Biological Effects of Static and Low Frequency Electro- Magnetic Fields: An Overview of United States Literature

**Richard D. Phillips
William T. Kaune**

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on the Biological Effects of Static and Low-
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BIOLOGICAL EFFECTS OF STATIC AND LOW-FREQUENCY
ELECTROMAGNETIC FIELDS: AN OVERVIEW OF UNITED STATES LITERATURE

by

Richard D. Phillips and William T. Kaune

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Battelle

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PREFACE

This document was prepared for the US/USSR Scientific Exchange Program, Problem IV, Topic 2 on the Biological Effects of Static and Low-Frequency Electromagnetic Fields. The purpose of the exchange is to evaluate current knowledge and to develop cooperative research programs with the Soviet Union to assess the possible health hazards of exposure to static and low-frequency electromagnetic fields. Following an exchange of national literature surveys, of which this document is a part, there will be an exchange of visits by experts of both countries. Six experts from each country will then meet in a joint workshop to review the state of knowledge and current research on this topic and propose a cooperative research program to solve unanswered problems. The cooperative research program proposed at the joint workshop will be initiated in 1978.

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INTRODUCTION

There has been a rapid growth of power and communication systems in the United States over the last several decades and this growth is expected to continue. With this growth there has been an increasing level of static and low frequency electromagnetic fields to which people and other life forms may be exposed. Recently, questions have been raised concerning possible deleterious effects of exposure to such fields. Of particular concern has been the large electric, low magnetic fields in the vicinity of power transmission systems and the small electric and magnetic fields produced by communication systems. In recognition of this concern and need for definitive information, a number of new research projects have been initiated to assess the potential biological effects of static and low-frequency electromagnetic fields. The goal is to supplement our current knowledge and obtain a scientifically sound data base for establishing reliable and valid exposure limits in order to insure public safety and health.

Several major symposiums and reviews of the literature on the biological effects of static and low-frequency electromagnetic fields have been published in recent years (Bridges, 1975a,b; Sheppard and Eisenbud, 1977; Liboff and Rinaldi, 1974; Llaurodo, Sances and Battocletti, 1974; Persinger, 1974; Kornberg, 1976; Bridges, 1977; Antoian, 1977; Benedick and Greenberg, 1974). These symposiums and reviews cover a broad area of research interests, ranging from interactions of biological systems with naturally occurring electromagnetic fields arising from atmospheric electricity and geomagnetism to biological responses to directly applied electrical currents. The scope of this overview will be more limited; it will focus on past and ongoing research in the United States concerned with the biological effects of static and low-frequency electromagnetic fields produced by power transmission systems and low-frequency communication systems. The fields produced by these systems, particularly by the power transmission systems, are the highest 60-Hz fields to which people and other life forms may be exposed.

POWER TRANSMISSION SYSTEMS

60-Hz Electromagnetic Fields

There are currently more than 40,000 circuit miles of overhead AC (60 Hz) transmission lines in the United States operating at extra-high voltages (EHV), 345 to 765 kV (Anon, 1975b). Typical values of the maximum vertical electric fields at 4 feet above ground level under EHV transmission lines range from 5 to 9 kV/m (Bridges, 1975a; Anon, 1974;

Anon, 1975b; Bracken, 1976). The corresponding ground level magnetic fields do not depend on the transmission line voltage but on the line current, spacing between phases, and height above ground. At midspan under a typical 765-kV transmission line, the ground level 60-Hz magnetic field is about 0.3 Gauss for a current of 2000 amperes in each phase (Bridges, 1975a).

The total current induced by the electric field between ground and a man standing in electrical contact with ground, known as the short-circuit current, is about 16-20 $\mu\text{A/kV/m}$ (Anon, 1975b). Magnetic fields produce circulating electric currents in the body with the current density reaching its maximum value near the surface of the body (Guy, 1976). Based on estimates from calculations on models, the current density from the magnetic field at the hips of an erect man under a 765-kV transmission line ($E = 9 \text{ kV/m}$, $B = 0.3 \text{ Gauss}$) would be about 10% of the current density induced by the electric field (authors).

The situation is somewhat different in EHV switchyards where the electric fields are not uniform and can range from typical values of 2 to 9 kV/m (Anon, 1975b) to as high as 14.6 kV/m (Miller, 1974). Total body currents induced in switchyard workers and live line maintenance workers can be appreciably higher than those occurring in persons standing under transmission lines (Barnes, 1967; Miller, 1967).

