Biologic Effects of Electric and Magnetic Fields Associated With Proposed Project Seafarer: (1977)

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Biologic Effects of Electric and Magnetic Fields
Associated with Proposed Project Seafarer

Report of the Committee on Biosphere Effects
of Extremely-Low-Frequency Radiation

Division of Medical Sciences
Assembly of Life Sciences
National Research Council

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National Academy of Sciences
Washington, D.C.
1977

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

This report has been prepared by the Committee on Biosphere Effects of Extremely-Low-Frequency Radiation in response to a request from the United States Navy for a study of the possibility that plants, people, and other animals would be harmed by the electric and magnetic fields associated with operation of the transmitter of the Seafarer communication system proposed by the Navy. The Committee was established in 1976 and charged (1) to assess the adequacy of existing data as a basis for determining biologic and ecologic effects due to Seafarer; (2) to identify the effects, if any, that may be of major concern; and (3) to identify critical inadequacies in the available data and suggest research projects designed to produce needed data.

The Committee was not asked to and did not consider such subjects as the necessity of the system, possible alternative submarine communication systems, technical feasibility, cost, or interference with telephone, radio, and television. Nor has the Committee explored in detail local ecologic effects that may be expected from the installation itself; these should not differ significantly from those associated with burying of telephone cables or natural-gas lines and with highway construction, on which there is a large body of knowledge and experience.

Seafarer (formerly Sanguine) is a system designed to provide communication with submarines and other military facilities from a single transmitting location in the United States. The system would function in the extremely-low-frequency (ELF) band of the electromagnetic spectrum at about 76 Hz, close to the 60 Hz used in electric power service. At this frequency, the signal could be picked up below the surface of the water, allowing submarines to remain submerged and thus reducing substantially their vulnerability to detection and attack. Because this is a long-range system with high power, a single transmitter should enable maintenance of essential communication links to strategic ocean areas.

The extremely low frequency implies that the wavelength of the Seafarer signal in air would be very long (about 2,500 miles, or 4,000 km). This, in turn, implies that the transmitting antenna must be very long, if it is to generate such a long-wavelength signal efficiently. The proposal is to install, in a grid pattern, 47 antennas, each 19-96 miles (30-154 km) long, with spacing 3.7 miles (5.9 km) between parallel lines. The present plan is to use underground cables, although transmission would apparently be equally good with wires overhead.

The proposal to erect such a large system has generated many questions and concerns within the scientific and lay communities, especially with regard to safety and to the impact on the ecosystem in the vicinity of a buried, electrically energized cable and within the grid pattern itself. In response to questions and concerns in many letters addressed to or referred to it, the Committee has assembled and evaluated the pertinent scientific literature and has consulted other scientists who either have contributed directly to knowledge concerning possible effects of ELF or, by reason of their specialized experience, can provide expert assessment of the available data.

Part I of this report has been prepared especially to facilitate understanding of the issues by readers who do not have professional scientific and technical training. This is done in recognition of the needs of concerned citizens and officials of the U.S. government to acquire a basic understanding of the facts—as far as they are known—on this controversial subject. The glossary is presented as additional background for Part I; it defines most of the electric terms and concepts used in the report. Part II, which parallels Part I, contains the technical documentation for the conclusions reached by the Committee. Part III consists of five papers written by members of the Committee and consultants for the use of the Committee in its deliberations.

The Committee acknowledges its indebtedness to all who responded to requests for assistance and thereby contributed to this report. The Committee is indebted especially to the persons listed as consultants.

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CONTENTS

GLOSSARY OF ELECTRIC TERMS AND CONCEPTS

Electric current is the flow of charged particles, usually of subatomic size. Current flowing in a wire might be compared with water flowing in a pipe. The rate of water flow can be expressed in gallons per minute; the rate of current flow is expressed in amperes (A).

Each Seafarer cable would carry about 100 A. By comparison, an electric toaster requires about 10 A and a 100-watt lightbulb requires about 1 A. Current is sometimes measured in thousandths of an ampere, or milliamperes (mA). A current as low as 25 mA, passed through the human body, can interfere with heart functioning and has been known to cause death.*

Voltage is the "pressure" that pushes current through a circuit. Water pressure can be expressed in pounds per square inch; electric pressure is expressed in volts (V).

Seafarer transmitters would apply several thousand volts to the antenna cables. Some large power lines operate at hundreds of thousands of volts, household outlets supply about 110 V, and a flashlight cell produces 1.5 V.

Conductance of a wire carrying a current determines how much current will flow with a given voltage. Conductance might be compared with the size of a pipe through which water is flowing. Highly conductive objects (such

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*Keesey, J. C., and F. S. Letcher. Minimum Thresholds for Physiological Responses to Flow of Alternating Electric Current Through the Human Body at Power-Transmission Frequencies. Naval Medical Research Institute Project MR005.08-0030B, Report No. 1. Bethesda, Md.: National Naval Medical Center, 3 September 1969. 25 pp.

as a copper wire) permit more current to flow with a given voltage. *Resistance* refers to the same property of an object (such as a wire). Saying that an object has high conductance is the same as saying that it has low resistance: resistance = 1/conductance.

Conductivity refers to how well a *kind* of material conducts electric current—copper, for example, rather than a copper wire of a particular size. It can also refer to soil types. The *conductivity of soil* is important in considering the possible effects of Project Seafarer, because variations in conductivity from place to place affect how much current will flow in specific areas near the antenna, and that in turn determines whether there will be local hazards—what might be called "hot spots." Conductivity of soil is also important because it partly determines the "connection" of an organism to a voltage produced by Seafarer. For example, standing on wet soil could in some circumstances pose shock hazards for people or animals where no hazard would exist on dry soil.

Power, measured in *watts* (W) or kilowatts (thousands of watts, kw) or megawatts (millions of watts, MW), takes into account both the voltage and the current that are used to operate a device or system. It is calculated by multiplying voltage (in volts) by current (in amperes). For example, a light bulb operating on 110 V and drawing 1 A of current would be using 110 x 1 = 110 W. Seafarer would require about 14 MW of power. A city of 100,000 people might require slightly less than 100 MW on the average.

Whenever current flows, it produces an *electromagnetic field*. In considering the electromagnetic fields that would exist in the area covered by Seafarer, it is useful to discuss two components of these fields: magnetic fields and electric fields.

A magnetic field is said to exist in a region if magnetic objects (those containing, for example, iron) in the region experience a force. A simple magnet has a magnetic field around it, and iron objects within the field are attracted to the magnet. The earth's magnetic field acts on the needle of a compass. An electric current passing through a wire also creates a magnetic field. This effect is put to use in electromagnets, for example. The intensity of a magnetic field is expressed in gausses (G). For a Seafarer antenna buried 6 ft (1.8 m) deep, the magnetic field at the soil surface directly above an antenna cable would be about 0.11 G. The earth's magnetic field is relatively constant at about 0.5 G. Magnetic fields within a few inches of some power tools and electric appliances range from 1 to 10 G, and even higher.

An electric field is said to exist in a region if charged objects in the region experience a force. Many people are familiar with static electric fields—they can make a person's hair "stand on end." Electric fields are described in terms of the voltage that exists over a given distance, usually 1 m (about 3.3 ft). A 12-V battery, connected to parallel metal plates 1 m apart, would create a field of 12 volts per meter (V/m) between the plates.

Electric fields can exist in various media, such as air, soil, and water. Those of most widespread concern in the case of Seafarer would be the fields in soil. If an electric field of 5 V exists between two points in soil 1 m apart, a voltage measurement taken between those points will show 5 V, and a person standing with one foot on each of those spots, in contact with the soil, would be in contact with 5 V.

An electric field in soil is sometimes expressed in terms of a step potential. This simply refers to the voltage that would exist between a person's two feet when he was taking a step. The step is assumed to be 1 m long, so a step potential of 5 V refers to an electric field of 5 V/m in soil.

Navy specifications call for an electric field of 0.07 V/m directly above an antenna cable buried 6 ft (1.8 m) deep. Ground terminal fields could be as high as 15 V/m. For comparison, the Navy has advised that, in surveying existing fields in the soil around homes (fields resulting from electric power systems), it found an average intensity of 0.09 V/m (171 readings taken).*

Electricity can flow as direct current--constantly in one direction through a circuit, as from a battery--or as alternating current--with the direction of flow changing. The current from household outlets is alternating current. Household current is supplied at a frequency of 60 cycles/second. That means that it undergoes a cycle--flowing in one direction, then the other direction, then back to the first direction--60 times each second. The unit for cycles/second is the hertz (Hz); 1 cycle/second is 1 Hz. Seafarer's current would be alternating at a center frequency of 76 Hz, which is similar to that of power systems. (See also the discussion of modulation below.)

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*U. S. Department of the Navy, Naval Electronic Systems Command. Sanguine System Final Environmental Impact Statement for Validation and Full-Scale Development, pp. 70-71. Springfield, Va.: National Technical Information Service, April 1972.

That Seafarer's current would be alternating would be important in considering the project's possible effects on surroundings, for the following reason. When a magnetic field is varying, it produces a voltage in nearby wires and other conducting objects. The variation can be one of two types: the source of the field can be moving, or the current creating the field can be alternating, which causes the field to grow and collapse alternately. Therefore, Seafarer's alternating current would create voltages in nearby objects, expecially in long metal objects like fences, pipelines, and utility lines. The electric field in the soil near Seafarer would also produce voltages in such conducting objects that are in contact with the soil.

Incidentally, the relationship between electricity and magnetic fields is the basis for electric motors and generators, as well as for broadcasting. In an electric motor, the current produces a magnetic force, which is applied to give rotary motion. In a generator, a moving magnetic field passes through coils or wire to produce a current.

Seafarer's electromagnetic field would also extend great distances--it would be detected and received by submarines. The field would be millions of times greater within the grid region than at submarines, however. The low-intensity field present at the submarines would enable them to receive instructions--the process somewhat comparable with the reception of conventional radio signals.

Wavelength is related to frequency. It can be visualized in the following way: Think of a radio signal traveling outward from a radio transmitter at the speed of light, 300 million meters/second. A wavelength is the distance that signal will travel during one cycle (one wave) at its frequency. High frequencies involve short wavelengths, and low frequencies involve long wavelengths. Suppose a radio signal is broadcast at 100 million Hz (100 MHz). Each cycle takes one one-hundred-millionth of a second. In that time, the signal will travel 3 m (about 10 ft).

Antennas one-half wavelength long are particularly efficient for broadcasting and receiving radio signals. In the example just given, an antenna about 5 ft long would be efficient. The frequency of 100 MHz is in the band used by FM radio stations in the United States, and indeed many FM antennas have an overall dimension of about 5 ft.

Seafarer, with its extremely low frequency, would have a very long wavelength--about 2,500 miles (4,000 km). That is why such a long antenna is to be used. Submarine receiving antennas would be shorter, perhaps a few hundred meters long. The tiny signal available from such an antenna would have to be detected and processed by extremely sophisticated receivers.

As described above, current in Seafarer cables would be alternating at a center frequency of 76 cycles/second (76 Hz). However, although power-system current alternates at a constant frequency (of 60 Hz), Seafarer's frequency would switch back and forth between two frequencies, probably 72 and 80 Hz. This variation would be a kind of modulation similar in some respects to FM (frequency modulated) radio. Modulating the frequency-raising and lowering it within this band-would be the means of sending information out to submarines. The modulation would be one aspect of Seafarer's signals <u>not</u> comparable with fields from power systems.

"Radiation" is a term sometimes applied to the electromagnetic fields of Seafarer. The term is accurate in the sense that a part of the field "radiates" to a distance, where it can be received. In a similar way, other radio and television signals are also "radiation," as is visible light.

Different types of radiation (radio, visible light, x rays) differ by virtue of their frequency or wavelength; those of lower frequency (ELF, radio, etc.) have lower energies, while the higher frequencies, including ionizing radiation, are of high energy and thus potentially more damaging.

SYMBOLS

A	ampere
AC	alternating current
A/m^2	ampere per square meter
^{o}C	degree Centigrade
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
CW	continuous wave
dB/octave	decibel per octave
DC	direct current
ELF	extremely low frequency
emf	electromotive force
^{o}F	degree Fahrenheit
g	gram
G	gauss

GHz	gigahertz
Hz	hertz
kg	kilogram
kHz	kilohertz
km	kilometer
kV	kilovolt
kV/cm	kilovolt per centimeter
kV/m	kilovolts per meter
kW	kilowatt
m	meter
mA	milliampere
mA/cm^2	milliampere per square centimeter
mg	milligram
mg%	milligram percent
mG	milliGauss
MHz	megahertz
min	minute
ml	milliliter
mm	millimeter
mmho/m	millimho per meter
MSK	minimum shift keying
mV	millivolt
mV/cm	millivolt per centimeter

mV/m	millivolt per meter
MW	megawatt
ohm-cm	ohm-centimeter
p	statistical probability value
R_C	contact resistance
R_I	body resistance
RMF	rotating magnetic field
rms	route mean square
R_S	source resistance
s	second (unit of time)
SIDS	"sudden infant death syndrome"
V	volt
V/cm	volt per centimeter
V/m	volt per meter
V_{max}	maximal total voltage
V/mile	volt per mile
µF	microfarad
µg	microgram
µm	micrometer
µV/cm	microvolt per centimeter
W	watt

I. OVERVIEW OF EFFECTS OF PROJECT SEAFARER

During the last 50 years, we have witnessed exponential growth in electromagnetic fields produced by man-made devices and engineering systems. This growth has accompanied development of communication systems that now blanket the earth. Extensions of these fields have also resulted from the vast and still growing network of electric power distribution systems that are increasingly international in their ramifications.

Organisms have always been exposed to a wide range of natural electromagnetic fields. Indeed, the evolution of life on earth has occurred in the presence of an unceasing flux of natural fields, derived in great measure from solar radiation and supplemented substantially at some frequencies by terrestrial electromagnetic disturbances, including thunderstorms. What influence, if any, these natural fields have, for example, on growth and development, on seasonal or other cyclic aspects of behavior, or on aging is only very poorly understood. It may therefore be a cause for concern that, lacking the basic knowledge about possible biologic and medical importance of these weak fields, we have, in virtually every aspect of civilized society, proceeded with the development and application of electric and electromagnetic generators that might cause exposure to fields that can be much larger than natural fields at the same frequency.

Therefore, while keeping in mind its charge to focus on potential problems associated with the Navy's proposed Seafarer communication project, the Committee has also been aware of the larger question: are there potential hazards in the exposure of living organisms to any such artificial extremely-low-frequency (ELF) fields? The Committee has considered relevant background material concerning the lower-frequency electromagnetic spectrum, especially in the region of 50-60 Hz associated with our electric power systems.

In its review, the Committee has acknowledged that essentially everything man undertakes entails some risks. Ideally, we should be able to define the risks, measure them, and compare them with measured benefits that are foreseen. Despite some gaps in knowledge, it is such an approach that citizens and their representatives may well use in reaching a decision about whether to build Seafarer. We certainly cannot expect to predict the consequences of any decision of this sort with 100% accuracy, but decisions must be made; the committee findings and the research it has recommended should contribute toward wise decisions.

The Committee has evaluated the Navy's plans from many points of view: environmental, ecologic, engineering, biophysical, biologic, and medical. In evaluating research performed, the Committee has endeavored to assess the merits, and indeed the validity, of individual studies. This has been necessary in a field in which the very nature of the research demands skills in many disciplines, including biophysics and engineering, as well as equivalent competence in design and observation of complex biologic experiments. The Committee has questioned many findings and discounted many of them because they failed to measure up to criteria, either in engineering aspects of the experimentally imposed fields or in experimental design. Its review has covered possible effects of ELF fields on plants, soil organisms, aquatic vertebrates, mammalian wildlife, birds, other animals, and man.

An announcement in July 1968 by a Wisconsin congressman that a U.S. Navy installation identified as Project Sanguine would be built in a large area of northern Wisconsin, including his district, stimulated intense public controversy that persists to this day. The establishment of a Sanguine test facility at Clam Lake, Wisconsin, in 1968 was preceded by Navy research on ELF electromagnetic radiation going back to approximately 1960.

The current means of communication with submarines involves a network of radio transmitters around the world whose messages can be received only when submarines operate at the surface or no more than a few feet below it. The Navy proposed Sanguine for sending signals to deeply submerged submarines throughout the world. In its simplest terms, the Seafarer system consists of multiple transmitters, each connected to antenna cables buried in the ground that in turn are connected to ground terminals. Alternating current flows in a loop--from one side of the transmitter, through the antenna cable, into the earth at a ground point, through the earth back to the other end of the cable, and back to the transmitter, thus completing the circuit. In flowing along this path, the current produces a signal whose strength depends on how well electricity is conducted, i.e., on the conductivity of the earth under the antenna. Because the nature of the soil and rock below the antenna cables has a profound influence on performance of the communication system, only a few locations in the United States have been identified for installation. For the current to flow deeply, and thus produce a more powerful signal, a low-conductivity bedrock is needed under the Seafarer site; very old, dry granite is highly desirable to ensure a strong, efficient signal. Other sites involve less efficient and therefore much more costly sets of circumstances. This explains the preference for such sites as Wisconsin and upper Michigan, which have an underlying formation of old, dry granite called the Laurentian Shield.

During the last 8 years, Sanguine, with its design altered several times and its name changed to Seafarer, has been proposed for and opposed in several states, each of which has the desired low-conductivity bedrock. The Navy is now focusing on the Upper Peninsula of Michigan, just north of the original Wisconsin site, as a preferred location for the proposed system. In the fall of 1975, Michigan Governor Milliken extended a conditional invitation to the Navy to consider the Upper Peninsula as a site for Seafarer. He stipulated that an analysis by the National Academy of Sciences of the possible biologic and ecologic effects would enter into his consideration in reaching a final decision on the matter.

As mentioned above, virtually all human activities entail some risk. This report should provide details and some definitive information on the effects—real, possible, and imagined—of ELF fields. It does not attempt to go further and weigh risks against benefits.

THE ANTENNA AND THE FIELDS

Antenna Design and Operation

Seafarer would consist of a grid-like pattern of many antenna cables, each carrying 100 A of current. A look at how one cable would function will show the basic concept of transmitting Seafarer signals.

Figure 1 shows the operation of an antenna cable. The cable itself is to be an insulated heavy aluminum wire about 2 in. (5 cm) in diameter. It would be many miles long, buried about 2.5-6 ft (75-180 cm) deep in the ground. Each end of the cable would be connected to a bare copper wire or a network of such wires--a ground terminal--to form an electric connection to the earth. Navy specifications indicate that a typical terminal might consist of two wires, each about 1.2 miles (2 km) long and at a 60° angle from each other.

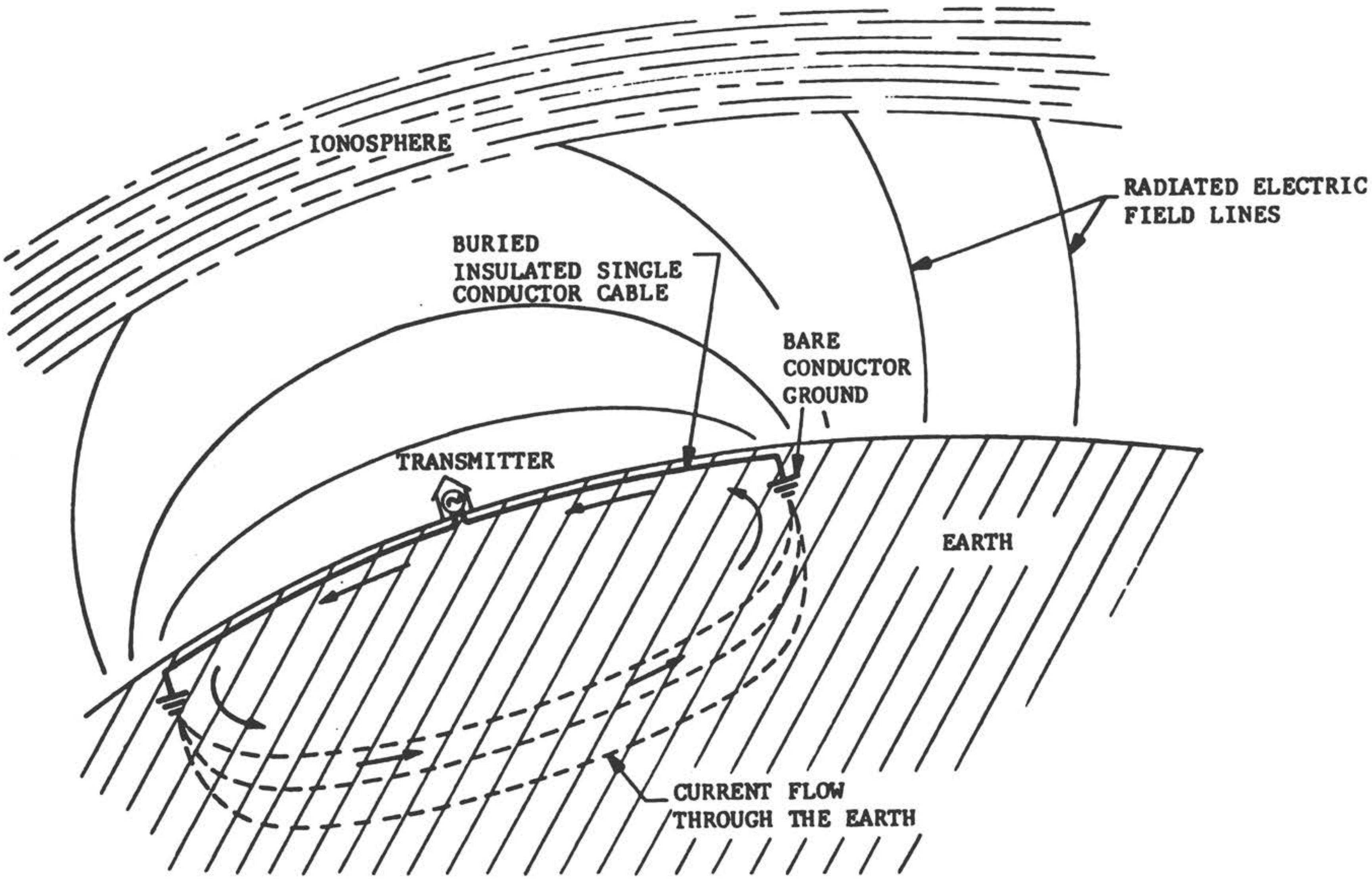


Figure 1. ELF transmitting antenna operation. Reprinted with permission from GTE Sylvania, Inc. ELF Communications Seafarer Program. System Design Study Report Michigan Region. Prepared for Naval Electronic Systems Command. Needham Heights, Mass.: GTE Sylvania, Inc., 12 January 1977.

A transmitting station within the grid would send electric current through the cable. The current would flow through the cable, into the earth at the cable end, deeply through the ground, and back to the other end of the cable. Thus, the circuit would be complete; the current would flow in a large loop consisting of the cable and the earth beneath it.

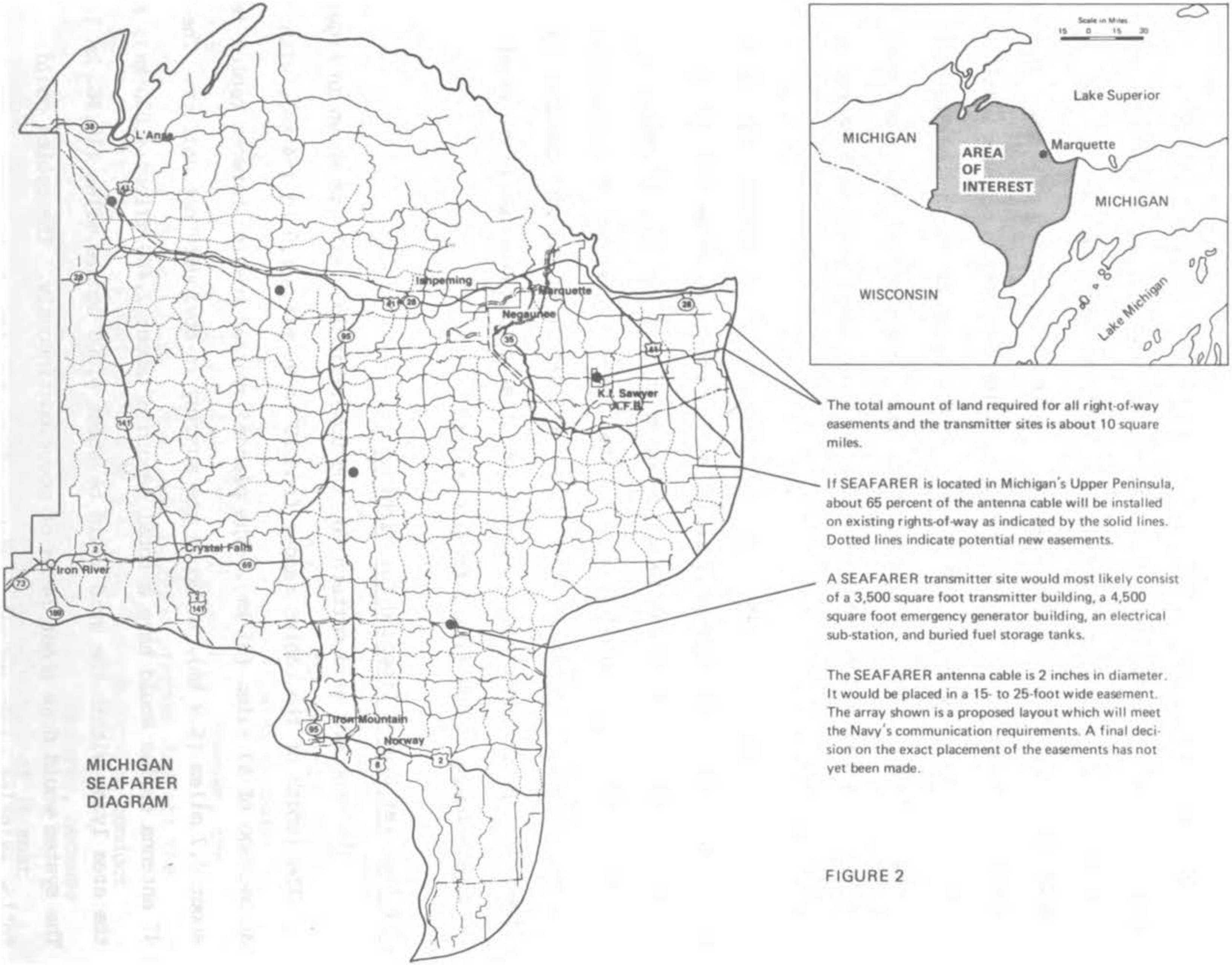
This flow of electric current would create electromagnetic fields in the earth and in the air above the earth. To put it another way, the current flow would produce a radio signal, similar in some ways to that of a radio or television station. This electromagnetic signal would radiate into the space between the earth and the ionosphere (a region of charged particles high in the atmosphere). Seafarer signals, unlike most other radio signals, would effectively penetrate downward from the atmosphere into oceans and could be received there. This unusual characteristic of the Seafarer signal would result from the extremely low frequency, which is to be about 76 Hz—a much lower frequency than used in other broadcasting. It would be about the frequency of our electric power systems (60 Hz), which, although they are not designed to send out signals, actually do so.

The strength of the ELF Seafarer signal that reached submarines would depend, in part, on the total length of the antenna (the combined length of all the cables) and on the amount of electric current flowing through it; longer cables and more current produce a stronger signal. However, the strength of the radiated signal would also depend on another factor: the conductivity of the earth below the antenna, i.e., its ability to conduct electricity. The lower the conductivity, the better for Seafarer, because low conductivity would cause the current to flow deeply—much of it must flow several miles into the earth—as it traveled from one end of an antenna cable to the other. The loop of current would be large and thus create a relatively strong radiating field. It is the conductivity of the subsurface (the bedrock), not that of the earth surface, that is important for signal radiation. Therefore, a long antenna, a large electric current, and a low-conductivity bedrock are three requirements for Seafarer. Because suitable subsurface conductivity is found in only a few areas of the United States—including northern Wisconsin, upper Michigan, south-central Texas, and some places in Nevada and New Mexico—the Navy has proposed building Seafarer in such places.

One antenna cable like that described above, even though hundreds of miles long, would not produce a signal strong enough to serve Seafarer's purposes. So the Navy plans to use a number of such cables. If cables are placed approximately parallel to each other, they can be made to function as one antenna equivalent in length to the total length of all the cables. To give better signal coverage, a second set of antenna cables would be added at right angles to the first, forming a grid.

The Seafarer System Proposed for Michigan

The proposed grid pattern for the upper-Michigan site is shown in Figure 2. The length of the cables ranges from 19 to 96 miles (30 to 154 km), with an average of 57 miles (91 km). The planned average spacing between cables is about 3.7 miles (5.9 km), although the spacing is obviously not uniform. The 47 antenna cables would have a total length of about 2,400 miles (4,000 km), and the area lying within the grid would be about 4,000 square miles (10,360 km^2). The system would draw about 14 MW of power continuously. The cables could follow existing roads and other rights-of-way for 64% of the total cable



MICHIGAN
SEAFARER
DIAGRAM

The total amount of land required for all right-of-way easements and the transmitter sites is about 10 square miles.

If SEAFARER is located in Michigan's Upper Peninsula, about 65 percent of the antenna cable will be installed on existing rights-of-way as indicated by the solid lines. Dotted lines indicate potential new easements.

A SEAFARER transmitter site would most likely consist of a 3,500 square foot transmitter building, a 4,500 square foot emergency generator building, an electrical sub-station, and buried fuel storage tanks.

The SEAFARER antenna cable is 2 inches in diameter. It would be placed in a 15- to 25-foot wide easement. The array shown is a proposed layout which will meet the Navy's communication requirements. A final decision on the exact placement of the easements has not yet been made.

FIGURE 2

length, thus avoiding some areas where cable installation would be more expensive, difficult, or undesirable. Power would be supplied to the cables by underground wires from five transmitter locations within the grid. The proposed size and power consumption of the overall system have been changed several times since plans were first made public, owing mostly to adaptation to different sites. If sites in either New Mexico or Nevada were used, the installation would be much larger than that in Michigan. The present proposal calls for total cable length and power to be roughly twice those in the 1976 Michigan design, because the earth's conductivity in the area was underestimated.

