lineman (n=2, 420 V/m) had the highest geometric mean exposures. These results are consistent with the previous studies that used less sophisticated instrumentation.

Electric field exposure data were collected for 998 electric utility employee volunteers during 2082 workdays as a part of the EPRI EMDEX Project (9). Absolute field levels cannot be placed on the resulting exposures because of limitations in the interpretation of recorded data. However, relative comparisons between job classifications can be made as shown in Figure 1. Because the sample of utility workers was not drawn randomly these results must only be considered suggestive of the industry as a whole.

As with the earlier studies, the electrical occupations of line worker, substation operator and utility electrician, all of whom work near energized high voltage equipment, showed the highest exposures. Utility occupations associated with generation facilities did not exhibit relatively high electric field exposures. Figure 1 also indicates that among those with high electric field exposures the distribution of workday exposures is highly skewed. The arithmetic mean of these distributions can be strongly influenced by a few high exposure days, and thus, may not be an appropriate indicator of central tendency for the group as a whole.

Magnetic Fields

Information on occupational exposures to 60-Hz magnetic fields has increased substantially over the past few years. Initial measurements took the form of point-in-time measurements near specific sources or in general work environments. However, with the advent of more sophisticated computer-based instrumentation and heightened interest in magnetic fields, the amount of data has increased substantially.

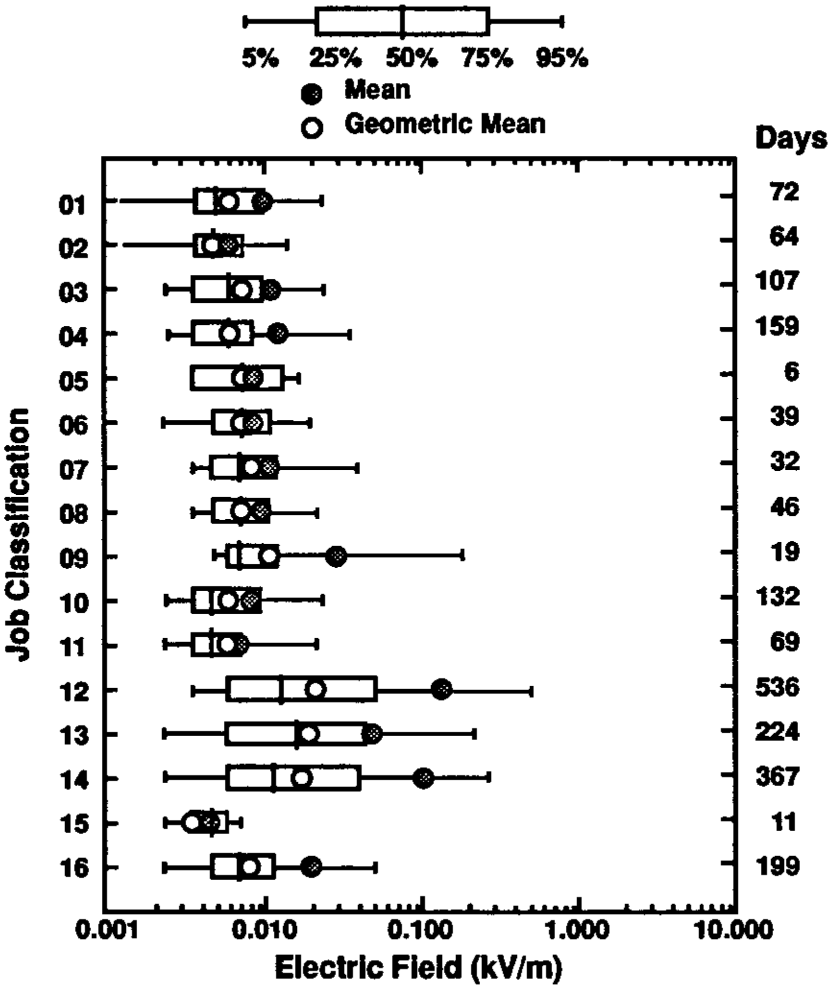


Figure 1. Distributions of electric field workday means by job classification. Arithmetic means can be dependent on a few high values and thus may not be indicative of values for the group as a whole.

Job classification Key:

01 - Mgrs & Supvsrs w/o comp
02 - Mgrs & Supvsrs w/comp
03 - Prof & Tech w/o comp
04 - Prof & Tech w/comp
05 - Cler w/o computer
06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

Environment and Source Characterization

Magnetic fields measured in 14 commercial and retail locations in rural Wisconsin and Michigan had a mean value of 1.1 mG (SD=2.0 mG) (2). Stuchly et al. (14) reported levels of 0.5 and 1.25 mG in a Canadian office and laboratory, respectively. In the same study, 60-Hz magnetic field levels 0.3 m in front of VDTs ranged from 1.5 to 7 mG. (A color television had a measured field of 12.5 mG at 0.3 m.) Measurements near seven VDTs indicated a range of 2.5 to 4.4 mG at 0.3 m from the terminals (15). As with electric fields, the fields near VDTs are very dependent on manufacturer and are being reduced by many manufacturers in newer models.

Lovsund et al. (16) surveyed magnetic fields in the electro-steel and welding industries in Sweden. Steel production with electric furnaces resulted in 50-Hz fields of from 1 to 100 G in work areas. Fields near 50-Hz welding machines exhibited a similar range of values.

Stuchly and Lecuyer (17) measured magnetic fields near 76 induction furnaces, 13 of which operated at frequencies below 1000 Hz. The average operator exposure for all 13 of these units exceeded 29 mG with a high of over 1 G. Given the distribution of operating frequencies for these units, induction furnaces are definitely a potential source of ELF exposures at other frequencies than the power frequency. Stuchly and Lecuyer (8) measured electric and magnetic fields at 60 Hz and its harmonics near 22 arc welders. Magnetic flux densities at six locations on the body of the welder averaged a few tens of mG with a range of 5 mG to 4.4 G. They cited welding machines as a likely source of high occupational magnetic field exposures. Most of the welders had the highest fields at 60 Hz but some produced the strongest fields at 120 and 180 Hz. Typical use of an arc welder entails having a current carrying cable very near the body which can cause very high localized fields.

Electrically powered vehicles are also a potential source of non-power frequency magnetic field exposures in work environments. Magnetic fields associated with an electric traction railway in Germany were reported by Paul et al. (18). The 16.67 Hz fields on a platform directly above the contact wire for the vehicle were in the range of 100-200 mG when a train passed. Preliminary results of an extensive set of measurements on and near an experimental Maglev vehicle in Germany have been reported by Cummings and Robertson (19). At the floor of the vehicle the magnetic fields are in the range of 100-300 mG while at head height they have diminished to less than 10 mG. The frequency of the fields is determined by the excitation frequency for the train which is dependent on vehicle speed.

Stuchly (14) in a review of human exposure to static and time-varying magnetic fields cited several measurements near electric transmission facilities. Four Canadian generating stations exhibited localized magnetic fields of 2.7 G with typical levels ten times lower. In six Canadian substations, maximum fields were in the range of 50 to 180 mG with typical levels of 10 to 50 mG. Fields of 1 to 120 G were reported for locations of possible worker occupation in generating plants in the Federal Republic of Germany. The same study also estimated magnetic fields above a superconducting cable carrying 13 kA were 1.4 G and .45 G for burial depths of 0.75 and 1.4 m, respectively. Bracken (20) reported magnetic field measurements along an inspection route in a 230 kV substation of up to 200 mG with a mean of about 40 mG.

More extensive occupational environment magnetic field measurements have been reported by Bowman et al. (7). The geometric mean field from 105 magnetic field measurements at "electrical worker" job locations was 5.0 mG. "Electrical worker" environments that showed elevated magnetic field levels (i.e., geometric mean greater than 20 mG) were: near industrial power supply for an electrician (n=1), 103 mG; near underground (n=3) and overhead (n=2) lines for powerline workers, 57 and 42 mG, respectively; near ac welding machines for welders (n=4), 41 mG; in transmission (n=3) and distribution (n=3) stations for power station operators, 39 and 29 mG, respectively; and near sputtering systems for electronic assemblers (n=1), 24 mG.

For secretaries in the same Bowman study the geometric mean field was 3.1 mG for those using video display terminals (n=6) and 1.1 mG for those not using VDT's (n=3).

From the limited measurements of Bowman et al. (7), it is clear that elevated magnetic field levels are found in occupational settings both inside and outside the electric utility industry. They also demonstrate that there are some "electrical worker" environments where magnetic field levels are comparable with the lower fields found in the residential or office environment.

Classification of magnetic field personal exposure measurements made during the EMDEX Project according to the environment in which they were recorded produces the results shown in Table 3 (9). As with electric fields, magnetic fields in this study were highest in utility-specific environments. In addition to the transmission line, distribution line and substation environments noted for higher electric fields, the generation facility environment also exhibited elevated magnetic fields relative to other occupational environments.

Sources of fields in the office environment which have been identified but not formally documented are electrical distribution transformers and wiring in vaults that are located inside large office buildings directly below work areas. For large heating, cooling and lighting loads these circuits can carry large currents resulting in relatively high 60 Hz fields (>100 mG) in the space directly above the vault. Such fields are often manifested by interference with VDTs (18).

Personal Exposure Measurements

The availability of small personal exposure meters has resulted in several investigations of occupational magnetic field exposure. In a Canadian study, the geometric mean of the time-weighted average of the weekly work exposure of 20 utility workers was 16.6 mG compared to 1.6 mG for 16 office workers (13). The geometric mean field for the office exposures was comparable to that observed during non-work periods for office workers and comparable to that for both groups during sleep when the exposure meter was not worn. Utility workers in all six of the job categories sampled showed elevated fields compared to a group of office workers. Transmission apparatus electricians (n=3) showed the highest geometric mean exposures, 34 mG. Given that personal exposure measurements tend to be lower than point-in-time measurements and the small numbers of samples involved, the results for the personal exposure measurements (13) and the area measurements (7) appear to be consistent although hardly conclusive.

Bracken (20) estimated the average field for eight transmission substation-operator workdays to be 6 mG based on measurements with a single-axis magnetic field exposure meter. This level was five to six times greater than the average field estimated for 9 office-worker days in the same study.

The results of personal exposure measurements of magnetic field in the EMDEX Project Occupational Study for 1882 utility worker volunteers during 4411 workdays are shown in Figure 2 (9). The jobs associated with utility operations (Jobs 10-14) generally have higher exposures than other occupations. This is most pronounced when the 75th and 95th percentiles of the workday means are compared. In general, the most highly exposed Job Classifications in Figure 2 appear to be substation operators and utility electricians.

The higher exposures for utility-specific occupations are also manifest in the analysis of measurements in occupied environments (Table 3). The tendency for higher exposures in utility-related work environments is true regardless of measure considered (measurements, partition mean or workday mean) and regardless of metric examined (median, arithmetic mean or geometric mean). Although certain combinations of measure and metric exhibit this pattern more dramatically than others, the utility-specific categories tend to be higher than their counterparts for all indices. In a study of telephone worker exposures, Breysse et al. (21) have also examined exposure rank among various telephone worker groups as a function of exposure index.

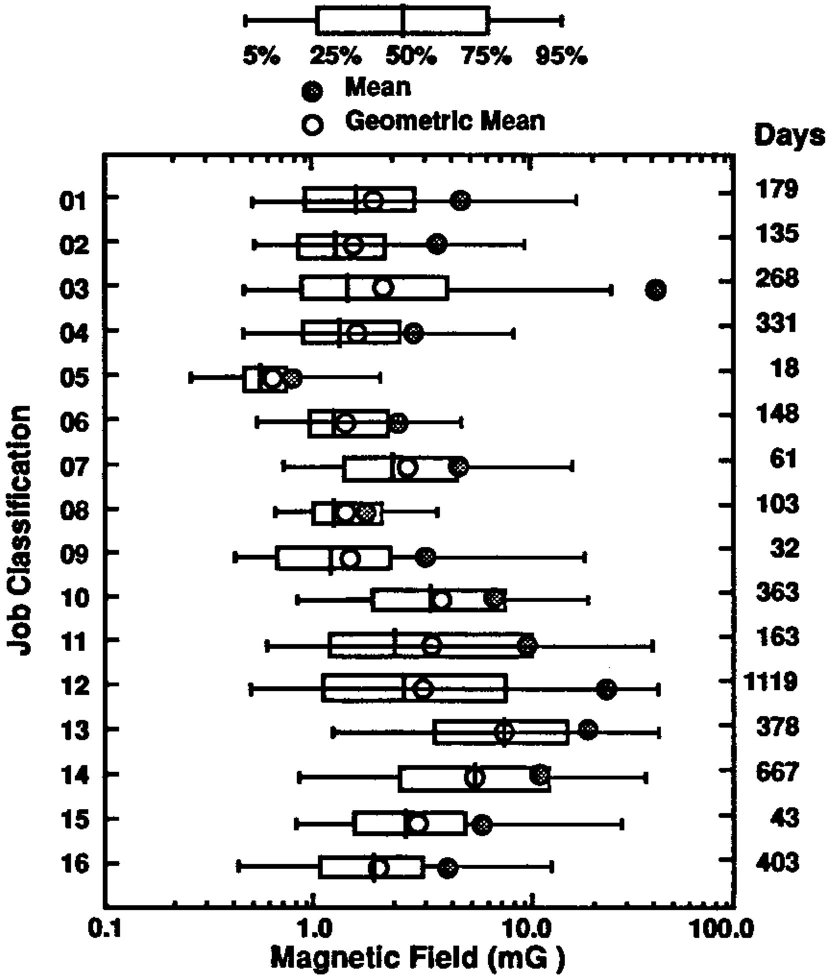


Figure 2. Distributions of magnetic field workday means for job classifications. Arithmetic mean values can be dependent on a few very high readings and thus may not be indicative of measures for the group as a whole.

Job classification Key:

01 - Mgrs & Supvsrs w/o comp
02 - Mgrs & Supvsrs w/comp
03 - Prof & Tech w/o comp
04 - Prof & Tech w/comp
05 - Cler w/o computer
06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

The appropriate choice of metric and summary measure is not clear for EMF exposures.

In the EMDEX Project Occupational Study, the arithmetic mean was used to express daily exposure for volunteers because it has a definite physical meaning: the time averaged exposure for an individual for a day. However, whichever metric and summary measure is selected for exposure data, it is clear that distributions of the quantity will be skewed.

