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Biomagnetic Effects: A Consideration in Fusion Reactor Development

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Fusion reactors will utilize powerful magnetic fields for the confinement and heating of plasma and for the diversion of impurities. Large dipole fields generated by the plasma current and the divertor and transformer coils will radiate outward for several hundred meters, resulting in magnetic fields up to 450 gauss in working areas.

Since occupational personnel could be exposed to substantial magnetic fields in a fusion power plant, an attempt has been made to assess the possible biological and health consequences of such exposure, using the existing literature. The available data indicate that magnetic fields can interact with biological material to produce effects, although the reported effects are usually small in magnitude and often unconfirmed. The existing data base is judged to be totally inadequate for assessment of potential health and environmental consequences of magnetic fields and for the establishment of appropriate standards. Requisite studies to provide an adequate data base are outlined.

Introduction

Fusion as a power source is receiving an increasing amount of attention. Several designs have been proposed, and the feasibility of each alternative is being studied. As we move closer to a working design, attention can be paid to potential biological hazards. Large magnetic fields and the emission of tritium and lithium are unique to some fusion reactor designs.

The results of a review of the current state of knowledge concerning the biological effects of magnetic fields alone and in combination with ionizing radiation are summarized in this report. The purpose of the review is to help identify areas where additional biomedical research is needed for establishing guidelines for reactor design and operation.

Although this evaluation was made of the potential biological effects associated with operation of fusion reactors, the effects of magnetic fields may also have implications for other situations. For example bubble chamber operations, cyclotron maintenance, eventual use of levitated trains, space travel, and work around high voltage systems may also result in exposure of people to fields greater than the geomagnetic background.

The references cited in this review represent only a fraction of the literature available on biological effects of magnetic fields. Additional material, for those who wish to obtain more detail, can be found in Busby (*1*), the volumes edited by Barnothy (*2, 3*) the English translation of the Russian work by Presman (*4*), and the recent review of Silver and Tobias (*5*) as well as in the bibliographies by Manganelli (*6*) and Davis, Pappajohn, and Plavinieks (*7*).

Some current fusion reactor concepts rely on the use of magnetic fields to confine high temperature plasmas. The magnitude and geometry of these fields will depend on the reactor concept ultimately employed. The Tokamak and Yin Yang configurations both have a large dipole field external to the biological shield. In the theta pinch design the external magnetic field should be small due to effective cancellation of opposing field coil elements which leave only high order multipole moments. The laser implosion concept utilizes a modest divertor field to protect its inner wall.

The most extensive calculations and plots of magnetic field patterns were performed for the Tokamak reactor as conceived in UWMAK-1 and based on a 5000 Megawatt (MW) thermal plant (*8*). Two types of magnetic fields will be encountered in

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a reactor based on this concept, a toroidal field produced by the main toroidal magnetic field coils and poloidal field produced by the plasma current, divertor coils and transformer coils. The toroidal field will be generated in the plane of the torus and the strength may vary from 10,000 gauss in the area surrounding the nuclear island to <1 gauss at the outer edge of the reactor building (about 50 meters). Since levels of ionizing radiation will limit access to parts of the reactor building, there may be little likelihood of exposure to the toroidal field.

The poloidal field, on the other hand, will radiate both vertically and horizontally relative to the torus and will require a distance of 500 m to reach <1 gauss. Poloidal fields of several hundred gauss may be encountered by people working in the transport and hot cell regions. Conceivably, these fields could be as high as 70 to 450 gauss. People working in the region immediately surrounding the reactor building and associated facilities could be subjected to field strengths of 1 to 70 gauss for substantial periods. Beyond the horizontal plant boundaries, the field strength will have decreased to background so population exposures will not be involved. Some wildlife, particularly birds, could be exposed to field strengths in the same range as those encountered by people working in the region surrounding the reactor complex.

Certain strategies such as use of a Mu metal liner in the wall of the reactor building or redesigning the transformer to balance currents may help reduce the field strengths outside of the reactor. However, higher field strengths may be produced if the resistivity of the plasma is lower than the presently used value or if different temporal factors are used.