Seafarer Fields

For effective communication with submarines, the ELF field that is of interest is the far field, i.e., the electromagnetic field in the far-away oceans. For biologic effects, the near field—i.e., the field near the source—is important, because it is much stronger than the far field. Submarines can pick up the weak far field by sophisticated electronic methods not available to biologic systems.

With electric and magnetic near fields, the most obvious concern is the potential danger of shock. But there could be other effects. In describing the fields that the project would produce, we shall discuss fields within the grid and those near the ground terminals separately. We shall also discuss the electric- and magnetic-field components separately, to make clear some important differences between them.

Electric Fields within the Grid

As described earlier, current flows through the earth from one end of a cable to the other. Most of it flows deeply, but some flows near the earth's surface and produces electric fields throughout the antenna grid.

Fields within the grid would be strongest directly over a cable--0.07 V/m, according to Navy specifications. Thus, a measurement of the voltage between two points directly over an antenna cable, and 1 m apart, would produce a reading of 0.07 V. If a person put one foot on each of those points, he or she would be in contact with 0.07 V, or about one-twentieth the voltage of a single 1.5-V flashlight battery. However, local soil conditions could result in voltages several times as high.

Measured over longer distances, the voltage would be higher. Two points 1 mile (1.6 km) apart would show about 110 V--more than enough to create shock hazards. Precautions would therefore have to be taken with fences, pipelines, and other long metal structures near antenna cables in which such voltages might appear. Away from a cable, the electric field would be weaker: 100 m away, it would be about half as strong; and within the grid, midway between cables, the field would be about 0.02-0.03 V/m. Near the intersection of two cables, the electric field would be somewhat stronger--about 0.1 V/m, depending on the operation of the system.

The electric field would also exist in the air above a cable. This air field would be of about the same intensity as that in the ground. But an organism in or on the ground would have a better connection to the field--in fact, the connection might be a million times better. If some sections of antenna cable were installed above the ground on poles, there would be an additional electric field: a vertical field in the air between the cable and the earth's surface. This air field would be considerably stronger than the earth field produced by a buried cable, but it would be much smaller than the air fields produced by most overhead commercial electric powerlines. It would also be much more localized than the earth and air fields already discussed.

Magnetic Fields within the Grid

The current flowing through an antenna cable produces a magnetic field that is strongest near the cable. However, with increasing distance from the cable, it decreases in intensity more rapidly than does the electric field. The Navy has specified a magnetic field of 0.11 G (Michigan proposal) at the earth's surface directly over an antenna; but 100 m from a cable, the field would be only about 0.002 G. The earth's magnetic field is about 0.5 G.

Because the magnetic field is so much stronger near a cable than even a short distance away, the field strength at the surface depends heavily on the depth of the cable. If the cable depth is 75 cm, instead of 180 cm, the magnetic field at the earth's surface would be more than doubled, to about 0.26 G. However, because the magnetic properties of soil are essentially the same as those of air, local soil conditions would not affect the field, and it can be calculated accurately. At cable intersections, the field could be about 1.4 times that along a cable. If the cable is placed overhead in some areas, the magnetic field could be large for birds or other organisms that could approach it closely.

Electric Fields Near the Ground Terminals

The Navy has specified a maximal electric field of 15 V/m for ground terminals consisting of long horizontal bare wires buried about 180 cm deep. The Navy has also specified that the design will limit the current through a person who is standing near a cable to 1 mA. However, this specification appears to be very difficult to implement in all cases; it is probable that local conditions (e.g., wet soil) and some activities (e.g., two people carrying an aluminum canoe) near ground terminals would expose people and animals to current higher than 1 mA and even to shock hazards.

The electric field in the ground-terminal areas is a direct result of the current that flows out of the long uninsulated grounding wire in all directions and into the earth. This current flow is greatly affected by the conductivity of the earth in the immediate vicinity. The conductivity varies from place to place--and from time to time, as moisture conditions change. Therefore, the current distribution and the electric field also vary. For example, suppose that a puddle of water a few meters in diameter overlies a horizontal ground wire, and that the surrounding area is quite dry. More current would be flowing through the highly conductive wet area than through the dry area. This concentrated current would produce much stronger electric fields in the dry soil around the edge of the puddle than would exist if the puddle were not present.

Magnetic Fields Near the Ground Terminals

A magnetic field is produced by the flow of current and is more intense near a concentrated current flow. The Seafarer magnetic fields would be less intense in the ground terminal areas than along an insulated antenna cable, because the current in the ground-terminal regions would diffuse into the earth over the length of the bare ground wire.

Antenna Fault Conditions

This discussion so far has dealt with field intensities to be expected near Seafarer when it is operating as designed. However, it is important to consider what happens when operation is faulty, for example, when a break develops in antenna-cable insulation.

Such breaks should be anticipated. The few miles of buried cables at the Wisconsin Test Facility developed several faults during several hundred hours of operation. Seafarer's 4,000 km of cable, although it may be of much better design, cannot be expected to be completely fault-free. Where a fault occurs in cable insulation, current can "leak out" into the ground, and that would create a substantial voltage difference over a few feet of earth. A person walking in the area could be exposed to hazardous step potentials.

A fault can be repaired when found. The problem is to find it quickly and disconnect the affected cable before people can be harmed. The Navy has presented plans to detect and repair faults; however, the adequacy of these plans has not yet been demonstrated.

Comparison of Seafarer Fields with Existing Fields

Seafarer would produce fields similar in several respects to those already common in the environment, such as electric and magnetic fields produced by electric power systems. What, then, would be noteworthy about Seafarer fields? What unique conditions would Seafarer bring to the environment?

One difference is in frequency and modulation; power systems are at a single frequency (50 or 60 Hz), whereas Seafarer's fields would switch back and forth (i.e., be modulated) between two different frequencies, probably 72 and 80 Hz (this is referred to as a nominal value of 76 Hz, which is the center frequency). Although one study suggested that such modulation has biologic significance, other work has not given similar indications.

Furthermore, an important and fundamental difference is that power systems use wires for the complete circuit, whereas Seafarer current must travel through the earth, that is, utilize a ground return; the resulting fields would be different in several ways.

Ground-Return Electric Fields in Soil and Water

Organisms are coupled to fields in soil or water more effectively than to fields in air, so the fields produced by Seafarer ground-return currents in soil and water should be of special concern. Although powerlines are not designed to send current through the earth, they do typically produce a small earth current, which results in an electric field in earth whose intensity is a small fraction of that of the Seafarer field.

Near the Seafarer ground terminals there would be earth fields of even greater magnitude than along the antenna cable. And, although powerlines also have ground terminals, these are designed to handle fault conditions in a system and are not for continuous operation with substantial current. Therefore, Seafarer ground terminals do not have a real counterpart in power systems.

Electric Fields in Air

Powerlines produce electric fields in air between wires and the earth. The vertical fields may be thousands of volts per meter, compared with less than 1 V/m in soil for Seafarer. Because of the differences between air fields and those in soil, however, these numbers alone cannot be regarded as a measure of the relative biologic impacts (or potential impacts) of the two situations.

If Seafarer cables are strung overhead in some places, they will also produce vertical electric fields. However, these will be less intense than those produced by many powerlines.

Magnetic Fields

In a powerline, current at any instant is flowing "out" through some wire or wires and "back" through others. Wires with opposite and equal currents produce magnetic fields that tend to cancel each other out. Because of such cancellation, magnetic fields near powerlines are less intense than they would otherwise be. Although powerlines sometimes carry currents much larger than those of Seafarer, the magnetic fields directly under them are typically about the same magnitude as those directly over a Seafarer antenna cable.

Fault Conditions

Another difference between Seafarer and power systems lies in the conditions that would be produced by faults, such as breaks in the cable insulation.

Buried powerline cables are generally encased in a heavy metallic shield, so insulation breaks are unlikely to produce leakage of current into the ground (as would be the case with Seafarer). In addition, the presence of this shield in powerlines means that an underground insulation break almost certainly results in a short circuit. The short circuit is obvious, so power can be quickly shut off and repairs made. With Seafarer, however, there is some question about how quickly faults can be detected. In the time between occurrence and detection, there might be hazardous fields.

Seafarer cables cannot be shielded to avoid the problem. A shield would compromise the transmission of radio signals by providing a return path for the current, which must flow deeply in the earth if Seafarer is to transmit effectively.

Fields Produced by Home Appliances

In addition to fields that result directly from wiring and nearby high-voltage lines, home lighting appliances, and electric equipment produce magnetic and electric fields. Magnetic fields as high as 25 G are common in areas near power tools, mixers, hair-dryers, and other devices with transformers or motors. However, few people or other organisms are close to the sources of such fields for long periods, so again the analogy to Seafarer is not totally appropriate.

Electric fields of home appliances may have strengths of many volts per meter, but the fields are usually in air. An electric blanket may produce a field of 200-300 V/m in air, but the electric current that flows in a person under that blanket is considerably less than that in a person who walks along a Seafarer antenna cable and whose feet make good contact with the soil.

BIOPHYSICAL AND EXPERIMENTAL CONSIDERATIONS

Coupling of Electromagnetic Fields to Organisms

If organisms are to be affected by electric or magnetic fields, they must be coupled to ("connected" to) the fields. Two kinds of considerations must be made in assessing the coupling of organisms to fields: the wavelength of the signal and the medium (air, soil, or water) through which the organism is coupled to a field.

Effect of Wavelength

As described by fundamental physical laws, electromagnetic energy comes in quanta ("packets"), which are determined by the wavelength of the radiation. At shorter wavelengths, there is more energy per packet. The "density" or "compactness" of energy is very important; an analogy might be drawn with an ordinary electric blanket that dissipates in about 5 s as much energy as is conveyed by a small-caliber rifle bullet in flight. The deadly effect that the bullet can have is a result of its energy's being put to work in a very short time and small area.

In a similar way, radiation can concentrate its impact on a target with destructive effect. But the energy actually brought to bear on structures in an organism depends on wavelength. At short wavelengths, measured in billionths of an inch or nanometers, we see the drastic disruptive processes associated with x rays and cosmic rays that are known to produce cancers and mutations by damaging structures in cells. These effects are possible, even though the total energy in the rays may be low, because the energy is concentrated.

At intermediate wavelengths, measured in millionths of an inch or micrometers, we move into the ultraviolet spectrum, which produces sunburn and some other effects; at slightly longer wavelengths, we move to visible light, which has such beneficial effects as permitting vision and providing the energy for plant growth.

Progressively longer wavelengths are those of radio waves, down to extremely low frequency, or ELF, with progressively less energy per packet. This energy-wavelength progression implies that all ordinary radio waves, from microwaves to ELF, can be absolved of suspicion of any "radium-like" action in which the particle (quantum) energy would be sufficient to damage cell molecules or structures.

Effect of Medium

The wavelength of the fields produced by Seafarer or another source is not the only consideration in evaluating possible effects on organisms. Near the system, the intensity of the fields and the medium in which they exist are also important. Fields in air must not be equated with fields in soil or water; the coupling, or connection, of the organisms to the fields is affected by the medium--specifically by the electric properties of the medium.

Suppose a source producing 100 V is connected to two parallel metal plates 1 m apart. A person standing between them would be exposed to an electric field (over 100 V/m) in air, but would probably not realize it. However, a person who touched the plates would become more effectively coupled and would receive a shock. Similarly, if the space between the plates were filled with soil, a plant or animal placed in or on the soil would have much more current pass through it than was the case in the air field, because the soil would couple the organism to the field much more effectively.

Conductivity of soil varies widely with moisture conditions and soil type. This variation is of special concern for Seafarer, because it can result in higher-than-specified field strengths at some places along antenna cables or ground wires. Water can produce even better coupling than soil.

Types of Effects

Electric and magnetic fields may produce effects in organisms. Some of the effects are well established and are associated with particular intensities of fields or electric current. Others are more speculative.

Heating

Electric current, passing through tissue, can produce heating much like that when current passes through a heating element in an electric appliance. However, heating great enough to be of any concern for organisms occurs only with currents far greater than Seafarer would typically produce.

Excitation

Electric currents can directly excite—cause response in—living matter. Applied voltages produce current flow, which in turn produces responses in humans and animals. The current can be categorized with respect to its effect, as follows: current that can be perceived (about 1 mA), "let-go" current (about 10 mA, the current that interferes sufficiently with muscle control, so that a person cannot let go of the current source once in contact with it), and current that will cause heart fibrillation (100 mA, or less). Some biologic systems are known to have special sensitivities to much smaller electric currents, even below 1 μA. Some of these responses may not involve classical excitation.

Field Force Effects

Electric fields exert a force directly on matter. Bits of lint are attracted to some types of clothing because of static fields. Seafarer voltages are much lower than those known to have any significant effect on living matter by this mechanism.

Magnetic-Field Effects

Less is known about possible interactions of magnetic fields with organisms than is the case for electric fields. Some bacteria are known to respond to magnetic fields, and increasing experimental evidence suggests that bees and birds are able to detect and use the earth's magnetic field. An important difference is that the earth's fields are steady (DC) fields, whereas Seafarer fields would be alternating (AC), about 76 times per second (76 Hz).

Design and Interpretation of ELF Biologic Experiments

In its review of experiments concerned with possible ELF field effects, the Committee has become acutely aware of the critical importance of how experiments are designed and executed and how results are interpreted. Even in experiments that appear to be impeccably planned, it is easy to come to incorrect conclusions. The Committee has examined a number of cases in which a claimed effect of an ELF field was very likely an effect of something else in the experiment and cases in which no effect was found, but the design of the experiment was such that probably none could have been found even if it did exist. Any experiment is subject to pitfalls (see Appendix E), and this is especially true in investigations of possible weak ELF field effects on organisms, where known or even postulated mechanisms by which ELF fields could produce effects are lacking.

Consider the matter of dose-effect relationships. Depending on the mechanism, an organism might respond in different ways to an increasing dosage of, for instance, light. There might be a threshold, below which no response occurs. Or the response might be directly proportional to dosage over a wide range. Or the effect might go through a maximum and decline at higher dosages, so that some effect occurs at low dosages, but not at higher ones. Or there may be positive effects at one dosage and negative effects at another; plant movements in response to light are classical examples of this.

Frequency is also related to mechanism in the design of experiments on effects of ELF fields. The importance of frequency is clear in the case of visible light—for example, blue light may have an effect where red light does not; a red safelight in a photographic darkroom will not expose enlarging paper, but blue light will. In biologic systems, as in photosynthesis or vision, one color may be very effective and another less effective. The interpretation of this is that some frequencies are absorbed and others are not; those absorbed have the potential for producing an effect, and those not absorbed cannot have effects. This is clearly applicable to Seafarer: without knowledge of the nature of the absorbing elements (and thus the mechanism), it is very difficult to know whether experiments done at frequencies other than 76 Hz are pertinent.

Among other matters to which attention must be given in this research are the possibility of synergistic effects (in which two agents act together to produce greater effects than the two separately), the existence of background ELF fields in the laboratory or research site, and the effects of duration and intensity of exposure. The possibility of latency--a delay in onset of the response--must also be considered.

Another reason for special concern in the evaluation of ELF research is that the stated exposure to an electric or magnetic field may not have been the actual exposure. An organism or substance placed in a field may change that field itself, and sometimes the coupling cannot be readily calculated.

For example, suppose that fruit flies were placed in a glass tube suspended between two plates, between which there is an alternating electric field of 1,000 V/m. If the glass were very clean, the field in air in the tube would indeed be about 1,000 V/m, but even a slight film of moisture on the tube would change the field inside. Or suppose that a man were asked to sit with his head between the two plates while electric signals from his brain were recorded. The field might produce some current in the person's skin and skull, but might or might not reach his brain. Therefore, although the experiment might be presented as a test of the effect of this field on the brain, the brain might not have been exposed to the field at all. Furthermore, the wires or other equipment for recording brain activity might be affected directly by the field: they might record ELF effects on themselves that would be interpreted as effects on the brain.

In addition, even with completely honest, cooperative, and well-intentioned people, it is difficult to avoid generating imagined symptoms. For example (see Appendix E), subjects in one experiment were asked to determine the presence or absence of ELF fields in a test procedure that usually involved switching the field on and off and then asking the subjects whether they could sense it. They could not. Some (not all) subjects experienced headaches every time they went through the test procedure. On some days, unknown to the subjects, the test procedure involved no exposure whatsoever to ELF fields. Nevertheless, the subjects prone to "magnetic headaches" reported an equivalent number on those days. This experiment indicates that the headaches were not due to the presence of an ELF field, but rather were, in a sense, psychologic reaction to the test procedure.

Other concerns caused the Committee to discount some of the experiments reviewed. In some cases, it was felt that blind scoring should have been used where it had not been. Blind scoring is a practice intended to prevent a scientist's expectations--conscious or subconscious--from influencing his results. For example, an experiment may involve two groups of plants, one exposed to a chemical and the other (a control group) not exposed. The results with two groups must be evaluated and compared. If the person examining the plants knows which ones were exposed, that might affect his evaluation. In two recently published cases, experimental effects that had been reported in the absence of blind scoring could not be confirmed when blind scoring was used. One case involved the induction of chromosomal aberrations with an ultrasound fetal monitoring device; another concerned a possible high rate of chromosomal abnormalities in people exposed to some aerosol spray adhesives.

The Committee found that some other ELF experiments lacked appropriate controls and that in some the descriptions of the physical setup made it difficult to be sure of the experimental differences between "exposed" and "control" organisms.

It should be stated that many of the studies that purport to show no effect of ELF fields are also not above criticism. The numbers of subjects studied were often too small to reveal any but the largest of biologic effects; known sources of concomitant variation were often controlled poorly or not at all, and could therefore obscure a real effect; the experimental endpoints were not always wisely chosen. The Committee has not enlarged on these inadequacies on an experiment-by-experiment basis, because, in the absence of an effect (whether real or artifactual), an appraisal of the possible impact of experimental shortcomings becomes an exercise in prophecy, rather than analysis.

Some of the criteria used by the Committee for assessing the results of research on ELF biologic effects are as follows:

- The techniques used should be chosen to avoid effects of such intervening factors as microshock, noise, vibration, and chemicals.
- Extreme care should be taken to determine the effective ELF field, voltage, or current in the organism.
- The sensitivity of the experiment should be adequate to ensure a reasonable probability that an effect would be detected if it existed.
- The experimental and observational techniques, methods, and conditions should be objective. Blind scoring should be used whenever there is a possibility of investigator bias; likewise, data analysis should be objective.

- If an effect is claimed, the results should demonstrate it at an acceptable statistical significance by application of appropriate tests.
- A given experiment should be internally consistent with respect to the effects of interest.
- The results should be quantifiable and susceptible to confirmation by other investigators. In the absence of independent confirmation, a result is classified for the Committee's purposes as preliminary.

BIOLOGIC EFFECTS OF ELF FIELDS

For the Seafarer communication system, the Navy has specified an operating frequency of 76 ± 4 Hz and maximal field intensities of about 0.1 V/m and 0.37 G directly over antenna cables in the grid. The fields would be less intense at greater distances from the cables. For the ground-terminal areas, the Navy has indicated that the maximal fields would be 15 V/m and 0.11 G.

Two classes of biologic effects have been considered and evaluated by the Committee. One of these is electric shock, classically associated with high-potential or high-current fields. On the basis of Navy specifications, the Committee has identified two types of circumstances under which shock hazards might be of concern: near ground terminals; and in cable failure (which may produce higher electric fields locally than normally anticipated). The hazard in the first case may be alleviated by altering the design of the ground terminals, and that in the second by developing a rapid and reliable detection system.

The second class of effects embraces diverse biologic responses to weaker fields, which have been studied in several organisms, as discussed below. In the review of these studies, it has been of great concern whether these responses to Seafarer fields might cause significant and adverse biologic perturbations. It is the Committee's considered opinion that there is not now any good evidence of such perturbations.

The Seafarer signal would be modulated, but relatively few of the studies reviewed by the Committee have involved modulated fields. With one exception, no differences in effect were observed between modulated and unmodulated signals. The exception, which needs confirmation, involved differences in nuclear replication intervals in a slime mold grown under strictly controlled laboratory conditions. The differences were equivalent to those produced by temperature changes of about 1°C, which would affect only slightly the growth and development of the organism.

The Committee sought and reviewed all relevant evidence. Most of the questions and studies can be grouped systematically for discussion according to the possible effects: shock hazards; genetics; fertility, growth, and development; physiology and biochemistry; behavior; and ecology.

Shock Hazards

Electric shock occurs as a result of the passage of electricity through the body. Body current can result from direct contact with conducting materials at different electric potentials or from exposure to air electric or magnetic fields. In Seafarer, the air electric and magnetic fields are far too small to produce body currents large enough to constitute a shock hazard. However, direct physical contact with conducting materials at different electric potentials can result in much larger body currents. The amount of current flowing depends, in the simplest terms, on how high the voltage difference is and on the resistance to flow--not only the resistance of the body, but the resistance of the "contacts" between the body and the objects. Thus, if one moistens one's fingers and touches the two poles of a battery, the current flows better (because salty water conducts better than dry skin), and one feels more of a shock.

The shock is felt because nerves are excited, and nerve impulses are generated. Nerve impulses themselves are electric in character, so current passage from an external source is a very effective way to stimulate nerves. Mild stimulation itself need not have any adverse consequences, but, as is well known, higher currents can have adverse and even lethal effects.

Electric shock of this type and the attendant hazards are well known. A rule of thumb is that one can feel a current of 1 mA (it will tickle); at 10 mA, the shock is so severe that muscles are paralyzed and one cannot release an object held in the hand (this is the "let-go" current); and at 100 mA, the heart stops its normal beating and goes into fibrillation. All these are approximate currents, and vary with the individual and other factors. The Underwriters Laboratories safety limit is specified at 5 mA.

The Committee believes that the Seafarer project as specified by the Navy would not systematically produce shock hazards. However, because of the large area covered (even by the ground terminals alone), the possible variations in soil conditions, and the many years of continuous operation, it is not difficult to visualize the possibility of shock if the 15-V/m specification for the ground terminals is used.

One case that is of concern involves wet earth or mud overlying drier earth of low conductivity. Such wet-over-dry conditions could result from rainfall or snowmelt. In these cases, there may be a shock hazard for a person walking directly over the ground terminals; and it may be more serious, for example, for two persons carrying an aluminum canoe or any long metallic object or for a person stepping onto a tractor that is hitched to a plow lowered into the ground.

Modification of ground-terminal design could reduce the maximal fields considerably and reduce the shock hazard. One possible modification mentioned by the Navy would involve the installation of vertical ground terminals into wells drilled in the earth.

A shock hazard could also arise as the result of cable faults. For instance, if insulation on an antenna cable in the grid became damaged and current leaked from it into the ground, very high fields could appear; these could be dangerous even without wet soil. Such a problem is complicated by the possible difficulty in finding faults. They might exist for some time before they are corrected. Several faults have appeared in the relatively short section of buried cable installed at the test facility in Wisconsin. A rapid and reliable method of detecting such faults is necessary to alleviate this problem.

Genetics

Genetic effects are those which cause an alteration in an organism's hereditary material, i.e., chromosomes or deoxyribonucleic acid (DNA). If genetic alterations, such as point mutations or chromosomal damage, were induced by low-frequency fields, there would be clear cause for concern, because such effects are generally detrimental and can affect both the organism itself and its offspring. Numerous environmental agents do have genetic effects, for example, ionizing radiation, fission products, ultraviolet light and chemical mutagens. But, on both theoretical and experimental grounds, the Committee believes that ELF fields are not likely to constitute a genetic hazard. The few experiments that have indicated possible effects have generally been poorly designed and have not yielded the same results on repetition. On the basis of a careful search and evaluation of the literature on this subject, it seems most improbable that additional studies would alter the Committee's conclusion.

Fertility, Growth, and Development

Reproduction and the attendant developmental processes represent crucial stages in the life history of an organism. An alteration in some developmental process during embryonic stages might result in a permanently impaired adult. A well-known example of an agent that causes such an effect is thalidomide, which does not damage the adult, but results in malformation in a developing embryo.

The Committee reviewed research on the subject that made use of mice, rats, chicks, and tadpoles. Several such studies reported effects on litter size in mice and on growth in rats and chicks. In some, poor design, inadequate data analysis, and other problems cast doubt on the findings. In only one case were any effects (altered growth rate in rats) attributed to fields at a low intensity comparable with those of Seafarer. When that experiment was repeated, no effect was found. In general, the evidence indicates that there should be no concern for possible effects of Seafarer on fertility, growth, and development.

Physiology and Biochemistry

This category includes alterations in the functioning of some basic cellular or organismic process that, although adverse, may be reversible. Effects of this type that have been suggested as due to fields like those of Seafarer include effects on cell division, an increase in serum triglyceride content in exposed humans, and alterations in circadian rhythms.

Cell Growth and Division

Cell growth is the fundamental mechanism whereby living matter increases in mass. Cell division is necessary either for achieving an increase in cell numbers or for maintaining a total cell population. Both processes may also be relevant to physiologic, behavioral, and ecologic phenomena.

A change in the rate of cell growth or division might or might not be harmful to the cells or population, depending on the particular conditions. For example, a small change in temperature (a few degrees) causes a change in cell growth rate, but is not deleterious so long as it is a balanced effect—i.e., so long as one biochemical process does not get out of line with others.

In most studies of cell growth and division biologic effects have been reported, but at intensities higher than those of Seafarer. However, one study, on the time between nuclear mitoses, used Seafarer intensities and reported effects. The Committee has examined this study carefully. It used an unusual cell system and involved scoring for induced synchronized mitoses in a large multinucleate cell. The absence of blind scoring was of special concern, because subconscious investigator bias is widely recognized as a source of error in science (as discussed earlier). From the data available and with the proposed ELF fields and frequencies, the Committee does not believe that the effect, if confirmed, is reason for concern. Other aspects of the growth and physiology of the cells appeared normal. The Committee nevertheless believes that there should be continued study of this general question, possibly with different types of experimental material.

Serum Triglycerides

Serum triglyceride concentrations in connection with ELF fields have aroused much interest and concern. The question originated with a study at the Naval Aerospace Medical Research Laboratory at Pensacola in 1971, which indicated that serum triglyceride content *might* be increased as a consequence of exposure to an ELF field. The researchers themselves questioned the validity of the observations; of a large battery of determinations, this determination was the only one in which some possible effect was suggested, and its relation to the ELF field was not clear. The experiment was discussed by an *ad hoc* Committee for the Review of Biomedical and Ecological Effects of ELF Radiation in a meeting (December 6-7, 1973) sponsored by the U.S. Navy Bureau of Medicine and Surgery. The *ad hoc* committee pointed out that the number of subjects was too small to exclude other possible causes and that the experimental design was inadequate in other respects. A study of personnel at the Wisconsin Test Facility was also deficient in many respects.

The *ad hoc* committee recommended (1973) the development of experiments with an appropriate animal model and studies with humans. Research has now been carried out with monkeys over extended periods, under nearly ideal conditions, and with excellent protocols. It yielded no indication of any changes in a variety of measured physiologic characteristics, including serum triglyceride content. The present Committee has not adopted the recommendation of studies with humans. Properly designed human studies present many difficulties; and human experiments with triglycerides compound the difficulties, because the values in man are known to be capricious and subject to a variety of poorly understood factors, such as stress in confinement and dietary replication. There is reason for much (perhaps more) confidence in well-described and well-executed experiments with animal models. On the basis of these experiments, the Committee believes that Seafarer fields will not have an effect on human triglycerie concentrations.

Circadian Rhythmicity

Circadian rhythmicity is related to the daily physiologic cycles exhibited by man and other organisms--for example, the sleep-wakefulness cycle and daily temperature cycles.

Circadian rhythms have been reported by some workers to be sensitive to ELF fields. Effects in human subjects have been reported by one laboratory. The experiments involved shielding against the natural background fields; there was a very slight increase in the period of the daily rhythm (about 15 min out of 24 h) and desynchronization between different rhythmic functions. These changes could be reversed (to normal) by the introduction of a weak electric field at 10 Hz. The proposed Seafarer antenna would be different: it would <u>add</u> to the natural background, not eliminate it, and the Seafarer frequency would be about 76 Hz, rather than 10 Hz. Furthermore, the experiments with humans eliminated all environmental time cues, whereas organisms exposed to Seafarer fields would be under natural conditions with respect to daily cycles of light and temperature. Experiments have been performed by another laboratory with silk tree leaflets, flour beetles, and mice under such natural conditions and with Seafarer frequency. No alterations in the circadian rhythmic phenomena were found.

The Committee concludes that there is no reason for concern about possible adverse effects of Seafarer on circadian rhythms.

Behavior

Behavior represents the results of complex processes and their interactions. An alteration of a behavioral response may reflect significant changes in physiologic or anatomic determinants. Effects could be exemplified by deviations in behavioral patterns involving predation, migration, reproduction, and territoriality. There are many examples of environmental factors that influence behavior, such as subliminal stimuli, pheromones, ultrasound, and drugs.

Experiments in the last 10 years have revealed that, as shown by behavior, some organisms have unexpected and unusual sensitivities to weak magnetic or electric fields. It appears that the organisms have some special sensory adaptation that permits them to perceive these fields in relation to particular biologic functions. These cases cannot be considered to be representative of how Seafarer fields would affect biologic systems generally, but rather are examples of perturbations in the normal behavior of some organisms based on the detection of fields. Each is a special case.

Fish

Some species of fish have an extraordinary ability to perceive electric fields and use it to detect prey. There seems to be no possibility that the proposed antenna would interfere with this phenomenon in the ocean, because the field strength in the oceans would be lower by several orders of magnitude than that used by the fish. Within the area of the antenna grid itself, the field intensities expected are comparable with those used by the fish, so that freshwater species might detect the fields. However, it is not known whether the fields, if detected, would interfere with the animals' normal behavior and, if so, to what extent the animals would be able to compensate or adapt. Experiments are required to clarify this.

Bees and Other Insects

Steady magnetic fields affect the orientation and the comb-building behavior of bees. The studies reported involved constant fields, not alternating fields as would be generated by Seafarer. Thus, the insects would probably not detect the Seafarer signal; and even if they did, it is not clear whether they would be adversely affected. This point should be investiated.

Magnetotactic Bacteria

An interesting recent discovery is that some bacteria exhibit magnetotaxis, i.e., they move toward the earth's magnetic north pole. It is probable that they also do not respond to an alternating field; if that is true, they could not be adversely affected by a Seafarer field. The new finding is nevertheless important and requires further study and evaluation.