Table 3

Magnetic Field Distributions for Environments in mG
a) by Partition Mean; by All Measurements

a) by Partition Mean

Magnetic Partition Means by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	std dev	geo mean	geo std dev
Generation	1814	0.09	0.51	1.28	2.63	7.04	37.34	1973.99	13.17	75.51	3.25	3.86
Transmission	712	0.15	0.35	1.87	5.98	15.42	61.62	630.56	18.22	50.82	5.44	4.77
Distribution	1771	0.09	0.26	0.66	1.58	6.11	63.68	14386.52	24.56	350.49	2.31	5.55
Substation	2360	0.09	1.09	4.57	10.56	22.06	63.11	26582.43	54.80	886.70	9.87	3.57
Office	3803	0.09	0.30	0.59	0.98	1.76	5.05	274.79	1.81	6.26	1.07	2.39
Shop	2243	0.10	0.30	0.67	1.15	2.16	5.68	244.93	2.45	9.81	1.23	2.60
Travel	7618	0.09	0.46	0.86	1.32	2.16	6.02	21474.04	5.46	247.08	1.44	2.25
Other	2328	0.09	0.25	0.59	1.11	2.43	10.97	1944.48	4.25	43.09	1.26	3.20
Home	3307	0.09	0.21	0.44	0.73	1.33	4.01	489.72	1.63	10.03	0.81	2.51
Travel (nonwork)	4790	0.13	0.45	0.85	1.18	1.67	3.43	388.00	1.61	5.96	1.21	1.88
Other (nonwork)	1494	0.09	0.23	0.53	0.88	1.62	5.03	43.57	1.56	2.55	0.96	2.49

b)by 10-Second Measurement Dstributions

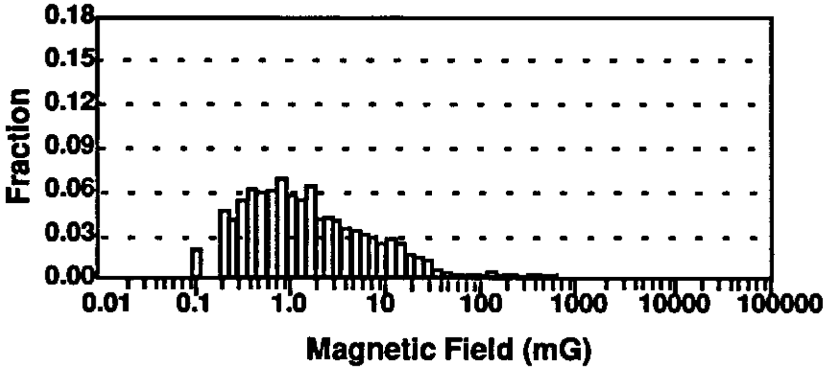
Magnetic 10-Second Measurements by Environment

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	std dev	geo mean	geo std dev
Generation	2365435	0.09	0.22	0.57	1.24	3.51	26.61	42169.65	8.35	117.04	1.55	4.29
Transmission	524275	0.09	0.17	0.60	2.79	11.09	51.88	3672.82	15.70	59.49	2.73	6.22
Distribution	1238612	0.09	0.17	0.38	0.97	3.59	63.83	43151.91	47.38	841.56	1.41	6.59
Substation	1753215	0.09	0.45	2.37	7.00	17.58	59.57	42169.65	34.43	629.49	6.17	4.45
Office	2690502	0.09	0.17	0.43	0.75	1.46	5.96	25409.73	2.07	83.61	0.82	2.84
Shop	1367358	0.09	0.17	0.45	0.88	2.02	6.84	34276.78	2.87	55.67	0.98	3.15
Travel	2056525	0.09	0.17	0.41	0.79	1.76	7.16	36728.23	3.09	139.02	0.88	3.14
Other	879383	0.09	0.17	0.38	0.79	1.97	9.44	25409.73	3.46	91.06	0.93	3.55
Home	3320924	0.09	0.17	0.33	0.61	1.22	4.32	3427.68	1.47	8.73	0.65	2.90
Trvl(nonwrk)	1165844	0.09	0.17	0.38	0.73	1.46	4.73	3845.92	1.56	11.67	0.77	2.86
Othr(nonwrk)	701983	0.09	0.17	0.36	0.61	1.27	5.19	1011.58	1.36	3.24	0.68	2.91

Bracken, 1990 (9)

The skewness of exposures and measurements within a group is demonstrated in Figure 3. The distributions of workday mean exposure and of all measurements collected by volunteers primarily assigned to transmission line environments are shown. These distributions range over several orders of magnitude with most values at low fields. The variability of magnetic field exposure experienced

a) All measurements



b) Workday means

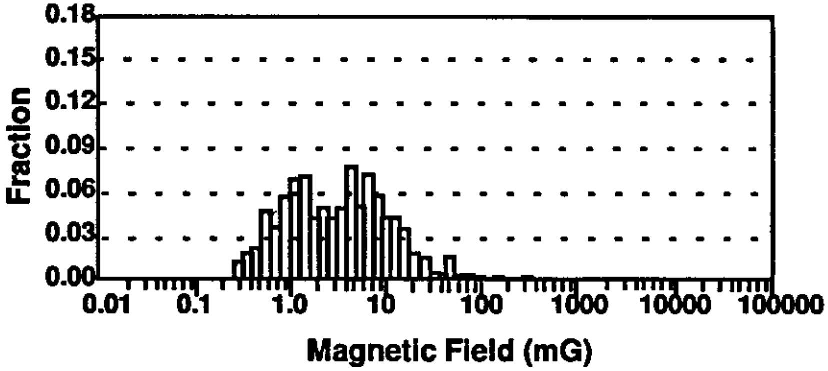


Figure 3. Distributions of magnetic field exposure measurements for workers with transmission lines as a primary work environment: a) all measurements n=1,209,371; b) workday means n = 357 days.

by a DC arc welder during a single workday is displayed in Figure 4. The magnetic field was recorded by an EMDEX worn at the waist of a DC welder operator. Thus, there is a large range of exposures experienced within a day, and even collapsing these measurements into daily means does not eliminate the large range of exposures exhibited by individuals within groups. The skewness of the distributions of exposure measures raises interesting questions as far as presentation and summarization and also has far reaching implications for study design. In particular care must be taken to acquire an adequate and diverse sample for estimating ELF exposures.

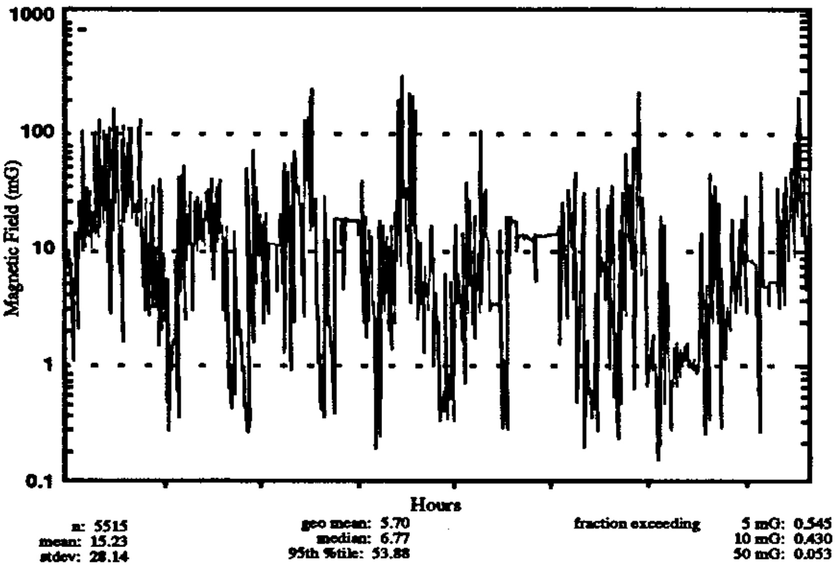


Figure 4. 60 Hz magnetic field exposure measurements for DC welder during workday

Besides indicating the skewness of exposure distributions, the large number of exposure days in the EMDEX study also provided estimates of variance which can be used to determine sample sizes for future exposure assessment studies (9). For example, the number of measurement days required to estimate a single generation facility worker's workday mean exposure to within 5 mG is 29 days; the number of subjects (with 2 days of measurements) required to estimate the workday mean to within 2 mG (5 mG) for generation facility workers is 239 or (39) volunteers.

Instrumentation

Instrumentation for exposure assessment varies with the type of measurement proposed. For point-in-time measurements and source characterization, survey meters are indispensable. They need to be portable, easy to read and reasonably accurate. For personal exposure assessment, light weight and durability are essential. For long-term measurements at a specific location of field variability, stationary recording systems can benefit from multi-sensor capability to simultaneously monitor fields and other parameters in many areas.

Electric field survey meters for area measurements related to exposure assessment are usually of the free-body type (22). The meters are suspended in free space by means of an insulated handle and the current induced between two electrodes (usually the case of the instrument) is detected and visually read by means of an analog or digital display. For accurate readings of the electric field, it is necessary to keep the meter away from the observer and other conducting objects. Although some commercially available meters have band widths of several hundred Hz, they have been designed primarily for use at power frequencies and their harmonics. Measurements over the entire frequency range from 10-1000 Hz require custom instrumentation.

There are numerous hand held magnetic field meters commercially available which can be used for characterizing sources and making point-in-time measurements. Survey meters and personal exposure instruments and survey meters for magnetic field were evaluated and compared at a recent workshop held under the auspices of the IEEE AC Fields Working Group (23).

A personal computer-based measurement system has been developed under EPRI sponsorship that is capable of capturing and analyzing wave forms in the ELF frequency range (24). This type of device, although not portable, does allow recording of data at several locations through the use of multiple probes. Although developed primarily for analyzing magnetic fields, the spectral content of electric fields can also be characterized.

Several small personal exposure meters have been developed for measurement of electric and magnetic field exposures (13, 25, 26, 27). For electric field exposures, these devices, like their survey meter counterparts, sense the electric-field induced current between two conducting surfaces. The induced current is proportional to the incident electric field and is recorded in one of several ways to serve as a measure of exposure. Magnetic fields are sensed with single or multiple coils that generate a voltage proportional to the instantaneous magnetic field. In the case of multiple orthogonal coils, the resultant magnetic field is computed from the square root of the sum of the squares of the fields from the three coils, or with one prototype device, as a true rms superposition of the field components.

Meters that are currently being used in exposure studies employ either microprocessor-based data storage of the fields three orthogonal components (13, 27) or a simple device that integrates the induced current (E-field) or voltage (B-field) over the period the device is worn to produce a single value of time integrated exposure (25, 28).

The EPRI-funded EMDEX (Electric and Magnetic Field Digital Exposure) meter is capable of monitoring and recording electric and magnetic field exposures for extended times (27). The data are stored in the memory of an on-board computer and can be down loaded to a personal computer for viewing and analysis. The EMDEX measures about 15x10x4 cm, has a mass of about 0.45 kg, and is usually worn in a belt-mounted pouch around the waist. The device measures magnetic fields up to 25,000 mG and electric fields up to 500 kV/m. The band width of the EMDEX is 40-400 Hz.

A second version of the EMDEX which is currently in production will measure the maximum as opposed to the resultant field and have the capability to measure harmonics up to 1000 Hz. (28).

Similar in function to the EMDEX is the "ElectroMagnetic Dosimeter" originally developed at the Institute de Recherche d'Hydro-Québec (IREQ) and now available commercially (13). This device measures and records five variables: electric field (50 or 60 Hz), three axes of magnetic field (50 or 60 Hz) and "electromagnetic disturbances" (5-20 MHz). Measurements are classified in 16 amplitude bins along a logarithmic scale covering 84 db. The upper limit of field readings is 40 kV/m for the electric field and about 4000 mG for the magnetic field. The three magnetic field readings are combined into a single bin for the resultant field prior to display and analysis.

The nature of electric fields introduces uncertainty in the electric field measurements made by any of these small exposure meters. The human body acts as a conductor and perturbs the electric field resulting in enhanced fields on certain parts of the body and attenuated fields at other locations on the body. Consequently, the measurement of electric field is fraught with uncertainty — it depends strongly on where the meter is worn, the orientation of the meter with respect to the field source, and the presence of any conductors near the meter. There have been few investigations of the variability of electric field measurements between persons for the same exposure or between days for the same person. The low sensitivity of practical electric field meters combined with the generally low levels of electric field present result in most measurements falling within the lowest scales of possible readings. This restricts the ability to measure or describe differences in exposure. The conversion of electric field measurements at the surface of the body to an equivalent unperturbed electric field is in most cases tenuous at best. Each activity, and even each person, has a different conversion factor and there is no simply exact mechanism to determine a conversion value.

Because of these limitations, reported electric field values should be considered only approximately representative of actual unperturbed field values. It is more appropriate to use electric field exposure measurements for an instrument in a relative sense to compare exposures between categories, rather than to suggest absolute field levels.

In an effort to overcome some of the shortcomings in measuring electric field exposures with exposure meters of small physical dimensions, a conducting vest was used as a sensor to investigate the effects of various activities on exposure measurements (29). However, there are practical constraints to a large scale deployment of such a device.

Exposure Models and Surrogates

As with other environmental agents, direct measures of EMF exposures are not always possible and it is necessary to use modeling or surrogates to estimate contemporary or retrospective exposures.

> Modeling of fields and exposures can be used for several purposes:
>
> - To estimate fields/exposures for situations that have not been measured;
> - To evaluate exposure surrogates; or
> - To construct prior exposures based on current data.

To support the initial research interest in electric fields associated with transmission lines, computer models were developed to calculate these fields. As interest in magnetic fields increased, computations of magnetic field were added. These models have been demonstrated to be accurate and useful because the geometry and currents of transmission lines are simple and the computations of electric and magnetic fields are well understood. Substations and electrical equipment are not as easily analyzed and attempts at computer calculations of fields from these sources for exposure assessment purposes are not tractable. Consequently, estimates of fields in most occupational environments must, of necessity, rely on measurements.

Because of the complex and variable nature of EMF exposure, there can be large differences in exposure during the course of a day, between days for an individual and between individuals within a particular job category. This suggests that accurate assignment of individual exposure through modeling may require time-activity modeling. In this approach it is necessary to consider the uncertainties introduced by both the field measurements and the time estimates. Often the uncertainty in the latter overwhelms the precision of carefully documented field measurements. The need to carefully consider the allocation of time in various occupations is shown in

Figure 5 where the fraction of the workday spent in various environments is shown for the job categories of the EMDEX Project (9). Although the utility worker categories of generation facility operator (Job 10) and lineman (Job 12) are both electrical workers, the generation worker spends over 90% of their time in the generation environment while the lineman spends 50% of their time in high exposure utility-specific areas and approximately 25% of their time traveling.