Populations of Concern

Since the magnetic field strength will decrease to background levels at the plant boundaries, the general public will not be exposed to the magnetic fields of fusion reactors. The major consideration in evaluating the possible consequences of exposure of people to a high magnetic field is, therefore, directed toward personnel working in the reactor and associated facilities. This group can be considered in view of the likely makeup of its various subgroups: (*1*) male and female, and (*2*) those with a potentially greater sensitivity to insult, which include those with identifiable medical problems, those with identifiable psychological problems, those with medical prosthetic devices, and pregnant women.

Magnetic exposure of other biological material in the environment surrounding the fusion reactor will probably be of minimal consequences. An exception to this might be birds for which evidence is accumulating that their navigation may be guided by geomagnetic information. Figure 1 illustrates that intensity of the magnetic field decreases with distance from the magnetic coils.

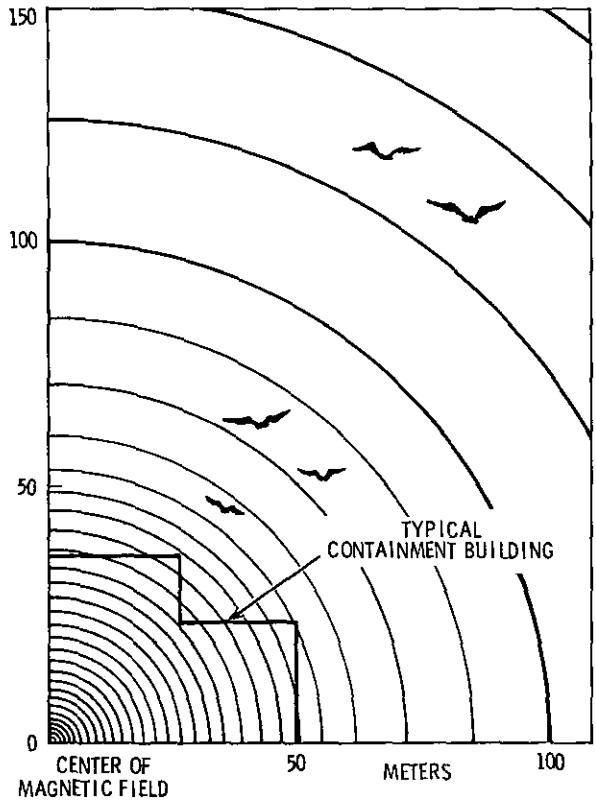

FIGURE 1. Intensity of magnetic field decreases with distance.

Summary of Literature

Human

The interest of people in the biological effects of magnetic fields goes back perhaps thousands of years to the connections that people made between health and the mysterious power of the lodestone. Present day interest in this area is indicated by the efforts of investigators to correlate disturbances in the earth's magnetic field caused by solar flares with incidence of death (*9*), mental disorders (*10*, *11*), and catastrophic events (*12*). In any retrospective epidemiologic study, cause and effect relationships are difficult to establish and the situation with magnetic fields is no exception.

During the past hundred years, studies have been performed to determine if man is capable of responding in some way to a magnetic field. Perhaps the first documented effect in man which was con-

sistently reproducible was that of seeing light flashes when the head was placed in an alternating magnetic field (*13*). This phenomenon known as magnetic phosphene has been studied in detail by a number of investigators and several hypotheses advanced to explain it. Barlow, Kohn, and Walsh (*14*) concluded that the retina was the probable locus of the effect and Valentinuzzi (*15*) developed a mathematical model to account for the excitation mechanism. Peterson and Kennelly (*16*) and Drinker and Thompson (*17*), using static magnetic fields of approximately 2500 gauss, reported no observable effect when the head was placed between the magnetic poles.

Beischer, Grissett, and Mitchell (*18*) have examined the response of human volunteers to an extremely low frequency (ELF) alternating magnetic field (10^{-4} webers). The subjects were confined for a 1-week period and exposed for either 10 or 22.5 hr at a time unknown to them. Measurements were made, including body temperature, heart rate, respiration rate, blood pressure, electrocardiograms, effect of stress, short-term memory, psychological response, and extensive blood and urine analysis. The only significant change found was a transient rise in serum triglyceride levels after cessation of exposure.