Appreciable research has been conducted on the induction of currents in humans and animals by 60-Hz electric fields (Anon, 1975b; Bracken, 1976; Barnes, 1967; Deno, 1975; Miller, 1967; Anon, 1972a; Anon, 1972b; Deno, 1977; Phillips, 1976a; Kouwenhoven, 1966). Induced currents from

transmission lines are too low to represent a serious shock hazard. At least 5 mA are required to produce a shock which is disabling and 60 mA or more is needed to cause fibrillation of the heart in adult humans (Keesey and Letcher, 1970). Currents of this magnitude would flow through the body only in fields greater than 350 kV/m and 4 MV/m, respectively (Deno, 1977). Several reports have summarized the effects of AC shocks on humans and animals (Reilley, 1977; Dalziel, 1968), and the subject will not be reviewed in this paper.

Secondary shocks, or spark discharge shocks, resulting from touching objects at different potentials have been studied by a number of investigators (Anon, 1975b; Bracken, 1976; Anon, 1972a; Phillips, 1976a; Reilley, 1977). Although such shocks are not life threatening and do not appear to produce permanent harm, they may produce a general stress response with repeated experiences which could account for some of the biological effects of electric field exposures reported in the literature.

Exposure to high-strength 60-Hz electric fields can produce nerve stimulation, due to piloerection and hair oscillation, and a tingling at the body surfaces next to clothing. These sensations become annoying to a small percentage of people starting at field strengths of about 8-10 kV/m (Zaffanella, 1972; Anon, 1975b). It has been suggested by several scientists that some of the reported biological effects of 60-Hz electric fields, particularly in furred animals, may be responses to this hair stimulatory effect (Bridges, 1975a, 1977; Antoian, 1977; Kornberg, 1976).

In 1962 studies were initiated by the American Electric Power Company on safety practices, field intensities, body currents and working environments related to high voltage transmission lines. In one of these studies medical examinations were conducted over a 9-year period on 11 linemen working on 138 and 345 kV transmission lines (Kouwenhoven, 1967; Singewald, 1973). Four of the men regularly worked on live lines while wearing conducting clothing and gloves, exposing their heads to 60-Hz electric fields up to 470 kV/m. The other men worked mostly with hot sticks and were exposed to maximum fields of 70 kV/m. During the period, seven extensive medical examinations were conducted at Johns Hopkins Hospital. No significant changes of any kind were found.

As part of the research program sponsored by the American Electric Power Company, a study was made (Knickerbocker, 1967) to determine whether exposure of mice to high-strength 60-Hz electric fields over a long time period affected reproductive ability or produced tissue damage. Twenty-two male mice were exposed to 160 kV/m for 6.5 hours/day, 5 days/week, for 10.5 months. An equivalent number of animals was sham exposed. All exposed and sham exposed male mice were bred to nonexposed virgin females during the nonexposure periods. Exposure to the electric field had no effect on reproductive ability. Body weights of the exposed and control mice did not differ. Gross and microscopic pathological studies made at the end of the experiment showed no relevant lesions. The only observed effect of electric field exposure was that the male progeny of the exposed animals had a lower body weight than male progeny of control animals. No differences were observed in the female progeny.

Few other studies were made in the 1960s to assess the biological effects of 60-Hz electric fields on experimental animals. Moos (1964) examined the effects of 60-Hz fields at 0.8 to 1.2 kV/m on activity of mice. In a series of five experiments involving alternating exposure (field-on) and control (field-off) periods ranging from 1 day to 1 month, Moos reported mice were more active during the dark period with the field on than with the field off. Results of daylight activity between field-on and field-off conditions were not consistent. In a second study, Moos investigated the effect of electric field exposure on the mortality response of mice previously treated with 900 R of ionizing radiation. No significant effect was observed.

In a recent study (Marino, 1976a) mice were allowed to mate, gestate and rear their offspring for three successive generations while being exposed to 60-Hz electric fields. Mice exposed to 15 kV/m vertical electric fields exhibited decreased body weights at 35 days postpartum and increased mortality rates during the first week after birth for three successive generations. Mice exposed to 10 kV/m horizontal electric fields exhibited decreased body weights for two successive generations but not increased mortality rates. The authors suggested the depressed body weights and increased mortality rates may have resulted from the microcurrents the animals experienced during exposure while eating and drinking.

In another study (Marino, 1976b) body growth, serum proteins and serum corticosterone levels were measured in rats after continuous exposure to vertical, 60-Hz electric fields at 15 kV/m for 30 days. In

a series of four replicate experiments, body weights of exposed rats were significantly less than those of controls in two experiments. Serum albumin was lower in the exposed rats. Serum corticosterone levels of exposed rats appeared to be lower than levels in controls in three experiments, but no measure of variance was made to allow an estimate of significance. When exposed animals were subjected to cold stress, the serum corticosterone levels in both experimental and control groups rose markedly and equally. This suggests the exposed animals were not suffering from the general adaption syndrome as a result of chronic exposure to a nonspecific stressor.