In examining occupational exposures it is also important to examine exposures in non-work environments encountered by the study of the population. Although occupational exposures are occasionally much higher than exposures encountered elsewhere, the contribution of para-occupational and residential exposures can be significant in many cases. Electric blanket use is one example of significant non-occupational exposure. For the EMDEX Project, the estimated relative contributions of work exposure to total time-integrated magnetic field exposure varied from 17% for clerical workers without a computer to 74% for substation operators (9). The expected contribution from work if all environments have equivalent fields is 27%. Thus, models should account for all significant avenues of exposure appropriately.

Surrogates are parametric or non-parametric schemes that are used to estimate the exposure of an individual to fields. Surrogates can be used to provide information on past, present or future exposure estimates. Appropriate analyses, preferably supported by measurements, link the surrogate to the exposure metric and provide the foundation for use of the surrogate. Surrogates that have been used for EMF occupational exposure measurements include job title, point-in-time measurements, and industry.

To date, one of the shortcomings of EMF exposure assessments has been the lack of confirming measurements for surrogates. There are, however, several research projects that are investigating methods other than personal exposure measurements for assigning exposure and that are verifying existing or proposed surrogate methodologies.

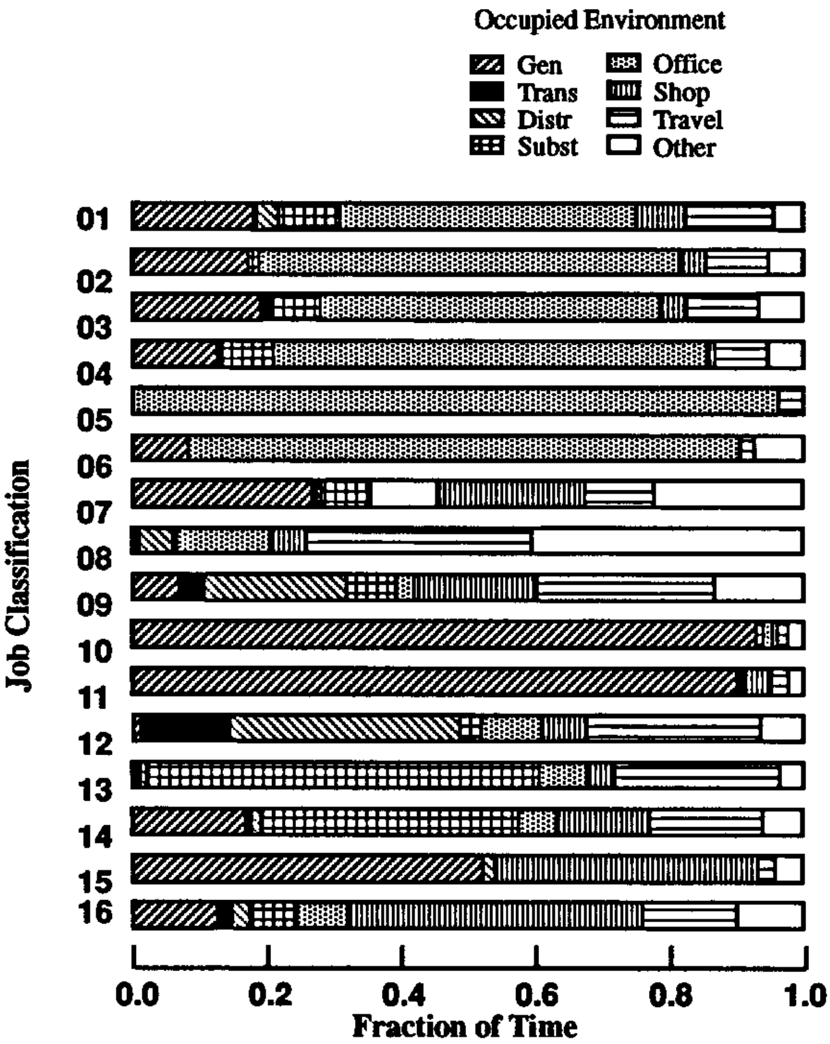


Figure 5. Fraction of workday spent in work environments as a function of job classification

Job classification Key:

01 - Mgrs & Supvsrs w/o comp
02 - Mgrs & Supvsrs w/comp
03 - Prof & Tech w/o comp
04 - Prof & Tech w/comp
05 - Cler w/o computer
06 - Cler w/computer
07 - Support Svce Occ
08 - Outside Cust Svce Op
09 - Drivers and Equip Op
10 - Gen Fac Op
11 - Gen Fac Mech
12 - El Pwr Line Workers
13 - Substation
14 - Electricians
15 - Welders
16 - Other Const Occ

(9) Bracken, 1990

The EMDEX Project analyses of electric and magnetic field exposures by job category (Figures 1 and 2) indicated that certain job titles within the utility industry do experience higher exposures. Similarly, the investigation of exposures for traditional "electrical worker" job titles is indicating that electrical workers as a group do have higher exposures (30). In addition to personal exposure measurements, this study is also utilizing expert panels to determine the time spent in performing various tasks, walk through inspections with point-in-time measurements and area measurements at the work site. The time data will then be combined with area measurements to generate an exposure matrix for each job title. Loomis et al. (31) have compared the results of 8-hour personal exposure measurements for 134 utility workers with the exposure assignments made by a panel of experts on the basis of job title. There was agreement between the ranking of exposures as low, medium, and high by the panel and the measured values thus providing confidence in this method of assigning qualitative exposures.

Ongoing research

There is an active research effort on exposure assessment in the United States and other countries. Of 126 EMF research projects underway, approximately 15 are related to occupational exposures (32). The Electric Power Research Institute (EPRI) is the most active sponsor with five active projects that include an exposure assessment component. These projects include: an assessment of magnetic and electric field exposure by job category (30); a study of telephone linemen to determine leukemia and other cancer risks from EMF (21); an electric and magnetic field measurement project for utilities, the EMDEX Project (33); an epidemiology study of utility workers (34); and an AC field exposure study that includes instrumentation development and modeling (28). Occupational exposure data from the EMDEX Project has just been released and the job category assessment and telephone workers study will be completed soon.

There is an exposure assessment component to a large utility worker epidemiology study being conducted jointly by Ontario Hydro, Hydro Quebec and Eléctricité de France. In this study, exposures will be measured using the IREQ developed personal dosimeter.

Additional EMF occupational exposure assessment projects are underway in Canada, Finland, Netherlands, Sweden, Switzerland, United Kingdom and the United States. There is also an informal group of International EMF Research Managers which meets on an annual basis to exchange information on research planning.

SUMMARY

Over the past decade considerable data have been collected on electric and magnetic fields in occupational environments. These data have taken the form of area measurements, source characterizations, and personal exposure measurements. Occupational EMF levels are highly variable in space and time. Exposures associated with these fields exhibit similar large variations during a day, between days and between individuals within a group. The distribution of exposure measures are skewed over several decades with only a few values occurring at the maximum field levels. The skewness of exposure measures implies that large sample sizes may be required for assessments and that multiple statistical descriptors are preferred to describe individual and group exposures.

Except for the relatively few occupational settings where high voltage sources are prevalent, electric fields encountered in the workplace are probably similar to residential exposures. Consequently, high electric field exposures are essentially limited to utility environments and occupations. Within the electric utility industry, it is definitely possible to identify occupations with high electric field exposures relative to those of office workers or other groups. The highly exposed utility occupations are linemen, substation operators and utility electricians. The distribution of electric field exposures in the utility worker population is very skewed even within a given occupation.

As with electric fields, magnetic fields in the workplace appear to be comparable with residential levels, unless a clearly defined high-current source is present. Since high-current sources are more prevalent than high-voltage sources, environments with relatively high magnetic field exposures encompass a more diverse set of occupations than do those with high electric fields. Within the electric utility industry, it is possible to identify occupational environments with high magnetic field exposure relative to the office environment. Utility job categories with the highest exposures are generation facility workers, substation operators, utility linemen and utility electricians. There are also higher exposures among traditional "electrical worker" job categories.

Outside the electrical utility industry, potential sources of high occupational magnetic field exposures at ELF are induction furnaces, welding machines, electrical transportation systems, and electrical distribution vaults. However, the use of low power electrical equipment such as small motors in close proximity to workers and possibly for long periods of time could also lead to high exposure situations.

Hand held survey instruments are available to perform area measurements at power frequencies but not at all frequencies within the ELF range. Sophisticated personal computer-based instruments are available to characterize areas and sources across the entire frequency range.

Personal exposure meters are commercially available for power frequencies and harmonics up to about 500 Hz. However, conversion of measurements with these devices to absolute electric field values is uncertain. The personal exposure meters, however, can be used to establish relative exposures between groups and individuals.

Exposure models and surrogates for EMF exposure are being developed and traditional exposure assessment methodologies such as job titles, time-activity analyses, and expert panels are being verified. Job title appears to be an indicator of average exposure but because of variability, a complete job history is preferred to a single title for exposure characterization.

The international research effort on EMF includes exposure assessment as well as laboratory and epidemiologic studies.

OUTSTANDING ISSUES

Exposure Metric

Because scientists do not agree on a mechanism for the effects of EMF fields, the choice of the specific agent for exposure assessment remains somewhat arbitrary. Recent epidemiologic studies seem to indicate the importance of magnetic rather than electric fields. However, magnetic and electric fields are correlated and some of the interactions with biological systems are similar, making a distinction between the two difficult. Laboratory research also indicates that effects may be frequency related. Further elucidation of mechanisms is needed before the appropriate choice of agent and, possibly, frequency is clear.

In order to perform an exposure assessment for an environmental agent, an operational definition for measuring the presence of the agent and exposure metric is required. To the extent practical, the exposure metric should be relevant to the effect of the agent on the receptor. For example, the concentration of lead in children's blood would be a better exposure metric for childhood lead poisoning than the presence of lead paint in their homes. There are several possible exposure metrics for EMF exposure. Perhaps the most commonly used has been time-integrated field exposure expressed in terms of kV-hr/m or mG-hr or, equivalently, as an average field in kV/m or mG. However, because there has not been clear evidence of effects related to time integrated exposure, this metric may not be the most appropriate. Numerous other metrics are possible (35).

Determination of an appropriate metric requires additional information from research studies on the effects and interaction mechanisms of ELF fields. However, until direction is available from such research, sufficient exposure data must be obtained to allow characterization in terms of several possible metrics. Identification of a comprehensive set of exposure metrics remains an issue for power frequencies and has not been addressed for other frequencies.

Exposure Indices and Summary Measures

Even without research supporting an exposure metric coupled to effects, it is still possible to develop and investigate exposure indices in the form of summary measures of exposure data or categorical parameters. The choice of exposure index can affect data collection, analyses and interpretation of results. The lack of an accepted mechanism for effects and the nature of EMF fields both argue that the selection of a single summary statistic for characterizing exposure may not be appropriate. Ongoing projects are beginning to investigate the relationship between various summary statistics and non-parametric indices as indicators of exposure (21).

The vast majority of occupational exposures, even among "exposed" groups, occurs at low field levels with relatively little time spent in high fields. In such distributions a few observations in the upper tail of the distribution can be very influential on the time-weighted (arithmetic) mean exposure. Thus, the arithmetic mean may not be a good indicator of central tendency for EMF exposures. Some research suggests that peak, rather than cumulative, exposures are of importance. If this is the case, time above a certain threshold might be a more appropriate summary measure. Obviously, choice of the threshold value would be crucial. Other hypothesized mechanisms could suggest other summary measures.

The uncertainty in identifying meaningful exposures and the skewness of the distributions of measurements argue strongly for utilizing, or at least exploring, more than one parameter to characterize exposure. Establishing relationships between these measures and selecting an optimum set of parameters will require additional research.

Common Protocols

There are numerous reports regarding occupational electric and magnetic field exposure measurements. In addition there are several on-going exposure assessment projects or epidemiologic studies that include exposure assessment. Unfortunately, no minimal set of common protocols has been established to facilitate comparison between studies or allow consolidation of their data. In an area with as much uncertainty as EMF exposure assessment, it is not desirable to establish a fixed exposure assessment protocol that would stifle research. On the other hand, there is a need for a basic set of measurements, analyses, and reports that could be used to link various investigations and facilitate comparison of levels and exposures at various locations.

Historical Exposure Models

Given the uncertainties in ELF exposure assessment and measurements, the extrapolation of contemporary measurements to historical exposures is difficult. Work is in progress to relate electric and magnetic field exposure to job category for electrical workers (36) and to establish the expert panel assessment as a means of determining EMF exposures (31). The results of these efforts should increase confidence in assigning historical exposures, especially among utility workers. However, identifying, quantifying and/or modeling historical exposures for other occupations will remain difficult until considerably more data are gained on non-utility occupational environments.

Database for Non-utility Environments

Several large studies have recently been completed or are currently in progress which will provide extensive data on electric and magnetic fields in utility environments at power frequencies and some harmonics. However, with the possible exception of video display terminals, no other occupational environments have been characterized sufficiently to provide baseline electric and magnetic field data at the frequencies of interest. Given the highly variable nature of ELF exposures, a carefully planned data collection effort will be required for a credible and cost-effective characterization of non-utility environments.

Scaling and Dose

Although exposure refers to the joint occurrence in space and time of a person and an environmental agent, it is important to recognize that exposure assessment, as defined here, is related to *in vivo* and *in vitro* studies. Not only must the exposure in such studies be quantified, but it must also be linked with practical human exposures for the purpose of risk assessment. However, without an accepted mechanism for biological and/or health effects, it is difficult to relate the dose, i.e. the actual amount of the agent that is acting on a biological system, to the exposure that is encountered. Thus, the scaling of exposures from the workplace to the laboratory and vice versa remains an issue for EMF research. Coupled directly to this is the development of dose concepts and models.

Health Effects and Risk Management

Although determination of health effects is outside the realm of exposure assessment, uncertainty about the risk from ELF fields remains the most prominent outstanding issue for exposure assessment. Determination of a mechanism or discovery of a threshold for effects would resolve many of the other issues and allow exposure assessment to more effectively support basic science and epidemiologic research.

ACKNOWLEDGMENTS

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MAGNETIC FIELD MANAGEMENT

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MAGNETIC FIELD MANAGEMENT

INTRODUCTION

Because electrical apparatus is ubiquitous in our modern society and because of the nearly limitless ways that electrical energy is used in these devices, we live and work in an extremely complex electric and magnetic field environment. At low frequencies, the management of the electric and magnetic fields associated with the individual operation of these devices, with all of their attendant spatial and temporal complexities, falls into two comprehensive categories; cancellation and shielding.