There are subjective studies which indicate that people exposed to magnetic fields experience a number of objectionable effects. Beischer and Reno (*19*) quoted results of the Soviet studies of workers who were engaged in the fabrication of permanent magnets. No estimate of field strength was given. The Soviets reported both bradycardia and tachycardia and a decrease in arterial blood pressure. The workers exhibited increased irritability, fatigue, occasional dizziness, altered appetite and headaches. Changes were found in the electroencephalograms, particularly during light stimulation. Hands were reported to exhibit a marbling pattern as well as itching, burning, and numbness. Beischer also reported that placing the hand in a 120,000 gauss field resulted in a feeling of bitter coldness and aching of bones along with a feeling as if ants were moving over the hands.

Friedman, Becker, and Bachman (*20*) exposed heads of patients to fields of 5–11 gauss modulated at either 0.1 or 0.2 cycles/sec (cps). Exposure to the 0.2 cps field slowed the reaction time significantly. Exposure to a 0.1 cps or a static field did not alter the reaction time. No consistent changes in EEG patterns accompanied the alterations in the reaction times (*21*).

The work of Cohen (*22, 23*) is of interest when considering the possible response of man to a magnetic field. In two very careful studies, he was able to demonstrate that there are very small magnetic fields associated with normal physiologic functions of the human body. He observed a magnetic field component which was similar to the EKG component associated with ventricular depolarization and repolarization. He also has found magnetic fields at the surface of the scalp which appear to be produced by alpha rhythm currents of the brain.

Nonhuman Primates

Data on nonhuman primates are provided by Beischer and co-workers (*24, 25*). They exposed squirrel monkeys to fields of 20,000–100,000 gauss and studied changes in the electrocardiogram. Breathing rates and R-wave amplitude were unchanged but there was a decrease in heart rate, an increase in sinus arrhythmia and an increase in the amplitude of the T-wave. Further investigation showed that part of the change in the electrocardiogram was due to an EMF generated by aortic blood flow.

Other studies with experimental animals and isolated organs or tissues indicate that neurological, cardiac, and other muscular function can be affected by magnetic fields. However, the magnitude of the field required is usually larger than would be encountered in a fusion reactor.

Growth and Development

Immature organisms often demonstrate an enhanced sensitivity to insults of various kinds including radiation, administration of toxic drugs and metals, and a variety of environmental challenges. The biochemical and physiologic processes occurring during differentiation and growth often amplify the damage that has been produced which facilitates detection and measurement of alterations inflicted by an agent. Several studies have attempted to utilize this concept for studying biomagnetic effects. Windle (*27*) reported an increased incidence of malformations in the chick after exposure to an ill-defined magnetic field. However, he found no developmental abnormalities when he used the silkworm. Perakis (*28*) found a retardation of development and an increased incidence of abnormalities of sea urchin eggs exposed to nonhomogeneous fields of 8,800 or 43,000 gauss. A uniform field of 33,000 gauss appeared to have no effect. Beischer (*24*) also reported retardation of development of the sea urchin egg with a field of 140,000 gauss. Neurath (*29, 30*) and Levengood (*31*) provide evidence for an effect of magnetic fields on development in their work with frogs and salaman-

ders. Evidence for the importance of the stage of development was presented by Levengood. The fields used in these studies ranged between 6,300 and 17,700 gauss with large gradients.

Another study by Levengood (*32, 33*) in which *Drosophila* pupae were exposed to approximately 150 gauss from a magnetic probe showed that the development time was increased significantly. Moreover, when treated males were bred to untreated females, the offspring showed an increased development time. This characteristic was transmitted for 30 generations and the number of progeny from these crosses were fewer than from control matings. Treated females did not carry the trait for increased development time. The ability of a magnetic field to affect development in *Drosophila* was further documented by Tegenkamp (*34*), who found an alteration of sex ratio as well as other genetic changes. Mulay and Mulay (*35*) also reported nongenetic abnormalities in *Drosophila*. Beischer (*24*), in contrast, found no effect of either homogeneous or nonhomogeneous fields on *Drosophila* development.