Birds

There is evidence (much of it recent or from experiments still in progress) that some birds are sensitive to steady magnetic fields and that geophysical magnetic cues may be used in orientation and navigation. There are a variety of lines of evidence, coming from radar tracking of migrating birds, the behavior of homing pigeons, and examination of individual orientation during nocturnal migratory restlessness. Most (but not all) experiments and observations have dealt with static-field effects, so it is not possible to predict responses to a complex matrix of alternating fields. It is also difficult to model accurately the extent by which the Seafarer antenna might alter orientation or, indeed, whether birds might be able to compensate for any possible effects. There is evidence that migratory birds experience some deviations owing to fields of the Seafarer type. But there is also evidence that actively migrating birds avail themselves of a variety of redundant cues; thus, the experimental distortion of magnetic fields does not necessarily imply that there would be a significant change in migration patterns. Although this might occur to some degree, the evidence is insufficient to provide an estimate of the effect of a modulated grid-like magnetic anomaly. The effects, if any, of field perturbations of an elaborate powerline grid have never been investigated. However, the Committee believes that continued experimentation concerning bird orientation and navigation is merited and that, before any antenna is constructed, the migration patterns in the area should be studied, so that they can be compared with patterns during antenna operation, and careful studies by radar tracking should be continued using available ELF sources, such as the Wisconsin Test Facility. It should be noted that most massive bird migrations occur along a broad front and at very high altitudes, where the Seafarer field would be extremely attenuated.

Mammalian Neurophysiology and Behavior

Physiologic functions in the mammalian brain are associated with the electric activity of its nerve cells. Two types of electric activity occur in brain cells. One involves nerve impulses that last only a few milliseconds. The other, apparently peculiar to brain cells, is the generation of slow, rhythmic waves with a frequency spectrum of approximately 1-100 Hz. These are familiar to us through the electroencephalogram (EEG), an important tool in diagnosing brain activity and functional state. Although there are preliminary reports of altered physiologic functions and behavior in mammals exposed to environmental electric (1-100 V/m) and magnetic (1-10 G) fields, these have not been confirmed and involved higher electric-field intensities and lower frequencies than those associated with Seafarer.

Behavioral tests in such ELF fields have been performed with rats, monkeys, and man. They include reaction-time studies, subjective estimates of the passage of time in monkeys, and a variety of operant-task performances. Many of these studies have had negative results at field strengths of 10-100 V/m and frequencies below 100 Hz, including the proposed Seafarer frequency of 76 Hz. However, some positive findings have been reported. In monkeys, shortening of subjective estimates of a 5.0-s interval by approximately 10% during exposure to fields at some frequencies between 7 and 75 Hz (no effects at 60 Hz) has been described, but replicate studies have not yet been reported. This study also suggested a markedly higher sensitivity to environmental fields at 7 Hz than to those at 45 and 75 Hz. No effects have been found at intensities below 1 V/m.

Calcium ions are essential in excitation in nerve cells. The binding of calcium ions in brain tissue may provide a sensitive index of interaction with environmental electric fields. The release of calcium ion from cat and chicken cerebral cortex was reported to be reduced by environmental fields with intensities of 10-56 V/m and frequencies of 6-20 Hz, but similar fields at 60 and 75 Hz were without effect. Again, confirming studies are not available.

Extrapolations from these laboratory experiments to the field conditions proposed for Seafarer suggest that the behavioral, neurophysiologic, and neurochemical effects reported occur only at air-field strengths well above those expected even in the immediate vicinity of the antenna and only at frequencies lower than those expected. Many of the observations are preliminary and need confirmation by further research. The character and magnitude of the effects, even if confirmed, do not appear to warrant concern, especially in view of the proposed Seafarer intensity and frequency.

Ecology

The interrelationships of organisms—animals, plants, and microbes—and their environments constitute at once the most sensitive and the most elusive potential indicator of a perturbation, whatever it might be. Indeed, the problem that we would face in an attempt to explain some ecologic change is that it might have been due to almost anything. Ecologic studies are nevertheless of fundamental importance, because they represent an integration of the results of all changes.

Plants

The possible effects on plants of electric and magnetic fields produced by Seafarer are of special concern, because of agricultural and forestry economies, as well as scenic quality. Plants form the actual framework for an ecosystem, directly influencing temperature, moisture, and nutrient availability, which in turn affect other organisms. Because plants are fixed in location and are tightly coupled to the current fields in the soil, they would be fully exposed to Seafarer, whereas the exposure of other organisms may be transitory. Plants reflect environmental stresses and have systems for detecting and responding to these stresses; they are used as reliable indicators of environmental pollution.

Among the papers concerned with possible effects in plants, none showed any effects that can be attributed to electric and magnetic fields similar to those expected to be produced along the properly functioning Seafarer antenna. In addition, there is no evidence of any effects on plants either at the Wisconsin Test Facility, which has been in operation intermittently for several years, or at a prototype facility in North Carolina. The ecologic effects of construction of the antenna system will be substantial, but not unlike the effects of other installations, such as gas lines and telephone cables.

Soil Organisms

As in the case of plants, there has been considerable interest in knowing whether soil organisms might be affected by ELF fields. Such organisms will be more strongly coupled to the fields produced by Seafarer than above-ground organisms. Effects on soil organisms, if any, might be expected to occur at a cellular level, and thus be generally important. A laboratory experiment on soil bacteria at 10 and 50 V/m showed no effect on metabolic activity. Studies at the Wisconsin Test Facility designed to detect ecologic changes that might provide evidence of ELF effects failed to reveal any changes that could be correlated with exposure to Seafarer fields. The Committee notes that, as in the case of plant studies, only major effects would have been detected in the field surveys of soil organisms undertaken. This is attributable in part to the inherent difficulties in separating possible small effects from effects due to other perturbing factors, such as soil water, soil temperature, and soil aeration, which were not measured.

CONCLUSIONS AND RECOMMENDATIONS

A number of concerns raised over the years that Seafarer ELF fields might constitute a source of dangerous—even catastrophic--environmental contamination have been examined and found invalid and unwarranted. The Committee's considered opinion is that such fields will not cause a significant and adverse biologic disturbance, except in the event of electric shock, which is of serious concern. In fact, apart from the possible result of electric shock, the Committee cannot identify with certainty any specific biologic effects that will definitely result from exposure to the proposed Seafarer fields.

The Committee concludes that shock hazards would exist near the ground terminals as now designed, but could be reduced by design changes. Shock hazards could also appear along antenna cables, as a result of insulation or cable breaks. To alleviate such hazards, it would be necessary to develop a rapid and reliable method of detecting cable faults, so that the faulty portions of the antenna system could be immediately disconnected.

Although the available data are extremely limited, some effects not related to shock may occur. Some organisms are able to detect steady weak electric and magnetic fields. If they also detect ELF fields, which oscillate, they may be affected, and the possibility of adverse effects cannot be fully ruled out. Thus, like many other perturbations introduced by man, this involves some uncertainty and calls for continuing research. If the Seafarer system is built, an energetic and carefully designed long-term program of monitoring should be coupled with basic research.

On the basis of the above considerations, the Committee offers the following recommendations:

1. Before a final decision to proceed with the construction of the Seafarer system, a reliable procedure for rapid detection of cable faults (insulation failure) should be demonstrated. There should be calculations to permit a probability analysis of the "worst case." There should be a method for determining the existence and likelihood of ground-conductor corrosion and its effect on the electric fields in the vicinity of ground terminals. If hazards associated with corrosion are identified, a detection system should be demonstrated.

2. If a decision is made to build the Seafarer system the following activities should be completed and reviewed by an appropriate agency before construction, and the plans for construction should take account of the results:

   a. The development of final detailed specifications for ground-terminal design (including details of measurement procedures and survey techniques for acceptance-testing) that will alleviate shock hazards near the ground terminals. A reduction of the maximal step potential by more than a factor of ten would be an important part of the final specifications.

   b. A more extensive and site-specific set of measurements of the spatial and temporal variations in soil conductivity, as a prerequisite to the ground-terminal specification; this is needed for reliable statistical estimates of extreme or worst-case step potentials and body currents.

   c. The installation of at least one vertical ground terminal in a test facility, to permit evaluation of this alternative ground-terminal design.

d. A baseline study using radar tracking of bird navigational patterns among migrating species in the vicinity of the proposed installation, to be continued when the Seafarer antenna is in operation.

e. Baseline studies to determine which of the species of fish that live in the area proposed for the antenna are sensitive to weak electric fields at Seafarer frequencies. These studies should determine the extent to which external Seafarer fields might interfere with the normal behavior of such fish, as well as any observable adaptation to such fields.

3. Beginning with a decision to build Seafarer and continuing into the period of its operation, research should be conducted to increase the knowledge of the basic biologic effects of weak ELF fields associated with Seafarer. This should include fundamental research concerned with the biophysics and physiology of magnetic- and electric-field detection and use, and studies of the related behavior of birds, insects, bacteria, and electrosensitive fish. In addition, research on the underlying mechanisms of cell division and on information processing and integration in complex nervous systems in relation to ELF environments should be conducted and evaluated as part of the requirement for continued monitoring of the operating Seafarer system for its possible effects on biologic systems.

Recognizing the limit of its charge, the Committee makes no recommendations as to whether the Seafarer antenna should be constructed. It will be up to the citizens and the government of the United States to consider the costs, risks, and benefits associated with the Seafarer system. The Committee's charge was to identify and evaluate the possible biologic effects. On the basis of the information available, the Committee concludes that, except for the possible electric-shock hazards, the likelihood of serious adverse biologic effects of Seafarer is very small. In any case, it is appropriate to recall here that the Navy's presentation at the Committee's first meeting (February 11, 1976) included a pledge that, if a functioning Seafarer antenna were found to have deleterious effects, its operations would be discontinued.*

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*From transcript of tape recording, Committee meeting of February 11, 1976:
Capt. Cobb: Sir, you are referring to the emergence of information that implies deleterious effects post-decision?
Dr. Calhoun: Right.
Mr. Marcy (Assistant Secretary of the Navy, Research and Development): Very simple. Let me go on record, if there are deleterious effects which are determined, that we will stop the transmission. That is a statement we have made to the Governor and to people at large.

II. TECHNICAL REVIEW OF PROJECT SEAFARER

ANTENNA, GROUND TERMINALS, AND CABLE FAULTS

This first section describes the antenna structure and fields within the antenna area, to clarify the nature of the ELF fields that would be created by Seafarer. It then treats the ground terminals, with attention focused on the special problems associated with the proposed, much larger, electric fields. Finally, the even larger electric fields that may occur as a result of Seafarer antenna malfunctions are considered.

Antenna

In the following description, attention is focused on the ELF fields close to the antenna, as opposed to the "far fields" at the receiver locations, because it is primarily the near fields that are of potential biologic concern. When specific dimensions or field strengths are stated, they are based on the Committee's understanding of the currently proposed Seafarer design for the upper Michigan region. It is important to emphasize that ELF fields similar in magnitude and frequency to those of Seafarer are already abundant in our environment. Except for the areas near ground terminals, Seafarer fields are smaller than the maximal existing fields measured.

The primary source of non-Seafarer ELF fields is our 60-Hz electric power supply. In addition to the fields associated with power transmission and distribution, there are surprisingly large 60-Hz fields in and near our homes. Magnetic fields greater than 10 G, about 100 times larger than proposed for Seafarer, have been measured close to some commonly used electric appliances.[1,2] Measured electric fields in the earth near the ground connection of the electric service entrance to homes are comparable with and sometimes nearly 10 times greater than the electric field in the Seafarer grid. The only Seafarer field that would be larger than the most frequently encountered existing ELF fields is the proposed maximal electric field near Seafarer ground terminals.

In view of the existence of these commonly encountered ELF fields, what is unique about the ELF environment of Seafarer? The answer to this question has four important elements:

- Ground terminals: The proposed maximal electric field in the earth at the ground terminals would be significantly larger than any frequently encountered comparable existing ELF electric field.
- Physical size: The electromagnetic fields of Seafarer would cover much larger areas than most commonly encountered ELF fields.
- Continuous operation: Seafarer would operate continuously, whereas many common ELF sources are energized or operate at maximal power for only short periods.
- Modulated signal: Seafarer would use a modulated ELF signal.

Seafarer Modulation

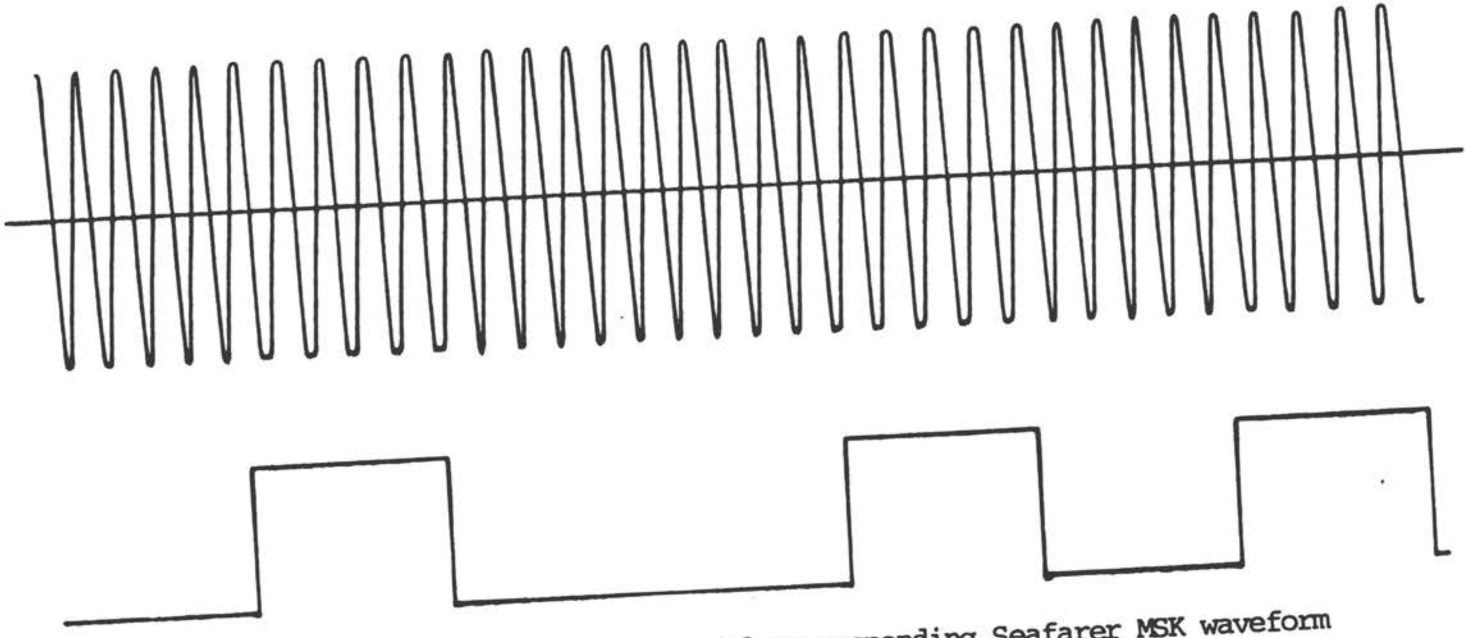
The Seafarer ELF transmitters would use a form of frequency modulation called minimum-shift keying (MSK). In this type of modulation, the signal consists of smoothly connected segments (chips) of sinusoidal signals of two distinct frequencies. In the Seafarer proposal, the two frequencies are 72 Hz and 80 Hz with a modulation rate of 16 chips per second[3] (a center frequency of 76 Hz and a shift frequency of 4 Hz). A typical waveform and frequency spectrum are illustrated in Figure 3. A transition from one frequency to the other would occur at the peak of a wave, to provide maximal phase continuity and hence minimize transient effects.

A code word comprises seemingly random pulses (chips), each lasting one sixteenth of a second. As shown in the figure, the frequency of the transmitter shifts between 72 and 80 Hz, depending on the value of the binary code during each chip. For practical purposes, the code for a particular message may be considered essentially nonterminating; i.e., the code could be continuously transmitted for long periods without repeating or ending. Thus, purely random modulation is an acceptable mode for biologic experimentation and has been used in a number of recent experiments.

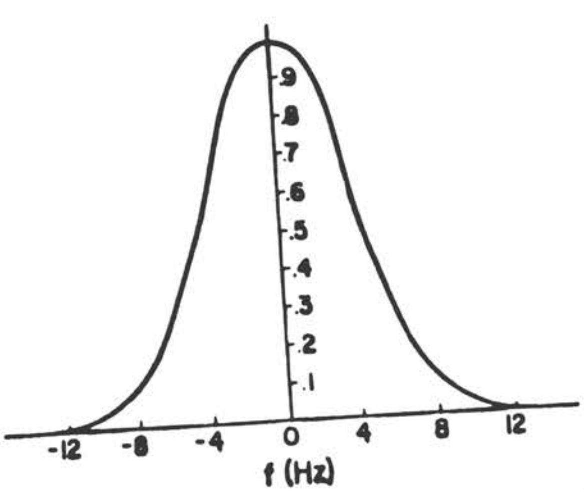
Basic ELF Transmitting Antenna[4]

The basic concept of ELF transmitting antenna operation is illustrated schematically in Figure 3. The antenna consists of an insulated single-conductor cable electrically energized by a transmitter at some point along its length and electrically connected to the earth at each end. The electric current resulting from the excitation supplied by the transmitter flows along the antenna cable and returns deep through the earth, forming a large single-loop closed circuit. This current loop creates electromagnetic fields in the earth and in the space above the surface of the earth. The intensity of the fields is greatest close to the antenna and, for most of the field components, decreases rapidly with distance from the antenna. However, a very small (but significant, from a communication point of view) component of the electromagnetic field is coupled into the space between

Figure 3



Pseudorandom binary-code sequence and corresponding Seafarer MSK waveform



Normalized power spectral density of Seafarer MSK with pseudorandom binary modulation the surface of the earth and the ionosphere and propagates in this space with only very slight attenuation. It is this small propagating component that ultimately results in the signal received at remote locations. Because the frequency is low, the wavelength of the propagating electromagnetic field is very large and the fraction of the total electric power input to the antenna that is radiated is very small. For Seafarer, with a proposed frequency of 76 Hz, the wavelength in air is about 2,500 miles, or about 4,000 km.

For a particular frequency, the strength of the radiated field (E_r) is known to be directly proportional to the product of antenna current (I) and antenna length (L) and inversely proportional to the square root of the earth conductivity (σ):

$$E_r \sim \frac{IL}{\sqrt{\sigma}} \quad . \tag{1}$$

Conductivity enters this relation because of the critical importance of the effective depth of the return current (the skin depth). Most of the return current flows at considerable depth, so the appropriate conductivity value is that of the subsurface materials, and not that of the surface layer. The proportionality expressed in Eq. 1 indicates the importance of placing the antenna in a region of low deep-earth conductivity, to minimize the required antenna length.

Because of the great length required to produce the required radiated-field strength, the proposed antenna includes a number of essentially independent antenna elements oriented parallel to each other and spaced far enough apart to avoid substantial local interaction. The effective length is then the sum of the lengths of the individual antenna elements, provided that the antenna currents are properly phased. Because the radiated field from such an array is directional, a similar array orthogonal to the first is necessary, to produce an omnidirectional field pattern. The resulting antenna is therefore an orthogonal grid of antenna elements, whose size and spacing must be chosen to meet the desired radiated-field strength.

The proposed grid pattern for the upper Michigan site is illustrated in Figure 2. The departures from the ideal square orthogonal grid that are evident in this proposal are a result of efforts to minimize some types of environmental impact (e.g., by maximizing the use of existing rights of way) while maintaining the required electrically orthogonal structure and exploiting regions of lowest conductivity. Table 1 summarizes the principal characteristics of the proposed array. Note that only five transmitter stations are proposed (see Figure 2) for locations, with each transmitter station feeding approximately 10 antenna elements through paired-cable feed lines. The lengths of the antenna elements range from 19 to 96 miles (about 30 to 154 km), with an average of about 57 miles (about 91 km). Although obviously variable, the average spacing between antenna elements is about 3.7 miles (about 6 km).

Structure of Antenna Elements[4]

An antenna element, as illustrated in Figure 1 consists of a buried insulated cable and two ground terminals. Although the final cable design is not yet complete, a basic configuration consisting of an aluminum conductor approximately 1-1/4 in (3.2 cm) in diameter and several insulating layers, producing an overall diameter of approximately 2 in (5 cm), has been established. The cable would be buried to a nominal depth of

6 ft (183 cm), with a minimal depth of 2-1/2 feet where rock or other restrictive conditions preclude deeper burial. There would be an access/test point in a buried vault approximately evey 5 miles (8 km) along each antenna element. In some cases (on longer elements), a series capacitor would be installed in or near one or more of these vaults to aid in

TABLE 1

Principal Characteristics of the Michigan Array[a]

	Full Array	Test Bed[b]
No. antenna lines, NS + EW	25 + 22	2 + 1
Total antenna length, miles	2,438	131
Fraction of antenna on existing rights of way, %	64	90+
Antenna current, A rms	99	99
No. power amplifiers	20	2
No. transmitter stations	5	1
ELF power required, MW	11.2	0.7
60-Hz power required,[c] MW	15.8	2.2

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[a] Data from GTE Sylvania, Inc. ELF Communications Seafarer Program. System Design Study Report Michigan Region. Prepared for Naval Electronic Systems Command. Needham Heights, Mass.: GTE Sylvania, Inc., 12 January 1977. 166 pp.

[b] A test facility consisting of three antenna elements. It is proposed that this facility be built before installation of Seafarer and ultimately become part of the system.

[c] Includes 10% contingency allowance.

distributing the cable voltage. Series capacitors would also be installed at the transmitter feed point and at each end of each element to compensate the reactive component of the antenna impedance. Surge arresters and disconnect switches would also be installed at the test points along the antenna.

Structure of Ground Terminals[5,6]

The ground terminals can be of two types: surface grounds or deep grounds. A surface ground consists of a horizontal length of uninsulated copper conductor buried to a nominal depth of 6 ft (183 cm). Vertical ground rods with lengths of approximately 20-40 ft (6.1-12.2 m) attached to the horizontal wire would be used where contact with higher-conductivity subsurface layers offered the advantage of lowering the near-surface current density and voltage gradient. The preferred configuration is two horizontal wires at an angle of approximately 60^o to each other and extending in the direction of the antenna element. Because the ground terminal functions by dispersing the antenna current in the earth, lengthening the ground wires is an effective means of improving its performance. Present Seafarer conceptual designs use up to 4,000 m of buried wire (2,000 meters in each of two legs), but even longer grounds are feasible. There is, however, an upper limit dictated by the physical laws governing the current distribution along the buried wire. Each ground terminal would be designed in accordance with local near-surface earth conductivity; hence, each terminal would differ in details of construction.

Deep grounds use a vertical grounding conductor (or series of conductors) placed in a drilled well. Conceptual designs call for a well 6-8 in (15.2-20.3 cm) in diameter up to 6,000 ft (1830 m) in depth to attain acceptable performance. The advantages of deep grounds include greatly reduced surface electric fields and smaller right-of-way requirements. They are, however, much more costly and present higher resistance and hence higher power requirements during operation. For these reasons, surface grounds have been the preferred type in all proposals for Seafarer.

Electromagnetic Fields

To describe the antenna electromagnetic fields, it is necessary to distinguish between the regions along the antenna elements (within the grid) and those near the ground terminals (along the periphery of the grid). It is also helpful to describe the electric and magnetic components separately to emphasize the different rates at which they decrease with distance from the antenna. The intensities given are generally those for nominal conditions with uniform earth conductivity, but brief comments on the effects of nonuniform conductivity and other departures from nominal conditions are included.

Electric Field near Antenna Elements

The electric field along the antenna elements can be viewed as a result of the portion of the total earth-return current that flows near the earth surface. This field is horizontal and parallel to the antenna elements, except near the crossing of two elements. Its maximal intensity at the earth surface occurs directly over the antenna element and has been set at 113 V/mile, or 0.07 V/m.[5] This specification is based primarily on the need to keep interaction with long electric conductors (powerlines, pipelines, wire fences, etc.) within acceptable limits and requires only that the average over long distances be below this maximum. Local earth-conductivity variations or the presence of grounded conducting objects could cause locally larger fields.

A summary of the methods used to calculate the electric field in homogeneous earth is in a U.S. Navy report.[5] Analysis indicates that the electric field decreases relatively slowly with distance from the antenna; distances exceeding 100 m are required to reduce the intensity by half. The result of this slow decrease is that the entire interior region of the grid will have a horizontal electric field with a minimal intensity of one-fourth to one-third the maximum of 0.07 V/m. Figure 4 shows the spatial variation for a case very close to the nominal design.

Near antenna intersections, the fields of the two elements will add; the resultant field will depend heavily on the time phase of the currents in the elements. For currents in phase, the electric-field strength will increase by a factor of $\sqrt{2}$. A pictorial representation of the electric-field distribution for in-phase currents is shown in Figure 5.

Because of the slow variation of the field with distance, burial depth is not an important determinant of the electric field. The field is continuous at the air-earth interface, so the air electric field over the region of the grid is also horizontal and of the same intensity as the earth electric field. This situation would be substantially altered at any locations where the antenna was installed above the ground. In these regions the (vertical) air electric field could be much larger, although the (horizontal) earth electric field would be essentially unchanged.

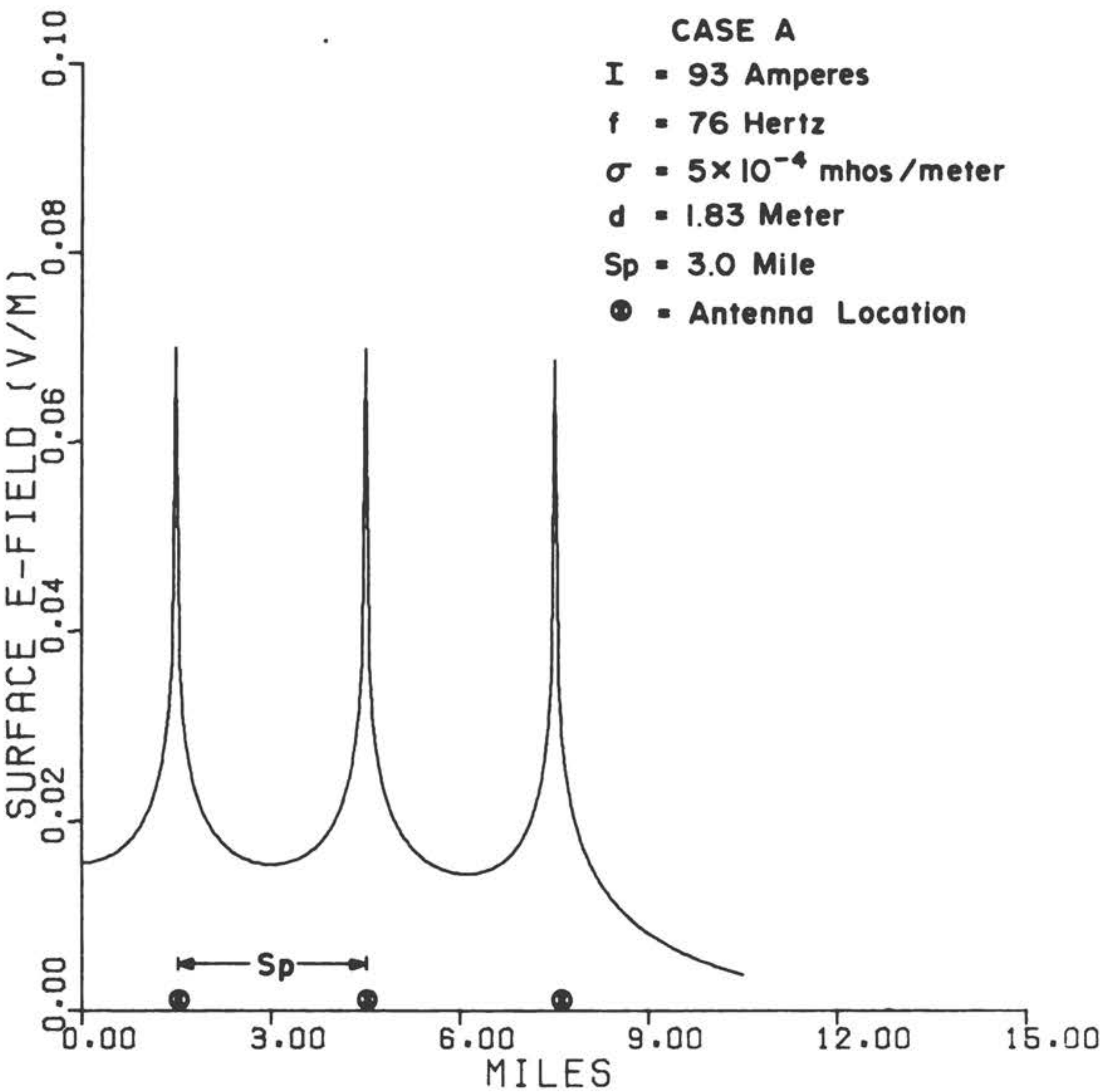


Figure 4. Magnitude of electric field vs. perpendicular distance to an array of parallel antenna elements. Reprinted with permission from Genge.[7]

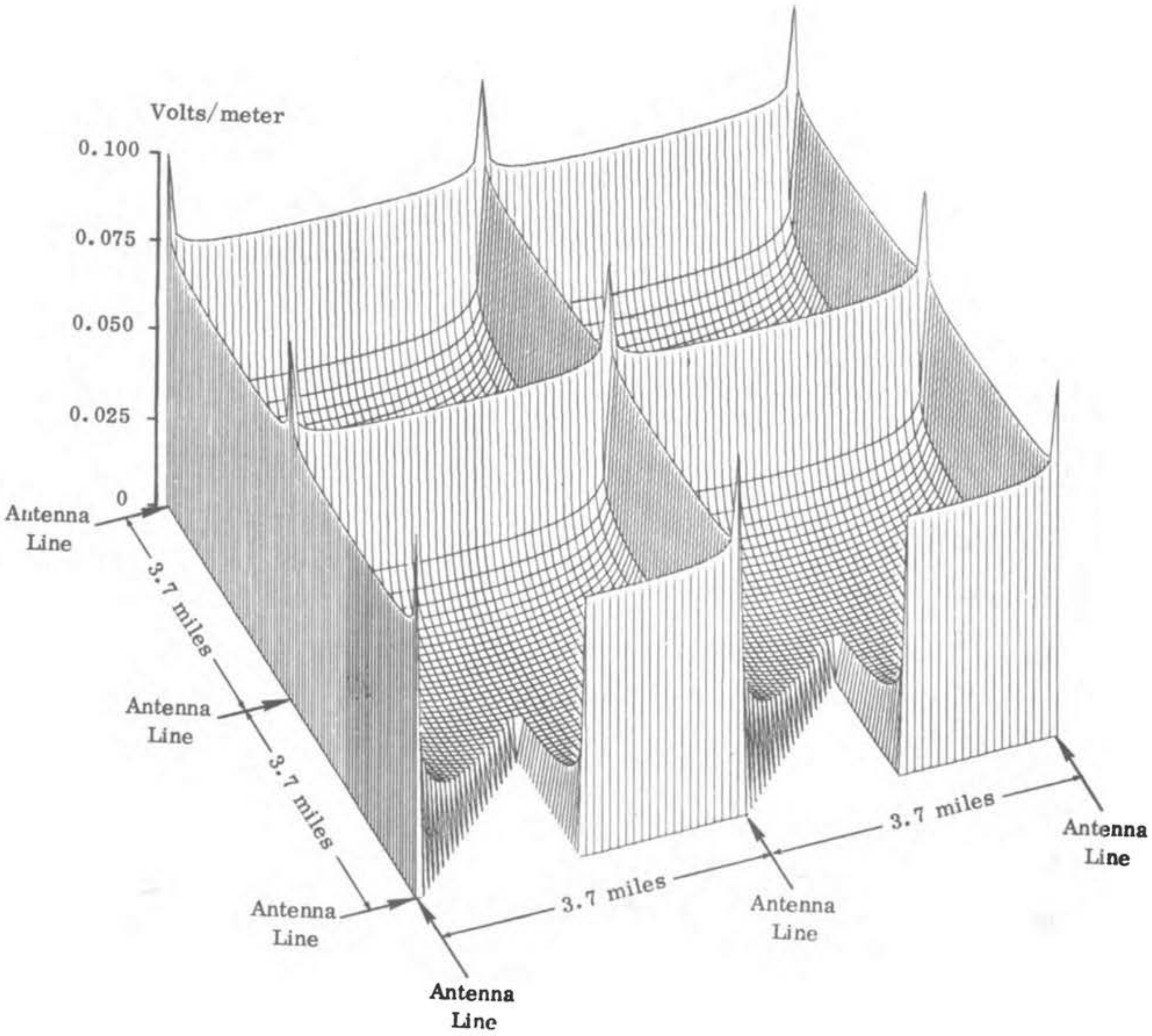


Figure 5. Variation of the electric field throughout a portion of the Michigan Seafarer array. Reprinted from U. S. Department of the Navy.[5]

Magnetic Field near Antenna Elements. The magnetic field along the antenna elements is most conveniently viewed as a direct result of the current in the elements and is well described by the simple proportionality relationship,

$$B \sim \frac{I}{r} \quad , \qquad (2)$$

where B is the magnetic flux density, I is the antenna current, and r is the radial distance from the antenna element to the point under consideration. The presence of the earth around the buried cable is essentially negligible, except as a barrier to close approach to the antenna element. The vector describing the direction of the field is tangent to a circle centered at the cable. It is clear from Eq. 2 that the maximal intensity occurs at the point of closest approach to the antenna element--typically the surface of the earth immediately over the element. For the proposed Michigan design this maximal nominal value is 0.11 G.[5] As for the electric field, there is a possible amplification by a factor of $\sqrt{2}$ in the vicinity of antenna intersections.