Assuming that the on-going biological research will give electrical designers a set of parameters which should not be exceeded in the space near the device which humans will normally occupy, then on first blush, all needed techniques are available and well understood. Therefore, no new R&D would seem to be required and we should be able to redesign, rearrange, or retrofit to meet any emerging electric and magnetic field criteria. Unfortunately, understanding first principles is not sufficient to deliver a viable and practical product.

Before starting the discussion of the effort needed to get from first principles to effective products, it will be useful to review some very basic concepts associated with electric and magnetic fields. While the electromagnetic spectrum is a range of frequency from 0 cycles per second (Hz) to above 10^{20} Hz, the focus of attention of this document will be on the Extremely Low Frequency (ELF) band of 3 Hz to 3000 Hz. In the ELF band, electric and magnetic fields can be treated independently of each other.

Magnetic Fields

The amount of magnetic flux density, as referred to in this discussion, has historically been measured with a unit called the milligauss. However, electrical engineers and physicists have agreed on a different unit, the tesla, as an international standard. These terms have simple scaling relationships between them. One tesla is equal to 10,000 gauss or 10,000,000 milligauss. One tesla is, therefore, a very large field and as such is awkward to use when discussing typical fields found in our environment. In many cases, authors of technical journals frequently use the microtesla which is 1/1,000,000 of a tesla. However, in many older journals, and in most general public literature, the unit milligauss has been chosen when reporting environmental magnetic fields. These units may seem confusing. Therefore, conversion information, as presented below, has been developed to help the reader translate the material given in this text to that given in other presentations and publications. In all cases, the material presented in this discussion will use the milligauss unit and distance measured in feet.

Conversion Between Magnetic Flux Density Units

1 milligauss (mG) = 0.001 gauss (G) = 0.0000001 tesla (T)
1 milligauss (mG) = 0.1 microtesla = 100 Gamma

All magnetic fields are caused by moving electrical charge. In the general case, a moving charge is called an electrical current by engineers and physicists. The unit used to quantify the magnitude of the current is the "ampere". In an electrical circuit, the current in the wires, or conductors, of the circuit produces the magnetic field. In many discussions of fields, the magnetic flux density is used when values are reported. In free space and non-ferromagnetic material, the magnetic field and magnetic flux density are related by a simple constant called the permeability of free space.

All circuits which carry electric currents, from major power lines to the wiring and appliances in homes, produce magnetic fields. The strength of these fields depends on the geometry of the circuit, the amount of current in the conductors of the circuit, and the distance the observer is from the circuit. If the circuit is a single wire and very long relative to the distance to the observer, a very simple equation

$$\mathbf{B = 6.56\ I/r} \qquad (1)$$

gives the magnetic flux density in milligauss. In this equation, **I** is the current in amperes in the wire and **r** is the distance from the wire to the observer measured in feet.

In more complex and typical cases, where more than one current is flowing and the circuit is not either long or simply a straight wire, a general form of an equation taken from classical physics, called the Biot- Savart Law, has to be employed to calculate these magnetic fields.

$$\mathbf{\Delta B = k \frac{I\Delta \times r}{r^3}} \qquad (2)$$

where **k** is constant, **I** is the current in an elemental conductor section Δ, **r** is the distance vector from the elemental conductor section to the observation point, and r is the magnitude of the vector distance [1]. Equation (1) was produced by integrating Equation (2) over an infinite length of a straight wire. There are two other circuit conditions where simple approximations of the Biot-Savart Law have been developed which aid in estimation of magnetic fields. For a point distance from two long parallel wires carrying equal currents but in opposite directions, the following equation gives the magnetic flux density in milligauss

$$\mathbf{B = 6.56\ Id/r^2} \qquad (3)$$

where **d** is the distance of separation between the two wires and is much smaller than **r**. This equation is valid when the observer is at a distance from the set of wires. This particular equation is more useful because it is a helpful model to estimate the magnetic fields from conventional house wiring to transmission and distribution lines. In most house circuits, the current flows into the device through one wire and returns in the second. In modern house wiring, these two current carrying conductors are very close to each other; less than a quarter of an inch separation between the two conductors. For a house circuit carrying a maximum rated load of 20 amperes, just a foot from such a conductor, the fields would be approximately 2.7 milligauss. Moving to a point five feet from this circuit, the field would be only 0.11 milligauss. For this circuit configuration, as the equation shows, the magnetic field diminishes as the inverse square of the distance from the conductor. A similar inverse square relationship exists for transmission line fields.

If we go to the even more commonly considered source of magnetic fields, current flowing in a loop of wire, there is again a relatively simple equation that allows us to calculate the magnetic flux density in the plane of the loop when we are remote from the loop. That equation is

$$\mathbf{B} = \frac{\mathbf{10.31\, I \times a^2}}{\mathbf{r^3}} \qquad \mathbf{(4)}$$

where a is the radius of the loop given in feet. A common example of currents flowing in a coil or wire is the burner on an electric range. For large 8-inch diameter burners with a 3-inch diameter open center and five concentric loops drawing 5 amperes of current, the magnetic flux density would be approximately 14.3 milligauss at one foot from the center and yet only 0.11 milligauss five feet from the burner. In all cases, fields from conductor loops decay very rapidly as you move away from the coil. The equation indicates that the field will diminish as the inverse cube of the distance. In fact, it can be shown that in all regions remote from a current loop, not just in the plane of the loop, the magnetic field decays with the cube of the distance. Therefore, when you move away from a loop of current, the field diminishes rapidly if the dimension of the loop is small relative to the observer's distance from the loop.

These three simplified relationships all stem from applying the Biot-Savart Law to the circuit geometry. The Biot-Savart equation is derived from the Ampere Law, which is one of the group of equations known as Maxwell's Equations for electromagnetic systems. A first principle of the magnetic field resulting from current in a conductor element is that the magnetic field varies inversely with the square of the distance from the conductor element. The changes in direction of the current and therefore the vector relationship of the magnetic field result in cancellation or addition of the magnetic field contributions from other field elements. By combining the fundamental l/r relationship with the mathematical description of the physical configuration of the circuit, the apparent change in exponential decay of field with distance are shown. These equations with different orders of decay, however are, in reality, the result of cancellation or addition effects.

Electric Fields

The electric field intensity, or simply electric field, results from the separation of charge. The usual letter symbol used in technical literature to denote the electric field is "E". In the context of this discussion, energized conductors are the usual source of charge. The unit of measure applied to electric field is Volts/meter or V/m. This is the international standard and also the generally used term in public discussions. However, when discussing electric fields found near very high potential sources such as extra high voltage transmission lines, the prefix "k" for kilo (1000) is generally used so that the unit is expressed in kV/m or 1000 V/m. Some scientific journals report field in Volts/centimeter or V/cm which is 100 V/m.

In many contexts, electric fields are more difficult to quantify than magnetic fields. Basic physics shows that not only are electric fields derived from charge separation but that force is always exerted on these charges.[1] If the charge exists in a medium which permits the charge to move, the medium is considered conductive and the electric field will adjust in magnitude and direction with the movement of the charge. Nearly everything in our environment is conductive and therefore impacts electric fields. At 60 Hz, air has a conductivity of less than 10^{-9} siemens. Metals have conductivities of greater than 10^{7} siemens. The human body has a mid-range conductivity of 1.5 to 0.01 siemens.[2]

The fact that nearly every physical object will distort the electric field makes the control technology very easy. Placing any grounded metallic surface between the electric field source and the subject will, as a practical matter, eliminate the electric field since the conductivity difference between air and metals is greater than 10^{16}, the metals will transport the terminating charge to the metal surface. At ELF frequencies, the metal surface can be as simple and inexpensive as 2 inch mesh chicken wire screen. The shielding efficiencies are greater than 10^4 (see Figure 1).

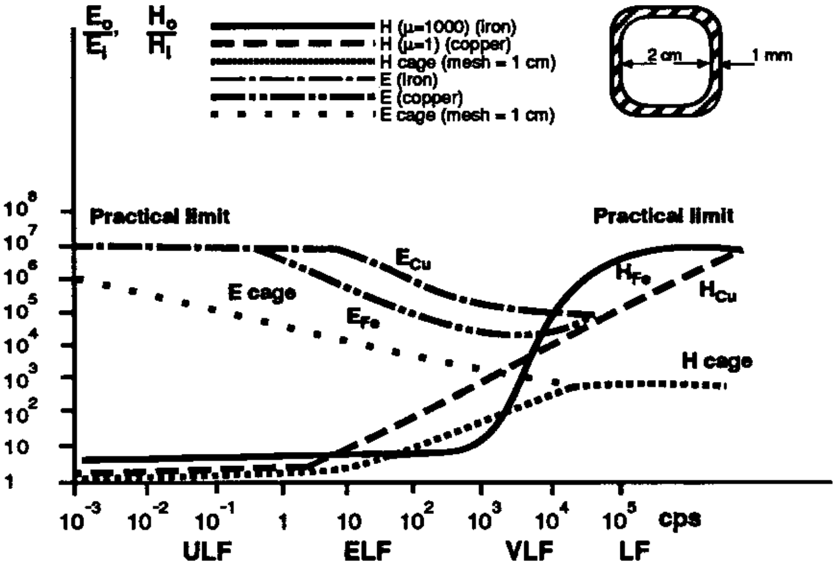


Figure 1. Practical shield factors for electric (Eo/Ei) and magnetic (Ho/Hi). Components at low frequencies for a special box or cage made of copper or steel (r=100 cm; d-0.1 cm; mesh distance 1 cm). The practical limit in respect to theory is due to idealization in the theory (Homogeniety, Smooth Surfaces, Perfect Joints A.S.O.)

Cancellation techniques also work for electric field management. Two conductors carrying charge to and from an electrical device, if placed close together, will effectively cancel the electric field from each individual wire at a remote site. However, for tools and plug-in appliances, a switch-off device may actually have larger electric fields than a switched-on device. This apparent paradox results from the switch breaking only one of the conductor circuits. If the plug is not polarized, there is a 50% chance that the break is in the ground circuit. Therefore the device "floats" to full line potential and an electric field is set up between the device and local grounds. A very common example of this effect is an electric blanket. Of course, for this simple example the fix is simple; just use a two pole switch, *if the application does not violate local code.*

While cancellation techniques work and in some cases are the only practical management technique for electric field control, shielding is usually much easier to apply. The subject can be shielded, such as in the extreme of live-line-maintenance personnel who work on energized extra high voltage conductor systems, or the device can be shielded such as placing a metal shroud around a pad-mount transformer. Since electric field shielding is generally applied as a direct consequence of maintaining electrical safety in the work environment, it is not likely that an extensive effort would be required to further manage electric fields. Therefore, the remainder of this paper will focus on the much more difficult problem of magnetic field management.

CANCELLATION CONSIDERATIONS

Achieving field management or control of magnetic fields below a certain level which may be demanded by the on-going biological research may require a technique with a tremendous dynamic range. For example, in electric power transmission, it has long been recognized that the attenuation of magnetic fields remote from a transmission line relies on the cancellation technique. The phase currents in a given conductor are effectively opposed by the current(s) flowing in the opposite conductor(s), either for single-phase systems or balanced multi-phase systems. Therefore, at distances remote relative to the spacing between the conductors, the magnetic field of one conductor is nearly canceled by the opposite fields created by the current in the other conductor(s). Should the requirement be to reduce magnetic fields at the edges of right-of- ways from 100s of milligauss to tens of milligauss; circuit techniques that have long been understood involving phase positioning in double circuit lines can achieve this cancellation effect. In fact, research at the EPRI-HVTRC facility has shown that a single-circuit transmission line can be constructed to have these same characteristics.[3] However, if the range of reduction required is not by one order of magnitude but by greater than two orders of magnitude, then other much more subtle phenomena must be accommodated. While most transmission line phase currents are nearly balanced, they are in fact always in some state of unbalance. That state of unbalance results in current return paths other than the intended three-phase conductors. This unbalance current return path will generally be through the earth's mantle. Wagner and Evans show that this equivalent depth of return is given by the equation

$$D_e = 2160/f \tag{5}$$

where D_e is in feet.[4] Under normal earth resistivities (=0.01 s) and with transmission lines of lengths from terminal to terminal much greater than the return depth, the effective return path for the unbalance (zero sequence 60 Hz) currents will be at depths of 2800 feet. Third harmonic currents would return at 1600 feet. Such effective return paths for the unbalanced current indicate that cancellation by $1/d^2$ relationship only occurs at great distances from the conductor system. Thus the complication is not the theory of how cancellation works, but is the reality of how electrical systems actually operate and how a system must be designed to operate.

The above example points out the need to examine each field management problem for basic electro-magnetic characteristics before selecting the magnetic field management strategy. Thus, this paper will not attempt to solve problems of controlling magnetic fields of specific devices or apparatus. It will discuss the general nature of magnetic field control problems associated with a variety of electrical apparatus classes.

While transmission and distribution lines are highly focused on by the public, little emphasis will be placed upon electric power transmission and distribution systems. The Electric Power Research Institute

(EPRI), the DOE, and the utility industry are spending considerable effort in evaluating the possible options for reducing magnetic fields associated with both transmission and distribution circuits. The article in Reference [3] gives an excellent discussion of the R&D underway and required to manage power delivery related magnetic fields. Therefore, little effort should be required by NIOSH on power distribution external to buildings.

The principal focus should be on the general category of electrical apparatus found in work sites that have considerable capability for producing magnetic fields. While the general public may not have extensive exposure to any one of these devices, specific classes of workers will find themselves consistently exposed.

Cancellation fields can be set up in some cases with very little cost penalty. In many cases, a principal source of magnetic fields is found to be that which radiates from the conductor systems leading to the tool or power apparatus. In such relatively simple cases, these fields could be canceled via compaction of the conductor systems. For example, a low voltage device, either a 120 or 240 volt service, is typically supplied by a power cord and the fields any distance from the cord are rapidly attenuated by the d^2 relationship. In the situation where the cords or leads have to be very close to the worker, then the added precaution of twisting or interleaving of these leads with each other will further reduce the field. The net effect of twisting a pair of conductors is that each individual conductor appears to occupy the same space. Therefore, the fields are much more effectively canceled because the spacing between the conductors is reduced to nearly zero.

Examples of where this has already been practiced are recent attempts by waterbed manufacturers and electric blanket manufacturers to significantly reduce the magnetic fields produced without impairing the ability of the device to generate heat as required to perform its function. This simple additional step makes it possible to produce devices that have very low magnetic field characteristics and not experience significant cost increase.