Marino et al. (in press) reported on a total of 10 experiments which suggested exposure of rats to vertical, 60-Hz electric fields at 15 kV/m for 30 days may result in decreased corticosterone levels, increased serum albumin and serum glutamic oxaloacetic transaminase, increased pituitary and adrenal weights, decreased water consumption and decreased body weights. However, only the decrement in water consumption was regularly demonstrated, suggesting the animals may have received shocks or perceived current flow when they drank during exposure. The other results were inconsistent.

Gann and LaFrance (1976) examined the cardiovascular response of dogs to controlled bleeding (10 ml/kg over 3 minutes) after a 5-hour exposure to 60-Hz electric fields at 15 kV/m. The cortisol secretion response to ACTH was not affected by exposure to the electric field. Several cardiovascular changes were observed at the end of the bleeding. Mean arterial pressure fell 5.9 mm Hg in the control group and 16.0 mm Hg

in the exposed group. Arterial pulse pressure fell 0.9 mm Hg in the control group and 10.9 mm Hg in the exposed group. Heart rate decreased about 9 beats/min in the control group but increased about 57 beat/min in the exposed group.

Several studies have been made on the effects of 60-Hz electric fields on in vitro preparations. Bassett and Herrmann (1968) reported an increased DNA and collagen production in cultures of fibroblast cells exposed to 100 kV/m. Gann and LaFrance (1975) exposed cultures of rat subcutaneous areolar cells to 60-Hz electric fields at 200 and 600 kV/m. Cell morphology and regenerative rates were not affected in the cultures exposed to 200 kV/m, but growth stopped and the cells died in the cultures exposed to 600 kV/m within 7 days after the start of exposure. Durfee et al. (1975) found cell growth was inhibited in cultures of embryonic chicken fibroblasts exposed to 60-Hz electric fields at 1 and 10 V/m. A similar inhibitory effect was observed in embryonic chicken kidney cells exposed to 60 Hz at 1 V/m, but not at 10 V/m. Growth rates of cultures exposed to 75 Hz at 1 V/m were also inhibited, but at 10 V/m growth rates were enhanced in both types of tissue cultures.

Several surveys of limited scope have been made to examine the influence of 60-Hz electric fields from EHV transmission lines on farm crops and animals. Busby et al. (1974) questioned 18 farmers on land near a 765 kV line. Responses by the farmers indicated no alterations in crop productivity, cattle, hogs, or in dairy production of grazing animals could be attributed to the electric fields from the transmission

line. Ware (1974) surveyed 125 farmers on land near a 765-kV transmission line and 116 reported no problems related to the grazing of their animals.

There is currently a lack of unanimity by U.S. scientists as to whether or not 60-Hz electric fields associated with transmission lines produce any adverse biological effects. Results from earlier studies are somewhat conflicting and contradictory. The need for additional biological research to clarify the situation has been recognized. This fact, in conjunction with the development of ultra-high-voltage (UHV) transmission systems capable of transmitting power at 1100 to 1500 kV, has led to the initiation of a number of new research projects to obtain definitive answers concerning possible health hazards of these low-frequency electromagnetic fields.

A major research project is in progress at Pennsylvania State University to investigate the ecological influence of electric fields. A number of experiments have been made to evaluate the effects of 60-Hz electric fields on meadow voles and birds (Bankoske, 1976). Exposure of meadow voles to 50 kV/m for 4 weeks had no effect on body weight, activity, behavior, or on the progeny of exposed voles born both during and after the exposure period. Results of the avian studies were mostly negative. Short-term exposures of developing chicken embryos to fields as high as 67 kV/m had no significant effect on hatchability, time to hatch, hatching weight, early weight gain, activity or gross behavior. Chronic exposure of newborn chicks to 40-80 kV/m for 8-22 days had no effect on growth or

electroencephalogram (EEG) patterns. Activity of chicks was found to be depressed for about 1 week after removal from a 22-day exposure to 40 and 80 kV/m. A transitory enhanced growth rate was observed in male chicks during a 20-day exposure to 40 and 80 kV/m, but no significant effect on weight was observed at the end of the exposure period. Similar results were reported by Krueger et al. (1972) where body weights of chicks exposed to 3.4 kV/m at 60 Hz or 3.6 kV/m at 45 Hz did not differ from controls at the end of a 28-day exposure period.