Only a few studies have been made of developmental effects in mammals. Barnothy (*36*) reported that exposures of young mice to either a homogeneous or an inhomogeneous field resulted in a decreased weight gain. The effect of the homogeneous field was more than that of the inhomogeneous field, although the differences were not great. Eiselein, Boutell and Biggs (*37*), using large groups of mice approximately 3 weeks of age, found no effect of a magnetic field on weight gain over a period of 11 days. The field varied between 8,800 and 14,400 gauss.

An extremely low frequency (0.5 Hz) rotating field of 0.5 to 15 gauss was imposed on pregnant rats for various periods during gestation (*38*). Offspring were found to have higher thyroid and testicular weights than the controls. A number of behavioral measures were also found to be altered in the magnetic field-treated animals. No differences were found in eosinophil counts, adrenal weights, blood sugar, or body weights.

Behavioral Effects

There are various other pieces of evidence indicating that organisms are capable of responding to the presence of magnetic fields. Studies of behavior among nonmammalian animals indicate varying degrees of sensitivity and responsiveness to magnetic fields. A recent paper by Keeton (*39*) presents evidence which shows that some species of birds depend on geomagnetic input for navigation. Keeton also refers to work which indicates that honeybees are sensitive to magnetic fields of a few gamma (10^{-5} gauss). These studies along with those which show that a diverse array of organisms can respond behaviorally to magnetic fields are important indicators of the ability of magnetic fields to affect some biological responses. Barnwell and Brown (*40*) and Brown (*41*) have shown that the directional movement of both planaria and snails can be influenced by placing them in a low level magnetic field. The effect was also influenced by time of day and lunar position. Gottlieb and Caldwell (*42*) found the behavior of snails to be influenced by imposition of a magnetic field. Again there was an interaction of time of day and month on the response to the field. The honeybee was shown to respond to a magnetic field (*43*). Their response tended to be a narcoleptic one in which they became rigidly fixed at a point corresponding to maximum field strength. Other studies (*44–47*) have shown behavioral changes for *Diptera*, electric fish, paramecium, and *Drosophila* when exposed to magnetic fields.

Experiments performed by Russell and Hedrick (*48*) indicate that mice allowed to choose between a low and high magnetic environment spent more time in the lower field. However, when the number of trips from a neutral position were counted, more were made into the high field. The food and water consumption was also higher in the high magnetic field.

Persinger (*49*) found that rats exposed prenatally to a low-frequency, rotating magnetic field exhibited less activity in an open-field test than did the controls. Persinger and Pear (*50*) used a suppressed response paradigm to test prenatally exposed rats and found them to be more easily suppressed than were the controls.

These varied studies indicate that a diverse array of organisms can respond behaviorally to a magnetic field. These data along with those reported for the human are important in that they show the ability of a magnetic field to affect certain biological responses.

Other Effects

The effect of magnetic fields on biological systems has been studied in a variety of ways. Hematologic studies (*51–54*) have been reported and the results vary from a marked effect on leukocyte levels as found by Barnothy and co-workers (*51*) to no effect as reported by Eiselein, Boutell, and Biggs (*37*). Neither group found an effect of a magnetic field on erythrocyte levels. Hackel (*53*), however, using an *in vitro* test system, found an enhancement of erythrocyte agglutination when the reaction took place in a magnetic field. A very in-

teresting study by Murayama (*54*) showed that sickled erythrocytes placed in a static field became oriented with their long axis perpendicular to the field.

Pathologic changes in the tissues of animals were reported by Barnothy and Sumegi (*55*), Kholodov et al. (*56*), and Friedman and Carey (*57*). Barnothy and Sumegi (*55*) reported marked changes in the adrenal of mice after exposure to a 9000 gauss field for 13 days while Kholodov et al. (*56*) found severe brain lesions in rabbits in their study. When Friedman and Carey (*57*) ascribed the results of the latter workers to an endemic infection found in rabbits, they also presented evidence that the effects of the infection were exacerbated by the magnetic field.