Attempting to have the power leads twisted or superimposed with each other relies on the ability of the conductor insulation system to withstand the added electrical stress. Even for the low voltage circuits, compaction must be carefully considered because eventually the insulation could be compromised and create a shock hazard. *Therefore, in exercising magnetic field control technologies, it is extremely important that long established practices for maintaining safety of the device must not be compromised.*

Electrical apparatus that consume considerable energy would generally be supplied by three-phase sources. Compaction may require the use of three- phase cables rather than single-phase cables. If single-phase cables are used, care in bundling of the cables within cable trays and the routing of the cable trays can be a very effective control technology. In many instances where strong fields have been found near transformer vaults in buildings, the source of magnetic field is the cable systems leading to and from the transformer vault.

The magnetic field produced directly from most apparatus exhibits the characteristics of loop current source fields. Therefore, a simple control technique may be to move the device, i.e. a compressor motor in a refrigeration unit, to the back of the unit's housing. This makes use of separation distance and, therefore, the $1/d^3$ characteristic. If the device function does not permit it to be moved, i.e., hand held tools, then more sophisticated and possibly expensive techniques must be employed.

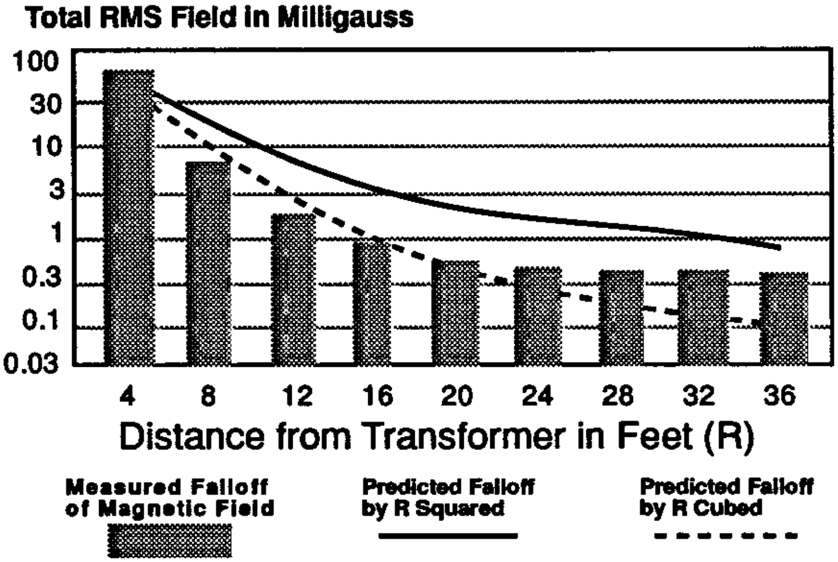
SHIELDING CONSIDERATIONS

Shielding of ELF magnetic fields requires either that: the magnetic fields be diverted around the volume considered to be sensitive to the magnetic fields, or the magnetic fields be contained within the device that produces the fields. Effectively accomplishing shielding at either the source or the subject requires extreme care in choosing the shielding material. The electrical properties of ferromagnetic materials are very complex functions of magnetic field frequencies and magnitudes. For strong magnetic fields, the highly non-linear saturation characteristics of ferromagnetic materials have been widely recognized and reasonably adjusted to achieve source shielding. However, only a few engineers and physicists are aware of the effects of coerciveness at very low magnetizing forces. Subject shielding invariability involves weak magnetic fields. Ferromagnetic materials that are normally considered to have very high permeability may have quite low permeability if being used to attempt to shield milligauss field levels. Thus, the problem of dynamic range encountered when trying to apply cancellation techniques reappears in a different form when attempting to utilize shielding techniques.

In the simplest terms, transformers operating at any power level could be considered devices which offer source shielding. Of course, operation of the transformer is dependent on the control of the flux paths so that the maximum flux linkage between the primary and secondary windings of the transformer is obtained. This control of the flux path is, however, the same as shielding in that the flux is steered or diverted from its normal free-space radiating pattern. Close inspection of the transformer magnetic circuit will reveal that there is still considerable leakage flux in a complex pattern about the coils and the transformer steel. This stray flux or leakage flux from the transformer (whose magnetic circuits are intentionally operated at magnetic flux densities of 11,000 to 14, 000 gauss) would appear to be a strong source of magnetic field even if only a very small percentage is leakage field. However, the electrical conductor paths in a transformer are loops or coils and as shown in the discussion above, at any significant distance (relative to the coil radius) the magnetic field falls off as the cube of distance. Figure 2 shows the results of actual measurements on a 300 kVA pad-mount transformer which supplies a small electronics firm.

When shielding is attempted with ferromagnetic circuits in low field regions, i.e., not the high intensity fields associated with the operation of transformers, motors, or other magnetomotive force devices, the permeability level of the ferromagnetic material may be drastically reduced. The ability of the ferromagnetic material in terms of shunting or shielding is highly dependent on the level of the flux

Figure 2. Lateral Profile of Magnetic Fields from a 300 kVA Pad-Mounted Transformer

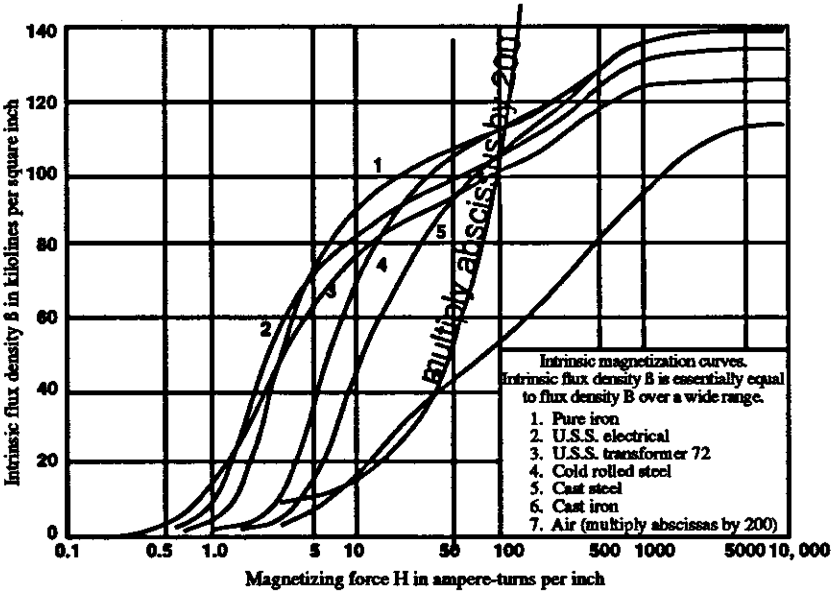


density to be shunted. While it is difficult to find this phenomena discussed with any significant detail in modern literature, Figure 3 from Reference [5] clearly demonstrates this basic characteristic of ferromagnetic metal was documented 60 years ago. Reference 1 merely states that the "initial relative permeability" of iron is 200.

Since magnetic field levels which are being investigated as possible levels of concern are in the order of tens of milligauss, it will be a significant problem to try to shield workers or the public from remote source magnetic fields with local ferromagnetic shielding devices. In fact as Figure 1 from Reference [6] shows, the best shielding from ELF magnetic fields may actually be achieved by non-ferromagnetic high conductive copper rather than by "high mu metal" materials. High mu metal materials have low conductivity, and as shown, for very weak fields, do not have high relative permeability. Copper has a relative permeability of 1, but copper is very conductive and the eddy currents that are set up by the weak magnetic fields in the copper sheet act as cancellation fields. Therefore, copper may be as effective if not more so than the ferromagnetic material. Unfortunately, neither of these are very effective, i.e., the shielding efficiencies are less than 10.

There is a further shielding problem associated with developing shielding devices remote from the magnetic field source. The shield region is actually a very small part of the overall magnetic circuit and, therefore, has very little impact on diverting magnetic fields once the magnetic fields' distance from the device starts to equal the dimension of the device. That is, the reduction in reluctance to the magnetic field's circuit path is minuscule and will have little or no effect on diverting of fields. Therefore, if for instance shielding were attempted along one wall of an office facing a distribution circuit, the shielding would only slightly reduce the field if the person stood directly next to the shield, even if a high permeability could be achieved. When the person moves half the dimension of the wall height away from the wall, the shielding would be trivial.

Figure 3. BH Curves of a Variety of Iron and Steel Products with the Region of Very Low Flux Density Shown.



Based on Wagner and Evans (4)

A further engineering consideration for any control technology using subject shielding is that these techniques would be inordinately expensive. To date, to be effective and practical, shielding is best when applied at the source of the magnetic field. This simple statement is not that easy to achieve because of the tremendous number of devices which exist that produce at least locally high magnetic fields. Achieving redesigns of these devices to manage and control these fields could be extremely expensive and therefore cost prohibitive in many situations. Retrofit to control these magnetic fields would essentially be out of the question in most cases.

There are companies that specialize in developing shielding devices for magnetic field sensitive products such as VDTs. Since reducing the field by an order of magnitude or less may be sufficient to reduce a magnetic field which had been producing visual distortion of the screen, such shielding is effective. However, in terms of getting orders of magnitude reduction, there are really no devices that are seriously proposed for remote shielding that can be utilized.

CONCLUSIONS

Magnetic field management will generally be much more complex than electric field management. While cancellation and shielding are control techniques that can be applied to either electric or magnetic fields, shielding is much more effective for electric fields. The appropriate control technology to apply will depend on: the magnitude of the field to be managed, the percentage of reduction desired, the dominant field being electric or magnetic, the physical characteristics of the source, the function of the source, and the function of the worker relative to the source.

Taking specific steps to managing a particular field environment may not be appropriate until field levels and characteristics (e.g. power frequency levels, degree of polarization, harmonic content, dB/dt transients, 60 Hz level changes, frequencies above ELF concurrent with power frequency levels, etc.) can be set by on-going scientific investigations.

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RESEARCH RECOMMENDATIONS FROM WORKSHOP PANELS

RESEARCH RECOMMENDATIONS FOR *IN VITRO*/CELLULAR MECHANISM STUDIES

INTRODUCTION

The research recommendations for *In Vitro*/Cellular Mechanism Studies are the result of deliberations and discussions of a panel of scientists with expertise in electric and magnetic fields (EMF) research and cellular processes. A focus for panel deliberations was provided by a plenary paper authored by Dr. Stephen Cleary. This paper summarized research results obtained using *in vitro* systems to investigate effects of extremely low frequency EMF on cellular processes. The plenary paper also described the advantages of *in vitro* studies for exploring, evaluating and more thoroughly understanding the underlying cellular interactions with EMF and the possible relationship of these effects to specific diseases in humans. Designing and conducting occupationally relevant *in vitro* studies requires information from other types of studies and disciplines. Addressed at the Workshop were *in vivo* studies, epidemiology, exposure assessment and control technologies. *In vitro* studies are thus one component of a larger effort involving at least four other equally important components. The agenda for *In Vitro*/Cellular Mechanism Studies must therefore involve information generated by other disciplines. This illustrates the need for a coordinated, integrated, interdisciplinary approach to achieve the desired result, namely protection of workers from adverse effects of extremely low frequency EMF exposure.

These research recommendations are included in the following categories:

- Relate *In Vitro* and Workplace Exposures
- EMF Dosimetry for the Cellular Level
- Theoretical Studies and Models
- Reference Criteria
- Research Priorities for Health End Points

RELATE *IN VITRO* AND WORKPLACE EXPOSURES

◆ **Correlate Exposure Parameters for In Vitro Studies with Potentially Harmful Exposures Found in the Workplace**

A detailed occupational exposure assessment must be conducted by qualified individuals in order to provide EMF parameters for *In Vitro*/Cellular Mechanism Studies. This assessment must provide appropriate ranges of the following exposure parameters:

(a) peak and average electric and magnetic field strengths;
(b) fundamental and harmonic frequencies of oscillating fields; frequency spectrum and timed dependence of pulsed or transients;
(c) amplitude and frequency of ambient (background) EMF;
(d) local geomagnetic fields (amplitude, declination); and
(e) concentration or amplitude of physical or chemical factors encountered in the workplace that may serve as confounders or co-stressors.

Occupational exposure assessments should be conducted on the basis of pertinent epidemiological studies linking EMF occupational exposures to specific health effects as well as pertinent existing information (e.g., intensity windows and resonance conditions) presently available from EMF *in vitro* and *in vivo* studies already in the literature.

EMF DOSIMETRY FOR THE CELLULAR LEVEL

◆ **Develop Methods of Occupational Dosimetry which Reflect Exposures at the Cellular Level**

Once appropriate exposure assessments have been conducted, the information must be utilized to construct laboratory exposure systems which duplicate established workplace exposures at the cellular level. For *In Vitro*/Cellular Mechanism Studies this is more complicated than simply exposing cells to the ambient fields described in the exposure assessments. While this might be appropriate for whole animal studies or for potential effects caused directly by the magnetic field, a number of endogenous factors are known to alter the electric field by the time they reach the target organ or cell in question. It is thus imperative that appropriate methods of theoretical and experimental dosimetry be developed and applied to permit accurate extrapolation of occupational EMF exposure levels to exposure at the cellular level.

THEORETICAL STUDIES AND MODELS

◆ Develop Theoretical Models to Clarify Mechanisms

Development of theoretical studies and models with particular emphasis on mechanisms that seem to hold promise (e.g., nonlinear and resonance concepts) must be an important part of this research agenda. These studies and models are necessary because of the multitude of possible experimental exposure parameters, and other conditions which need to be elucidated prior to conducting definitive *In Vitro*/Cellular Mechanism Studies. Theoretical studies are further warranted because of the unique nature of reported EMF biological effects including nonlinear, non-equilibrium phenomena. Theoretical models must provide information for "hypothesis" testing and concurrently reduce the number of experiments necessary to achieve scientifically credible results. Models may be many or singular. A form of theoretical research coupled with actual laboratory studies might be the utilization of a single robust model to examine the importance of specific EMF parameters on selected molecular and cellular processes. The parameters investigated would be occupationally relevant as well as consistent with one or more theoretical mechanisms. Whereas predictions derived from this model might not be directly applicable to an occupational setting, the utility would lie in providing direction and valuable insight regarding the interpretation and assessment of occupationally relevant *in vivo* or *in vitro* studies.