In another study by Krueger et al. (1975a), fecundity of chicken was investigated after males and females had been exposed to 60-Hz electric fields at 16 kV/m for 84 days. Egg production was reduced in exposed hens. No effect was observed in fertility, hatchability, gross embryonic morphology, sex ratios, or egg shell quality.

Durfee et al. (1975) exposed chicken eggs to 60- and 75-Hz electric fields at 1, 10 or 3600 V/m throughout the holding and incubation period. No significant effects were observed on hatchability, embryonic mortality, memory consolidation or posthatching body weights.

Carter and Graves (1975) exposed chicks to 60-Hz electric fields at 0, 40 or 80 kV/m continuously from 1 day after hatching until 22-24 days after hatching, at which time electroencephalograms (EEG) and electrocardiograms (ECG) were made. Detailed evaluation of the EEGs did not disclose any significant differences among treatment groups. Heart rates of birds exposed to 40 or 80 kV/m were significantly higher than those of unexposed controls, with the 80 kV/m group having a significantly higher rate than the 40 kV/m group. The authors also investigated the heart rate

response of the birds to auditory stimuli, a broody hen call and a 500 Hz tone, but no clear differences in responses among treatment groups were evident.

Three major research projects have recently been started at Battelle, Pacific Northwest Laboratories. One project is concerned with possible ecological effects of a 1100-kV transmission line test facility and the other two projects are laboratory studies designed to investigate the biological effects of 60-Hz electric fields on small and large animals. In the small animal study (Phillips, 1976b), a large multidisciplinary research team is conducting a comprehensive series of screening experiments on rodents to cover areas of hematology, serum chemistry, immunology, central nervous system function and structure, neurophysiology, animal behavior, endocrinology, pathology, bone structure and function, cardiovascular function, metabolism, prenatal and neonatal growth and development, and teratology. The large animal project (Phillips, 1976c) will involve continuous exposure of miniature swine to 60-Hz electric fields over several generations with routine measurements made relative to reproduction, growth and development, behavior, hematology and serum chemistry. In addition, any effects observed in the small animal study will be evaluated in the miniature swine.

Several experiments of the Battelle studies have been completed. Acute exposure of swine to large 60-Hz electric fields produced no gross behavioral effects (Phillips, 1976a). A field of 50 kV/m produced hair stimulation (piloerection and hair oscillation), and preliminary data was obtained that indicated swine may perceive the presence of electric fields at 30-35 kV/m. In the small animal studies (Phillips, *et al.*, 1977),

heart rate measurements were made on rats after exposure to 60-Hz electric fields at 80 kV/m for 8 hours/day for 5 days. No effect was observed at the end of 8 or 40 hours of exposure. In another experiment it was found that rats spend more time in the shielded (unexposed) side of a two-compartment shuttle box than in the unshielded (exposed) side at fields of 90, 105 and 130 kV/m, but no side preference was observed at lower field strengths.

Several other research projects have been initiated recently to evaluate possible biological effects resulting from exposure to 60-Hz electric fields (Kornberg, 1976). The effects of electric fields on bee behavior and honey production under natural conditions are being studied. An epidemiological study of health of linemen and switchyard workers is now in progress. Another research group is investigating the effects of electric fields on cardiac pacemakers implanted in nonhuman primates. Scientists at the Brain Research Center in Los Angeles are investigating the effects of 60-Hz electric fields on animal behavior and on central nervous system function. A study at Battelle is being made to examine genetic effects of 60-Hz and static electric fields on bacteria and fruit flies.

It is anticipated that results of these and other studies will help clarify the current uncertainties about the possible biohazards of electric fields and provide the baseline data needed to establish criteria for safe exposure limits for humans and other life forms.

Static Electric Fields

Electrical power in the United States is transmitted primarily at 60 Hz. The only EHV direct current (EHV-DC) transmission system currently

in operation is the ± 400 kV Celilo-Sylmar Intertie between northern Oregon and southern California. Little meaningful biological research has been conducted that simulates exposure to such a system. Factors in addition to the static electric and magnetic fields must be considered, such as ion currents, air ions, and possibly ozone. Studies are in progress at Bonneville Power Administration to characterize EHV-DC systems for subsequent biological investigations (Bracken, in press).

Several biological studies concerned with electrostatic fields have been published. Lott and McCain (1973) investigated the effect of a static electric field at 10 kV/m on the EEG and hypothalamic electrical activity of rats as indices of the animal's perception of the field. During exposure EEG activity increased and posterior hypothalamic activity appeared to decrease. No significant effects were noted in ECGs, respiratory function or rectal temperature.