There have been many attempts to treat various diseases with magnetic fields and varying degrees of success have been repoed. One of the most interesting studies was that of Pautrizel et al. (*58*), who found that mice and rats could be protected against *Trypanosoma* infection by treating the animals with a magnetic field. This protective effect appeared to be mediated through the humoral immune system.

Radiation + Magnetic Field

Consideration must be given to effects of combined exposures of organisms to magnetic fields and radiation, since personnel working in fusion reactors will have the potential for exposure to both.

Forssberg (*59*) reported the results of an experiment to study the combined effects of magnetic fields and x-radiation on the survival and development of *Drosophila*. He found that exposure of *Drosophila* eggs to 165 R while in a magnetic field resulted in a higher mortality than from radiation alone. The magnetic field in a large number of experiments increased the mortality by about 17%.

Amer (*60*) found that exposure of the flour beetle, *Tribolium confusum*, to a magnetic field protected against radiation-induced wing abnormalities. Exposure to a magnetic field also protected against temperature-induced abnormalities (*61*). Results suggested that the protective effect of the magnetic field was equivalent to cooling the organism about 1.5°C/8000 gauss. Therefore, they examined the effect of a magnetic field on liquid crystals which undergo changes in coloration with changes in temperature. They found that application of a 6300 gauss field resulted in a gradual change in color from blue to orange which is the same as that observed when the temperature of the liquid crystal is lowered (*62*).

Barnothy and Barnothy (*63*) have also studied the effect of magnetic fields on survival of mice after irradiation. They found an enhanced survival if mice were first exposed to a magnetic field and then irradiated. They ascribe the protective effect to an increased leukocyte concentration found after exposure to a magnetic field.

Sikov (*64*) examined the effect of simultaneous exposure of mice to radiation and magnetic fields. He found some suggestion that there was an interaction of the two agents when certain parameters were examined. The effects of the magnetic fields were not large and were somewhat inconsistent. It should be noted, however, that only acute exposures (30 min) were used, so that the time available for interaction of the field with the organism was very limited.

General Evaluation

Studies of the possible biological effects of magnetic fields should emphasize field strengths below 750 gauss, since it seems unlikely that any significant exposures to higher fields will occur. However, use of higher fields will undoubtedly be necessary to fully define the experimental systems studied. It would also appear that the field will be static but inhomogeneous. The organisms which are apt to encounter significant fields are humans (working personnel) and birds. The exposure to lower animal forms and plants should be of little significance, since the field will be limited to the reactor area.

Studies have been performed to examine the response of biological systems to magnetic fields. Many of these have employed rather large fields for limited periods and have not used adequate numbers of experimental subjects for good statistical analysis. The results have been highly variable and often nonreproducible.

Various biological parameters have been studied in animals exposed under many experimental conditions to magnetic fields ranging from a few gauss to 140,000 gauss. The systems studied have included electrical activity of the brain and heart, blood composition, growth and development, genetic defects, tumor growth, and function of enzymes. Several attempts also have been made to correlate human behavioral patterns with naturally occurring changes in the earth's magnetic field. A substantial proportion of the many studies reported in the literature has been unable to detect any change in biological structure or function even after exposure to high intensity fields. Others have found significant changes after exposure to even low strength fields.

Changes in the electrical activity of the brain and heart have been found after exposure of humans, monkeys, rabbits, and pigeons to fields of 500 to 91,000 gauss. There have also been field studies in

which correlation has been made between changes in magnetic field and behavior. Documentation has been fairly extensive in these areas although more information is obviously needed.

Some investigations have obtained results which suggest that pre-existing lesions may be exacerbated in the presence of magnetic fields while other studies suggest that changes are due to nonspecific stress. These are important areas for further study since people with certain extant medical problems might form a sensitive subpopulation which should be identified.

The genetic effects of magnetic fields have been studied primarily in lower organisms, houseflies and flour beetles. Changes in mortality and induction of wing abnormalities have been reported. In at least one study, there appeared to be some synergism between the effects produced by irradiation and magnetic field exposures.