Unlike the electric field, the magnetic field decreases quite rapidly with distance, as indicated by Eq. 2. Compared with the electric-field spatial distribution, the magnetic field is highly localized along the antenna elements and decreases to very small values elsewhere in the grid. The distribution is illustrated in Figure 6 which emphasizes the highly localized nature of the antenna magnetic field.

The strong variation of the magnetic field with distance makes burial depth very important. For example, in regions where the cable burial depth

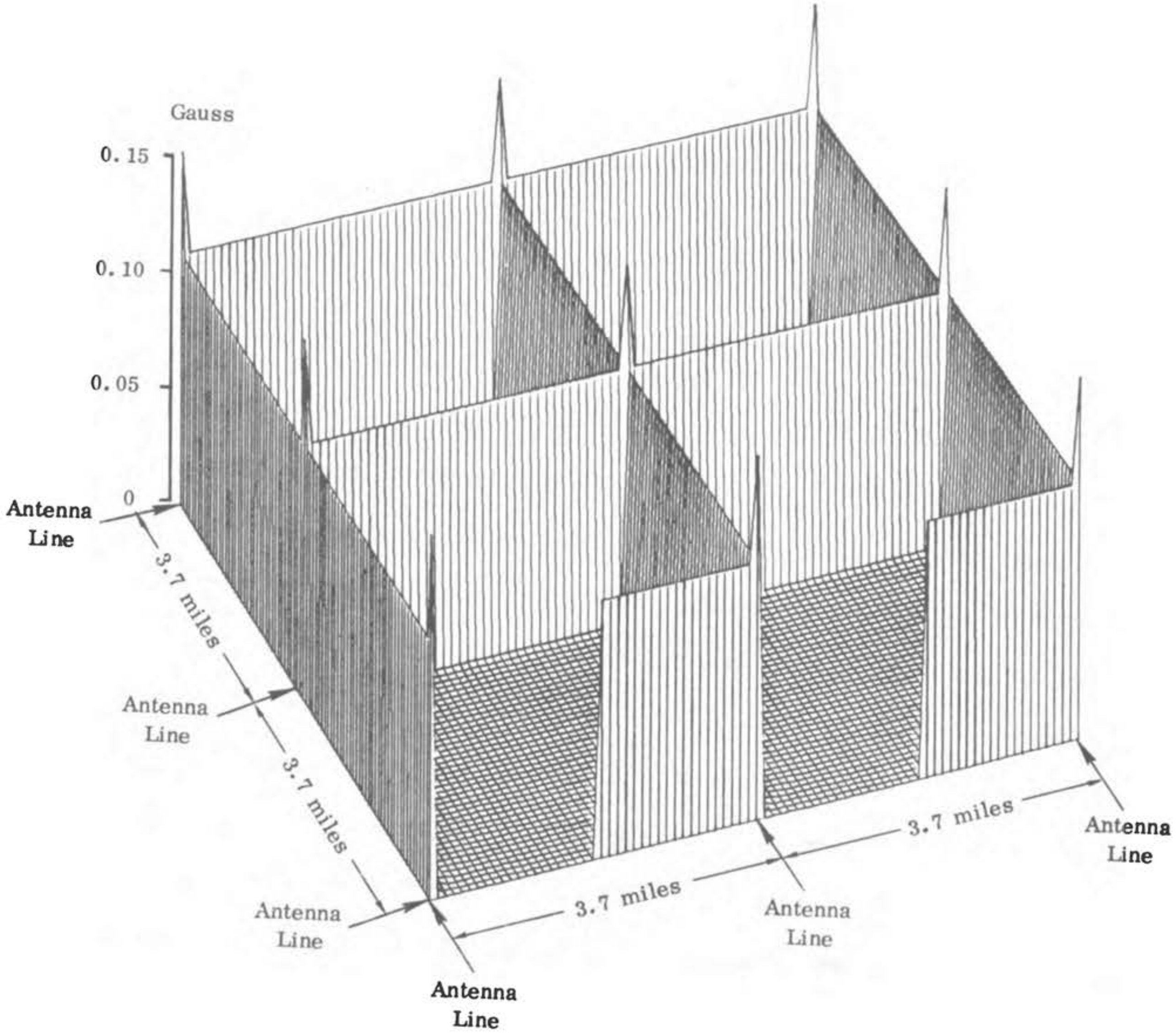


Figure 6. Variation of the magnetic field throughout a portion of the Michigan Seafarer array. Reprinted from U. S. Department of the Navy.[5]

is 2.5 ft (76.2 cm), instead of the nominal 6 ft (183 cm), the magnetic field at the earth surface would increase from 0.11 to 0.26 G. If the shallow burial were at an antenna intersection, the value could be further increased by a factor of $\sqrt{2}$, to 0.37 G. In regions where the antenna is installed above the ground, the maximal magnetic field could be very large, depending on the distance of closest approach to the antenna that is allowed by the details of construction and the use of restrictive barriers.

Electric and Magnetic Fields near Ground Terminals.[5] The electric field (step potential) near ground terminals is a direct result of the current flow out of the buried uninsulated ground wire into the earth. The current distribution (and electric field) is determined by the ground-wire geometry and the earth-conductivity magnitude and spatial variation in the vicinity of the ground terminal. Local variations in earth conductivity can cause large changes in the local electric field, compared with that in a region of uniform conductivity. Such local regions of anticipated high electric field must be found and remedial action planned during site surveys. After construction, tests of actual electric fields and additional remedial measures must be carried out.

Because the antenna current is localized in the earth near the ground terminal, as opposed to being widely distributed in the earth as it is along the antenna, the electric field is much larger near the ground terminals than along the antenna. The specification of maximal electric field at ground terminals has been a subject of much concern to the Committee and is described separately later.

The magnetic field near ground terminals will have a maximum near the feed point equal to that of the antenna. Because of the dispersion of current into the earth, the magnetic field along a ground wire will decrease with distance from the feed point to very small values near the ends of the wire.

Summary. The following simplified summary descriptions of the electromagnetic fields produced by the proposed Seafarer system are sufficient for most biologic-interaction studies (values at earth surface):

- Antenna electric field: 0.07 V/m nominal maximum (0.10 V/m near intersections) with essentially the entire region of grid at intensities one-fourth to one-third the maximum.
- Antenna magnetic field: 0.11 G nominal maximum (0.37 G near intersection with shallow burial) highly localized along antenna elements.
- Ground-terminal electric field: 15 V/m maximum and 1 mA body-current maximum, localized along horizontal ground wire.
- Ground-terminal magnetic field: 0.11 G nominal maximum (0.26 G with shallow burial), highly localized near feed point of ground terminal, steadily reduced along horizontal wire.

Comparison of Seafarer with 60-Hz Power-System Electromagnetic Fields

There are many similarities between the Seafarer antenna system and a conventional 60-Hz electric power transmission and distribution system. But there are also differences, of which the most important are:

- Seafarer is designed to operate with a 100% earth-return current whereas power transmission systems usually have a nominal zero earth-return current. Single-phase power distribution circuits are often unbalanced and return a fraction of the current through the earth; however, the major portion of the return current is in the (grounded) neutral conductor.

- Seafarer is a relatively low-voltage buried (solid-dielectric--insulated) system, whereas power systems are typically high--voltage overhead (air-insulated) systems.
- Seafarer, of necessity, uses a modulated signal, whereas power systems have nearly ideal sine-wave voltages and currents.

As a result of these differences, some field components of the two types of systems are very different in amplitude and spatial distribution, whereas other components are quite comparable. The following comparisons begin with the components that are most similar.

Magnetic Field: As in Seafarer, the magnetic field under a powerline is a direct result of the current in the conductors. However, the powerline is a multiconductor system in which the sum of the currents in the conductors is nearly zero. Although the current in a power line is often much larger than the Seafarer current, the height of the line and the tendency toward substantial cancellation of fields from separate conductors combine to produce fields near the ground of about the same amplitude as in Seafarer. Actual measurements under high-voltage lines yield values of 0.05-0.6 G,[2,8,9] which approximate those expected in the Seafarer system. The powerline magnetic-field vector rotates in a vertical plane, and the field is somewhat less localized than the Seafarer magnetic field; however, the two systems can still be considered similar, with respect to their magnetic fields near ground level.

Horizontal Electric Field Away from Ground Terminals: The horizontal electric field in the earth under a (balanced) powerline is nominally zero. However, because the line is not completely symmetric, there is a small earth current that gives rise to an earth electric field similar to the horizontal electric field in the Seafarer grid. Although there have not been many actual measurements, there are some data[2,8] to suggest that an intensity of 0.01 to 0.03 V/m approximates that to be expected under balanced lines, which is less than the 0.10 V/m near Seafarer antenna intersections and comparable with the Seafarer intensity at points in the grid away from the antenna elements.

Horizontal Electric Field near Ground Terminals: The major ground terminals in power systems are designed primarily for handling fault conditions, and not for continuous operation with substantial earth current. The nominal electric field near these ground terminals is therefore zero, although it is unlikely that this ideal is ever attained. The electric field in the earth near Seafarer grounds is therefore properly viewed as having no real counterpart (on the scale of Seafarer ground-terminal size) in a power system. The localized fields of about 0.05-0.50 V/m that have been measured near small ground terminals (driven ground rods) in power distribution networks[1,10,11] were too localized to be compared with Seafarer.

Vertical Electric Field in Air: Because of the charge on an energized conductor, there is an electric field in the insulating medium between the conductor and other conducting objects in the vicinity. In an overhead powerline, this results in an electric field in the air surrounding the line. Near ground level, the field is nearly vertical and uniform, because of the relatively large separation between the conductors and the surface of the earth. In the buried antenna elements of Seafarer, the electric field resulting from the charge on the antenna cable is entirely in the insulation around the cable. For the buried antenna elements, there is therefore no external vertical air electric field; hence, this component of power-system electromagnetic fields will not exist in Seafarer.

The amplitude of the air electric field under a powerline depends primarily on the voltage and height of the line. Electric fields up to about 10,000-17,000 V/m (10-17 kV/m) have been measured under modern high-voltage lines.[8,9,12,13] The large difference between these electric fields and the much smaller ones present as earth electric fields in Seafarer should not be interpreted as a measure of the relative potential biologic impact of the two types of fields. Because of the high conductivity of most biologic materials, compared with air, the preexisting air electric field is very much greater than the internal electric field in a specimen placed in the field. The reduction factor is approximately 10^5-10^7, depending on geometry and conductivity. Air electric fields are sometimes described as high-impedance fields and the coupling to conductive objects referred to as capacitive coupling, to emphasize the contrast with the low-impedance conductive coupling associated with an electric field in a conductor like the earth. The coupling of electromagnetic fields to biologic systems is treated in greater detail later.

Vertical air electric fields would exist in Seafarer only where the antenna elements or ground-terminal feed points were routed overhead instead of being buried. The relatively low voltage of Seafarer, compared with power-system voltages, should result in air electric fields much smaller than in power systems; exact values would depend on construction details that are not available.

Summary. Although Seafarer and electric power systems differ in many details of field orientation and spatial variation, the following summary provides a useful simplified comparison of the various field components.

- Magnetic field: High degree of similarity; Seafarer maximum of 0.37 G within the range of the 0.05-0.60 G measured in power systems; fields highly localized along right of way in both systems.
- Horizontal electric field in earth (away from ground terminals): Similar; Seafarer maximum of 0.10 V/m somewhat larger than measured 0.010-0.030 V/m of power systems; fields centered on right of way in both systems; electric field in Seafarer grid away from antenna elements about the same as those immediately under powerlines.
- Horizontal electric field in earth (near ground terminals): No counterpart on scale of proposed Seafarer ground terminals in power systems.
- Vertical electric field in air: Essentially lacking in Seafarer; fields up to about 10-17 kV/m under powerlines.

Ground Terminals

With surface grounds as proposed by the Navy, a large area along the periphery of the antenna grid would continuously have substantially greater electric fields than the interior of the Seafarer grid. The combination of great size and continuous operation at these higher intensities would produce a unique situation, which must be carefully examined to assess possible hazards.

Structure of Horizontal Ground Terminals

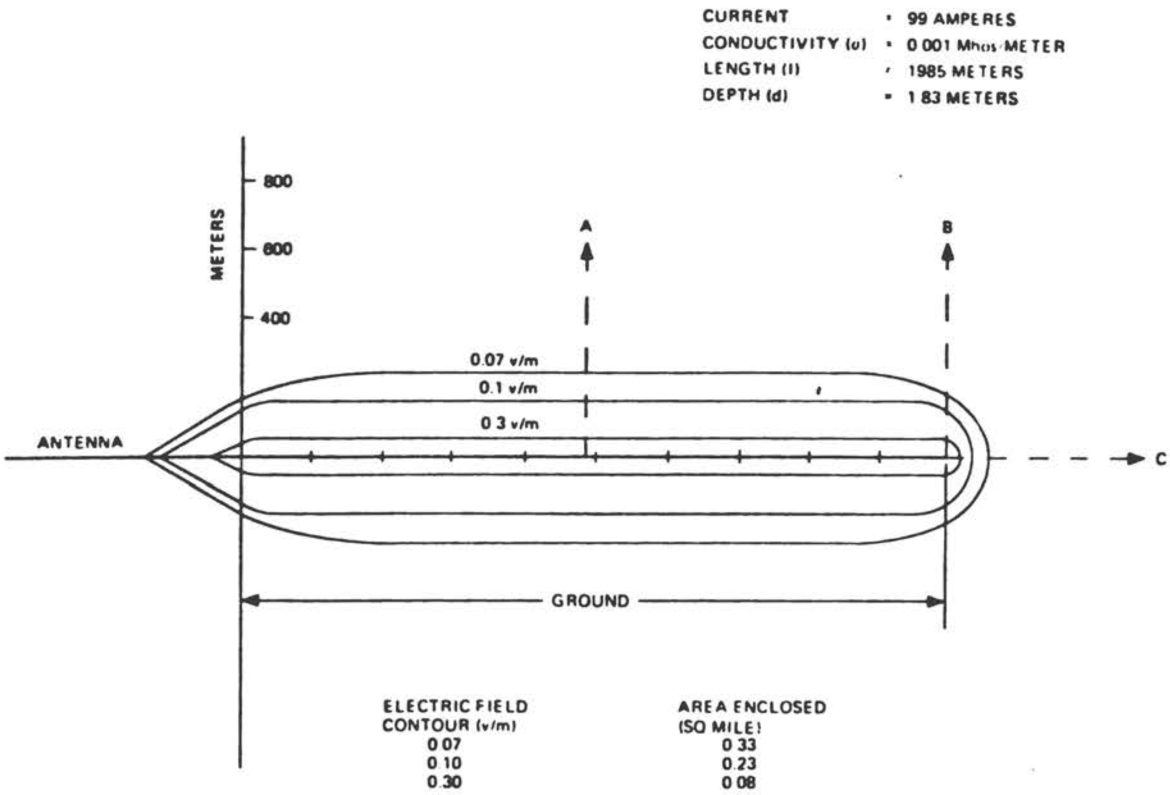
A horizontal ground terminal is simply an uninsulated wire buried a few feet below the earth surface and electrically fed at one or more points. The Seafarer proposal specifies a burial depth of 6 ft (183 cm) and a single feed point.[5] Although many configurations are possible, including a single straight wire and many wires radiating outward from the feed point as extremes, the Seafarer proposal calls for two ground wires at an angle of 60° to each other. The two conductors would have their common feed point at the end of an antenna cable and would each be directed approximately 30° away from the direction of the antenna element in a V. This configuration is referred to as a V-ground.

Although the design of a ground terminal can be initiated by assuming a uniform earth, local conductivity variations cause important changes in the earth current distribution and the resulting electric field. For this reason, the Seafarer proposal involves a design procedure that depends strongly on measurements made after installation.[14] On the basis of these measurements, remedial measures would be taken to reduce electric fields where required. Remedial measures might include insulating portions of the ground wire or installing vertical ground rods electrically attached to the horizontal wire. Because of the variety of conditions to be expected over a region as large as the Seafarer grid, the ground terminals can reasonably be expected to include various combinations of required remedial modifications.[15] Thus, although the general structure of a horizontal ground is very simple, the final details of construction may be complex, and no two ground terminals are likely to be the same.

The measurements to be made to define areas requiring remedial modifications and the final acceptance measurements are critical to the design of acceptable horizontal grounds. Careful consideration of earth conductivity changes caused by moisture, temperature, etc., must be included in planning these measurement programs.[15] It is important to emphasize that no detailed descriptions for acceptance measurements have yet been presented. Evaluation of a proposed measurement program and monitoring of the program during construction are crucial to the acceptance of horizontal ground terminals in a Seafarer system.

Magnetic Fields near a Surface Ground

As in the case of an antenna element, the magnetic field near a surface ground depends primarily on the current in the conductor and the distance from the conductor. The present proposal is to use a minimal burial depth of 6 ft (183 cm) for ground wires,[5] so the maximal magnetic field along the ground terminal will be no larger than the nominal field for the antenna elements (0.11 G). Furthermore, because the current in the ground wire decreases with distance from the feed point, the magnetic field will also decrease. Thus, only the region in the vicinity of the feed point will



ELECTRIC FIELD CONTOUR (v/m)	AREA ENCLOSED (SQ MILE)
0 07	0 33
0 10	0.23
0.30	0 08

Figure 7. Constant electric-field contours for a buried horizontal ground wire. Reprinted from U. S. Department of the Navy.[5]

have a magnetic field comparable with that of the antenna with the remainder of the ground terminal having a magnetic field that decreases approximately linearly with distance from the feed point. There is, therefore, no special magnetic-field problem at ground terminals, and the conclusions regarding magnetic-field effects for the antenna are also applicable to ground terminals.

Electric Fields near a Surface Ground

The surface electric field near a ground wire depends on burial depth, current, and earth conductivity and is strongly affected by local conductivity variations. Although these variations cause major effects, solutions for homogeneous-earth conditions are useful for initial design and estimation of the effects of large-scale conductivity variations. The equations describing the surface electric field near a straight horizontal ground wire in uniform earth have been presented elsewhere.[5,7,14,15,16] Figures 7 and 8 illustrate the variation in the fields along a single buried wire. Note that the maximal electric field occurs at a distance equal to the burial depth in a direction perpendicular to the wire or at the end of the wire and that the two maximal values are equal. The maximum along the length of the wire is more important, because it is present over a far greater region. Away from the ends of the wire, this electric field is represented by the simple expression,

$$E_X = \frac{IX}{\pi\sigma L(x^2 + d^2)} \quad , \tag{3}$$

where

I = current in ground wire, A

σ = earth conductivity, mho/m

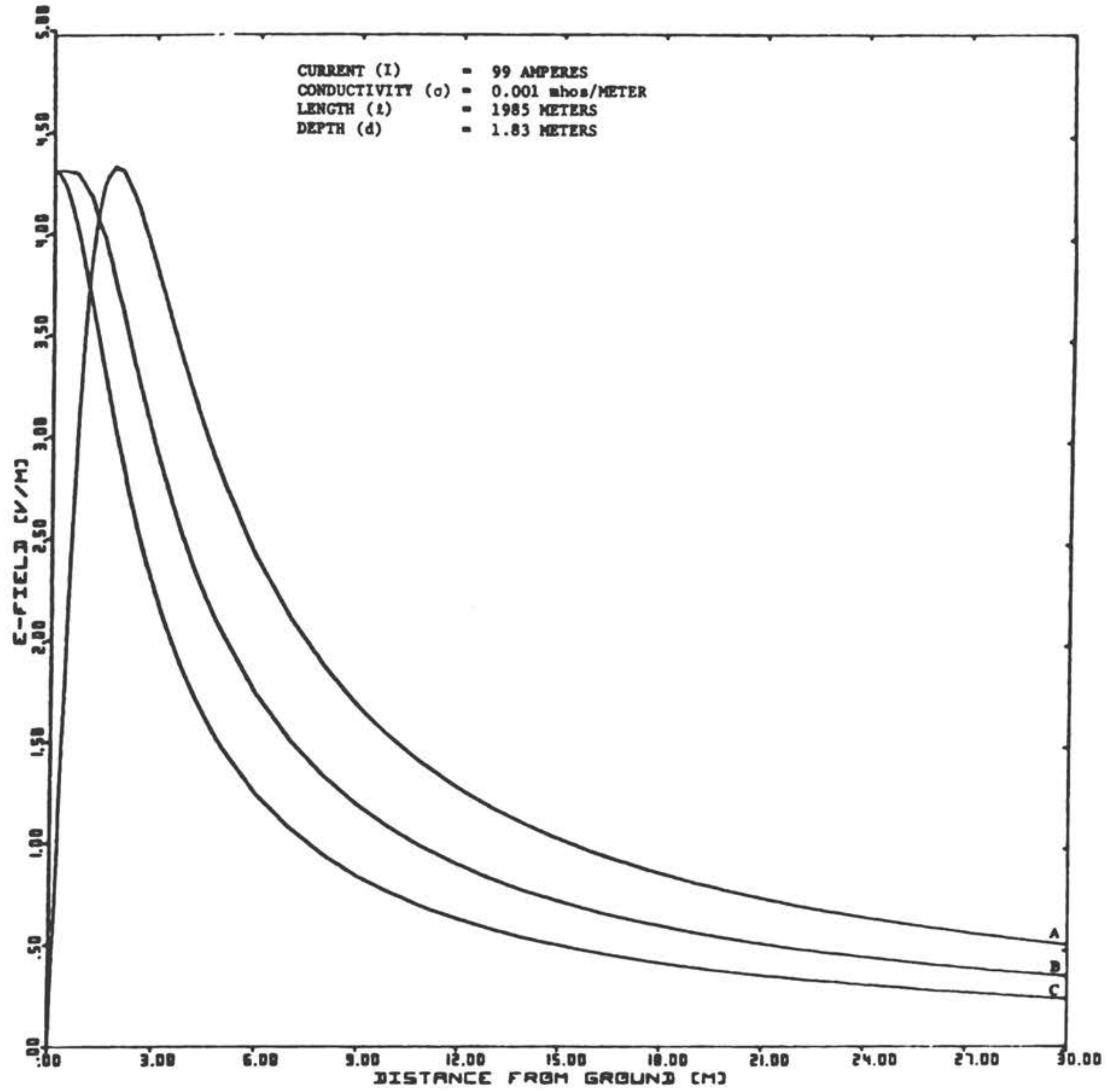


Figure 8. Electric-field profile for three paths away from a buried horizontal ground wire (see Figure 7). Reprinted from U. S. Department of the Navy.[5]

L = length of wire, m

d = depth of burial, m

x = perpendicular distance from point over wire on surface, m, and

E = electric field in direction perpendicular to wire, V/m.

The maximum occurs at x = d and is given in volts per meter, by:

$$E_{max} = \frac{I}{2\pi\sigma dL} \quad . \tag{4}$$

Sample Ground Terminal in Uniform Earth

The electric field along a V-ground is somewhat more complicated, because of the interaction of the two legs of the ground. Figures 9 and 10 illustrate the predicted electric field for the same characteristics as in Figures 7 and 8. Because each leg of the V-ground has the same length as the total wire in Figure 7, the maximal fields are smaller in Figures 9 and 10. Note, however, that, near the apex of the V, the electric fields are much larger than would occur if the V were opened into a single straight wire. Because this is primarily a local effect, the expression in Eq. 3 can still be applied along the length of each leg of the V-ground. The region near the apex of the V (the feed point) would have to be considered separately or the field in this region reduced by remedial means, such as insulating a portion of the wire.