Marino et al. (1974) exposed groups of rats for 30 days to static electric fields at 0.3 to 19.7 kV/m. Vertical (0.6-19.7 kV/m) or horizontal (0.3-9.8 kV/m) exposures had no effect on growth rate or final body weight. Changes were reported in the serum protein fractions of rats exposed to vertical fields: albumin was elevated in groups exposed to 2.8, 5.6 and 19.7 kV/m; alpha and gamma globulin fractions were depressed in the group exposed to 19.7 kV/m; beta globulins were elevated in the groups exposed to 5.8 and 19.7 kV/m. It is not known if these changes are significant, since measurements were made from pooled blood samples and no estimates of population variability could be made. The authors also noted an unexpected

incidence of secondary glaucoma in animals exposed to vertical fields. This glaucoma only affected the right eye and was not observed in controls or in the group exposed to horizontal fields. It is possible the secondary glaucoma could have developed from pre-existing uveitis commonly found in a small fraction of laboratory rats.

In another experiment (Marino, 1974), female mice were injected with Erhlich ascites tumor cells and then exposed to horizontal static electric fields at 8 to 11 kV/m for 14 days. More chromosomal abnormalities in tumor cells were observed in exposed than in control mice. No host animal cells showed chromosomal abnormalities.

There is a need for additional research on the possible bioeffects of exposure to static fields, particularly with respect to exposure to DC transmission systems. For the latter studies potential sources of bioeffects need to be identified and appropriate exposure systems need to be designed to simulate in the laboratory the environment under an EHV-DC transmission line.

COMMUNICATION SYSTEMS

Considerable biological research has been conducted in conjunction with the development of an extra-low-frequency (ELF) communication system known as Project Sanguine. The system will transmit signals at 45-75 Hz from a grid antenna system buried in the earth. The electric field strength in the ground and air above the antenna grid is about 0.07 V/m, decreasing with distance from the grid. The magnetic fields above the lines are about 0.13 Gauss. A detailed description of the antenna system has been reported by Baker (1974).

Although the electric and magnetic fields that would be produced by this communication system are small, there has been considerable concern about possible effects on biological and ecological systems. A comprehensive research program to assess possible bioeffects of exposure to low-level electromagnetic fields at low frequencies was started in 1968 and still is in progress. Rozzell (1974) has summarized the research program, and results from studies completed to date have been compiled into three large volumes (Anon, 1975a, 1977a) and also have been summarized (Anon, 1977b).

An abbreviated summary of research studies and results on physiology, growth and development, behavior, genetics and biochemistry is given in Tables I-V.

Except for the studies by Coate et al., (1970) and Noval et al., (1976), no effects were observed in the physiology studies (Table I). The only significant effect observed by Coate et al. was a higher lactation index in the second generation of the exposed group than in the control group. The meaning of this difference is unclear. In the study by Noval et al. (1976), exposed rats gained weight at rates 20-30% slower than controls and had less abdominal fat. Reduced choline acetyltransferase in the brain stem and elevated liver tryptophase pyrrolase were also noted in the exposed animals. Mathewson et al. (1977) were unable to confirm these findings in a subsequent study.

Coate et al. (1970) investigated the effects of low frequency electromagnetic fields on germination, growth and development of corn, buckwheat and sunflowers. Although no effects were found on corn or buckwheat,

seedling growth of sunflowers was retarded (Table II). Rosenthal et al. (1975) repeated the experiment with sunflowers and were unable to confirm the results of the earlier study.

A series of experiments have been made on the response of the slime mold Physarum polycephalum to 60- and 75-Hz electromagnetic fields (Table II). The time interval between successive mitotic divisions of exposed cultures was appreciably longer than that of controls after 90-120 days of exposure (Goodman, 1975, 1976a; Marron, 1975). Sexual and asexual life cycles were not affected, but a retardation in reversible protoplasmic streaming was observed. Apparently the changes were not permanent; cultures removed from the electromagnetic field recovered in about 30-50 days. Additional studies were made at lower field strengths, five- and twenty-fold weaker, and no effects were observed.

In another experiment, Goodman et al. (1976b) investigated mitotic rate, protoplasmic streaming, respiration in microplasmodia, and glucose transport across the cell membrane of Physarum polycephalum exposed to 45-, 60- and 75-Hz sinusoidal or modulated 76-Hz electromagnetic fields at 0.14-0.7 V/m and 0.4-2 Gauss. They found the mitotic cycle was lengthened, the shuttle streaming period was slowed, and the rate of respiration was depressed. Also, modulated fields appeared to induce the alterations sooner and at lower intensities than sinusoidal waves.