Evidence for an influence of magnetic fields on growth and development has been presented from studies on frogs, salamanders, fruit flies, sea urchins, and mice. Of the various studies reported, most have been performed at field strengths above 2500 gauss and the results have varied markedly from no effect to complete prevention of development, depending upon the laboratory performing the study.

There are reports of changes in several other biological parameters as a result of exposure to magnetic fields. Although many of the results are controversial, they do provide guidelines for design of more definitive experiments in the future.

Recommended Areas of Research

A list of general information requirements for assessment of environmental effects of magnetic fields was presented in the document, "Information Requirements for Controlled Thermonuclear Environmental Statements" (*65*) and is reproduced in Table 1.

The items listed seem to be valid for consideration of research needs in the biomagnetic field, except for the item on effects on plant systems; since the magnetic fields will not extend beyond the fusion power plant perimeters, plant species will not be affected.

The following areas would appear to warrant the greatest attention.

NEUROLOGIC FUNCTION AND BEHAVIOR: Epidemiological studies and laboratory investigations indicate that behavior and other neurological functions are affected by magnetic fields. One study suggests that pre-existing lesions of the brain are exacerbated by magnetic fields. This area of neurologic function and behavior warrants additional attention to carefully define changes likely to occur.

Table 1. Information Requirements for the Assessment of Environmental Effects of Magnetic Fields.

Magnetic field patterns for the several reactor concepts.
Behavioral, physiological and morphological consequences of exposure of mammals to 1 to 500 gauss fields, particularly prolonged exposures
Behavioral, physiological and morphological consequences of exposure of avian species to 1 to 200 gauss fields
Consequences of combined exposure of mammals to magnetic fields up to 500 gauss and to several radionuclides, particularly tritium, likely to be encountered in fusion reactor plants
Consequences of exposure of people with implanted electronic medical devices to magnetic fields of 0.1 to 500 gauss
Sensitivity of people with extant medical problems, recognized or subclinical, to exposure to magnetic fields, alone or in combination with radionuclides or other stresses
Effects on plant systems
Effects of magnetic field gradients versus constant field
Effects of magnetic fields on differentiation and on the development of embryos and fetuses
Development of acceptable and testable hypothesis for interaction of magnetic energy with biological material

EFFECTS OF LONG-TERM EXPOSURES: The effect of long-term exposures to magnetic fields has not been sufficiently studied. Results of studies which have been reported are in conflict. Properly designed and carefully executed long-term experiments are needed for better evaluation of the long-term effects.

SENSITIVITY OF IMMATURE ORGANISMS: There is evidence derived from nonmammalian studies that developing organisms are more sensitive to magnetic fields than are the mature organisms. Since the immature organism is more sensitive to many kinds of insults, it is imperative that additional attention be given to this area.

POPULATIONS WITH ENHANCED SENSITIVITIES: Although developing organisms represent one population which may be potentially sensitive to the effects of magnetic fields, there are other populations which may have enhanced sensitivity, for example, persoss with existing psychological or medical problems and those with implanted medical devices such as pacemakers or metal prosthetic devices.

INTERACTIONS WITH NOXIOUS AGENTS: Since we do not live in an isolated environment, it is important to know whether magnetic fields can act in conjunction with other noxious agents to produce an effect different from either agent alone. From the literature available effects could be postulated

which might be additive, synergistic or antagonistic. Radiation is such an agent; there are others including cigarette smoke, and exposure to known chemical carcinogens.

PERSONAL DOSIMETRY: Although adequate instrumentation is available for measurement and characterization of fields used for experimental studies, a personal dosimeter is needed to provide supporting data for epidemiological studies. The instrument should be compact enough to be easily carried by personnel working the occupational situations and yet capable of providing integrated doses under a variety of exposure conditions.

EFFECTS ON BIRD NAVIGATION: It is conceivable that avian species could encounter significant fields and since there is good evidence showing the influence of magnetic fields on bird navigation, further study will be necessary to determine if the presence of the magnetic field from a fusion reactor will affect bird behavior.