Proposed Maximal Fields and Currents for Seafarer Grounds

Appendix A of the December 22, 1976, Navy specification of electric and magnetic fields for Seafarer grounds[5] specified the maximal fields and body currents near Seafarer grounds and is reproduced here, as Figure 11

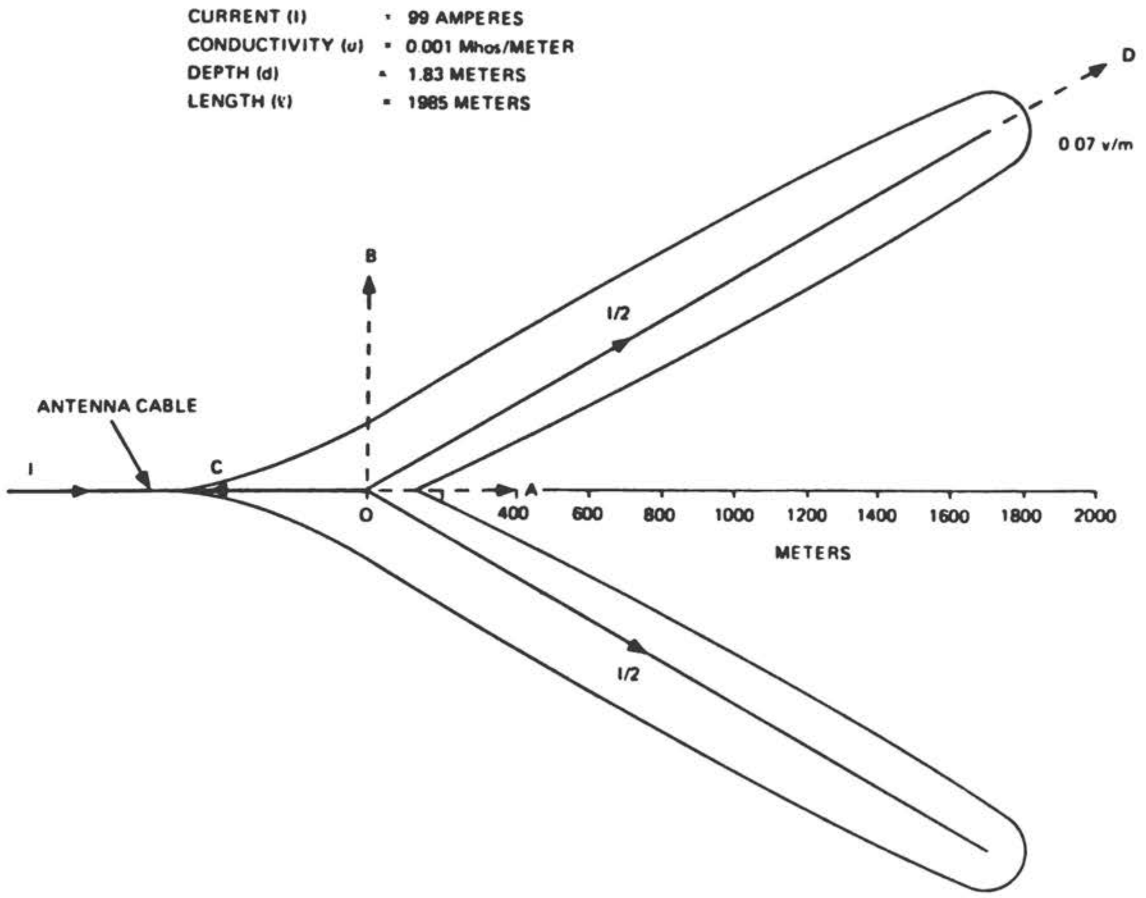


Figure 9. Constant electric-field contour for a horizontal V-ground structure. Reprinted from U. S. Department of the Navy.[5]

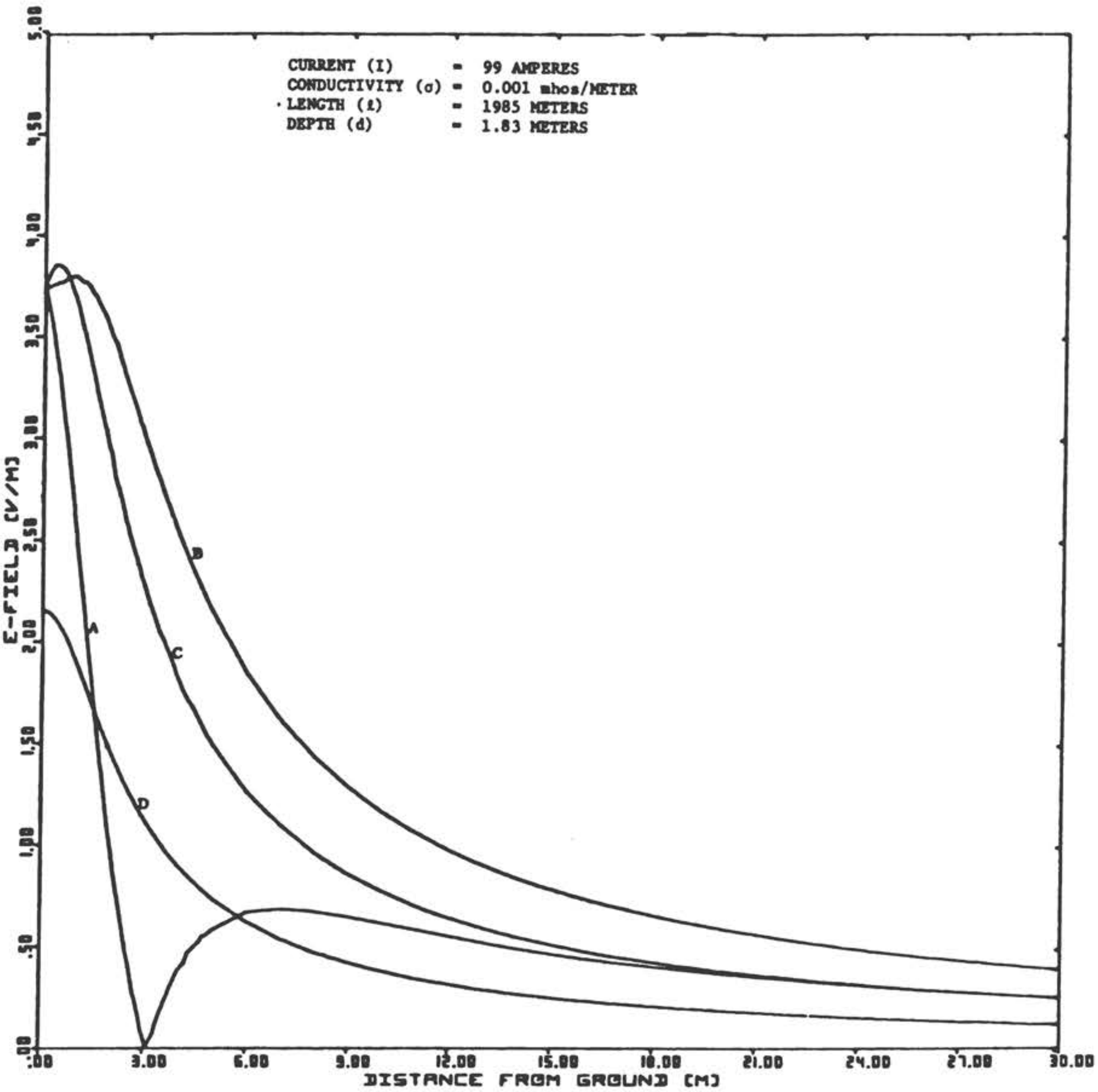


Figure 10. Electric-field profile for four paths away from a buried V-ground structure (see Figure 9). Reprinted from U. S. Department of the Navy.[5]

APPENDIX A - MAXIMUM FIELDS AND CURRENTS NEAR GROUND TERMINALS

The grounding assemblies of the Transmitter Segment shall be designed using the following documents for guidance to ensure public safety and environmental compatibility:

1. "Guide for Safety in Alternating Current Substation Grounding," AIEE No. 80, March 1961.
2. "Recommended Guide for Measuring Ground Resistance and Potential Gradients in the Earth," AIEE No. 81, May 1962.

When the Transmitter Segment is operating at nominal antenna current, the maximum surface gradient averaged over any 1-meter span in the vicinity of any grounding assembly shall not exceed 15 volts/meter.

The design of ground terminals shall be such as to limit the maximum possible body current flow to less than 1 milliampere for a 1-meter step. This maximum body current flow shall be calculated from the following equation:

$$I_b = \frac{E_{max}}{R}$$

where: I_b = maximum possible body current for a 1-meter step (amperes)

E_{max} = maximum surface voltage gradient average over a 1-meter span (volts/meter)

R = worst case current path resistance (ohms).

The worst case resistance shall be computed from the following equation:

$$R = 1000 + \frac{5}{\sigma} \text{ ohms,}$$

where: σ = soil conductivity (mhos/meter) at the location under examination.

When making the necessary soil conductivity measurements for these computations, due consideration shall be given to its seasonal variation.

The bare wire portions of grounding assemblies shall not be located near bodies of water (e.g., streams, rivers, ponds, or lakes). The distance between the bare wire portion of a grounding assembly and a body of water should be large enough to limit the electric field in the water to less than 1 volt/meter.

Figure 11. Appendix A of December 22, 1976, Navy specification.[5]

for convenience. The most recent draft environmental impact statement (DEIS)[17] discussed this proposal and presented a graph relating maximal electric field and soil conductivity; the graph is reproduced here as Figure 12. The DEIS[17] also discussed the maximal voltage that would be permitted between a wire fence or other long wire and the earth anywhere in the Seafarer grid. This maximum, 6 V, presumably also applies in the vicinity of ground terminals and is included here as part of the ground-terminal proposal. Table 2 summarizes the ground-terminal maximal fields, body current, and fence voltage (the nominal antenna values are included for comparison).

TABLE 2

Summary of Proposed Maximal Fields, Body Current, and Fence Voltage near Seafarer Ground Terminals

	Antenna (Nominal)	Ground Terminal (Maximum)
Magnetic field, G	0.11[a]	0.11
Electric field, V/m	0.07[b]	15.0
Body current, mA	—	1.0
Fence voltage, V	6.0	6.0

---

[a] 0.37 G with shallow burial near antenna intersection.

[b] 0.10 V/m near antenna intersection.

Adequacy of Ground-Terminal Proposal

The adequacy of the proposed maximum, 6 V, is considered for each component and in terms of several possible modes of exposure in the following sections. It is important to emphasize that, although the area covered by

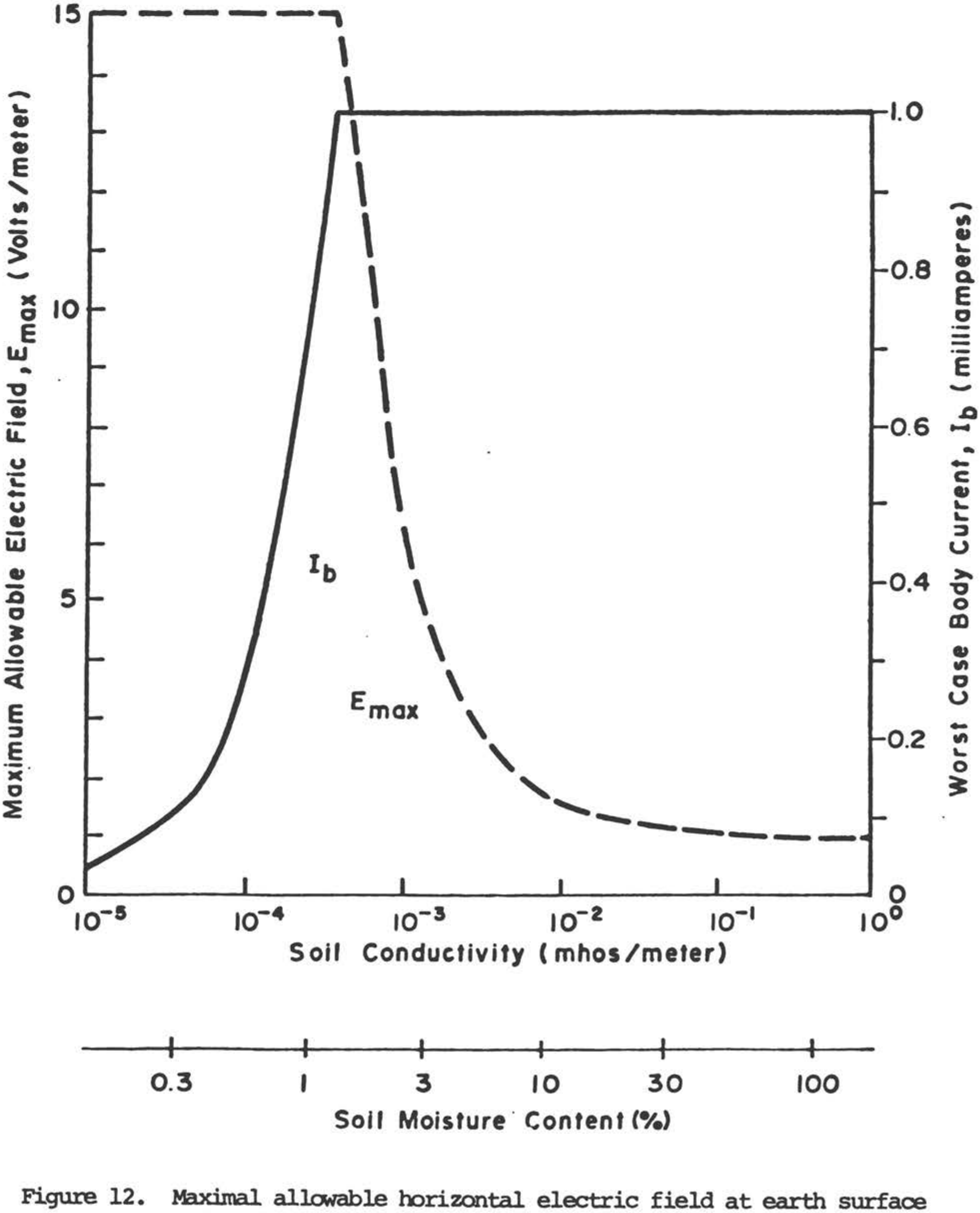


Figure 12. Maximal allowable horizontal electric field at earth surface and resulting worst-case body current flow for a 1-m step vs. soil conductivity and soil moisture content. Reprinted from Naval Electronic Systems Command.[17]

ground terminals is smaller than the entire Seafarer grid, it is still a large region. Taking a typical ground terminal as consisting of two 2,000-m ground wires, the total ground-terminal length would be about 400 km (250 miles). Because the Seafarer system is proposed to operate continuously, the entire length of this ground system must be considered as a source of maximal fields under all conditions of exposure--in sharp contrast with many other ELF sources, which are operated for only short periods or involve only small, isolated regions of possible maximal exposure.

Magnetic Field. Magnetic-field exposure is the same as or less than that along the antenna elements. Therefore, there is no special problem along the ground terminals, and the conclusions regarding magnetic-field effects for the grid region are also applicable to the ground terminals.

Step Potential. The most obvious and common human exposure at ground terminals would occur as people walked about over the buried ground wires. This situation gives rise to the term "step potential," which is simply the voltage along the ground between a person's two feet. For a 1-m step, the maximal exposure would be very close to the maximal electric field, or 15 V. The hazard associated with this exposure depends on the effective resistance that limits the current flow through the body and the resulting actual body current.

Numerous studies have been carried out to determine acceptable and hazardous body currents for humans and animals (for references, see Figure B-3 on p. B-6 of Naval Electronic Systems Command[17]). The most important figures (for uninterrupted currents and hand-to-hand contact) are:

current is perceptible at	0.5-1.0 mA,
Underwriter's laboratories specification is	5.0 mA,
let-go (tetanization) current is	6.0-10.0 mA, and
fibrillation occurs at	20.0-100.0 mA.

Three of these are expressed as ranges because they depend on the body weight, variations in cross section of the current path, and the substantial differences between individuals of roughly comparable weight. In general, children have the lowest tolerance.

The amount of body current that results from exposure to a given voltage depends on the total resistance of the circuit formed by the source and the body. The most important components of this circuit resistance are source resistance (R_S), contact resistance (R_C), skin resistance (R_E), and internal resistance (R_I). Of these, contact resistance and skin resistance are typically large (thousands of ohms), but can become very small if the contact surfaces are wet and the skin is broken. For worst-case conditions, these two limiting resistances should be neglected. The internal resistance is reportedly 120-300 ohms.[17,18] For wet conditions, a total body resistance ($R_E+R_C+R_I$) of 500-600 ohms is often recommended,[18,19] and 1,000 or 1,500 ohms is also suggested as being representative of typical conditions.[20,21] The use of these body resistances and the currents described earlier results in applied body voltages for various responses as listed in Table 3. These represent estimates of worst-case conditions, inasmuch as actual contact and skin resistances vary greatly in individual cases.

The voltages in Table 3 are not directly comparable with Seafarer step voltage because the source resistance is neglected. For Seafarer, this source resistance is the resistance of the earth under the contact points of the feet and is highly variable and depends on earth conductivity (discussed in some detail in the next section). For the present, it is important to observe that 15 V is higher than all but the fibrillation voltage in Table 3 and that reduction of body current by the source resistance is necessary if 15 V is not to be hazardous.

TABLE 3

Approximate Body Voltage to Attain Various Body Currents

	Voltage, V			
Body Resistance, ohms	Perception, 0.5 - 1.0 mA	Underwriter's 5 mA	Let-go, 6.0 - 10.0 mA	Fibrillation, 20 - 100 mA
Internal resistance, 200	0.1 -0.2	1.0	1.2-2.0	4-20
Total resistance: 500 (wet)	0.25-0.5	2.5	3.0-5.0	10-50
1,000	0.5 -1.0	5.0	6.0-10.0	20-100
1,500	0.75-1.5	7.5	9.0-15.0	30-150

One-Milliampere Body-Current Limitation. The Seafarer ground-terminal specification indicates that all ground terminals will be designed to limit possible body current to a maximum of 1.0 mA. If this were attained over the entire region of the ground teminals for all conditions, the Committee would be satisfied that there would be no hazardous conditions at Seafarer ground terminals. However, the attainment of this specification appears very difficult, and test procedures to guarantee that the criterion is met under all seasonal variations and possible occurrences have not been presented. Such test procedures and acceptance standards would have to be a part of any final proposal for surface grounds.

The major problem with the 1.0-mA body-current criterion is that the source resistance of the Seafarer ground system is proposed as a primary means of limiting body current.[16,17] This source resistance is a result of the voltage drop caused by the concentration of ground current under the contact points of the body with the earth. It can be estimated by assuming a disk of appropriate size in contact with the earth. For a 10-cm disk and uniform earth conductivity, the resistance of one such contact point is:[15,16]

$$R_S = 2.5\sigma \; ; \tag{5}$$

the resistance of two in series, as would occur for normal step-potential calculations, would be twice this value. For the anticipated range of earth conductivities,[15] Table 4 lists the values of R_S for uniform earth.

TABLE 4

Source Resistance, R_S, of a 10-cm Disk on Uniform Earth

Conductivity (σ); mhos/m	Source Resistance (R_S); ohms
0.0001	25,000
0.001	2,500
0.01	250
0.10	25

Clearly, for the lower values of conductivity, the source resistance is an important means of limiting body current. The problem is that this source resistance is highly variable, and this variation must be included in the consideration of worst-case conditions. The proposed step-potential limitation represented in Figure 12 is based on the use of the source resistance computed from (two times) Eq. 5 to compute body current. However, this figure does not consider the strong variation in earth conductivity that can occur over time and space. Some of the most important of these variations are:

- Spatial variation of earth conductivity along a ground wire: This results in large changes in maximal electric field along the ground wire, and not necessarily corresponding changes in body current.[21-27] Figures 13 and 14 illustrate the large variations that were found to occur in one of the Wisconsin Test Facility ground terminals. Table 5 lists actual measurements at this site and illustrates the greatly different variation of step potential and body current along the terminal.
- Earth layering, which can increase body current by reducing the source resistance much more than the electric field is reduced:[16] This occurs because the source resistance depends very strongly on the near-surface conductivity. Hence, the high surface conductivity would result in much greater body current during the spring thaw, than at other times of the year.
- Local regions of high conductivity, such as that resulting from a small wet area surrounded by a dry region: This could markedly lower the source resistance and have only a small effect on surface gradient. The area around the wet, high-conducting area would actually have an increased electric field.

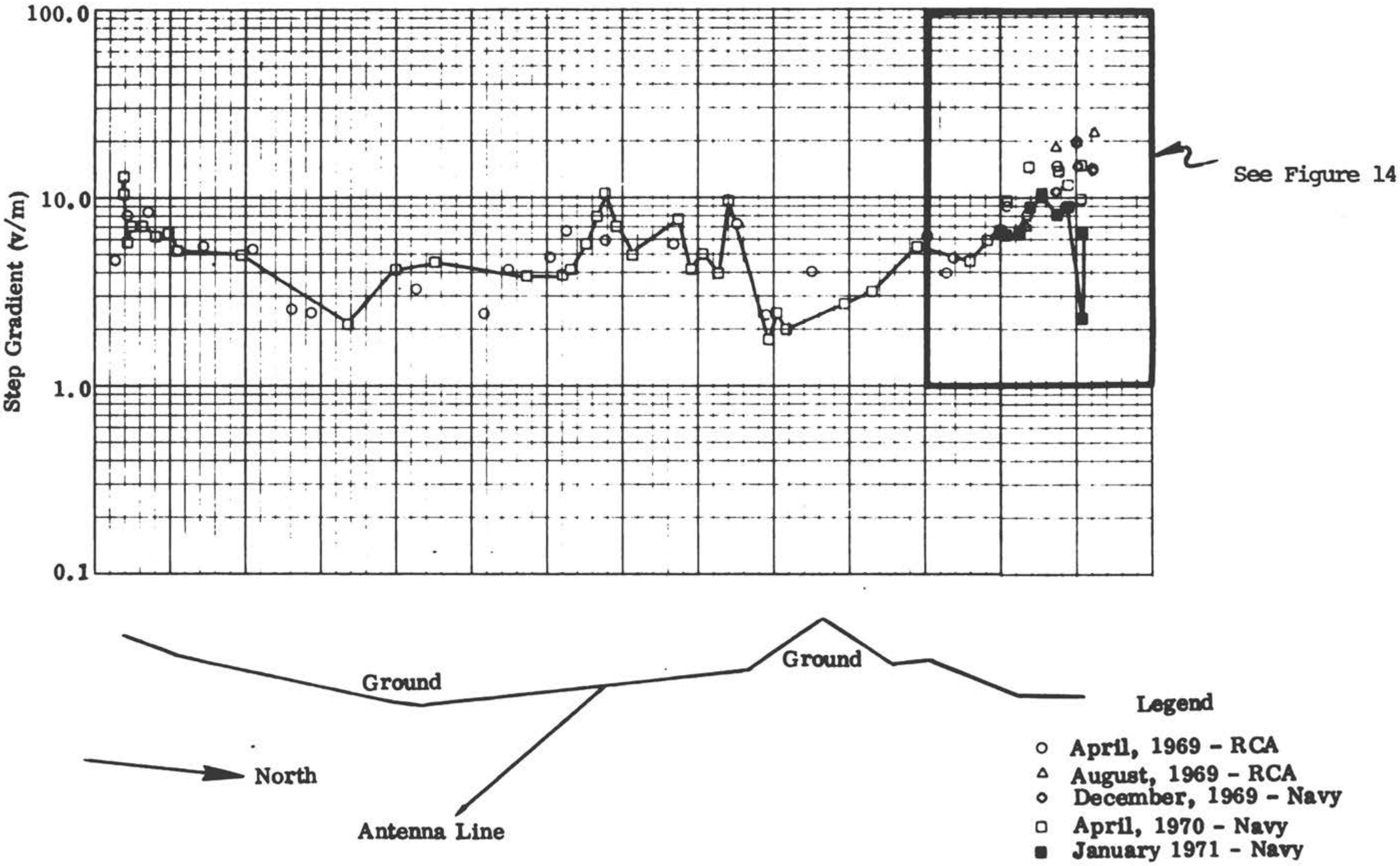


Figure 13. Step-gradient measurements at the west ground terminal (antenna line current, 300 A). Reprinted with permission from Hobson and Goldman.[27]

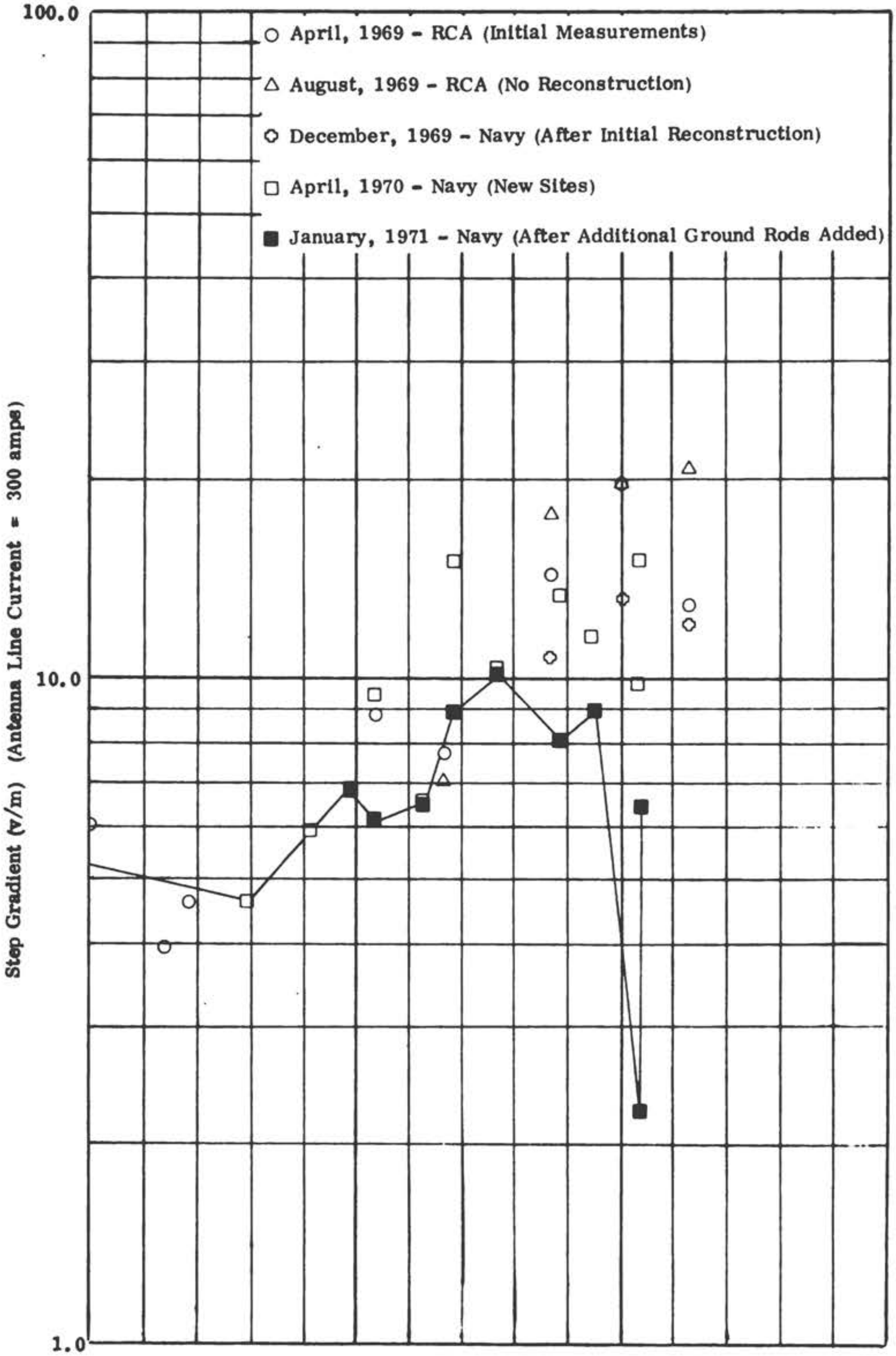


Figure 14. Step-gradient measurements taken at the north end of the west ground terminal. Reprinted with permission from Hobson and Goldman.[27]

TABLE 5

Maximal Step-Gradient Measurements at West Ground Terminal[a]

Site	Step Gradient (R = ∞), mV/A in antenna	Current in R (I), μA/A in antenna			Extrapolated to 700 A			
		510Ω	1,500Ω	5,100Ω	Step Gradient, V in 5 ft	I, mA 510Ω	1,500Ω	5,100Ω
1	29.3	14.5	9.3	4.5	20.5	10.2	6.5	3.1
2	24.0	5.3	4.1	2.5	16.8	3.7	2.9	1.7
3	36.0	3.6	3.1	2.4	25.2	2.5	2.2	1.7
4	66.0	10.6	7.5	4.1	46.2	7.4	5.3	2.9
4[b]	106.0	16.5	14.0	9.5	74.0	11.6	10.3	6.7
5	100.0	17.6	14.4	8.6	70.0	12.4	10.1	6.0
5[b]	100.0	16.0	14.8	9.4	70.0	11.2	10.4	6.4
6	73.0	13.3	10.7	6.3	51.1	9.3	7.5	4.4
6[b]	88.0	21.5	14.2	7.2	62.0	15.1	9.9	5.0
7	39.8	5.5	4.2	2.3	27.8	3.8	2.9	1.6
7[b]	35.0	3.8	3.4	2.3	25.0	2.7	2.4	1.6
8	45.0	22.0	13.0	5.2	31.5	15.4	9.1	3.6
9	30.5	15.8	9.0	4.1	21.4	11.1	6.3	2.9
10	21.0	19.8	9.6	3.5	14.7	13.9	6.7	2.5
11	28.0	24.0	10.3	3.3	19.6	16.8	7.2	2.3
12	21.0	11.2	7.3	3.3	14.7	7.8	5.1	2.3
13	12.0	13.8	5.7	1.9	8.4	9.7	4.0	1.3
14	16.0	15.8	7.2	2.5	11.2	11.1	5.0	1.8
15	12.5	15.6	6.5	2.1	8.8	10.9	4.6	1.5
16	12.1	13.5	6.1	2.0	8.5	9.5	4.3	1.4
17	26.0	3.0	2.6	1.7	18.2	2.1	1.8	1.2
18	26.0	3.7	3.3	2.2	18.2	2.6	2.3	1.5
19	42.0	3.8	3.3	2.5	29.4	2.7	2.3	1.8
20	23.0	16.5	8.5	3.4	16.1	11.6	5.9	2.4
21	41.0	2.6	2.8	2.1	28.7	1.8	2.0	1.5
22	27.5	8.2	5.7	3.1	19.3	5.7	4.0	2.2
23	33.0	7.7	5.7	2.4	23.1	5.4	4.0	1.7
24	12.0	0.7	0.7	0.5	8.4	0.5	0.5	0.4
25	20.0	10.5	6.4	2.6	14.0	7.4	4.5	1.8
26	23.2	20.0	10.4	3.4	16.3	14.0	7.3	2.4

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[a] Data from RCA Corporation Communications Research Laboratory.[26]

[b] Repeat.

- Long-term changes in the ground-terminal conductor condition and the local earth conductivity: These can cause large changes in both step potential and body current. Because the body current depends strongly on the conductivity of the upper few centimeters of earth, it is more likely to exhibit large changes. A recent series of measurements taken at the Wisconsin Test Facility supported this statement;[28] the largest step-voltage change in two sets of measurements 7 years apart was about 5 to 1, whereas body-current changes of up to 20 to 1 were found. Most step potentials and body currents were lower in the later measurements, but increases of 5 to 1 in step potential and 8 to 1 in body current also were found.

These and similar arguments all indicate that source resistance cannot be relied on to limit body current. The greatest hazard will occur in regions where the bulk (average over the region to a depth of several meters) conductivity is very low and the corresponding electric field would be allowed to reach 15 V/m. Although the hazard with respect to step potential is probably small, there is no margin of safety. This is unacceptable for a system that has the size of Seafarer and that is subject to continuous operation.

Other Possible Occurrences. Although the most common exposure near ground terminals would be simple foot-to-foot exposure during walking, other more severe situations could occur. In addition to moderate increases in exposure caused by someone's falling into two-hand--two-foot contact, much more severe situations could occur if long conducting objects were involved. For example, a tractor and plow with the plow in the earth or a person dragging a length of irrigation pipe or other long conductor would permit contact with a remote point much in the same way as a wire fence along the antenna. Unlike the situation along the antenna, the electric field is not constant along lengths of several meters, so the exposure is not expressed simply as the maximal field times the length of the object.

A reasonable and simple approximation for the maximal total voltage (V_{max}) between two points on the earth near a ground terminal can be obtained by integrating the electric field of Eq. 3 from the point over the ground wire out to a specific distance. The result is:

$$V_{max} \cong d\, E_{max} \ln \frac{x^2+d^2}{d^2} \quad ; \qquad (6)$$

which for the Seafarer burial depth of approximately 2 m yields the results in Table 6.