REFERENCE CRITERIA

◆ Develop Reference Criteria for Experimental Design and EMF Field Characterization

To reduce ambiguity and uncertainty in progressing toward a unified understanding of biological actions of EMF, standardized criteria for conducting and reporting the results of *in vitro* studies must be encouraged. This must include means of linking experimental results obtained in one laboratory with those from other laboratories. This can be accomplished by replicate experiments in several laboratories. Specific aspects of a study might be repeated before an investigator moves ahead in testing new hypotheses. Replication of experiments will provide a means of identifying confounders that are responsible for divergent results from different laboratories. Intrinsic to the concept of research reference criteria is the selection of appropriate tissues and cells, complete with rationale. Lastly, the nature of *in vitro* studies indicate the need to control a number of experimental variables. These variables must be considered in developing standardized experimental criteria. Above all, the research criteria should place equal consideration on the selection, control and replication of the EMF parameters as on the importance attached to maintaining and replicating studies of effects on tissues and cells.

RESEARCH PRIORITIES FOR HEALTH END POINTS

◆ Define the Significant Health End Points

From an occupational perspective, the disease of greatest concern with respect to EMF exposure is cancer. In view of this, the highest priority should be assigned to *in vitro* studies which help to define the nature of this problem. This may be accomplished by *in vitro* studies of the effects of occupationally relevant EMF on the proliferation of normal human cells (including immune system cells), and transformed cells. These studies should provide insight regarding EMF-induced cancer promotion and possible immunosuppressive effects; the latter as they relate to the cancer process. Several molecular events/processes intrinsic to cell proliferation and carcinogenesis are amenable to investigations employing *in vitro* techniques. Among these are biomolecular synthesis, intercellular communication, regulation and induction of ornithine decarboxylase, binding and transport of cations (principally Ca^{++}) and other cell membrane-dependent events. Other targets for EMF occupationally induced adverse effects that should be investigated using *in vitro* methods include: the male and female reproductive systems, endocrine and neuroendocrine systems, alterations in fetal development, and non-cancer aspects of immune system function. Regardless of the disease or system being investigated, the focus of *in vitro* research should be on:

(a) mechanisms of interaction of EMF with biological systems;
(b) the delineation of those EMF parameters that may be particularly critical in these interactions;
(c) the physiological consequences of those interactions; and
(d) the relationship to EMF related diseases.

Elucidation of the mechanisms of EMF effects on biological systems and potential health impairment provide a starting point for worker protection and a means of intervening to affect disease outcomes.

RESEARCH RECOMMENDATIONS FOR *IN VIVO* STUDIES

INTRODUCTION

Panel deliberations on *in vivo* research needs evolved from the review of past research in the plenary paper authored by Dr. Larry E. Anderson. Much previous *in vivo* research into effects of extremely low frequency electric and magnetic fields (EMF) has been exploratory in nature. Experiments have been conducted to demonstrate the presence or absence of biological effects, and there have been essentially no theoretical bases concerning likely mechanisms for, or consequences of EMF exposure. Many of the efforts have been pilot studies. Replication has not been attempted frequently, and when it has been attempted, ability to replicate observations has seemed poor. Apparent explanations for this include inadequate characterization and reporting of exposure conditions and insufficient quality control. Many of the research recommendations presented below are directed at resolving these issues.

As determined by this NIOSH assembled panel, some phenomena have emerged which are of sufficient credibility or potential importance to form a basis from which hypotheses can be generated and a logical research agenda can be developed.

One of the most interesting of the biologic phenomena resulting from *in vivo* experiments using EMF exposure is the inhibition of nocturnal melatonin syntheses in the rodent pineal gland, a key finding of considerable importance in its own right. In addition, the pineal gland is closely tied to the central nervous system (CNS). Inhibition of melatonin synthesis forms a basis on which hypotheses can be developed; specifically those regarding plausible mechanisms for epidemiologically observed associations between presumed power frequency EMF exposure and the incidence of cancer. This is especially true for hormone-dependent cancers such as breast cancer, in both males and females, and prostate cancer. Pineal effects also provide a basis for formulating hypotheses relative to the effects of EMF exposure on the development, maturation, and degeneration of critical systems and processes such as those involved in CNS function and mammalian reproduction.

Melatonin inhibition produced by EMF exposure provides a basis for studying the interactions of EMF exposure with factors such as occupation, shift work, trans-meridian travel, sleep disturbance, medication, and age. Changes in calcium ion binding to cell surfaces and changes in the movement of calcium ions across cell membranes are other EMF biological effects that have been repeatedly observed *in vitro* and which might relate to altered melatonin and neurotransmitter synthesis, disturbance of CNS electrical activity, and alteration in cardiac function.

Based on these considerations, the *In Vivo* Panel identified seven major research recommendations. Within each of these areas, specific recommendations were identified.

- Conduct studies with scientific rigor
- Meticulously characterize EMF exposures
- Characterize the critical effects of EMF
- Study neuroendocrine dysfunction produced by EMF
- Conduct definitive studies of the role of EMF in carcinogenesis
- Study reproductive and developmental effects of EMF
- Study cardiovascular effects of EMF

CONDUCT STUDIES WITH SCIENTIFIC RIGOR

As indicated in the Introduction, results from *in vivo* research on EMF usually have not been replicated. Replication has usually not been attempted, and when it has been, the ability to replicate has been poor. The *In Vivo* Panel considered as its first priority the following recommendations to improve reproducibility and credibility of extremely low frequency EMF research and reporting.

- **Design Experiments to Test Specific Hypotheses, Based upon the Best Evidence from Prior Research and Theory.**

- **Define Exposure Regimens Carefully and Thoroughly.**

- **Improve Reproducibility and Validity Through Use of such Methods as Improved Documentation, Quality Assurance, Experienced Personnel, Interlaboratory Studies, and Double-Blind Control Procedures.**

- **Conduct Studies in a Logical Progression Once an Effect has been Established.**

  The critical exposure parameters (electric or magnetic field, field strengths, intermittency, and dose response) should be determined as well as the critical biological parameters (species, age, diurnal variations).

- **Validate *in Vitro* and Epidemiology Findings with *in Vivo* Studies.**

  Effects on calcium ions, alterations in cell to cell communication, malformations in pulsed EMF-exposed chicken eggs, and reports of occupational cancers are examples of phenomena which should be pursued with mammalian *in vivo* experiments.

- **Repeat Studies in Several Species such as Rodent, Primate and Human to Aid in Extrapolation of Findings and to Establish Predictiveness of Animal Data.**

- **Increase Communication between Laboratories, Government Agencies, Workers, and the Concerned Public.**

CHARACTERIZE EMF EXPOSURES

There are many variables of EMF that can be manipulated or controlled in *in vivo* experiments and the *In Vivo* Panel considered the following items of high priority for the conduct, reporting, and interpretation of studies.

- **Use the Latest Available Technology for Exposure Systems.**

- **Require Substantial, and to the Extent Possible, Completely Documented Characterization of EMF Measurements, Including Ambient Fields.**

  The characterization should include:
  (a) electric and magnetic fields and their combinations;
  (b) continuous versus intermittent application;
  (c) field strength and intensity;
  (d) frequency;
  (e) type of field—sinusoidal vs. pulsed; and
  (f) rate of change for pulsed fields (dB/dt)

- **Define EMF Exposure in Relation to Possible Interactions with Biological Rhythms (e.g., Light/Dark Cycle; Shift Work; Extended Workdays; Diurnal CNS Functions such as Mood, Alertness and Task Performance; Variation in Stage of Maturation; and Seasonal Variations in Functions of the Reproductive System).**

CHARACTERIZE CRITICAL EFFECTS OF EMF

Ascertaining of critical effects on which to focus research is essential. While some effects have emerged as the most repeatable and most plausible, none have been well established and fully characterized. The following recommendations are necessary to firmly delineate the critical effects of EMF.

- **Use Scientifically Accepted Methods;**
- **Stress Quality Assurance Procedures, Experimental Design, and Quality Control of Exposures;**
- **Formulate and Test Hypotheses Based on Previous Studies and Theory;**
- **Conduct Studies to Replicate Key Findings;**
- **Determine which Factors of the Exposure Variables are Associated with Biological Effects and Determine Dose-Response Relationships for Those Effects; and**
- **Develop an Understanding of Mechanisms by which Biological Effects Occur.**

NEUROENDOCRINE DYSFUNCTION PRODUCED BY EMF

Reports of neuroendocrine dysfunction have appeared in the literature, but few have been confirmed. The key exposure parameters have not been defined and dose-effect relationships have not been established. Inhibition of melatonin synthesis appears to be an established effect from which linkage to other effects may evolve. In addition, behavioral effects need further attention, as do other effects on the central nervous system, including sleep disturbances. The *In Vivo* Panel recommends the following research on neuroendocrine dysfunction.

- **Characterize Neural, Endocrine, and Neuroendocrine Responses to Power.**

  Endocrine functions need to be confirmed, and extended as appropriate. For example, for melatonin:

  (a) characterize effects in relation to exposure parameters;

(b) determine mechanisms of interaction with species variables, exposure variables, and with other organ systems; and

(c) determine the endocrine linkage to the possible role of EMF in carcinogenesis, immunology, mammalian reproduction, and behavior.

The following additional recommendations are made for research on the nervous system.

- **Conduct Definitive Dose-Response Studies on Behavioral Effects.**

- **Study Central Nervous System Processes such as Short-Term Memory, Arousal, Attention, and Learning, Using Electrophysiologic, Pharmacologic and Other Methods.**

- **Determine the Potential for EMF Exposure to Produce Sleep Disturbances or Alter Mood.**

DEFINITIVE STUDIES OF THE ROLE OF EMF IN CARCINOGENESIS

Several epidemiology studies raise concern for electrical workers, as well as the general population. It is incumbent upon the *in vivo* research community to diligently pursue this issue as per the following recommendations.

- **Conduct *in Vivo* Tests of Tumor Initiation, Promotion and Progression by EMF.**

  (a) concentrate on leukemia, brain, and hormone-dependent tumors;

  (b) use animal models with predictable background tumor incidence;

  (c) design experiments to detect tumors with statistical power that is acceptable by current design standards;

(d) use appropriate, including positive and negative, controls; and

(e) conduct careful dosimetry of tumor initiators, promoters, and EMF.

REPRODUCTIVE AND DEVELOPMENTAL EFFECTS OF EMF

Some human studies, as well as animal studies, have shown effects on reproduction and development. However, many of the studies have been pilot in nature, have used inappropriate models, or might not be relevant to workers. Most studies reporting effects on animal development have utilized chick embryos, a test model which has limited use in predicting human risk but is useful in evaluating mechanisms. Therefore there is a need for further research as follows.

- **Study Potential Reproductive and Developmental Effects of EMF Exposures, Including Mechanisms of Interaction, Using Appropriate Models and Protocols.**

- **Study Shifts in Patterns of Development, Maturation, and Degeneration of Animal Systems such as the Nervous, Reproductive, and Immune Systems.**

CARDIOVASCULAR EFFECTS OF EMF

Effects of EMF on the heart beat of dogs and human subjects have been reported, leading to the following recommendations.

- **Conduct Confirmatory Studies in Humans and Other Animal Species, Especially Primates.**

- **Characterize the Critical Exposure Parameters.**

- **Conduct Mechanistic Studies related to the Effects of EMF on such Phenomena as Calcium Ions and Neurotransmitters and Their Role in Cardiovascular Function.**

RESEARCH RECOMMENDATIONS FOR EPIDEMIOLOGIC STUDIES

INTRODUCTION

Based on the plenary paper by Dr. Gilles Thériault, there are several "generations" of epidemiology studies of workers exposed to electric and magnetic fields (EMF). These studies can be categorized in the following way:

First Generation

Hypothesis generating studies, including proportionate mortality ratio (PMR) analyses of State mortality data and standardized mortality ratio (SMR) analyses of large occupational groups of workers not specifically designed to study EMF.

Second Generation

Hypothesis testing studies with little or no information on exposure. Exposure was mostly defined by job/occupation with expert judgement alone defining exposed groups.

Third Generation

Hypothesis testing with improved data on exposure. Most of these studies are ongoing and involve male utility workers where the exposures are to 60 and 50 Hz fields. The primary hypothesis being tested in these studies is that exposure to such fields is associated with an increase in cancer, especially leukemia and brain cancer.

In light of these previous and ongoing studies, the Epidemiology Panel considered the gaps in occupational epidemiologic studies of EMF, and the types of information that are needed before new studies can be conducted which will contribute new knowledge to the field.

Research Recomendations

The Panel believed there was a need to conduct additional epidemiologic studies especially in occupational groups other than utility workers; and other potential health effects need to be considered besides leukemia and brain cancer. The following recommendations related to the epidemiology of EMF in the workplace were discussed.

- Characterization of exposure
- Health effects/responses of interest
- Methodological issues
- Potential worker populations to study

CHARACTERIZATION OF EXPOSURE

◆ Develop Better Exposure Information

The panel's primary recommendation was the need for better information on exposure. Researchers should consider conducting exposure assessments or surveys of selected occupational groups/jobs in order to characterize their potential for exposure to EMF. This will provide needed information to select highly exposed populations for study. The epidemiologists need to work with those planning the exposure assessments to determine which jobs/occupations need to be characterized. It is important to consider EMF exposures other than 60 and 50 Hz and groups other than male utility workers.

◆ Characterization of Exposure in New Epidemiologic Studies

All new epidemiologic studies should include a characterization of exposure. Lack of good exposure information has been a major gap in most of the epidemiologic studies done to date. Other parameters such a harmonics, resonance, and high frequency transients should also be characterized.

HEALTH EFFECTS/RESPONSES OF INTEREST

The panel prioritized the responses of interest as follows.

- **Cancer — (based on previous study results)**

  (a) Leukemia
  (b) Brain cancer
  (c) Breast cancer (in women and men)
  (d) Malignant melanoma
  (e) Non-Hodgkins lymphoma (NHL)

- **Reproductive Effects**

  (a) Cancer in children of exposed workers
  (b) Adverse pregnancy outcomes (including low birth weight, miscarriage and birth defects)
  (c) Disordered ovulation
  (d) Diminished fertility in men and women
  (e) Sperm abnormalities

- **Other Health Effects - (based on hormonal changes observed experimentally)**

  (a) Sleep disorders
  (b) Behavioral changes (including depression and suicide)
  (c) Motor neuron diseases
  (d) Immunologic changes

- **Non-disease end points and biomarkers**

  The epidemiologist and experimental biologist need to work together to identify relevant biomarkers based on *in vitro* and *in vivo* studies. The issue of melatonin is an example.

METHOLODOLOGICAL ISSUES

◆ **Develop Common Protocols**

Common protocols should be developed for both exposure assessments/characterization as well as the epidemiologic analyses, so that studies can be combined for future meta-analysis. This may be important for obtaining the necessary sample size to address various hypotheses.

◆ **Conduct Multi-center Studies**

Multi-center studies should be considered, so that large enough populations of sufficient size are available for study. This approach is currently being used for some of the ongoing studies of utility workers.