MECHANISMS: More confidence can be placed in experimental data if the mechanism of action can be ascertained. At least, it is desirable to have a working hypothesis which can account for the data obtained. It seems necessary, therefore, to have additional work to derive a theory which could account for the interaction of magnetic fields and biological systems.

A systematic study of the influence of field characteristics on biological effects is needed because the question remains: Are there major differences in the biological effects produced by static, alternating, homogeneous, and gradient fields and is the orientation of the organism in the field important?

As the general areas are considered further, formulation of a program in somewhat greater detail seems necessary to facilitate the orderly acquisition of applicable information. An outline of specific approaches to these problems is presented in the Appendix. In these studies, it seems reasonable to emphasize the use of fields less than 750 gauss although it will be desirable to utilize higher fields to fully define the experimental system.

These recommendations should serve as a basis for discussion among scientists active in biomagnetic research. It is anticipated that these discussions will help to refine these concepts and approaches and lead to a definitive program of research to provide the information essential to fusion needs.

APPENDIX

Research Areas for Examination of the Biological Effects of Magnetic Fields

I. Behavioral studies
  A. Animals with normal behavior patterns (rodents and primates)
    1. Variety of tests for neurologic and behavioral effects
    2. Conditions of exposure to magnetic fields
      a. Static fields
        (1) Varying field strengths
        (2) Uniform versus gradient fields
        (3) Animal position varied relative to orientation of field
        (4) Varying exposure times
      b. Alternating fields
        (1) Wide range of frequencies
        (2) Variation of conditions as for static fields
  B. Animals with abnormal behavior patterns
    1. Employment of models used for other behavioral studies such as for psychosis or neurosis
    2. Similar exposure conditions as for normal animals

II. Moderate and long-term studies (rodents)
  A. Use 3-month exposure under wide range of field conditions
    1. Hematologic and clinical chemistry studies
    2. Growth
    3. Pathologic changes in variety of organs
    4. Functional changes
      a. Electrophysiologic measures
        (1) Electrocardiogram (ECG)
        (2) Electroencephalogram (EEG)
      b. Liver function
      c. Measures of circadia rhythm
      d. Simple behavioral tests
    5. Response to stress (cold, heat, electrical shock, or swimming performance)
  B. Lifespan studies
    1. Selected field conditions
    2. Most measures used under short-term study (II-1)
    3. Spontaneous tumor incidence

III. Effects on development
  A. Lower organisms (to obtain large numbers of test animals for statistical purposes, fish

may be an excellent system)
1. Static and alternating fields
2. Morphologic development
3. Behavioral development
4. Ability to cope with stress
   a. Cold
   b. Predation

B. Rodents
1. Varying field conditions (static versus alternating; uniform versus gradient)
2. Reproductive performance of exposed adults
   a. Fertility
   b. Litter size
   c. Incidence of malformed offspring
   d. Sex ratios of offspring
3. Postnatal performance
   a. Growth
   b. Survival to weaning
   c. Neurologic and behavioral development
   d. Physiologic fitness
   e. Reproductive ability
   f. Tumor incidence
   g. Other pathology

IV. Combined exposures
A. Radiation + magnetic fields
1. External radiation + magnetic fields
2. Internal emitters + magnetic fields.
   a. Tritium
   b. Prolonged exposures

B. Drug and dietary insult
1. Alcohol + magnetic field
   a. Alcohol + magnetic field
   b. Pathologic effects of alcohol
   c. Behavioral consequences associated with alcohol intake
2. Iron deficiency + magnetic field
   a. Hematologic changes
   b. Serum chemistry evaluation

C. Smoking
D. Exposure to carcinogens

V. Survey and evaluation of people presently exposed to magnetic fields
A. Evaluation of exposure conditions
B. Routine medical evaluation
C. Behavioral evaluation

VI. Effects on birds
A. Behavioral
1. Homing behavior
2. Migration

B. Functional

VII. Mechanisms of interaction of magnetic fields with biological material
A. Cellular studies
B. Subcellular studies
C. Molecular studies

VIII. Development of a personal dosimeter

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