No behavioral effects have been observed in rats, pigeons or primates exposed to 45-75 Hz electromagnetic fields at strengths up to 100 V/m and 10 Gauss (Table III). However, some marine animals do perceive electric fields in water at about 10-20 V/m (Coate, 1970). Turtles that perceive such fields will leave the field area and fish orient their bodies to

minimize the head-to-tail potential difference (Coate, 1970). The perception threshold for amoeba is about 500 V/m at 1-100 Hz (Friend, 1975). Significant membrane disturbances occur at twice this level, and the amoeba starts to become elongated in a direction perpendicular to the applied field at levels above 1000 V/m. Other marine animals, such as shrimp, snails, crabs, scallops, etc., perceive current densities between 1-50 mA/cm², depending on the species and frequency of the field (Straub, 1972). McCleave et al. (1974) found that Atlantic salmon (Salmo salcer) and American eels (Anguilla rostrata) detect ELF electric fields at 0.007-0.07 V/m but not magnetic fields at 0.5 Gauss. Neither activity nor circadian rhythm were altered by electromagnetic fields at these levels.

Gavalas-Medici et al. (1970, 1976) demonstrated a frequency-dependent effect of electromagnetic fields on schedule-controlled behavior of primates. The interresponse times of monkeys in lever press responses in an operant behavioral task were significantly shorter and less variable during exposure to 7-Hz fields at 10 V/m than during no field (unexposed) time periods. No effects were observed at any frequencies tested at 1 V/m, nor at 60 nor 75 Hz at 10 V/m. The effect at 7 Hz appeared to be dose dependent, with higher field strengths producing even shorter interresponse times. At 56 V/m, a significantly shorter interresponse time was observed at 75 Hz, but not at 60 Hz.

In an early study, Coate et al. (1970) reported an increased sex-linked lethal mutation rate in fruit flies exposed to low frequency electromagnetic fields (Table IV). Subsequent studies by Bender (1976) and Mittler (1971, 1972) failed to confirm this finding. No cytogenetic effects were observed in bacteria (Coate, 1970) or plants (Miller, 1976).

Bawin and Adey (1976) exposed in vitro preparations of cat and chick brain tissues to 6-75 Hz electric fields at 5-100 V/m for 20 minutes and observed a reduced calcium efflux at 6 and 16 Hz. Thresholds were about 10 and 50 V/m for chick and rat tissues, respectively.

Several studies have been made to evaluate possible effects of electromagnetic fields on human psychobiology and performance. In one study (Beischer, 1973) 10 subjects were exposed to 1 Gauss at 45 Hz for periods up to 24 hours. A large battery of physiological and psychological tests were made throughout the study. No effects were seen except for elevated serum triglycerides in 9 of the 10 exposed subjects at 24 to 48 hours after the exposure period. Similar trends were not seen in any of the 5 control subjects. In a second study (Gibson, 1974) psychomotor performance tests were made on human subjects exposed to 1 Gauss at 45 Hz for 24 hours. There were no significant performance decrements attributable to the exposure.

A number of studies and surveys have been made at the Sanguine Test Facility in Wisconsin over the last 9 years to evaluate possible effects of the electromagnetic fields on the ecosystem in the area. No adverse effects have been produced on plants (McCormick, 1971; Rosenthal, 1976b), soil arthropods or annelids (Greenberg, 1972, 1973, 1974a), local birds or mammals (Seale, 1976), nor on wood lice, redworms, earthworms, slugs or red-backed salamanders (Greenberg, 1974b, 1976). A clinical evaluation was made on personnel working at the Sanguine Test Facility and no effects attributable to the electromagnetic fields were found (Krumpe, 1974).

Some effects on bird orientation were noted on pigeons (Graue, 1974), ring-billed gull chicks (Southern, 1975) and migrating birds (Williams, 1976). Pigeons and some migrating birds changed their flight orientation slightly when close to the energized antenna.

CONCLUSIONS

Based on a long history of experience with electric fields by the utility industry, it appears that intermittent and repeated exposures to strong 60-Hz electromagnetic fields from present power transmission systems have no obvious adverse effect on the health of man. It has been recognized recently that this belief must be tested by carefully designed and executed experiments under laboratory conditions where precise control can be exercised over coexisting environmental factors. A number of studies have been initiated in response to this need to evaluate possible effects from both acute and chronic exposures.