◆ **Use Existing Data Bases to the Extent Possible**

The use of existing databases should be explored. If there are appropriate populations that have been previously studied, they should be further evaluated if exposure to EMF can be documented. For example, a large cohort mortality study of aluminum reduction workers has been conducted, where the effects from magnetic fields have not been evaluated. This population is exposed to strong magnetic fields created by the use of direct current. There are also existing studies of welders that could be reanalyzed. The use of registries that might be used to identify cases for case/control studies should be evaluated. An example of this type of registry is the birth defects registry that has been developed by researchers at the Centers for Disease Control.

◆ **Formulate Appropriate Hypotheses**

Hypotheses need to be well formulated based on previous epidemiologic studies or on laboratory findings, and appropriate study designs need to be planned. For example, incident cancer studies rather than mortality studies should be considered for cancers with a potentially prolonged clinical course, such as breast cancer. This may involve the use of cancer registries.

- **Identify Potential Confounders**

  Potential confounders need to be identified. For the cancer studies, smoking and other occupational exposures may be important, including benzene (for leukemia) and sun rays (for melanoma). Other potential confounders (depending on the population under study) include soldering fumes, solvents, polychlorinated biphenyls, etc. Other factors related to the demographics of the population may be important as well, such as, socio-economic status.

- **Improve Analytical Techniques**

  Analytical techniques need to be improved to control for confounding; and interaction should be examined, e.g. interaction between chemical exposures and EMF exposure, especially if EMF acts as a cancer promoter.

- **Continue Hypothesis Generating Studies**

  Hypothesis generating studies, such as PMR studies based on union or company death benefit records should continue to be pursued. The International Brotherhood of Electrical Workers (IBEW) or Utility company/union records are examples of such study groups. These studies should include as much information as possible on potential exposures, and should only be done to focus or refine hypotheses.

POTENTIAL WORKER POPULATIONS TO STUDY

The goal in any new epidemiologic study is to identify a population with known "high" exposure to EMF. The importance of electric versus magnetic fields is not completely clear at this time. Ideally, it would be preferable to identify a population where a subset is highly exposed, but where there is also significant variation of exposure to EMF with no other confounding exposures.

- **Identify Exposed Women Workers**

  There is a need to identify an exposed population of women workers so that the hypotheses relating to reproductive effects and breast cancer can be addressed.

- **Identify Populations Exposed to Non-Power Line Frequencies**

  Populations exposed to EMF at frequencies other than power line frequencies of 50 and 60 Hz should be studied.

- **Study Rare Diseases**

  Rare diseases of interest require large populations that can be identified through existing data bases such as company personnel or union records.

- **Worker Populations to be Studied**:

  (a) Health care workers especially intensive care unit (ICU) nurses, users of nuclear magnetic resonance instrumentation, and workers involved in shifts that could alter their melatonin levels;
  (b) Welders;
  (c) Aluminum reduction potroom workers;
  (d) Electric railroad workers; and
  (e) Other workers who work around electric machinery/ motors.

Research Recommendations for Exposure Assessment Studies

Recent epidemiologic research has generated substantial scientific interest in the possible association between exposure to electric and magnetic fields (EMF), principally from AC electricity, and adverse health outcomes, such as leukemia and brain cancer. The need for conducting exposure assessments has been emphasized throughout this workshop for three reasons. First, the validity of these epidemiologic studies and the applicability of the results to other worker populations depends, in part, on careful quantification of exposure to electric and magnetic fields. Second, the results of such assessments in worker populations may influence the selection of exposure conditions for *in vitro* and *in vivo* experimental studies. Third, the design and implementation of control measures to reduce worker exposures will rely heavily on the information obtained in conducting such assessments.

There has been considerable progress during the past decade in documenting EMF exposures, primarily in the utility industry. However, much research remains to be done. The Exposure Assessment Panel identified specific research needs in the six general areas suggested by Dr. T. Dan Bracken in his plenary paper.

- Measurement guidelines
- Exposure metrics in epidemiologic studies
- Measurement instrumentation
- EMF dosimetry
- Non-utility sources of exposure
- Worker communication

The specific research needs identified by the Panel are discussed below.

MEASUREMENT GUIDELINES

- **Develop Procedures for Evaluating Worker Exposures**

  The industrial hygienist or health physicist is the health professional most often charged with assessing occupational exposures to electric and magnetic fields. Since their formal training usually has not covered EMF, guidance is needed to assure adequate exposure evaluations. Further, if standardized measurement protocols are used, researchers can compare exposure data from various sources measured by different investigators. Such protocols should specify measurement parameters, such as distances, frequencies, duration and number of measurements, and other physical parameters, similar to the guidance of the Institute of Electrical and Electronics Engineers (IEEE) for measuring electric and magnetic fields near power lines.

- **Develop Procedures for Comprehensive Exposure Assessment**

  Comprehensive EMF measurements should be conducted in research studies to characterize the emissions and exposures from both industrial equipment and consumer products. The data generated should be used in analyzing potential hazards, specifying exposure and dose parameters for biological studies, selecting worker groups for inclusion in epidemiologic investigations, and determining the need for, and types of, control technology required to ameliorate worker exposures. Detailed protocols should be developed to assure comparability of the measurement data. They should include types of measurements to be made, instrumentation requirements, and measurement procedures, including the location and duration of the measurement and the frequency range.

- **Design and Evaluate Training Programs**

  Most health and safety professionals have minimal training, education or experience in assessing EMF exposures. These professionals will require specialized training programs on the basic EMF principles, the possible health effects from EMF exposure, the applicable occupational exposure guidelines, and the standardized measurement protocols. The programs should include instrument demonstrations and laboratory sessions involving measurements of EMF sources, using both survey meters and personal dosimeters, and data analysis should be discussed. Methods for evaluating the effectiveness of these training programs should be developed and implemented.

EXPOSURE METRICS IN EPIDEMIOLOGIC STUDIES

◆ Develop Better Methods for Measuring Exposure in Epidemiologic Studies

Epidemiologic studies often employ only simple exposure hierarchies, such as exposed vs. unexposed occupations. More accurate measurements of worker exposures are needed. Uniformity in conducting exposure assessments will allow researchers to define exposed occupations and job titles more accurately, to identify potential surrogate measures for exposure, and to reconstruct exposures in retrospective studies. This research should also determine whether it is feasible to integrate the results of comprehensive worker exposure assessments into simpler techniques or exposure indices for use in large epidemiologic studies of occupational groups. These simpler methodologies might include questionnaires, expert panel evaluations, job/task classification matrices, or exposure prediction models.

Research is needed to determine the field variables that are thought to have biological significance, and to design instrumentation to measure these variables adequately. For example, some researchers have suggested that the orientation and frequency of the field, in addition to the exposure duration and variability, are significant variables in producing effects in experimental studies. Further, since non-work exposures may be important contributors to total EMF exposure, personal dosimeters should be used to record and store both occupational and non-occupational exposure measurement data over extended time periods. Research is needed on how to analyze measurement data, including summary statistics and exposure prediction models.

MEASUREMENT INSTRUMENTATION

◆ Evaluate Instrument Performance and Develop Quality Assurance Programs

Many companies manufacture both survey instruments and personal dosimeters for measuring electric and magnetic fields. The manufacturers provide specifications on the technical characteristics of their instrumentation, including frequency response, accuracy, dynamic range, isotropic response, and susceptibility to electromagnetic interference. However, an independent assessment of these instruments is needed to assure the user that the instrument will perform according to the manufacturer's specifications and that the measurement data obtained with the instrument are precise and accurate. Such evaluations should be conducted by an independent body (e.g., a government agency) or a university or private laboratory under supervision of an independent organization. The results of this independent testing should be disseminated.

Instrumentation used to assess occupational EMF exposures must be evaluated on a long-term basis. Important operating characteristics (e.g., frequency response, accuracy, and reproducibility) should be tested extensively to determine that the long-term instrument response is stable. Measurement and calibration standards must be developed for manufacturers and testing laboratories to use in quality assurance programs. For data logging instruments, quality assurance measures are needed because of the vast quantity of data that can be accumulated.

◆ Develop and Evaluate Contact Current Meters

Extremely low frequency electric and magnetic fields induce currents in exposed humans. These currents result from the interaction of the field with the body through inductive and capacitive coupling, and the induced current is a measure of the field energy absorbed by the body. Meters will be required for measuring currents induced by both electric and magnetic fields. In addition, the electric field can cause contact currents upon touching any conducting object in the field. These currents may cause shocks and/or burns when a worker touches the object. Thus, an instrument is needed to measure the potential contact currents in the workplace. All current meters must be evaluated to assure that they provide accurate and meaningful measurements of these currents without enhancing the worker's exposure.

- **Develop Instruments for Measuring Transient Fields**

Workers are often exposed to large transient magnetic fields generated by switching currents produced, for example, when equipment is cycled on and off. These transient fields are of short duration, on the order of milliseconds or less, and can not be quantitated adequately by currently-available survey meters. In addition to the peak value of magnetic flux density, the change in this quantity per unit time, dB/dt, also has possible significance for hazard assessment. Personal dosimeters are needed that will measure these transient magnetic fields and their time rate of change. This will allow adequate assessment of occupational exposure to these fields.

EMF DOSIMETRY

- **Develop Modeling Techniques for Dose Assessment**

Present exposure assessment techniques allow the measurement of only electric and magnetic field strength in the environment. These field strength measurements do not determine adequately a worker's EMF exposure. These fields are capacitively and inductively coupled to the worker's body, resulting in the production of both surface and internal induced currents and electric fields. Dosimetric modeling techniques are needed that will estimate the distribution of these currents and electric fields throughout the body, based on measurement of the unperturbed electric and magnetic field strengths and their spatial and temporal variations.

The determination of these induced fields and currents and their distribution in anatomical models of humans is an important phase in the study of mechanisms of interactions between these fields and human tissues and organs. The identification and investigation of these interaction mechanisms is a critical first step in specifying a dose measure for use in both epidemiologic and laboratory studies.

NON-UTILITY SOURCES OF EXPOSURE

♦ Identify and Rank Non-Utility Sources of Exposure

Data are lacking on EMF exposures in non-utility occupations. This research and hazard surveillance would identify sources of exposure in non-utility industries. Criteria should be developed for use in establishing priorities for selection of sources and work places where exposure assessments will be conducted. For example, occupational sources of exposure can be classified according to power consumption, source-worker distance and duration of worker exposure to the source. High priority should be given to industries having high electrical power consumption, equipment operating at high current, and sources near workers. Of particular interest are work places with welding equipment, electrical transportation, large motors and electric furnaces.

After the non-utility sources and work places have been cataloged, exposure assessments should be conducted for these occupations, based on the ranking and the magnitude of the exposed population. More extensive exposure assessments must be carried out according to the measurement guidance discussed above. Particular attention should be given to measuring a worker's exposure over extended durations with personal dosimeters. This will allow tracking of the time history of the exposure intensity, including peak values, fluctuations in the intensity over time, and time-weighted-average values. The results of these assessments can be compared with those from utility occupations and relative exposure rankings among and between the occupational groups can be derived.

- **Determine the Size of the Exposed Population**

Limited exposure measurement data and other factors indicate that workers in different work sites or using different sources may have vastly different exposures. The number of workers exposed to electric and magnetic fields of various magnitudes should be determined for different job titles, occupations, and industries. In conjunction with exposure data, this population information can be used to identify groups for epidemiologic studies and to provide input into determining priorities for designing and implementing control measures.

- **Collect Existing Occupational Exposure Data**

The Electric Power Research Institute (EPRI) and other groups have collected considerable data on worker EMF exposure for a number of occupations in the utility industry. Limited exposure data are also available for occupations and work places in non-utility industries. Recent epidemiologic investigations that have included exposure assessment have been conducted on workers in a number of non-utility occupations. The feasibility and utility of collecting worker exposure data from these studies and other data sources in a central repository for analysis should be evaluated.

WORKER COMMUNICATION

◆ Develop and Validate Ways of Effectively Communicating Exposure Information to Workers

The concepts of electromagnetic fields, their generation, and the resulting worker exposure are complex and difficult to explain in non-technical language. The problem is further complicated by our lack of understanding of the mechanisms by which these fields are absorbed in biological systems and the impact of such exposure on worker health. Thus, providing workers with a perspective on EMF exposure and its attendant risk is a difficult task and requires an understanding of their viewpoints and concerns about EMF exposure. Ways of effectively communicating with workers regarding these concepts and issues must be developed and validated.

RESEARCH RECOMMENDATIONS ON METHODS FOR REDUCING EXPOSURES

INTRODUCTION

The reduction of exposure to electric and magnetic fields (EMF) can be accomplished through the evaluation of existing EMF sources and the causes of these fields, taking steps to reduce their magnitudes and through research and development into control technologies not yet available. Some mechanisms of exposure reduction can be accomplished with available technologies while other approaches will require long term research and development. Accomplishing a reduction in human exposure to low frequency EMF is dependent on a knowledge of what effect the various field parameters have on the relative biological effectiveness of the field. This may include the fields frequency, magnitude or strength, wave form (harmonic content), duration, electric and magnetic components and their phase relationships, etc. It is possible, for example, that a reduction in one field parameter may result in an increase in the magnitude of another parameter with unknown consequences. Without an understanding of the relative importance of the parameters, a comprehensive strategy for exposure reduction is difficult to achieve.

The research recommendations for methods for reducing exposures are the result of discussions of a panel of scientists with experience in EMF controls. The panel began it's discussion following William Feero's paper and plenary presentation on "Magnetic Field Management." The scientists, upon concluding their discussions, identified the following needs.

- Identify and characterize EMF sources
- Review and recommend electrical code changes
- Continue research on field cancellation techniques
- Materials research
- Work practices
- Substitution
- Transient suppression
- Personal protective equipment
- Training and education

A summary of the needs suggested by the panel members is outlined below.

IDENTIFY EMF SOURCES

◆ Identify and Characterize EMF Sources

The identification and characterization of EMF sources are important to any control strategy. Attention should be paid to the magnitude of the EMF as a function of frequency and phase. This information will be useful when determining the effectiveness of the various controls and help to ensure that controlling one portion of the frequency spectrum does not increase fields in other portions of the spectrum.