TABLE 6

Approximate Maximal Voltage over Various Distances near Surface Ground with Depth = 2 m

Distance, m	Voltage, V_{max}
2	$1.4\ E_{max}$
4	$3.2\ E_{max}$
6	$4.6\ E_{max}$
8	$5.7\ E_{max}$
10	$6.5\ E_{max}$
12	$7.2\ E_{max}$

The possible hazard associated with even a relatively short conductor is readily apparent. Consider, for example, a tractor and plow whose total length is 6 m. With the plow embedded in the earth, the voltage between the front of the tractor and the ground below would be $4.6\ E_{max}$, or about 70 V at $E_{max} = 15$ V/m. If uniform earth conductivity is assumed at the largest conductivity for which 15 V/m would be permitted ($\sigma \cong 3.5\text{x}10^{-4}$ mho/m--see Figure 10), the source resistance (R_S) from Eq. 5 is about 7,000 ohms. However, for someone touching the front of the tractor, the two feet are now parallel paths to the ground, resulting in a total source resistance of 3,500 ohms. The body current would then be predicted as 70/4,500 or 15.6 mA (using a body resistance of 1,000 ohms). The situation could be much worse if the ground under the person were a small region of relatively high conductivity, such as a small puddle. This would greatly reduce the effective source resistance but would have almost no effect on the voltage on the tractor and could result in body currents approaching 70 mA, or even more.

It is not difficult to construct other situations involving conducting objects that would yield similar results. Various types of pipes, aluminum boats, chains, etc., could all be brought into the vicinity of ground terminals and create hazardous conditions. There is a strong parallel between these situations and the long-conducting-fence problem identified and addressed in the Seafarer proposal. The mitigation standard of maximal allowable voltage between a long conductor and earth of 6 V[17] could be applied to these situations. If 6-12 m is accepted as a reasonable maximal length for objects that could readily be transported into the region of a ground terminal, this would require restricting the maximal electric field along the ground terminal to a range of 0.8-1.3 V/m. For normal step-potential considerations, this would provide a safety factor of about an order of magnitude before let-go currents could be attained. In the worst-case conditions associated with conducting objects 6-12 m long near the ground terminal, the body current would be limited to approximately the Underwriter's Laboratories 5-mA specification. It would also place the wire-fence mitigation level and the ground-terminal specification in correspondence, rather than roughly an order of magnitude apart, as in the present proposal.

Vertical Ground Terminals

To reduce the surface electric field at a surface ground requires either increased length or deeper burial. In regions of low conductivity, the attainment of maximal fields of about 1.0 V/m could require very long or very deeply buried horizontal wires. Because very low conductivity would probably be associated with the occurrence of bedrock near or at the surface, the construction of very long horizontal grounds would likely be difficult in such regions.

An alternative is the vertical or well ground,[6] consisting of a veritcal conductor placed in a drilled well. If the upper portion of the ground conductor is insulated, the surface electric field can be reduced to very low values. This type of structure could be a suitable alternative to surface grounds in regions where surface conductivity is unsuited to attainment of acceptable surface electric fields.

Conclusions and Recommendations

The present specification of a 15-V/m maximal electric field or a 1-mA maximal body current is judged to be inadequate to ensure safety from shock hazards along the ground terminals. Long conducting objects (aluminum boats, irrigation pipes, etc.) brought into the region of ground terminals could create serious, possibly lethal, shock hazards. Although the step-potential hazard would probably be slight, there is little margin of safety. Hence, variation over time could result in hazardous step potentials along a ground terminal that originally was acceptable.

A reduction in the specified maximal electric field at ground terminals would reduce these hazards. If the maximal field were reduced by about one order of magnitude, approximately a tenfold safety factor for step potential would result, and the hazard associated with long conductors (up to 12 m) would be reduced to nonlethal, although still possibly painful, shocks. This change would also bring the ground-terminal specification into closer correspondence with the 6-V mitigation level for long conductors (wire fences, etc.) within the grid. A reduction of an additional order of magnitude would bring the ground-terminal fields into close correspondence with the fields within the grid and would make the shock hazard at ground terminals negligible, except for very long conductors (e.g., long wire fences).

The Committee recommends that:

- The test-bed facility include at least one vertical ground terminal, to allow evaluation of this alternative design as a means of attaining reduced electric fields at ground terminals.
- The final detailed specification of ground-terminal electric fields, including details of measurement procedures and survey techniques for acceptance testing, be reviewed by an appropriate group before any construction is initiated.

Cable Faults

The proposed Seafarer antenna would consist of about 2,400 miles (about 3,860 km) of insulated cables and would cover about 4,000 square miles ($10,360\ km^2$). For such a large system that operates continuously, malfunctions cannot be completely avoided. It is therefore necessary to consider possible hazards due to malfunctions.

Failures within the generating stations offer no unusual features and do not in general affect the population at large. Attention is therefore concentrated on cable faults. Three types of cable faults can be readily identified: breaks in the insulated cable (type a), breaks in the ground-terminal wires (type b), and faults in the insulation (type c).

Some information about cable faults is available from the Wisconsin Test Facility.[29] Following the recommendation of the *ad hoc* Panel on Sanguine of the National Research Council,[31] installation of a buried antenna under the north-south overhead antenna was completed in March 1973. In the 2 years after its installation, this underground antenna was energized for a total of 362.8 h, and three cable faults were detected; two more cable faults have since been reported (Table 7).

TABLE 7

Cable Faults at the Wisconsin Test Facility

Fault	Date of Discovery	Step Potential
1	October 1973	120 V/m (April 1, 1974)
2	August 1974	164 V/m
3	June 1974	Not measured
4	June 1975	Not measured
5	August 1975	Not measured

The reasons for the cable faults are varied: splice failures, mechanical damage during road restoration, and possibly lightning.

From the experience at the Wisconsin Test Facility, it is clear that cable faults occurred frequently and that these faults could lead to step potentials that are hazardous. Although the frequency of occurrence is expected to be reduced greatly by the use of new types of cables, a reliable system of detecting and locating cable faults is necessary. The proposed Seafarer antenna consists of 47 independent cables, so the de-energizing of one or two cables would not seriously affect the operation of the antenna. Accordingly, once a cable fault were detected, the location of the fault could be found with the malfunctioning cable disconnected. So far as possible biologic hazards are concerned, the important point is to have a rapid and reliable system of detecting cable faults.

Of the three types of cable faults listed earlier, those of type a would greatly alter the antenna impedance and thus could be found easily. Type b faults are most likely to result from ground-conductor corrosion. Although this problem was not addressed in the Seafarer proposal, means for preventing corrosion and detecting ground-cable breaks should be developed before installation of Seafarer.

Cable faults of type c would change the current in the cable only slightly, because the current leaked to the surrounding earth would be relatively small, and, unlike similar faults in power cables, could not be detected by observing the unbalance of the circuit. Because the current would change only slightly, these faults would hardly affect the function of the antenna as a radiating system. To observe cable faults of type c, the detecting system must be sensitive to the leakage of less than 0.1% of the current.[30]

A detecting system for type c faults has been proposed. In this system, high sensitivity would be achieved by superimposing a DC voltage on the AC signal. Because of the capacitors near the ground terminals, the DC current would be very small in the absence of a cable fault, provided that the capacitors did not have parallel-connected bleeding resistors. If there were a DC cable fault of type c, the DC current would increase greatly, and this increased current would signal the presence of a cable fault.

The proposed detecting system may therefore be adequate (i.e., sufficiently sensitive) for DC cable faults of type c. Because the Seafarer antenna would operate at approximately 76 Hz, the faults to be detected, to avoid biologic hazards, would be AC faults. All DC faults are also AC faults, and most AC faults are probably also DC faults. The question that needs to be answered is whether all AC faults at 76 Hz are also DC faults. The Committee is unable to find a definitive answer to this question. A reliable system of detection of cable faults must be demonstrated before a final decision to proceed with installation of the Seafarer antenna.

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BIOPHYSICAL PRINCIPLES

Introduction

Understanding the effects of ELF electric and magnetic fields on biologic organisms or systems and evaluating the many experimental results that have been reported can be very difficult. A set of quantitative, easily applicable rules that are biophysically adapted from fundamental physical laws to make them conform to ELF data can be very helpful. Some of these rules are not exact, but in the few instances where deviations are significant, they can be dealt with as special cases with special biophysical models.

The casual language of convenience in which we tend to call ELF fields "electromagnetic" fields is apt to lead us into error: there is a radiative or electromagnetic term in the ELF field that is all-important in long distance communication, but its biosphere effects are trivial. In the near field, common engineering usage sets a lower limit of 5% of a wavelength inside of which separate consideration of the E fields (electric fields), the I fields (electric-current fields), and the H fields (magnetic fields) and their derivatives constitutes an adequate representation of Maxwell's basic laws.

Let us be extraconservative and use 1% of a wavelength for a typical 76-Hz ELF field in air or free space. The wavelength here is $(3 \times 10^8)/76$ m, or 4×10^6 m, or 4,000 km, which is 2,500 miles. Any organism or bio-element smaller than 40 km, or about 25 miles, in diameter can thus be examined adequately solely in terms of its electric-, magnetic-, and current-field characteristics.

Magnetic-Field Interactions

We may examine, separately and in combination, what these fields can do to a biosystem. A magnetic field will act on magnetically permeable molecules, macromolecules, and composite bodies to orient the unit in the direction of the field (across it in the case of diamagnetic elements) and to polarize the element more strongly, in accordance with its permeability. With materials of high permeability (μ = 1,000-100,000) such as iron or permalloy, one must carefully distinguish between the H (exciting) field, traditionally measured in oersteds,* and the B (induced or flux) field, traditionally measured in gausses. So far as we know (and scientists have looked for them in trying to find magnetic-field sensors in birds and other reported field-orienting organisms), there are no naturally occurring highly permeable components in organisms, with the possible exception of newly reported permanent moments in some microorganisms. Consequently, we can assume that, at ELF frequencies, ambient magnetic fields in biomaterial are the same as external fields; thus, we can use the gauss without special provisions. For reference, it should be remembered that the steady earth field is about 0.5 G and that in the typical American home one is also subjected to a pervasive ELF ambient 60-Hz magnetic field somewhat less than this, which rises to perhaps 20-40 G when one handles ordinary electric equipment, such as a hair dryer, a food mixer, or an electric drill.

Uniform ELF magnetic fields do not cause net translational forces on permeable elements of biosystems, and so do not cause particles to "move," unless there happen to be mechanical linkages to convert rotation to translation in submicroscopic analogy to the mechanical rack and pinion.

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*1 oersted = 79.6 A/m.

For a field to cause movement of molecules, a spatial gradient must be present; i.e., the field must change with distance. In simplistic terms, the elementary magnetic dipole must find its positive end in a different strength from its negative end; otherwise, the two forces cancel exactly, and no net force is experienced.

It is widely recognized that, for "soft" permeable magnetic particles, the translational force will be proportional to the product of the field strength and the spatial field gradient at the particle location. These forces can collectively be called "field-generated forces."

Magnetically Induced Currents

ELF magnetic fields produce another secondary effect, callled eddy currents, that could conceivably produce biologic effects. Conductive, or for that matter electrically susceptive, material in which a changing magnetic field exists has induced in it an EMF, which can be thought of as the source of eddy or secondary currents.

At ELF field strengths and frequencies, these internal currents are very small; but they must be considered as possible transduction mechanisms, in view of the very sensitive current-detecting organs now known to exist in several fish species. To establish order of magnitude for these currents, consider a large loop of conductive tissue that might reasonably be found in a human head. This loop might be 30 cm long and have an area of 50 cm^2. If this loop lay in a plane normal to a strong environmental 60-Hz ELF magnetic field of 1 G, an EMF of 189 μV would be induced in it. With a typical tissue impedivity of 500 ohm-cm, this will produce an AC 60-Hz current density in the tissue loop of 0.0126 $\mu\text{A/cm}^2$ (and incidentally one-fourth of a cycle out of time phase with the magnetic field). This current density is of the same general magnitude as that produced by the cumulative stray currents escaping from the brain cells that produce the familiar EEG brainwave signatures, which are generally considered to have trivial influence on brain function. They have been called the noise of the brain's motor.

Electric-Field Concepts

Turning next to the electric and electrostatic aspects of ELF fields, there is at least one simple but relatively unfamiliar field measure that it is essential to define, if we are to think easily of the electric fields inside and outside living organisms: the Maxwell displacement-field current density. This current flows in materials, even though they are perfect electric insulators, or in empty space itself, by virtue of the time rate of change of an electric field. We need a field-form for this current that will remove the mystery from the currents flowing into and out of the surface of an organism, grounded or insulated, and into the surrounding nonconductive space and often strongly influenced by the size and shape of the organism itself as it distorts its surrounding field.

At this point, it would be useful to review briefly the terminology used in describing ELF fields, especially for conditions in which electric-current fields that produce biologic effects are mixtures of displacement currents and conduction currents, both brought about by changing electric fields. Ohm's law, I = V/R, applies to DC currents (I), potential differences or voltages (V), and resistance (R) in circuits made up of components connected with conductors, such as wires, with each component considered as "lumped" in one place and all the currents between them concentrated into a conducting "wire."

ELF systems differ in two important aspects from these basic circuit systems: currents can flow not only because of potential difference, but also because of time rate of change of electric fields (displacement currents) and because of the time rate of change of magnetic fields (induction or eddy currents); and the currents flow in the bulk of the biologic organism and its environmental surroundings and are not confined to wires or highly localized channels. We must therefore substitute a measure of the field densities--flux per unit area--for the simple total flow. To do this, we introduce a new form of Ohm's law, making separate provision for the displacement and induction currents; these are sometimes called "imaginary currents," because they are "intangible" in ordinary Ohm's-low terms, but they are just as real, with respect to shock potential and possible biologic interaction.

For simple resistance, we introduce impedance (Z), which is made up of the familiar resistance (R), added by proper mathematical technique (complex addition) to the term reactance (X), so that $Z \overset{=}{\sim} R + jX$, where j is $\sqrt{-1}$. Because we want to be able to use the extended concept of conductance, G, which is the reciprocal of R in ordinary circuit theory, we introduce the new measure Y (admittance), which is similarly made up of a "real" term, G, plus a new term, susceptance (B), so that $Y \overset{=}{\sim} G + jB$. One must be careful, however, to carry out the reciprocal calculation in complex terms, so that, although $Y \overset{=}{\sim} 1/Z$, G is *not* always equal to 1/R, and B is *not* always equal to 1/X.

To go to the simplest formation that will cover ELF interaction with biologic systems, we must generalize these AC forms of Ohm's law to a field form; that is, we must state them so that we can measure in field-density terms equivalent to amperes per square centimeter, etc.

There is already a widely familiar terminology for resistance and conductance that has been used for decades by physical chemists and physiologists. Resistivity is the density of resistance and must be measured in terms of ohm-centimeters or a dimensionally equivalent measure, such as ohm-meters. The need for the length unit arises because ohms for a uniform material is equal to the resistivity times the length of path divided by the conductor cross-sectional area, and so a "length" unit is left over in the denominator and must be incorporated in resistivity to balance. Conductivity is familiar as the reciprocal of resistivity and has corresponding dimennsions, reciprocal ohms per unit length. Conductance is often expressed in mhos (from ohm spelled backward), so a typical conductivity unit will be the mho-centimeter.

By simple extension of terminology, the field forms of impedance become impedivity, made up of classical resistivity combined with reactivity by standard complex addition. Admittivity becomes the combination of conductivity and susceptivity.

These units are not really a complication, but actually make it very easy to think of ELF system relationships. We quickly learn to think of the displacement-current density as an easy measure of the field effect representing the displacement current deposited on an animal surface as a result of the admittivity of air, which is almost totally due to susceptivity, because the conductivity of air is nil.

Electric-Field Interactions

An illustration of the practical usefulness of these relationships is to be found in converting the ELF-field statements as they are ordinarily given into more biologically relevant equivalents. It is likely that, with only rare exceptions, such as the raising of hair in extremely strong electrostatic fields, ELF fields produce their effects on biologic organisms by virtue of the ordinary electric-current fields that they produce in or at the surface of the organism.

ELF electric-field strengths are traditionally expressed in volts per meter wherever they may be—in earth, in water, or in air. A typical value for a Seafarer ELF field might be 0.1 V/m. An impedivity of earth might be 5,000 ohm-cm; of a puddle of water, 1,000 ohm-cm; and of soft, nonfatty biologic material, 500 ohm-cm. The impedivity of air at 60 Hz, typical for ELF, is 3×10^{10} ohm-cm.

In any medium, the electric-current density, the measure that is biologically pertinent, can be calculated by dividing the electric-field strength in volts per centimeter by the local impedivity in ohm-centimeters. Corresponding units of volts per meter and ohm-meters will, of course, give equivalent current densities in amperes per square meter.

Because the ELF horizontal electric field in the air just above the ground is about the same as that just below the earth surface, consider the effects of this same field strength on organisms living in and above the earth. The current field in the earth would be 0.001 V/cm divided by 5,000 ohm-cm, or 2×10^{-7} A/cm^2; in a puddle of water, 10^{-6} A/cm^2; and in body tissue, 2×10^{-6} A/cm^2. In air, the field-current strength would be only 0.001 V/cm divided by 3×10^{10} ohm-cm, or 3.33×10^{-14} A/cm^2. A very common threshold strength of current field for biologic stimulation in 1 mA/cm^2. The earth- or water-living organism might thus find in this same electric-field strength of 0.1 V/m a current between one-thousandth and one five-thousandth enough to stimulate it. In air, the corresponding field current of 3.33×10^{-14}

A/cm^2 is lower by a factor of 3×10^{10}, or 30 billion, than that which might be expected to produce sensation.

Current fields must be continuous, so these fields that impinge by virtue of displacement current on a biologic object continue into that object without change in strength. It is common in ELF research reports to substitute the free field—i.e., the field measured or calculated for the system with the organism removed—for the electric field with the organism present. This is convenient and avoids difficult calculations and approximations, but it is inaccurate. Indeed, it is like assuming that the light intensity deep inside a human body, illuminated from outside, is the same as that which would be measured if the body were not there.

Within the surrounding insulating medium and at the surfaces with which it makes contact, the density of the displacement-current field, in amperes per square centimeter, is proportional to the normal electrric-field strength and also proportionnal to the time rate of change of field, hence, directly proportional to frequency. Inside biologic tissue, displacement currents continue to flow and are indeed enhanced if the dielectric constant for the material is high. In the case of watery fluids, this factor will be about 80; it may be much higher for some biologic structures. In spite of this enhancement, however, these currents are usually trivial, with respect to ionic conduction currents. Consider a strong ELF 60-Hz field of 300 V/m impinging on a tissue surface with its attendant current density of 10^{-10} A/cm^2. The dielectric impedivity of the tissue might be $3/8 \times 10^9$ ohm-cm, and its conductive impedivity about $1/2 \times 10^3$. Less than one-millionth of the current would then be carried by displacement current, and the potential gradient in the tissue would be lower by a factor of 30 million than that in the environment; 1 μV/cm for an external 3,000-V/m field.

It is interesting to compute the total current that results from exposure to a typical 60-Hz ELF field. Using the impedivity of air at 60 Hz, we immediately see that the displacement-current density flowing into the skin of a subject exposed to an electric 60-Hz field of 100 V/m—a common indoor value near electric lighting fixtures—will be 1/3 x 10^{-10} A/cm^2, or about 30 picoamperes/cm^2 (30 pA/cm^2). If the whole body surface of about 1 m^2 were experiencing this field strength, of uniform density and polarity, a grounding current of about 1/3 μA would flow. Experience shows that currents of 0.1-1 μA are typical in a room that is not expecially prepared, so the assumed field is not unrealistic.

One can feel currents by direct stimulation from an ordinary electrode contact at about 1 mA. Are such currents likely to be produced by grounding a body in an ELF electric field? Not very likely, because the whole body surface would have to be in a field of 3,000 V/cm, or 300,000 V/m, which is vastly beyond Seafarer fields and not far from the range where spark discharges will begin from local surface irregularities. A phenomenon of electrostriction allows an animal to detect much smaller currents than this by tactile forces as a dry skin surface is moved over a charged conductor. Here, a mere 10-20 V with only a few microamperes per square centimeter at the skin surface may cause perceptible dielectric forces in the skin with local field strengths of perhaps 10,000 V/cm with as little as 2-4 μA of total current.

When animal target of electric fields is unconnected by conductors to any other part of the ELF field, it must receive opposite-polarity displacement current at various parts of its surface, whose total integral must be zero. It will automatically, according to basic principles, be driven to an AC potential with respect to ground at which this result is achieved.

With these measures of the biologic fields to be expected as a consequence of ambient ELF fields, we can make plausible models for observed or anticipated effects.

Coupling

This section deals with the "coupling" of external fields into tissues of man and other organisms. For low frequencies, the relationship of internal and external fields[32] is simply given by

$$E_i/E_a = f\rho/(6 \times 10^{11}) \qquad (7)$$

where f is the frequency in hertzes and ρ is tissue resistivity in ohm-centimeters, assuming a spherical shape. Thus, for $f = 60$ Hz and $\rho \sim 10^3$ ohm-cm, $E_i/E_a = 10^{-7}$. For an ellipsoid approximating man,[4] with the field parallel to the long axis of the body, the ratio will be about 4×10^{-7}. These theoretical results are well supported by experimental evidence, including studies of ELF injected currents in phantoms of man and man himself.[34] However, all mathematical models assume homogeneity and, hence, uniform current density. This assumption is somewhat in error, and optimal current densities may be somewhat larger than estimated from above quoted equations. For example, heart is a better conductor than surrounding lung tissue and therefore may well concentrate current to some extent; but cerebral tissues are somewhat insulated by the skull. The agreement of the total injected current, as measured on man, with theoretical calculations inspires confidence in the modeling and inplies that differences in local current density are insufficient to affect the total current. It is probable that local current densities in soft tissues may vary by less than a factor of three or ten from those estimated from theory. But experimental data on this are limited. Allowing for this fact, we estimate maximal current densities induced in man by a vertical field to be around 10^{-9} A/cm^2, or 10^{-6} mA/cm^2 for an external field of 1 V/cm and 60 Hz. This is 10 times higher than in a homogeneous spherical model. This current density is the bulk-tissue current density, and corresponding membrane current densities are several orders of magnitude lower, because most of the low-frequency current passes through extracellular space. It is also a million times lower than the bulk-tissue current density of about 1 mA/cm^2 needed to cause stimulation of excitable membranes.

Eddy Currents

The above considerations do not include the eddy currents that are induced by magnetic fields. Consider a conducting spherical object surrounded by air and exposed to an external magnetic flux B. Electric currents are produced that circulate in planes perpendicular to the direction of the magnetic flux. The strengths of these currents and corresponding fields are proportional to the distance from the center of the sphere and greatest at the periphery of the equatorial plane. The magnitude of the field strength, E_i inside the conducting sphere in the equatorial plane is found by Eq. 8:

$$E_i = f\ r\ B\pi \quad , \qquad (8)$$

with E_i in volts per meter, distance from the sphere center (r) in meters, frequency (f) in hertzes, and magnetic flux (B) in webers per square meter.* Table 8 compares internal field-strength values (E_i) and current densities (j)

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*1 gauss = 10^{-4} weber/m^2.

TABLE 8

Internal Field Strength and Current Density Generated by 60-Hz Magnetic Fields

		Internal Field Strength (E_i), V/cm	Current Density (j), mA/cm^2
Case I:	B = 0.1 G	2×10^{-6}	2×10^{-6}
	E = 0.1 V/m	10^{-10}	10^{-10}
Case II:	B = 1 G	2×10^{-5}	2×10^{-5}
	E = 10 kV/m	10^{-5}	10^{-5}

generated by 60-Hz magentic fields of 0.1 G and 1 G, with values caused by electric field strengths of 0.1 V/m and 10 kV/m, respectively. The values chosen are typical for Seafarer fields (Case I) and fields experienced under high-voltage transmission lines (Case II). A resistivity of 1,000 ohm-cm has been assumed for body tissues, i.e., a value slightly above reported values.[27] These data demonstrate that currents induced in a biologic object above ground in the Seafarer case are largely due to the magnetic component as long as $B > 10^{-5}$ G, which is the case for most of the area. The electric component is negligible by comparison. In the transmission-line case, the E- and B-induced current densities are comparable. Hence, actual induced currents by the sum of magnetic and electric fields are almost comparable for the transmission-line case and the Seafarer case, even though the electric fields in air differ by a factor of 10^5. For a more detailed discussion of E- and B-induced fields, see Spiegel.[38]

The principles outlined above pertain largely to spheres. Much additional work has been done for more complex shapes (see, for example, Barnes et al.,[4] Deno,[10] and Baughn [Appendix A to this report]). These efforts indicated substantial modifications of the values for internal fields and current densities; but they did not indicate any need to correct the conclusion that internal current densities induced by Seafarer fields are many orders of magnitude below those needed for nervous stimulation.

The principles outlined here deal largely with currents induced in bodies surrounded entirely by air. Symmetry considerations suggest that similar results pertain to the case of half-spheres and spheroidal models of man in contact with ground and otherwise surrounded by air. There are, however, important other classes of effects with respect to which Seafarer fields are anticipated to be of considerably higher potential risk. These include, in particular, the cases when two parts of the human or animal body are in direct contact with different potentials (two-contact case), such as when two legs or extremities are in contact with different potentials (step potential) and when two legs are in contact with one potential and the arms are carrying a metallic object that is in contact with another potential. The Committee has not been particularly concerned about the hazards of induced currents (no-contact case), because induced currents and current densities are exceedingly low. But it is concerned about the possibility of hazards associated with a two-contact case near the ground terminals.

Heating

The effects of undue heat development from exposure to electric fields need not concern us here. They require internal fields much greater than those created by external fields of some volts per centimeter. Heating from electric currents is considered potentially hazardous if it is considerably greater than that resulting from basal metabolic rate and if it occurs in all or most of the exposed body. For example, man's basal metabolic rate corresponds to a current density of around 1 mA/cm^2, or to an <u>in situ</u> field of about 1 V/cm. An external field of 1,000 kV/cm, which is many orders of magnitude higher than Seafarer fields, would be required to generate this.

Excitation and Tissue Current Density

Basic axonology has advanced impressively during the last four decades, establishing some of the important achievements of modern biophysics.[8] Membrane currents and membrane potentials needed to lead to the propagation of action-potential spikes are rather well understood, although the mechanism that leads to the time- and voltage-dependent sodium and potassium gating currents and the influence of calcium on these gates remain unresolved. Briefly, membrane potentials may well respond to small stimuli—a few millivolts or perhaps even less. But the stimulus needed to generate propagation of action potentials is about 10 or 20 mV across the membrane and must have a minimal duration. The experimental advances of modern axonology were cast more than two decades ago into a set of equations, the Hodgkin-Huxley (HH) equations.[16] These equations, which continue to be considered of value, even though modifications have been suggested, have been the subject of intense study and may be used to predict the onset of spike potentials.[7,13] Only recently, some work has been done with AC voltages and related clamp technology.[20] More extensive work has dealt with pulese, all of which appears consistent with the long-established observation of the "all-or-nothing" type of stimulus needed to evoke a transmission of action potentials. The stimulus needed is at least several millivolts across the membrane for periods in the millisecond range and with AC frequencies below about 100-1,000 Hz, depending on the strength of the stimulus.

In summary, it can be said that modern axonology suggests that, at frequencies below 100 Hz, membrane potentials of some millivolts must be applied, to cause excitation. The fact that this is far above the noise level across the membrane suggests that more subtle effects are possible. It is also notable that membrane potentials in the millivolt range correspond to field strengths in the membrane of several volts per centimeter. Changes in molecular conformation are considered possible at such field strengths, even though no detailed model has been suggested.

The considerable work that has been done on the HH equations, and as pertinent to the problems faced by the Committee, includes further advances and modifications proposed by FitzHugh,[13] Palti and Adelman,[20] and others. Some of these models have been linearized for small applied signals and alternating fields. The nerve admittance magnitude displays, above the potential-frequency plane, sometimes broad maximums and sometimes exceedingly sharp singularities, depending on the model chosen and the membrane type considered[9] (W. J. Adelman, Jr., personal communication, 1976; L. J. DeFelice, personal communication, 1976). These damped or fairly sharply turned admittance resonance effects are related to the interactions of the capacitive and inductive dispersion terms that characterize membrane behavior and can occur in some of the models treated only a few millivolts off the resting potentials. The significance of these possible "resonances" to threshold of stimulation has not been treated yet.

More recently, attention has again been paid to linear measurements. There appears to be little doubt that the linear admittance of the squid axon membrane includes a capacitive dispersion that is not included in the HH model.[40] Measurements with broadband noise as a signal source and rapid sampling of the frequency band of interest may indicate even greater complexities in the behavior of the linear admittance, as observed by small-amplitude signals.[12,22]

Thus, present theory and measurement do not yet provide a concise answer with regard to thresholds for excitation effects of alternating fields. In general, calculations with pulses indicate that millivolt potentials are necessary for excitation, even though fractional millivolt effects may well be possible under as yet unknown circumstances. Clearly, modern axonology does not explain how microvolts across membranes may be of any significance.

The translation of membrane potentials induced by alternating fields into tissue current densities is somewhat complicated. For cell suspensions, appropriate extensions of classical Maxwellian field concepts have been developed whose electric properties are related to cellular parameters[8,26] and whose induced membrane potential is related to average bulk current density as a function of external field, membrane conductance and cellular volume concentration.[32] For spherical cells suspended at a low concentration, the membrane potential, ΔV equals 1.5 ER (E = field outside cell, R = radius). Because E in turn is related to the specific impedance of the suspension, ρ , and the current density, j , by $E = j\rho$, $\Delta V = 1.5\ Rj\rho$. Thus, for 10-μm cells, a membrane potential of 1.5 mV corresponds to a current density of 1 mA/cm^2 (typically, ρ = 1,000 ohm-cm). The applicability of these formulas to the more dense tissue configuration cannot be exact, but appears justified, because Maxwellian mixture formulas appear to be fairly predictive at higher cellular-volume concentrations. It follows that membrane potentials of some millivolts correspond to tissue current densities of about 1 mA/cm^2, with a fairly considerable range of uncertainty extending from less than 0.1 mA/cm^2 to about 10 mA/cm^2, depending on membrane resistance values (assumed to range from 1 to 1,000 ohm/cm^2) and cellular volume concentration, i.e., extracellular space.