Considerably more attention needs to be paid in future studies to the details of the interactions of an animal and its environment with applied electric fields. For example, it has now been shown that rats individually housed in close proximity to each other can have their short-circuit currents reduced by about 35% due to mutual shielding (Phillips, 1977). The possibility of transient discharges between an animal and its watering system has existed in many past studies. In addition, substantial steady-state 60-Hz currents may pass between certain kinds of watering systems and a drinking animal. Watering systems must be designed to eliminate these artifacts, reducing these currents as much as possible and quantitatively documenting

any residual current. Animal exposure systems must be carefully designed and surveyed to insure that they are free of corona discharge and ozone formation. Finally, one must be alert for the possibility of stress-induced biological effects due to hair stimulation or other forms of electric field perception; the mechanisms of these phenomena and their physiologic effects have yet to be fully elucidated.

All past experiments exposing animals to electric fields have been characterized by simply reporting the unperturbed field strength; that is, the field strength with no animals present. In many cases, details of how this quantity was determined were not given. However, the electric field strength at the surface of the body is the relevant quantity for determining the induced currents and fields inside the body and for understanding surface phenomena such as hair stimulation. This quantity depends not only on the magnitude of the unperturbed field but also on the shape of the animal body and its orientation with respect to the applied field. Since the shape and orientation of an erect human in a given field is very different from that of a laboratory animal, detailed measurements of the perturbed field and induced currents in the animal must be made before results obtained with that species can be translated to the human situation.

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TABLE I. Summary of Physiology Research

Test Subject (Investigator)	Electromagnetic Field			Exposure Time	Parameters Examined	Results
	Electric (V/m)	Magnetic (Gauss)	Frequency (Hz)			
Dogs (Coate, 1970)	10, 20 plus 0.5 mA current	1, 2	45, 75	16 h/d, 5 d/w, for 3 weeks	Behavior, body weight, EEG, ECG, testis, eyes, clinical chemistry, hematology, pathology, body temperature, blood pressure	No effect
Rats (Coate, 1970)	10, 20	1, 2	45, 75	16 h/d, 5 d/w, for 3 weeks	Fertility, reproduction and development	Increased lactation index exposed rats in second generation
Rats (Noval, 1976)	0.1-100	--	45	30-40 d	Body weight, brain and liver enzymes	Reduced growth rate, reduced amount of abdominal fat, reduced choline acetyltransferase (brain stem) and elevated liver tryptophane pyrrolase
Rats (Mathewson, 1977)	0-100	--	45, 60	28 d	Body weight, hematology, serum chemistry, pathology	No effect
Mouse (Krueger, 1975)	100	--	45, 75	to 36 d	Body weight, blood chemistry, susceptibility to virus infection	No effect
Mouse (Beischer, 1975)	--	1	45	1-7 d	Body weight, liver weight, liver triglycerides, behavior, pathology	No effect
Primate (Grissett)	20	2	72-80	1 yr +	Body weight, blood chemistry, ECG, EEG, body temperature, respiration rate, blood pressure	No effect to date. Study still in progress.

TABLE II. Summary of Growth and Development Research

Test Subject (Investigator)	Electromagnetic Field			Exposure Time	Parameters Examined	Results
	Electric (V/m)	Magnetic (Gauss)	Frequency (Hz)			
Seeds and Plants (Coate, 1970)	10, 20	1, 2	45, 75	9 d	Seed germination, seedling growth	Growth retardation of sunflower seedlings
Sunflowers (Rosenthal, 1975)	1, 10	1	75	--	Germination and growth	No effects attributable to EM field
Plant and Soil Microorganisms (Gardner, 1975)	10, 50	--	45	Various	Growth and metabo- lism	No effect
<u>Physarum</u> <u>polycephalum</u> (Goodman, 1975, 1976a) (Marron, 1975)	0.017- 0.7	0.05-2	45, 60, 75	to 700 d	Biochemical and physiological processes	Slower mitotic division rate; retardation in reversible protoplasmic streaming.
<u>Physarum</u> <u>polycephalum</u> (Goodman, 1976b)	0.14-0.7	0.4-2	45, 60 75; modulated 76	various	Biochemical and physiological processes	Mitotic cycle longer; shuttle streaming slower; respiration depressed.
Chickens (Durfee, 1976)	1, 10 3600	1, 5, 8, 30	45, 60, 75	from egg holding to 28 d post- hatching	Development, growth and behavior	No effect
Tadpoles (McKinney, 1977)	0.1-2.5	--	45	150 d	Growth and development	Inconclusive
Mice (Krueger)	100	--	76	various	Litter size, serotonin metabo- lism and terato- genesis	In progress