REVIEW AND RECOMMEND ELECTRICAL CODE CHANGES

◆ Recommend Code Changes to Reduce EMF Exposure

One source of magnetic fields in buildings is multiple ground return paths in building wiring. Multiple grounds are the result of electrical code or maintenance and repair practices that do not consider generation of magnetic fields. The objective of reviewing the electrical code would be to identify:

(a) those sections of the National Electrical Code that are concerned with commercial building grounding systems;
(b) why existing practice has developed to the point it is now; and
(c) how existing practice/code requirements might be altered to reduce occupational exposures to EMF resulting from dispersed neutral return currents in the building's ground system.

Source reduction is a primary approach to reducing exposure to any hazardous physical or chemical agent. Research into computer modeling of magnetic fields from building wiring can offer designs for placement of wires in new construction that would reduce exposures to EMF and would potentially identify mechanisms for reducing existing fields.

- **Develop Safe Installation Practices**

Electrical wiring installation practices should be developed that will lead to lower EMF levels in the workplace. Also, installation practices must be carefully reviewed to ensure installers and users are not placed at increased risk of electrocution, fire or other hazards as a result of changes in wiring practices.

- **Develop Computer EMF Models**

EMF intensities can be estimated with computer models. When computer models are available, recommendations to modify the electrical code to apply these models should be made.

CONTINUE RESEARCH ON FIELD CANCELLATION TECHNIQUES

- **Use Computer Models of Fields to Develop Control Strategies**

EMF intensities can be estimated through the use of mathematical models using principles of electricity and magnetism. Computers could be used to calculate field strengths and test designs of measures to reduce fields. Development and validation of methods is required. Validation, to adequately model building features, may require the construction of laboratory facilities so that experiments can be conducted to determine the number of necessary parameters. The key electrical parameters incorporated into the model(s) and computer simulations can then be adjusted to determine the resulting magnetic field sensitivity to the various parameters.

- **Review Industrial Equipment and Appliance Design to Reduce Exposure**

  The wiring and circuit design of industrial equipment, power tools and office appliances should be examined for methods to reduce EMF. Controls are best implemented during the design and fabrication process. Still, retrofit also may be required.

- **Develop Cancellation Techniques**

  The routing and location of wiring in buildings, tools, appliances and other equipment can result in cancellation of EMF through the interaction of opposing fields. Active or passive methods can be devised that will reduce EMF through phase cancellation. Research and modelling in these techniques is needed.

MATERIALS RESEARCH

- **Develop More Effective Shielding Materials**

  Shielding offers another effective approach to reduce or eliminate exposures from EMF. Electric fields can be reduced or eliminated with the use of conducting materials. Magnetic fields are more difficult to shield, generally requiring more expensive materials, which often must be formed into special shapes and then annealed. The effectiveness of commonly used shielding materials is uncertain at low magnetic field strengths (under 0.5 gauss). Research is needed to develop better materials for shielding from magnetic fields. For example, superconducting materials do not allow magnetic fields to penetrate. Continued research into the development of high temperature superconductors may result in improved magnetic field shielding materials.

WORK PRACTICES

- **Develop Generic Administrative Controls to Reduce Exposure**

  Where cancellation, shielding and personal protective equipment controls are ineffective or impractical, administrative controls of work practices, such as increasing the distance between the worker and the source and minimizing exposure times, should be used. Task redesign and workstation design methods should be developed. Modelling of EMF (once developed, described earlier) should consider the location of workers, work stations, etc., relative to the routing of building wiring and the location of the building's structural steel. There are special situations where it may be impossible to reduce EMF intensities (e.g., substations, cable tunnels, and electrical vaults). When this occurs, robots could be used to do the work. Development of robots for these situations is needed.

SUBSTITUTION

- **Design More Efficient Appliances (Tools, etc.)**

Once EMF sources have been identified, appliances that generate lower EMF should be designed. Also, higher efficiency appliances may have lower field intensities. When this occurs substitution could be recommended (care should be taken to understand the EMF from the substitute).

TRANSIENT SUPPRESSION

- **Reduce Transient EMF**

Large transient EMF intensities can occur when equipment is switched. Modification to a circuit design can often reduce the generation of transient fields. A study of generic approaches to such modifications would be useful.

PERSONAL PROTECTIVE EQUIPMENT

- **Develop Appropriate Personal Protective Equipment**

Personal protective equipment is recommended for use when other control measures are not completely effective or in emergency situations. Personal protective equipment for use in shielding against exposure to EMF is not currently available. Material research results may yield light weight, practical materials that can be fashioned into functional garments.

TRAINING AND EDUCATION

- **Include EMF Source Reduction in Training Curricula**

Training and education are usually not considered control techniques. Still, education of professionals and workers in the concerns associated with exposure to EMF will help to reduce future EMF exposures. Electrical engineering curricula can be used to discuss the sources of EMF and teach concepts that reduce or eliminate them. Therefore, future engineers will design equipment that have low field characteristics. Workers can be taught about the sources of EMF and concepts to reduce their exposure to EMF. Knowledge at all levels can provide the most permanent approach to eliminate the risk associated with EMF exposures.

GLOSSARY OF TERMS ON ELECTRIC AND MAGNETIC FIELDS

Glossary of Terms on Electric and Magnetic Fields

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GLOSSARY

Admittance (Y^+). A ratio of current to voltage which includes information on the relative phase of these quantities. The complex sum of the conductance and the susceptance of a circuit. The reciprocal of the impedance.

Ampere (A). The M.K.S. unit of current, a flow of one coulomb of electric charge per second.

Anisotropy. Having a property which depends upon direction with respect to the structure of the material.

Anode. The positive electrode. The electrode from which positive ions are formed or negative ions are discharged.

Antinode. The position of maximum amplitude in a standing wave.

Arc. A discharge of electricity through a gas.

Beats. Periodic variations that result from the superposition of waves having different frequencies.

Benign Tumor. A noncancerous or nonmalignant growth.

Biphasic. Changing from positive to negative.

Capacitance. The property of a system of conductors and dielectrics which permits the storage of electric charge and electric energy when potential differences exist between the conductors.

Capacitor. An object which stores electric charge and electric energy.

Charge, Electric. Like mass, length, and time, electric charge is a fundamental quantity required to explain measurable forces and is the fundamental unit from which other electromagnetic quantities are developed.

Charge Density. Charge per unit area.

Conductance. The ratio of current to voltage in a circuit which absorbs but does not store electric energy. The reciprocal of resistance. The real part of the admittance. The part of the admittance which is related to loss of electric power.

Conductivity, Real. A property of material which when multiplied by the electric field gives the free current density.

Conductivity, Complex. A property of material which gives the ratio between current density and electric field and includes the phase difference between the two field quantities. When written in polar form ($\sigma^+=\Sigma e^{j\phi}$), Σ is the ratio of the magnitudes of the current density and the electric field and ϕ is the phase difference between them. When expressed in rectangular form ($\sigma^+ = \sigma + j\omega\varepsilon$), the real part (the first term) is the real conductivity and the imaginary term (preceded by $j = \sqrt{-1}$) is the angular frequency $\omega = 2\pi f$ multiplied by the permittivity ε of the material.

Conductivity, Effective Homogeneous. The conductivity of an object viewed as though its dielectric properties were uniform throughout.

Conductor. An object which allows a current of electricity to pass continuously. A wire or combination of wires suitable for carrying current.

Continuous Wave. A time dependent function of constant amplitude, not gated or pulsed.

Corona. A luminous discharge due to ionization of the air surrounding a conductor which occurs when the local electric field exceeds the dielectric strength of air.

Coulomb (C). The M.K.S. unit of electric charge—the basic electrical quantity.

Counterion. A free charge which is held near a fixed or immobilized charge by the requirement of electroneutrality.

Current, Electric. The flow of electric charge.

Current Density. Current per unit area.

dB. Decibel, ten times the logarithm to the base 10 of a power ratio.

Dielectric Constant. A property of material which when multiplied by the permittivity of free space determines the electric energy stored per unit volume per unit electric field.

Dipole. Positive and negative charge bound together in such a way that the center of gravity of the positive charge is separated in space from the center of gravity of the negative charge.

Dipole Moment. The product of charge and separation of charge centers in a dipole.

Discharge. The release of stored charge from a capacitor or a battery.

Dispersion. Frequency dependence—frequently in a quantity which, to a first order, can be considered to be a constant, e.g., the velocity of propagation of electromagnetic waves.

Displacement, Electric (D). A field quantity whose source is in net free charge which has been created by separation of charge.

Electric Field (E). The force at a point in space which would be experienced by a unit electric charge. The gradient (space rate of change) of the work required to move a unit electric charge from one position to a nearby position.

Electrode. An electric conductor for the transfer of charge between an external circuit and a medium.

Electroosmosis. The movement of a charged fluid as the result of the application of an electric field.

Electrophoresis. The movement on ions—usually colloidal ions or cells with net electric surface density—in an electric field.

Electrophosphene. A sensation of light which results from electrical stimulation of the eye.

Electrostatic. A condition in which the electric charges are at rest.

Electromagnetic Interference (EMI). Disturbance in the operation of an electronic device which results from the presence of undesired local electric or magnetic fields.

Epidemiology. The study of the incidence of disease in its natural setting.

Equipotential. A line or surface characterized by a single electric potential or voltage.

Extra-High-Voltage (EHV). When pertaining to transmission lines, values ranging from 240 - 800 kilovolts.

Extremely-Low-Frequency (ELF). In the most limited sense, the frequency range from 30 - 300 Hz. In this work, extremely low frequency has been used for any frequency above zero and less than 300 Hz.

Farad (F). The M.K.S. unit of capacitance.

Ferromagnetic. Having a field dependent permeability somewhat greater than air. Usually ferromagnetic materials have relatively high permeabilities and exhibit hysteresis.

Flashover. Arcing between conductors when the local electric fields exceed the dielectric strength of air.

Gamma. One nanotesla.

Gauss (G). The c.g.s. unit of magnetic field. Replaced by the M.K.S. tesla. One tesla = 10^4 gauss.

Harmonic. An integral multiple of a fundamental frequency.

Hertz (Hz). The unit for frequency—the number of complete cycles of the quantity per second (cycles/second).

Homogeneous. Spatially uniform material properties.

Impedance (Z^+). A ratio of voltage to current which includes information on the relative phase of these quantities. The complex sum of the resistance and the reactance of a circuit. The reciprocal of the admittance.

Induced Currents. Currents which flow in an object as a result of exposure to an electric or magnetic field.

Inhomogeneous. Material properties which are not everywhere the same.

Insulator. A nonconducting material.

Ion. An electrically charged atom or chemical radical.

Joule. Newton-meter, the M.K.S. unit of work.

k. Kilo-. If prefixed to a symbol, it means one thousand (i.e., multiply by 10^3).

Kilovolt/meter (kV/m). One thousand volts per meter.

Meter (m). The M.K.S. unit of length.

m. Milli-. If prefixed to a symbol, it means multiply by 10^{-3}.

M. Mega-. If prefixed to a symbol, it means multiply by 10^6.

Magnetic Field (B). A vector quantity which describes the forces of interaction between electric currents and includes contributions of both macroscopic and microscopic (atomic level) currents.

Magnetic Field Intensity (Magnetic Field Strength) (H). A vector quantity which describes the forces of interaction of macroscopic electric currents.

Mechanism. A quantitative or qualitative model or concept which explains a set of experimental observations.

M.K.S. Meter-kilogram-second, the generally accepted basic units for electromagnetic fields from which all other units are derived.

Monopole. A particle with a single charge.

Monotonic. A function whose slope is either positive or negative but not both.

MV/m. One million volts per meter, megavolts per meter.

n. Nano-. If prefixed to a symbol, it means multiply by 10^{-9}.

Negated. Used here to describe a reported biological effect which was not confirmed on subsequent tests in an independent laboratory.

Newton. The M.K.S. unit of force (one kilogram centimeter per second per second).

Normal. Perpendicular to.

Norton Equivalent Circuit. Representation of an electric circuit as a single current source and shunt impedance.

Oblate. A flattened sphere—in the extreme a disk shaped object.

Octave. A factor of two in frequency.

Ohm. The M.K.S. unit of resistance. One volt across an object with a resistance of one ohm will pass a current of one ampere.

Order of Magnitude. Roughly a factor of ten.

p. Pico-. If prefixed to an electrical unit, it means multiply by 10^{-12}.

p. If prefixed to a chemical symbol, it implies a logarithmic expression of concentration.

Parallel Circuit. An arrangement of circuit elements such that each has the same voltage.

Phase. The measure of the progression of a periodic waveform in time or space from a chosen instant or position. Most high voltage, a.c. transmission lines have three conductors or conductor bundles with the phase of the voltage in each advanced 120° or one-third of a cycle relative to the others. In the vernacular, a conductor is sometimes referred to as a "phase" as in "the outer phase of the line."

Permeability. A property of a material which if multiplied by the magnetic field intensity H gives the magnetic field B.

Permittivity. A property of a material which if multiplied by the electric field E gives the electric displacement D.

Perturbed Electric Field. Modification of an electric field by the presence in it of a conducting object.

Piezoelectricity. A property of certain asymmetric crystalline materials that relates the electric field to the mechanical strain.

Postulate (Hypothesis). A mechanistic predication of the outcome of an experiment. A suggested explanation for a set of observations.

Pressure. Force per unit area.

Potential, Electric. The work required to transport a unit electric charge from a reference position to another position.

Prolate. An elongated sphere—a cigar shaped object.

Relaxation. A process that can be described as an exponential function of time.

Resistance. The ratio of the voltage across an object to the current flowing through it.

Saw-Tooth Wave. A time-dependent function consisting of a series of alternating increasing and decreasing ramps.

Series Circuit. An arrangement of circuit elements such that each has the same current.

Siemen (Siemen/meter). The M.K.S. unit of conductance (conductivity).

Short-Circuit. Loaded with zero resistance or impedance.

Square Wave. A time-dependent function consisting of a series of discontinuous changes.

Susceptance. The ratio of current to voltage in a nondissipative circuit. That part of the admittance which is related to the storage of electric energy.

Tesla (T). The M.K.S. unit of magnetic field.

Thevenin Equivalent Circuit. The representation of a circuit as a single voltage source and series resistance.

Ultra-High-Frequency (UHF). 300-3000 MHz.

Ultra-High-Voltage (UHV). Above 800,000 volts.

Vector. A quantity which has both direction and magnitude.

Very High Frequency (VHF). 30-300 MHz

Volt (V). The M.K.S. unit of voltage or potential.

Volt/meter (V/m). The M.K.S. unit of electric field.

Voltage—Voltage Difference. The electric potential—the work required to transport a unit electric charge from one point to another.

Watt. One joule per second, the M.K.S. unit of power.

μ. Micro-. If prefixed to a symbol, it means one-millionth (i.e., multiply by 10^{-6}).

$\neq$. Not equal to.