An abundant and quite consistent literature exists on two-contact hazards, including threshold-of-perception currents, "let-go" currents, and currents leading to fibrillation. Order-of-magnitude thresholds in terms of total-body current and estimates of the corresponding current densities are in Table 9.[32] For a more detailed survey of the field, see Keesey _et_ _al_.[18] and Schwan.[32] Keesey _et_ _al_. listed, for the 99.5% adult-male release threshold of 9 mA, contact potentials of 1.8-13.5 V for corresponding body resistances of 200-1,500 ohms. Internal body resistances, not including skin impedence, range from 600 to 1,500 ohms and that, correspondingly, a voltage guide number of safe

TABLE 9

Approximate Threshold Currents

Threshold	Current
Perception	1 mA
Let-go	10 mA
Fibrillation	100 mA

exposure of 6-15 V appears appropriate. Lowest-voltage fatalities quoted by Schwan were stated for 46 and 47 V, supporting the idea that fatal currents are almost one order of magnitude higher than threshold values of "let-go" currents. It is apparent from the literature that a body current of 1 mA is close to perception threshold, and that 10 mA is rather unpleasant, if not dangerous. Corresponding body contact potentials for a 1,000 ohm body would be 1 and 10 V, respectively. It appears, therefore, that the Navy figures of 1-mA body current and 15-V contact potential correspond to the extremes of the range from perception to above the let-go threshold. An additional element that impinges on the margin of safety of the Navy's recommendations for step potentials is the Navy's use of a body impedance of 1,000 ohms. This figure is usually quite conservative, but worst-case figures may well be lower, ranging down to about 600 or 800 ohms (Simbel,[37] Schwan[30]). Navy specifications rely, for the realization of a conservative body-current limit of 1 mA, on a theoretical model that is too simple to deal with in reality, because it assumes a uniform soil conductivity and thereby derives an inappropriate worst-case source impedance. This approach may well cause unpleasant, if not dangerous step potentials.

Threshold of Sensation

Extensive work has been carried out on thresholds of sensation. Usually, the total current needed to elicit the effect in question is quoted. However, approximate estimates of current densities are possible from cross-sections of involved excited structures.[32] It appears that quoted threshold values depend heavily on frequency, with a minimal threshold value of about 1 mA/cm^2 corresponding to internal (interstitial) field-strength value of about 1 V/cm at frequencies between DC and 100 Hz.

Additional data are available from studies of the current needed to excite cardiac tissues with pacemakers.[23] These studies indicate that the threshold value in terms of current density may also be a function of the volume of excited tissue. Published values vary from less than 0.1 mA/cm^2, if current is injected with large electrodes, to 10 mA/cm^2 and even higher for smaller electrodes.

Finally, a considerable amount of work has been carried out on efforts to stimulate cerebral tissues for purposes of electroanesthesia and electrosleep.[19] Again, total current values are usually quoted, and it is not entirely clear what fraction of the applied current actually penetrates into brain tissues. However, the data indicate current-density thresholds of about 1 mA/cm^2, with a factor of uncertainty perhaps up to 10.

It appears, therefore, that experience on sensation threshold, let-go currents, fibrillation, cardiac pacemakers, and electrosleep and electroanesthesia is consistent with the principles suggested by modern electrophysiology and axonology. These principles, developed for single cellular entities, suggest a threshold of very approximately 1 mA/cm^2 bulk time current density, which corresponds to _in situ_ field strengths of about 1 V/cm. However, this figure can be only very approximate, and weaker interactions have been reported. For example, Terzuolo and Bullock[42] estimated the intensity of the voltage gradient in the saline solution surrounding a neuron (stretch receptor of the crayfish) when an imposed polarization was just great enough to cause a noticeable change in the frequency of firing. Very weak fields in the medium around the cell were sufficient. These fields correspond to 0.01 V/cm and 0.02 mA/cm^2, which are lower than current densities that can excite cardiac tissue if applied with larger electrodes.[23] Schmitt, Dev, and Smith[24] recently pointed out that "interaction [in the central nervous system] is mediated by graded electrotonic changes of potential and is transmitted through high sensitivity (submillivolt threshold) synapses rather than by the lower sensitivity (20- to 100-mV threshold) synapses typical of projection neurons." Thus, unusual sensitivities at current density and field magnitudes less than one-tenth the 1-mA/cm^2 and 1-V/cm figures, and corresponding membrane potentials of some milivolts, have been demonstrated. Even weaker interactions are discussed later.

Field-generated Force Effects

Electric fields can directly interact with matter and create forces that can act on molecules, as well as cellular and larger structures. Most of these interactions are reversible and do not necessarily have demonstrable biologic effects. An example is the movement of ions in an AC field, which is inconsequential, provided that the field is weak enough to prevent undue heating from molecular collisions (i.e., below about 1 V/cm, corresponding to 1 mA/cm^2 in a physiologic medium). Another example is the orientation of polar macromolecules. For field-strength values of interest here, only a very partial preferential orientation with the field results. Complete orientation and consequent dielectric saturation requires field strengths of thousands of volts per centimeter.*

Electric fields can interact just as well with nonpolar cells and organelles in the absence of any net charge. These "ponderomotoric" forces are well known and understood. Any system exposed to an electric field will tend to minimize its electric potential energy by appropriate rearrangement. This statement is equally true for DC and AC fields, because the potential energy is a function

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*But changes of this magnitude occur in membranes on depolarization. Hence, field-induced orientation and changes in orientation of membrane molecules appear possible. Corresponding tissue current densities would be in milliamperes per square centimeter, as discussed above.

of the square of the field strength. Inasmuch as the induced dipole moment of a cell or large particle depends on both the square of field strength and the volume, it is not surprising that the threshold field to overcome thermal agitation is proportional to $R^{-1.5}$, where R is the effective radius of the particle. Experimental evidence confirms the principle; threshold field values for responses of 10-μm cells are about 10 V/cm.[33] But for 10-nm macromolecules, they are about 10 kV/cm and comparable with the fields needed for complete orientation, owing to the existence of a typical dipole moment of about 10 debyes.

The field effects may be manifest as movement, orientation, deformation, or destruction of cells in inhomogeneous fields.[31,33,36] Some of these effects can be very dramatic near the tip of a small electrode.[11]

Experimental and theoretical evidence indicates that pulsed fields cannot have greater effects than continuous fields of the same average power. Hence, modulation is not expected to have special effects.

Field forces due to the induced dipole moment of the field have been listed as evidence of nonthermal action of electric fields on biologic systems. However, the effects require fairly large field strengths frequently above those which give rise to heating or stimulation of excitable tissues. The field forces also depend heavily on the electric properties of the particle considered and its environment. Hence, the threshold above noise is a strong function of frequency and has been proposed for purposes of cell classification.[21] In general, available evidence and present understanding indicate that significant effects with field-evoked forces above thermal noise require field strengths above 1 V/cm in the medium, unless cellular dimensions are well above 100 μm. Corresponding field values in air would be a million times higher. Reported biologic manifestations of field-generated electric forces appear to have much in common with some magnetic effects on bacteria. Further details and references are provided later, in the discussion of magnetotactic bacteria; see also Schwan[33] for the relationship of threshold field values of these effects compared with thresholds for membrane interactions. Membrane dielectric breakdown appears to occur at somewhat higher field values corresponding to invoked membrane potentials near 1.5 V.[44]

Some Extraordinary Membrane Systems

Verh high sensitivities to electric fields have been demonstrated in a variety of electrosensitive fish species. Sharks can detect external fields as small as 0.01 μV/cm (A. J. Kalmijn, personal communication, 1976). Because fish tissues have a higher resistivity than the surrounding seawater, external field strengths are of about the same magnitude as _in situ_ internal tissue values. Important organs utilized by electrosensing fish are long tubular structures, the ampullae of Lorenzini. They appear to sample the field strength over most of their total length and apply this total potential to the endreceptor epithelium of the ampullae. Because these structures are more than 10 cm long, the field strengths quoted above result in receptor potentials of 0.1 μV. The fish is aided in detecting these exceedingly small membrane potentials, in the presence of a typical noise level of about 1 μV across the membrane, by the low-band-pass characteristics of the ampullae of Lorenzini.* The ability to detect

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*Waltman[43] investigated the almost ideal cable properties of the ampullary receptors, and Kalmijn gave the following low-pass 3 dB-points: 300 Hz for a 1-cm canal, 0.04 cm in diameter; 9 Hz for a 10-cm canal, 0.12 cm in diameter; and 3 Hz for a 20-cm canal, 0.12 cm in diameter. The bandwidth of 300 Hz would be more comparable with that of axons than with 9 Hz, which appears to be a typical observed figure for sharks. But it requires a shorter canaal and requires an external field 10 times larger to yield the same endreceptor potential threshold.

the small fields decreases rapidly and nonlinearly with increasing frequencies above 8 or 10 Hz. Thus, the signal-to-noise ratio is about 100-fold higher than characteristic for tissue sensitivity to electric currents. The receptor potential of 0.1 μV would therefore correspond to sensitivities of around 0.01 mV on a broad-band basis extending to 1,000 Hz.

This potential is one one-hundredth of the typical value of about 1 mV cited for the threshold of nervous stimulation. But potentials only 10 times larger have been cited as involved in electrotonic conduction processes in the brain.

The evolutionary development of highly sensitive combinations of field-integrating tubular structures with sensitive receptor-membrane structures may well be related to the high conductivity of water, compared with that of air, favoring adequate "coupling" of external fields. The fishes' reception mechanism clearly operates much more closely to noise level, than to single axons, which operate at 1,000 times above their noise. Thus, although virtually nothing is known about the details of the biophysics and electrophysiology, the ampullae of Lorenzini and their endreceptors may be viewed as single small receptor units with high sensitivity.

Cerebral sensitivities to weak electric fields obviously do not rely on the existence of large structures, such as the ampullae of Lorenzini. But if there are cellular structures whose sensitivity is comparable with that of the ampullae endreceptor membrane system, fields smaller than suggested by modern axonology by a factor of $10^{4}-10^{5}$ can be detected. These responses must be restricted to smaller frequency ranges, to emerge above noise, and are possibly limited to frequencies below 50 Hz.

In recent years, evidence of subtle effects of ELF fields on biologic systems has been increasing (see Adey[2,3] and Appendix B). Some of this work is discussed in greater detail in the section on mammalian neurophysiology and behavior. Of particular note is the report[5] that cerebral calcium binding is sensitive to weak ELF fields. These effects are reported to be sensitive to frequency and amplitude, with "windows" in the frequency domain at about 6-16 Hz and in the field magnitude at about 10-60 V/m in air. This corresponds to *in situ* bulk tissue gradients of around 10^{-7} V/cm. Compare this sensitivity with the 10^{-8} V/cm in the most electrosensitive fish species.

The electrosensitive fish integrate the field strength over the ampullae of Lorenzini to a membrane voltage of 10^{-7} V. Cell membranes, however, perceive potentials that have been obtained by integration of the field over the cellular dimension (see Appendix D). Thus, for 100-μm cells, the sampling factor is 1,000 times smaller than in the case of the fish. Membrane potentials resulting from tissue fields of 10^{-7} V/cm are about 10^{-10}-10^{-9} V across the membrane. This value is considerably below that typical for most sensitive fish. It would require an unusual degree of molecular cooperativity not yet demonstrated and extending over several cellular dimensions. A rather high degree of frequency selectivity is also called for, in that the quoted value of 10^{-9} V is only one one-thousandth of a typical membrane noise level of about 1 μV.

Several attempts have been made to model such highly cooperative effects. Some of these, however, concern only the very-high-frequency range, about 100 GHz, where water loses its dampening properties.[14] Other attempts[15] have not yet been subjected to critical analysis and are still qualitative, even though attractive. The possibility of highly cooperative phenomena that are field-induced and take place in the membrane structure is interesting. Available dielectric data could well support such a concept, but also permit different interpretations (see Appendix D). The few cases where cooperative effects of electric fields have been demonstrated so far require fields greater than 10 kV/cm (G. Schwarz, personal communication, 1977; see also Schwarz[35]).

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BIOLOGIC EFFECTS OF ELF FIELDS

Genetics

The elementary units of biologic information, which make up the genetic endowment an offspring receives from its parents, are linearly arrayed along nuclear structures called chromosomes. A chromosome contains a helical macromolecule, deoxyribonucleic acid (DNA), which consists of a linear sequence of smaller units, termed nucleotides (or bases). The type and order of the nucleotides constitute a code that determines the structure and regulation of the offspring's enzymes. Changes in the sequence of the nucleotides that an offspring has inherited from one or the other parent occur spontaneously on occasion. These changes may be relatively minor, in the sense that an alteration in a single base might have no readily recognizable consequences to the organism, or they may be profound and involve thousands of bases, which might amount to the loss or addition of a portion of a chromosome. In either event, the phenomenon, mutation, results in a difference between the biologic information that an organism may transmit to its offspring and that which was inherited. Experience suggests that most newly arisen mutations are deleterious, that is, they reduce the bearer's capacity to survive, reproduce, or both.

Almost a half-century ago, it was demonstrated unequivocally that mutations can be induced. Ionizing radiation, such as x rays and gamma rays, and such particles as neutrons increase the rate of mutation in a predictable manner that is related to rate of administration and other variables. A variety of chemicals, such as nitrogen mustard, many of which are known to predispose cells and tissues to cancer, also increase the rate at which mutations occur. The biologic comparability of induced and spontaneously occurring mutations has been actively debated; it will suffice here to state that much of the controversy has centered on whether radiation-induced mutations at a single genetic locus involve a base substitution or the loss of a minute amount of DNA. It is agreed, however, that induced mutations, like spontaneous mutations, are generally deleterious.

Man's exposure to an ever-increasing and bewildering array of potentially mutagenic chemical compounds through environmental pollution, changing life styles, and the exuberance of the pharmaceutical industry and modern medicine prompts apprehension that his burden of inherited disease and disability may increase. It is natural for this concern to embrace ionizing and nonionizing radiation as well. Insofar as this report is concerned, the biologic issue can be simply stated: Does extremely-low-frequency electromagnetic radiation produce mutations, either alone or synergistically with other agents?

Evidence that bears on the mutagenicity of exposure to ELF radiation is sparse; it consists of some *in vitro* and some *in vivo* observations. We shall summarize these findings separately.

In Vitro Studies

Compelling evidence of the mutagenicity of ELF electromagnetic fields would exist if such fields could be shown to affect DNA *in vitro* or to alter the cytogenetic characteristics of cultured cells. Experiments of both kinds have been done. Insofar as the former is concerned, it can be argued that dissociation of chemical bonds within a macromolecule, such as DNA, will occur if the energy absorbed from the electromagnetic field exceeds the product of the bond energy and the minimal number of broken bonds necessary to provoke structural changes. The amount of absorbed energy needed to produce such changes cannot be predicted exactly, but it is known that the energy of the hydrogen bond (perhaps the weakest bond of all) is nearly 5 kilojoules (5 kJ).

Radiowave energy at 100 Hz is only about 1.1×10^{-9} kJ/einstein. Thus, prior considerations suggest that radiowave energy in the frequency range of concern here is too small by many orders of magnitude to produce nonthermal effects on the structure of DNA. Takashima[23] failed to observe structural changes in DNA from exposure to pulsed energy at a voltage of 300 V (peak-to-peak) across the radiation cuvettes. Frequencies ranged from 10 Hz to 10 kHz and from 100 kHz to 10 MHz, that is, through all the low- and audio-frequency ranges and much of the radio range as well. Changes in optical density and viscosity were used as criteria for strand separation and thus structural change. Hamrick,[10] working with much greater absorbed energy, reported that microwave radiation (2,450 MHz CW) "has very little, if any, effect other than the effect of thermal heating on the secondary structure of DNA as determined by comparison of thermal denaturation curves." Thus, although the data are restricted and the experiments based on energy alone might warrant repeating, there is no evidence that ELF radiation produces changes in DNA.

Some years ago, Heller and Teixeira-Pinto[11] reported that pulsed radiofrequencies at 27 MHz induced chromosomal aberrations in growing garlic root tips exposed to such radiation for 5 min. They reported linear shortening of chromosomes, pseudochiasmata, amitotic division, bridging, and irregularities in the chromosomal envelope. These effects, although obtained with energy high enough to be thermally significant, indicated that nonionizing radiation in the radiofrequency might be effective as a mutagenic agent. However, studies have not revealed comparable changes. Thus, for example, Coate and Hoo[6] examined onion (*Allium cepa*) root tips grown under several different sets of experimental conditions. These included 72-h exposure to 45 and 75 Hz at each of two different electric field strengths (10 and 20 V/m) and at two magnetic field strengths (1.0 and 2.0 G). For comparison, root tips were grown in only the earth's magnetic field (approximately 0.6 G) and the ambient 60-Hz electric field (about 0.05 V/m). They noted no chromosomal effects attributable to exposure to these electromagnetic fields. Similarly, Miller and his colleagues[17] exposed the roots of the broad bean, *Vicia faba*, to electric and magnetic fields comparable with, but greater than, those associated with Seafarer. They observed no chromosomal anomalies among the exposed roots; nor were there differences between exposed and control roots in growth and mitotic indexes.

Gann and LaFrance[7] have examined the effect of 60-Hz fields on the growth and survival of cultures of subcutaneous cells of the rat. They found that exposed cells invariably died at high field intensities (600 kV/m), but there was no discernible effect of exposure on the cultures at lower field intensities (200 kV/m). The former effect was not attributable, in their view, to changes in either the culture medium or the environment, but their experiments shed no light on the mechanisms that may be involved. The experimental apparatus consisted of a pair of brass electrodes 2 in (5.1 cm) apart. A block of phenolic material with holes to receive glass tubes containing the cell specimens was placed between the plates. Assuming that the glass tubes are completely dry, the field intensity at the surface of the agar in the tubes is judged to be about the same as the average field intensity. However, because of the likely presence of a thin layer of water over the cells themselves, the field intensity at the cell surface is likely to be smaller by many orders of magnitude. At the highest field intensities used in this experiment (600 kV/m), it is likely that field amplification at discontinuities (e.g., at the interface between the tubes and supporting holes) could result in local fields strong enough to result in corona. The authors stated that "secondary effects from ozone, nitrodioxide, corona, and toxic contaminants were excluded," but there is no indication of how they went about checking for the potential secondary effects. For example, it would be nearly impossible to determine whether the cell colonies were in corona. It seems, then, that an important point of this experiment is that no effects were observed at 200 kV/m, well above Seafarer intensity. As indicated above, the physical factors associated with the conduct of the experiment at the higher field strength (600 kV/m) introduce complications, making it probable that the effects resulted from factors other than the electric field itself. These studies do not suggest a hazard at the field intensities associated with Seafarer.

In Vivo Studies

Mutagenic effects can be assessed *in vivo* through studies of changes that involve specific identifiable loci or measurable attributes of a population presumed to reflect genetic variation, but not assignable to specific loci. The former has been called the "specific-locus approach"; it has an intuitive genetic appeal and is undoubtedly the assay of preference, but it is not always practicable. The latter, the so-called "population characteristics approach," has generally been used where the genetic details of an organism are poorly understood--that is, where few, if any, specific genetic loci have been identified. Here one seeks evidence of changes in fertility, mortality, growth, and similar characteristics presumed to depend, at least in part, on genetic events. Evaluation of the mutagenic effects of ELF radiation on microorganisms and *Drosophila* has generally been of the former variety; studies of the effects of such radiation on mice and rats have been of the latter kind.

There is only one report of a possible mutagenic effect of ELF fields on bacteria: a study conducted at the Hazleton Laboratories by Pledger and Coate.[21] These investigators examined the frequency with which auxotrophic mutants appeared in cultures of Escherichia coli, strain B, exposed to electromagnetic fields of different strength. As previously described in connection with Coate and Hoo's onion root tip studies, two electromagnetic frequencies (45 and 75 Hz) were tested, at two electric-field strengths (10 and 20 V/m) and at two magnetic-field strengths (1.0 and 2.0 G). The "control" groups were exposed to the ambient electromagnetic field, namely, 60 Hz (about 0.05 mV/m) and 0.6 G. Twelve cultures were assigned to six groups, with two replicate cultures per group; thus, only four of the eight possible variations of frequency and electric- and magnetic-field strengths were studied. (It is not clear why a complete factorial design was not used.) No mutagenic effect of the different electromagnetic fields was demonstrable, as measured by the occurrence of auxotrophs; nor was a lethal or growth-inhibiting effect of the radiation observed. It is important to point out that the bacteria were exposed to the electric fields by immersion of electrodes (Nu-way and studs coated with a mixture of graphite and styrofoam dissolved in ethylene dichloride) in the culture medium. The electrodes each had a surface area of 9 cm^2; the total current passed through them was approximately 5 mA. Thus, the current density in the medium was approximately 0.5 mA/cm^2. Near the Seafarer ground return terminals (1 m), the current density is estimated to be approximately 1 $\mu A/cm^2$; along the antenna, the current density would be considerably reduced.

Somewhat more evidence is available on Drosophila melanogaster, but some of it is conflicting. Coate and Negherbon[5] studied the response of wild-type

(Oregon-R) cultures of *D. melanogaster* to exposure for 48 h to 45- and 75-Hz electromagnetic frequencies at 2.0 G and 20 V/m. Again, the "controls" were reared under ambient conditions, i.e., 0.6 G and a 60-Hz field of 0.05-V/m intensity. Three treatment groups were involved and three replicates of each. Five exposed males were placed in breeding bottles with five virgin Muller-5 females. Their progeny were examined, and then one heterozygous female and five Muller-5 males were placed together in each of 50 breeding bottles per replicate to provide an F_2. (This technique varies, it will be noted, from the more common procedure of placing a single exposed male in a breeding bottle. The argument against the use of five is that it is not clear how many exposed chromosomes are being tested, because the mating behavior of the individual flies cannot be determined.) Both "treated" groups exhibited effects consistent with the induction of sex-linked lethal mutations; that is, 5.5 and 4.7% of the cultures at the 45- and 75-Hz regimens lacked males (evidence of a sex-linked lethal mutation), whereas all control cultures contained males. There was, however, a diminution in the overall numbers of F_2 females in the "treated" groups with wild-type males, compared with the "treated" cultures without wild-type males; this led the investigators to suggest that their results were best explained by either the occurrence of a delayed dominant mutation or a procedural artifact. The authors did not favor the latter possibility, but exhibited an almost equal reluctance to accept the former. They argueed that, in the absence of an *a priori* or physical reason to expect such a large mutagenic effect from electromagnetic fields of such low strengths, their results required confirmation in much larger samples and demonstration that the effect is dose-related.

The obviously important biologic implications of Coate and Negherbon's study prompted work by others. Bender[2] exposed *D. melanogaster* males for 48 h to electromagnetic fields with the same properties as those used by Coate and Negherbon. They were then mated to Muller-5 females, and 585 exposed X chromosomes were studied (with 294 control X chromosomes). Cultures that lacked wild-type males (evidence of a sex-linked lethal mutation) occurred in both the control and the experimental groups (41 control cultures, 35 cultures at 45 Hz, and 38 cultures at 75 Hz). These differences were not found to be significant. Maintenance of the cultures for two additional generations did not suggest that these mutations were semilethal. Bender concluded, therefore, that such weak ELF fields have no mutagenic effect.

The neatest and most comprehensive *Drosophila* experiments were those of Mittler.[18,19] He exposed adult *Drosophila* males with a genetically labeled X chromosome for 5 days to 75-, 60-, or 45-Hz, 10-V/m, and 1-G electromagnetic fields. They were then mated to females that had a differently labeled X chromosome and were homozygous for eye-color mutants known to be on chromosomes II and III in such a manner as to obtain three different broods of flies. His experimental design made it possible to identify five different genetic events: the occurrence of sex-linked recessive lethals, translocations between chromosomes II and III, loss of the X or Y chromosome, nondisjunction, and dominant lethals. He found no increase in any of these events at any of the three frequencies tested. In earlier experiments, Mittler[18] had examined the effect of stronger magnetic fields (11,000 G) and x irradiation singly and together on the mutation rate in Oregon-R males. The experimental procedure involved mating the exposed males to Muller-5 females, isolating F_1 females, and examining their offspring for evidence of recessive sex-linked lethals. The frequency of recessive sex-linked lethals in males exposed to the magnetic field alone was 0.11% (Oregon-R males are reported to have a spontaneous rate of recessive sex-linked lethals of 0.09%). Males exposed to 3,300 roentgens of x ray had a rate of 9.29% sex-linked lethals; whereas males exposed to both x ray (3,300 roentgens) and a stationary (DC) magnetic field (11,000 G) had a rate of 9.08%. These experiments not only failed to suggest an effect of magnetism alone or its ability to potentiate an x ray effect; they also provided evidence that there is no procedural error, because the rates of x-ray-induced sex-linked lethals were in accord with extensive prior experience.

Other studies on the mutagenic effects of strong magnetic fields have had less important results. The relevance of most of these studies is moot, both because of the field strengths and because the fields have been induced by DC rather than AC. We shall, however, examine them briefly for whatever merit they may have. Close and Beischer[4] reported no evidence of mutagenicity in Drosophila exposed to fields of up to 120,000 G for up to 1 h. Similarly, Mulay and Mulay[20] failed to observe effects on Drosophila exposed to fields of 100-400 oersteds (7,960-31,830 A/m) for one to three generations. Tegenkamp,[24] however, also working with Drosophila, reported both specific mutations and deviations in the sex ratio in the offspring of flies exposed to fields of up to 520 oersteds (41,380 A/m) for 24 h. Levengood[14,15] used a magnetic probe and claimed to find altered developmental times in Drosophila that emerged from "treated" pupae. This alteration, expressed only through exposed male pupae, was said to persist through many (up to 30) generations after exposure, but gradually diminish in importance with time. No simple chromosomal genetic mechanism can be advanced to account for these findings; indeed, they are even inconsistent with the results anticipated on the basis of cytoplasmic inheritance. More importantly, Posch[22] has also studied the effects of brief periods of treatment of Drosophila pupae with a magnetic probe. The exposure time and techniques were similar to those of Levengood. No effect was discerned in either the exposed organisms or their progeny. Finally, Götz and Götz[8,9] have examined the effect of very-low-frequency magnetic fields on progeny yield and sex ratio in Drosophila. Flies were raised in steady or rotating homogeneous 9.6 kHz magnetic fields of about 2.5 G--a field strength more similar to that which will obtain with Seafarer than were the field strengths in the experiments previously described. They found no significant increase in progeny yield or alteration in the sex ratio; their results excluded, they asserted, a genetic hazard of the magnitude that had previously been regarded as occurring in a frequency-modulated high-frequency field.

So far as we know, specific-locus studies have not been undertaken on any mammals. However, a number of multigenerational studies on mice and rats have been reported. Knickerbocker, Kouwenhoven, and Barnes[12] exposed 22 male mice to a 60-Hz field energized to 160 kV/m; in the course of 10.5 months, each animal accumulated an exposure time of nearly 1,500 h. No untoward effect of exposure was observed in the exposed animals, nor was there an effect on their ability to reproduce. Their male progeny, however, were consistently slightly lower in weight than the young of control males; their female progeny were not so affected. The significance of this is uncertain and, indeed, was questioned by the authors. The field strength was very large; when the animals stood up, corona was heard. Furthermore, the exposed animals did not drink during the exposure period, because of electric shocks from the water bottle; the exposure period was interrupted for 40 min to allow the animals to drink water. Control animals had water available *ad lib*. Exposed and control progeny were kept in different parts of the room; the exposed group faced a window, the controls a wall. Marino, Becker, and Ullrich[16] have examined the effect of continuous exposure to low-frequency electric fields over three generations of Ha/ICR mice. Three groups were involved; a control, a horizontally exposed group (60 Hz at 10 kV/m), and a vertically exposed group (60 Hz at 15 kV/m). Random samples were drawn from each generation of animals to produce the next. The authors found no consistent effect on litter size, but reported an increase in mortality (in the vertical field only) and a decrease in weight gain (again, largely in the vertical field). The significance of these findings is compromised by an obvious flaw in the experiment: mice in the vertical fields were exposed to steady-state inductively coupled microcurrents of 5 μA when either eating or drinking, because of grounding; the transient discharges, particularly for the vertical field, were probably perceptible and would result in a decrease in water consumption. There was a relatively high mortality of mice in the vertical fields (10% F_1, 58% F_2, 38% F_3); if the mothers were reluctant to drink, then a carry-over to nursing could be expected. In two series (F_1 and F_2), the horizontal-field mice weighed less than controls ($p < 0.001$); in the third (F_3), the horizontal-field mice averaged more than controls. Thus, it seems that exposure to vertical fields resulted in fewer offspring and offspring with lower growth rates; whether the growth rate was related to the ELF field itself or to secondary factors cannot be evaluated.

Baum and his associates[1] have studied the effect of continuous exposure to pulsed electromagnetic radiation (peak field intensity, 447 kV/m) on Sprague-Dawley rats. With exposure for 94 weeks, they observed no effect on reproductivity; nor did they observe any abnormalities in the progeny. Parenthetically, they observed no increase in the frequency of chromosomal aberrations in the exposed animals, compared with the control group.

Finally, Krueger and his colleagues[13] have investigated the effects of electromagnetic fields on fecundity in chickens. One experiment involved an ELF electric field at a frequency of 60 Hz and a calculated electric field of 1,600 V/m, and another involved a low-frequency magnetic field at 60 Hz and a field strength between 1.0 and 2.0 G. They recorded no consistent effect of either field on fertility, hatchability, or sex ratio. No macroscopic abnormalities attributable to these fields were detected.

Conclusion

On both theoretical and experimental grounds, we believe that ELF fields are not likely to constitute a genetic hazard. The few experiments that have indicated possible effects have generally been poorly designed and have not yielded the same results on repetition. On the basis of a careful search and evaluation of the literature on this subject, it seems most improbable that additional studies would alter our conclusion.

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Fertility, Growth, and Development

Developing organisms may be more sensitive to environmental conditions than adults. The Committee reviewed reports concerned with possible alterations in animal fertility, growth, and development that might be caused by ELF fields. Table 10 summarizes the data from several experiments.