TABLE III. Summary of Behavioral Research

Test Subject (Investigator)	Electromagnetic Field			Exposure Time	Parameters Examined	Results
	Electric (V/m)	Magnetic (Gauss)	Frequency (Hz)			
Fish, Turtles, Ducklings, Rats, Fruit Flies, Dogs (Coate, 1970)	10, 20	1, 2	45, 75	5 h	Perception and behavior	Bluegill fry perceived field at 10 V/m; some turtles perceived and left field at 20 V/m.
Atlantic Salmon and American Eels (McCleave, 1974)	0.007-0.7	0.5	60, 75	1-24 h for 10 d	Detection, activity, and circadian rhythm	Detected electric fields but not magnetic fields.
Amoeba (Friend, 1975)	0-25,000	--	1-10,000	During tests	Perception and behavior	Perception threshold was 500 V/m; membrane disturbance at 1000 V/m.
Marine Animals (Straub, 1972)	to 60 mA/ cm ² current	--	25-500	During tests	Perception and behavior	Threshold for perception <50 mA/cm ² , depending on species and frequency.
Rat (Coate, 1970)	10, 20	1, 2	45, 75	80 d	Avoidance and escape learning	No effect
Pigeon and Rat (Marr, 1973) (deLorge, 1974)	100	to 2	45, 60, 75	During tests	Operant behavior: perception, preference, temporal discrimi- nation	No effect
Primate (Grissett, 1971a,b)	--	3, 7, 10	45	Variable to 42 d	Operant behavior: Reaction time, reinforcement ratios, efficiency ratios	No effect
Primate (deLorge, 1972, 1973a, 1973b)	0-7.4	10	10, 45, 60, 75	Variable to 20 d	Operant behavior: reaction time, short-term memory, motor activity	No effect
Primate (deLorge, 1974a,b)	--	8.5	15, 45	Variable to 5 d	Operant behavior and blood chemistry	No effect
Primate (Gavalas-Medici, 1970, 1976)	1-100	--	7, 45 60, 75	4 sessions 4 h each	Behavior and brain activity	Decreased interresponse time with threshold at 10 V/m at 7 Hz. Effect dose-dependent
Primate (Gavalas-Medici)	1, 10, 56	--	76, modu- lated at 60	--	Behavior and brain activity	In progress

TABLE IV. Summary of Genetic Research

Test Subject (Investigator)	Electromagnetic Field			Exposure Time	Parameters Examined	Results
	Electric (V/m)	Magnetic (Gauss)	Frequency (Hz)			
<u>Drosophila</u> <u>melanogaster</u> (Coate, 1970)	20	2	45, 75	48 h	Genetic mutations	Possible dominant lethal mutation
<u>Drosophila</u> <u>melanogaster</u> (Bender, 1976)	20	2	45, 75	48 h	Genetic mutations	No effect
<u>Drosophila</u> <u>melanogaster</u> (Mittler, 1971, 1972)	10	1	40, 60, 75	various	Genetic mutations	No effect
Bacteria (Coate, 1970)	10, 20	1, 2	45, 75	2 h	Genetic mutations	No effect
Plants (Coate, 1970)	10	0.5-17	75	72 h	Cytogenetics	No effect
Plants (Miller, 1976)	10	0.5-17	75	1 h to 6 d	Cytogenetics, mitotic index, plant growth	No effect
Soil Microorganisms (Rosenthal, 1976a)	1	1	60	16 w	Microbial popu- lation in soil	No effect

TABLE V. Summary of Biochemical Research

Test Subject (Investigator)	Electromagnetic Field			Exposure Time	Parameters Examined	Results
	Electric (V/m)	Magnetic (Gauss)	Frequency (Hz)			
In vitro: Brain and Liver Organelles - rats and guinea pigs (Riesen, 1971)	6.3, 155	50, 100	60	to 110 min	Liver subcellular particles and brain mitochondria	155 V/m affected brain mitochondria; 50-100 Gauss affected nerve ending particles at 0°C.
In vitro: Skin, Microsomes and Mitochondria - frogs (Straub, 1975)	0.2 to 560 mA/cm ²	--	45, 60, 75	Various	Microsomal ATPase; mitochondrial oxi- dative phosphory- lation	No effects except increased potential difference across frog skin at 0.4 mA/cm ²
In vitro: Brain - cats and chicks (Bawin, 1976)	5-100	--	1, 6, 16, 32, 75	20 min.	Calcium efflux from in vitro cat and chick brain tissues	Decrease in efflux of calcium at 6 and 16 Hz at 10 V/m (chick) and 56 V/m (cat)
In vitro: Cells - chicken (Green)	1-10	1-8	76	--	In vitro cell growth	In progress

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