TABLE 10

Experiments on ELF Effects on Fertility, Growth, and Development

Field Intensity[a]	Animal	Effect Reported	Investigators
160 kV/m (air)	Mice	No	Knickerbocker *et al.*[9]
15 kV/m (air)	Rats	Yes	Marino *et al.*[15]
1-5 kV/m (air)	Rats	Yes	Dumanskiy *et al.*[5]
1.4-3.6 kV/m (air)	Chicks	Yes	Krueger *et al.*[10,11]
0.001-3.6 kV/m (air)	Chicks	No	Durfee *et al.*[6]
0.1-100 V/m (air)	Rats	Yes	Noval *et al.*[18]
2-100 V/m (air)[b]	Rats	No	Mathewson *et al.*[16, b]
100 V/m (air)	Rats	No	Dumanskiy *et al.*[5]
100 V/m (air)	Mice	No	Krueger and Reed[12]
10 and 20 V/m (clay)	Rats	No	Coate and Reno[3]
12.5 and 25 V/m (water)	Tadpoles	Yes	McKinney[17]
0.1 and 1 V/m (water)	Tadpoles	No	McKinney[17]

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[a] These values are given as specified by the investigators. However, comparison is very difficult, because the experiments are often designed and reported in terms that make it virtually impossible to estimate electric fields and current densities within the organisms and at their surfaces. It is even more difficult to determine the gradients of the fields, which might well be crucial. Animals immersed in conductive media (e.g., water) are clearly special cases. Current densities in animals in contact with high-admittance surfaces or in small quarters, where animal size and movement alter fields grossly, are significantly indeterminate in field expression. This table, therefore, should not be construed as a comparison of equivalent expressions in terms of gross field.

[b] Attempted replication of work by Noval *et al.*[18]

Mammals

Exposures to 160 kV/m. In a study by Knickerbocker, Kouwenhoven, and Barnes,[9] 22 male mice were exposed to a 60-Hz field of 160 kV/m for 6.5 h/day, except on weekends and holidays, for a total of 1,500 h during the course of 10.5 months. Each male was bred with two virgin females per month, and eight of the litters produced each month were studied after being trimmed to four pups each. The weight of each mouse was recorded weekly from birth to 90 days of age. No alterations were observed in the general health, behavior, or reproductive ability of the exposed animals. Necropsies performed after exposure failed to show any pathologic changes.

The number of litters per month did not differ between exposed and control groups, except for a decrease in the number of litters from exposed males in the second month of breeding, which did not appear again when this phase of the study was repeated with a new stock of animals. The only other observed difference between the exposed group of mice and the parallel control group was a slightly smaller weight (4%) in the male (but not female) offspring of the exposed mice. The difference, although statistically significant ($p < 0.05$) was of questionable biologic importance.

Although some possible effects were suggested by the study, experimental difficulties cast doubt on the value of the results. According to the authors, the electric field (160 kV/m) resulted in an audible corona discharge when the animals stood up on their hindlegs to reach their water bottles; thus, the mice were "discouraged" from drinking. For this reason, the exposure period was interrupted once a day by a 40-min "water break," during which the field was off. The exposed mice were thus essentially deprived of water while the field was on, whereas the controls had access to water. Also, the progeny of the exposed males were kept in a rack separate from the control progeny. One group (the exposed) faced a window, whereas the other faced a wall. This raises the question of whether more direct exposure to daylight and the opportunity to lose slightly more heat by radiation were implicated in some of the observed differences.

Exposures to 50 kV/m. Bankoske *et al.*[2] studied the effects of electric fields on meadow voles exposed to 50 kV/m for 4 days. There was no effect on weight. Later exposures to 50 kV/m lasted for 4 weeks. At the conclusion of the exposure, the voles were weighed and examined. Progeny from the exposed voles born both during and after the exposure period were also kept under observation. No abnormalities in behavior or outward appearance were observed.

Exposures to 1-15 kV/m. In a series of experiments by Marino *et al.*,[15] rats 21-30 days old were exposed continuously for 30 days to a 60-Hz electric field of 15 kV/m. Some exposed groups weighed less than some control groups. Serum protein changes were reported, with the suggestion that this is consistent with chronic exposure to a nonspecific environmental stressor and the development of the "general adaptation syndrome." After 30 days of exposure the animals were weighed, and decapitated and the pooled serum from groups of rats was analyzed electrophoretically for α-, β-, and γ-globulin and albumin fractions and fluorimetrically for 11 hydroxycorticoids. According to the authors, significant ($p < 0.05$) changes in the animal weights (decrease), albumin (increased), and corticosterone (decreased) were observed. The results, however, were not internally consistent. Weight was significantly depressed in only three of 10 studies. In one of the experiments, the mean starting weight among the exposed animals was significantly lower than among the controls. Serum corticoids in eight of 10 studies ranged from 6.0 to 14.6 µg/100 ml among exposed rats and 6.4 to 22 µg/100 ml among controls; the median was 14.2 µg/100 ml. Seven of the exposed groups and four of the control groups were below the median. Finally, serum corticoids were measured in subpools of two or three rats. The results were presented without standard deviation, and statistical analysis consisted of determining both serum corticoids and albumin as a grand mean of depression in the experimental animals plus or minus the standard error.

The authors suggested that electric fields are "stressors." Because increases in corticosterone and cortisol are usually noted in chronically stressed animals, whereas decreases were noted here, one would have to question the authors' conclusion. In attributing an effect to a stressor, it is essential that the experimental design be such that all extraneous sources of variation are controlled. This apparently was overlooked: in some experiments, control animals were housed three to a cage and exposed animals were caged individually. In addition, some data were eliminated before analysis. Exposures were initiated within 1-4 days of acquisition of the animals. It is thus difficult to see any significant cause-and-effect relationship in these experiments.

In another study by Marino et al.,[14] rats were exposed to static (DC) 2.8-, 5.6-, and 19.7-kV/m, horizontally and vertically polarized fields. The authors reported that "no differences in the curves of weight gain versus time were seen between the control and experimental groups during the 30-day exposure period for any field strength or orientation." There was a 17% incidence of secondary glaucoma in rats exposed to the vertical electric fields, compared with 0% in the rats exposed to the horizontal field and control rats. This lesion, which was noted only in the right eye, was explained by the authors as an exacerbation of a pre-existing uveitis. (It should be noted that glaucoma is commonly found in 1-2% of laboratory rats.) According to the authors, the rats exposed to static fields also had a significant change in albumin content and changes of varied statistical significance in the α-, β-, and γ-globulin fractions of the serum protein.

In a third study, Marino *et al.*[13] exposed three generations of mice to 60-Hz, 100-kV/m horizontal or 15-kV/m vertical polarized fields. Mice were allowed to mate and deliver and rear their offspring for three successive generations while continuously exposed to the electric fields. According to the authors, mice exposed to the vertical electric field had decreased body weight 35 days post partum and increased mortality rates for three successive generations. Mice exposed to the horizontal electric field had decreased body weight for two successive generations.

Plastic cages (15 x 30 x 15 cm) with metal tops were used in these experiments, except for the horizontal-field group, which had plastic cage tops. The mice had continuous access to water via a bottle with a metal tube that protruded downward about 5 cm from the cage top. Continuous access to food was provided via a trough that protruded downward about 7 cm from the cage top. In each case, the trough was constructed of the same material as the cage top. The relatively high strength vertical and horizontal electric fields induced vibration in the vicinity of the cages of about 0.025 mm/s, which according to the authors was smaller than the ambient vibration in the absence of the electric fields.

The authors used weight as the criterion for biologic effects. In the first generation, males and females reared in both the horizontal and vertical electric fields were significantly smaller than the controls, when measured 35 days post partum. Larger decreases in average body weight and a high mortality were seen in the vertical field in the second generation 8-35 days post partum; 10 weeks post partum, the differences between the experimental and control weights had narrowed considerably. A high mortality rate was again seen in the vertical-field groups in the third generation; however, according to the authors, the only group whose body weights were significantly affected were the males exposed to the vertical electric field.

The authors pointed out that "the vertically-exposed mice experienced, after weaning, microcurrents of the order of 5 μA when eating or drinking, because both acts necessitated touching ground conductors. The horizontally exposed mice, on the other hand, experienced much less microcurrent"—but the authors did not state how much less. The authors also noted that "the possibility must, therefore, be considered that the greater weight depressions and increased mortality in the vertical mice may be related to the grounding microcurrents." Such microshocks may contribute to the disparity of results. The influence of microshocks, the lack of data on the survival and weight at various times during the nursing period, and the absence of control of litter size to avoid overnutrition or undernourishment of the nursing pups make the results of these studies unsatisfactory as a basis for assessing the influence of ELF radiation.

Exposures to 0.1-5 kV/m. In a study by Dumanskiy et al.,[5] male rats (strain and body weight not specified) were exposed to a 50-Hz electric field at 0, 0.1, 1, 2, and 5 kV/m for 4 months (22 h/day). The rats were exposed in plastic cages (5-15 rats/cage) between parallel electrodes separated by 1 m. Measurements were made after 1, 2, 3 and 4 months of exposure.

Clinical signs included alopecia and hyperemia of the mucous membranes of nose and eyes. There was a tendency toward increased weight gain. Necropsy revealed "dystrophic" and vascular changes in the brain, myocardium, liver, kidneys, adrenals, and thyroid. "Normalization" occurred 2 months after exposure. The authors reported that exposure to 1-5 kV/m affected the "functional state" of the nervous system, as indicated by reduction in blood cholinesterase content and reduced number of sulfhydryl groups in the blood. Contrary to the authors' assertion, an altered blood cholinesterase content is not a reflection of modified nerve conduction.[4]

Dumanskiy *et al.*[5] also concluded that exposure to electric fields (1-5 kV/m) increased adrenal activity and reduced thyroid function. The former was based on increased concentrations of hormone byproducts (17-ketosteroids) in the urine, and the latter on reduced metabolic activity of the thyroid (slow iodine-131 uptake and release) and lowered thyroxine blood content. It is difficult to evaluate the reported changes, because insufficient details were provided. The information on thyroid function indicated that thyroid activity was reduced in the 2- and 5-kV/m groups at 1 month and in the 1-, 2-, and 5-kV/m groups at 3 months. The authors suggested that metabolic processes would be altered as a result of electric-field effects on the nervous and endocrine systems. They reported that exposed animals had increased blood concentrations of glucose and metabolic byproducts (urea and residual nitrogen) and urinary concentrations of sodium and potassium ions, although no methods or data were given to support the statements. These findings are not consistent with the reported increase in adrenal activity and reduction in thyroid function.

Exposures to 100 V/m. Experiments were performed by Krueger and Reed[12] to detect possible physiologic effects of exposure of 3-week-old male mice to fields of 45 and 75 Hz at 100 V/m. The criteria used were growth rate, serotonin metabolism, and alteration in susceptibility to infection with influenza virus.

Mice were weighed individually at the start of each experiment (day 0) and twice a week thereafter. The arithmetic means and 95% confidence intervals were calculated for each period. Two preliminary experiments were performed at 45 Hz and 5 V/m peak-to-peak (1.75 V/m rms), the first lasting 30 days and the second 36 days. There was no significant difference in rate of growth between the animals exposed to ELF conditions and the controls.

The largest test series involved six experiments at 76 Hz and 100 V/m. There was no evidence of any influence of ELF conditions on the growth of mice during exposure periods of 12-36 days when growth was most rapid.

In general, there were no detectable differences between mice kept in the ELF environment and controls, as reflected in rates of growth, concentrations of serotonin in blood and brain, or susceptibility to challenge with measured amounts of influenza virus.

Exposures to 0.1-100 V/m. Noval et al.[18] exposed young rats for 30-51 days to 45-Hz electric fields at 0.1-100 V/m to determine whether exposure to ELF fields has any effect on development. Exposed rats apparently had a 23-30% decrease in weight gain, compared with controls. The effect did not appear to depend on field strength. Exposed rats appeared to have less abdominal fat than controls. The activity of the neuronal enzyme choline acetyltransferase was lower in some, but not other, portions of the brain of exposed animals. There was no change in choline acetyltransferase in controls. Liver tryptophan pyrrolase activity seemed to be increased in the exposed animals, but adrenal weight did not appear to be affected. The authors reported that their findings were consistent with those of Marino _et al._[15] However, Noval _et al._[18] reported that exposure to a 45-Hz field caused an increase in plasma corticosterone in this experiment, whereas the serum 11-hydroxycorticoid content was generally decreased in the Marino study.[15] The animals were sacrificed by "brief exposure to ether or halothane"; either has been shown to cause an increase in corticosterone within 2 min. This may account for the high plasma corticosterone values even in the controls.

According to the authors, the results suggested that rats may have brain stem neurons that are involved in the rate of weight gain and stress responses and that may be sensitive to 45-Hz fields. In this study, however, rats had normal activity, as well as eating and drinking behavior, during maintenance in these fields. The rats living in the 45-Hz fields were "leaner," yet moved about, ate, and drank at the same rate as unexposed control rats.

According to the authors, this could be interpreted as a sign of a more efficient, healthier rate of growth in the presence of the 45-Hz fields, or it could be considered a sign of detrimental growth conditions. The smaller amount of abdominal fat in the exposed rats is unusual. All the rats in this experiment, however, were leaner than would be expected for rats fed _ad lib._

In reviewing this study, it is important to note that the experiments were conducted in a refurbished railroad car. It is most likely that the steel structure of the car provided some shielding comparable with that of a

Faraday cage. Results of tests in such an environment are very difficult to interpret.

To establish whether the decrease in weight gain noted in the Noval *et al.*[18] study was caused by exposure to the applied vertical electric field or by some other factor associated with the experimental protocol, Mathewson *et al.*[16] exposed rats to vertical electric fields of 0, 2, 10, 20, 50, and 100 V/m at 45-Hz for 28 days. There were 18 groups of 16 rats each at five electric-field strengths. Exposures were conducted in six identical chambers, which were horizontal, air-gap, parallel-plate capacitors. Each chamber could have its applied electric field individually varied and contained 16 uniformly illuminated cages. Each cage was designed to house one animal, to allow food and water consumption to be measured, and to produce minimal perturbation of the applied field. Electric- and magnetic-field map data indicated that 45- and 75-Hz magnetic fields were at less than 2 mG, and electric-field variations within the cage areas were typically within 5%.

The animals were quarantined for assessment of general health and equilibrated in the irradiation facility before exposure. Exposures to electric fields at 2-100 V/m were performed for 28 days. During exposure, each animal's weight, food, and water consumption were measured regularly. At the completion of exposure, each animal was sacrificed, and blood and plasma samples were obtained. Selected animals from each group were subjected to a complete necropsy. A complete blood count was obtained for each animal, and the concentrations of the three major classes of metabolites in plasma were estimated by measuring the concentrations of total protein, globulin, glucose, cholesterol, triglyceride, and total lipid. These measurements permitted comparison of the metabolic state of the irradiated animals and their respective controls, which would be helpful if altered growth (defined as body-weight change per day per animal) were observed. No statistically significant differences were found between exposed and control animals in growth, food and water consumption, clinical chemistry values, and necropsy findings.

The results of the studies by Marino *et al.*,[15] Mathewson *et al.*[16] and Noval *et al.*[18] are summarized in Table 11.

Coate and Reno[3] designed a study to determine whether exposure to ELF electric and magnetic fields has any effect on fertility. Rats were bred and the young were reared while exposed to 45-and 75-Hz continuous-wave fields at 10 and 20 V/m and 1 and 2 G. The study was continued through the second generation. Some offspring were reared to adulthood and mated to produce a second generation similarly exposed. The collected data included conception rates, embryonic development, condition of various body tissues, and viability of the offspring.

No significant adverse effects of ELF exposures were seen in these studies. The only significant effect was on the lactation index (ratio of numbers of pups alive at 21 days to pups alive 24 h after birth), which was higher in the exposed groups than in the control groups. A significant difference was obtained only in the second-generation study, for which there is no good explanation. In general, the lactation index in these studies was low (23.3% F_2 controls; 28.8% at 20 V/m and 2 G); this reflects influences of animal housing and care.

Magnetic Fields. Persinger, Ossenkopp, and their co-workers[19-27] reported studies in which rats were exposed to rotating magnetic fields (RMF) of 0.5 Hz at 0.5-30 G. Rats that were exposed continuously during prenatal development

TABLE 11

Comparison of Studies of Effects of Electric Fields on Rats

Characteristics	Marino *et al.*[15][a]	Mathewson *et al.*[16]	Noval *et al.*[18]
Field	15 kV/m, 60 Hz	2-100 V/m, 45 Hz	0.1-100 V/m, 45 Hz
Duration	28 days	28 days	28 days
Eating[b]	E<C (1/5)	No difference	No difference
Water consumption[b]	E<C (5/6)	No difference	No difference
Body-weight gain[b]	E<C (1/6)	No difference	E<C; some apparent within 2-3 days of start; no field intensity-effect relationship
Biochemical changes	Yes, but inconsistent	No	Yes, but inconsistent
Corticosterone[b]	E<C (2/5)	——	E>C ($p<0.05$)
Adrenal size[b]	E>C (1/6)[c]	No difference	No difference
Activity	——	——	Normal

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[a] The first four trials of this study are not considered here, because of absence of food and water consumption data and variable population density in cages. Parentheses enclose fractions of experiments that were significant.

[b] E = exposed groups; C = control groups.

[c] No histology.

under these conditions but, removed at birth, displayed less ambulatory behavior but greater defecation in an open-field test at 21-25 days of age compared with controls.[19,21] There were greater decrements in ambulation for male rats than for female rats exposed to the RMFs, although statistical significance was evident only in the earlier study.

Rats exposed on fetal days 13-16 or postnatal days 1-4 were later tested in a delayed conditioned-approach (DCA) situation, which used the step, impulse, and ramp signal procedures of schedule change.[22,24-26] Applications of such changes to reinforcement delivery are associated with transient behaviors that supposedly can differentiate populations of animals that are not separable by more static schedule procedures. In this modified DCA paradigm, rats were trained to press a lever for water reward in the presence of a tone and not to press during its absence. A week later, a 10-s delay was instituted in a step-like manner, so that water reward was delayed for 10 s after the onset of the tone. The prenatally exposed rats did not differ from the controls, with respect to responses emitted during the delay period. However, rats that had been exposed during the first 3 postnatal days made a significantly greater number of responses during the delay period than controls or prenatally exposed animals. This transient effect was attenuated at the later session.

At 70 days of age, the rats exposed in utero demonstrated significantly greater suppression (relative to controls) of lever-pressing response on the third and fourth days after suppression was begun, but this difference disappeared over the next few days. There was a suggestion of some relation to field intensity, but no quantitative demonstration.

Also noted were decreased ambulatory behavior, increased defecation, less lever-pressing in a Sidman avoidance situation, greater conditioned suppression, increase in thyroid and testis weight, and increased bar-pressing in DCA--all compared with controls. These findings are apparently consistent with open-field and Sidman avoidance data that suggest that RMF-exposed animals are more reactive to novel and aversive stimuli. Unpublished data collected by Persinger and Lafreniere indicate that adult changes associated with RMF exposure during day -2 to +5 of age can be diminished to control values by re-exposing these subjects as adults to the same field.[22]

Persinger, Ludwig, and Ossenkopp[25] presented a review paper that revealed some inconsistencies among the earlier studies. The authors noted the earlier reported difference between groups in rate of lever pressing, but there was never a difference in the actual number of reinforcements received. This was not mentioned in the original publication. The authors also originally reported that rats exposed to RMFs respond differently from controls in a conditioned-suppression paradigm. In a review paper published later,[22] it was reported that that difference occurred only on one of several days of running and at only one of several shock intensities used.

In their review, Persinger _et al._,[22] stated that earlier findings on ambulatory behavior might have been due to strange responses of the controls (rather than of the experimental rats). The authors had actually examined several other measures of general activity in those earlier studies, and there was no reliable difference in rate of wheel running or lever-pressing.

Ossenkopp, Koltek, and Persinger[20] also examined several endocrine and blood characteristics in rats that had been exposed to RMFs prenatally. They reported increased thyroid and testis weights relative to controls. They also reported no significant difference from controls in thymus and adrenal weights, blood glucose, and eosinophil count.

Persinger, Glavin, and Ossenkopp[23] measured circulating-eosinophil content, and adrenal, testis, and thyroid weights of RMF-exposed adult rats. No significant differences were noted in eosinophil content or adrenal weight between exposed and control groups. Animals exposed to the RMFs for 10 or 26 days had increased testis weights. Thyroid weights were significantly lower than those of controls in the 10-day exposed animals, although the RMF-exposed groups had a greater variance in thyroid weight. Different body-weight gains and increased water consumption were also noticed in the RMF-exposed groups.

In the earlier publication,[20] the authors speculated that the increase in thyroid weight probably reflected a hypothyroid state, because the rats exhibited behavior suggestive of hypothyroidism. Their research would then be consistent with some observations of others at that time that might be explained if the rats did indeed have hypothyroidism. This could have been determined by appropriate thyroid-function studies or histologic examination of the thyroid; there was no mention of such examination. In a later review,[24] however, it was pointed out that body temperature had been determined originally and that there was no difference between the two groups (suggesting no difference of thyroid function), but it was not originally reported. It was noted that the earlier observed changes in thyroid weight probably reflected a hyperthyroid state. The inconsistencies and contradictions in these studies are evident.

No judgment as to the effects of ELF exposure can be made on the basis of the published works of Persinger and his colleagues.

Other Vertebrates

Exposure of Chickens. Krueger *et al.*[10] studied the growth of chicks exposed to electric fields estimated at 3.4 kV/m (60 Hz) and 3.6 kV/m (45 Hz) or magnetic fields estimated at 1.2 G (60 Hz) and 1.4 G (45 Hz) from birth until 28 days of age. The electric fields were generated by applying 800 V between an aluminum cover plate and the metal cage, thus producing a nonuniform field distribution whose intensity was not readily measured. They reported that chicks exposed to electric fields at either frequency had a growth rate that was slightly, but not statistically significantly ($p > 0.05$) lower. Statistically significant results were found for the 45-Hz magnetic-field exposure ($p < 0.01$). No difference in activity or behavior was detected.

Giarola and Krueger[8] reported that chicks exposed to 45- or 60-Hz fields of 3.5 kV/m and at 1.3 G had 5% and 11% reductions in growth in the electric and magnetic fields, respectively. No differences in survival or behavior were noted. The cage design was such that a shock hazard existed when the chicks moved to the side of the cage to obtain food or water.

In a later report, Krueger *et al.*[11] exposed groups of four hens and one cock in metal cages (galvanized wire) for 12 weeks to 60-Hz fields of 1.6-3.6 kV/m and 1.4 G. They found a reduction in egg-laying; weight gain, fertility, hatchability, and sex ratio were normal. There are several matters of concern in this study. In the control groups, one cock died and one cock proved to be infertile. Dosimetry was inadequately described. Details of growth and feed intake were not presented. The metal cages again created inhomogeneous fields, and shocks could easily be produced when the chicks ate, drank, or touched the sides of the cages.

Durfee and associates[6] investigated the response of chickens to 45-, 60-, and 75-Hz fields of 1, 10, and 3,600 V/m and 1, 5, 8, and 30 G. Continuous exposure was maintained throughout the egg holding, incubation, and hatching periods and through the first 4 weeks after hatching. Electric fields were produced between parallel plates, and Helmholtz coils provided a uniform magnetic field for the incubators or cages. Embryo development was observed, and social behavior in chicks and adults, development of embryo tissue cells incubated in culture, and carbon dioxide production in developing embryos during incubation were followed.

Analysis of the data showed no effect on hatchability, embryo development, metabolic activity of the embryos, early posthatching growth and development, pecking memory consolidation, and growth and development of the sexually immature birds. Although there was an indication that exposed birds were more dominant in their social behavior than unexposed birds, the data were insufficient to permit firm conclusions; the authors noted that "no clear statement can be made."

It is of interest to compare the studies and results of Krueger and Giarola _et_ _al_.[8,10,11] and Durfee and associates.[6] Giarola and Krueger used metal brooding cages (61 x 91 x 30 cm) "with feeders and waterers attached to the outside of the cages." The top of the cage was replaced by an electrically insulated aluminum plate; the cage floor apparently served as ground. Twenty-five chicks were placed in each cage for 28 days. The authors were apparently aware of "the nonuniformity of the electric field to which the chicks were exposed" and indicated that "variations of up to 100 percent in the electric field could exist." It should be noted that the cage design did not eliminate shock hazard to the chicks, the fields being substantially higher at the cage corners and in the areas through which the chicks had to put their heads to eat or drink. Because of the size of the cages, the large number of chicks per cage (25), and the fact that the chicks increased their weights to about 6 times their initial weights, it is reasonable to assume that the birds began to fill the cage, thereby forcing exposure to cage corners, etc. This would explain why growth decrease was not detected until the birds were approximately 21 days old. Also noteworthy is the statement that, "when evaluated statistically, the 5 percent in growth was not significant, but consistent in direction for the two experiments." It must be concluded that the studies by Krueger and Giarola used experimental cages of faulty design, which resulted in inhomogeneous fields and a very strong possibility of electric shocks to the chicks as they ate, drank, or touched the cage.

An improved experimental design was used by Durfee _et_ _al_.[6]: plastic chick housing compartments, with parallel metal plates outside the cages' sides. Durfee _et_ _al_. concluded that there was "no significant or consistent effect on the growth of male or female chicks." All experiments were conducted in Jamesway egg incubators. The improved experimental design in the experiment by Durfee _et_ _al_. no doubt explains the difference between their results and those of Krueger and Giarola.

Bankoske _et_ _al_.[12] have reported results of initial tests on developing embryos and young birds (domestic fowl) exposed to intense electric fields of up to 67 kV/m. These included studies on egg hatchability, chick or embryo activity, and chick growth and behavior. The effects reported were small and, in the authors' opinions, of questionable significance. For example, in one experiment there was a slight increase in growth in exposed chicks, but only during the early stages of growth. The authors concluded that they had demonstrated no detrimental effects of either brief or prolonged exposure to AC electric fields.

Tadpole Metamorphosis. Batches of tadpole eggs were exposed to electric-field intensities of 0.1-25 V/m at 45 Hz in laboratory tanks.[17] The hatchability, time required for hatching, and mortality were determined. Metamorphosis was evaluated by the appearance of hind legs, loss of tail, and survival to adulthood. Tadpole and frog counts were made at 2-week intervals for 21 weeks; by that time, all tadpoles had either undergone metamorphosis or died. There was increased mortality and the percentage of metamorphosis decreased in the 12.5- and 25-V/m groups compared with controls. Those exposed to 1 V/m or less were not affected. At 25 V/m and 45-75 Hz, the current density in the water is 0.25 A/m^2, assuming a water resistivity of 100 ohm-meter, and, in the tadpoles themselves, the current density was about 5 times higher. It should be noted that there was no statistical treatment of data. There was a high variation in mortality among the control groups. In the exposed groups, there was no correlation between voltage and mortality.

Sudden-Infant-Death Syndrome

Eckert[7] attempted to establish a relationship between sudden-infant-death syndrome (SIDS) and electric and magnetic fields. The first part of Eckert's paper dealt with investigations in Philadelphia, Pennsylvania, and essentially quoted material from three unrelated references without presenting any data. The second and major part of the article reported the author's investigations in Hamburg, Germany. Eckert pointed out that close to each area of high SIDS there may be electric ground currents caused by railroads or well-conducting earth as a result of high groundwater level, etc. He indicated that infants living in higher apartments are less vulnerable: 73% of all cases occurred in cellar, ground-level, and second floor apartments.

SIDS usually occurs in an infant who was thought to be in good health or whose illness appeared to be so mild that a fatal outcome was not anticipated.[1] There are many possible causes of sudden unexpected death in infancy.[28] A review of over 100 publications related to SIDS has failed to reveal an acceptable cause-and-effect relationship for SIDS.[28]

Numerous relationships have been investigated to determine etiologic or correlative factors for SIDS.[28] These factors include a higher incidence during the colder months; lower socioeconomic status; occurrence between midnight and 6:00 a.m.; maternal factors, such as type of infant care, marriage, age of mother, and smoking; infant factors, such as prematurity, metabolic and endocrine status, breastfeeding, number of siblings, and twins; familial recurrences; and etiologic factors, such as suffocation, bacterial or viral infection, and toxic chemicals. Given this array of possible complicating factors, virtually none of which are controlled or even considered in Eckert's study, his findings do not allow a cause-and-effect association.

Conclusion

A review of the literature indicates that fertility, growth, and development would not be adversely affected by the electric and magnetic fields produced by Seafarer. A wide range of animal subjects has been exposed to electric fields of different intensities under a variety of conditions. The reported effects are comparable in magnitude with natural biologic variabilities, related temporal factors, or normal biorhythms that are not otherwise accounted for. Intervening factors, such as microshocks and poor experimental design, can account for many of the reported observations.

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Cell Growth and Division

In cell division, two processes take place. First, material, mainly DNA, within the cell is duplicated. Second, the cell undergoes mitosis, during which replicate sets of chromatids (half of each chromosome) move to opposite cellular locations and the cell divides into two new cells. Such processes are often cyclic and occur repeatedly in cells that are increasing in number.

Cell growth occurs during the period between divisions. This period is the fundamental unit of time at the cellular level, in that it defines the life cycle of a cell. It is generally believed to comprise three stages: a stage before DNA synthesis, the first gap (G_1); DNA synthesis (S); and a stage after DNA synthesis, the second gap (G_2). Cell division or mitosis (M) follows G_2.

If a population of cells is brought into the same continuing fixed pattern of relative phase, they are considered phase-locked or synchronized. If no such coherent relationship exists, they are considered asynchronous. "Synchronous" is used strictly to imply being locked in identical phase, but is often used more loosely to imply any phase-locking. The great value of a cell population in which many of the constituent cell groups are in a nearly identical phase is that enough material can be obtained to allow bulk biochemical measurement of cell-cycle stages. In practice, however, many cell cultures become desynchronized within a few cycles.

Cell growth is generally studied by comparing various characteristics of control and experimental populations of cells, such as number of cells, number of cells in mitosis, cellular macromolecular synthesis (e.g., of DNA and RNA protein), and cellular metabolic rates. A perturbation in cell growth is generally experimentally reflected in departure from normal values; a perturbation might or might not be harmful to the cells or population. There is a sizable body of literature on perturbations in cell growth and division due to ionizing radiation, toxic agents, microwaves, ultraviolet radiation, and heat. The physical and chemical mechanisms involved in these perturbations are generally understood.

With regard to ELF effects on cell growth and division, there have been several studies, some at rather high intensities.

Slime Mold: Weak fields

An interesting and long-term set of experiments conducted at Seafarer intensities has been reported by Goodman *et al.*,[4] who used a slime mold, *Physarum polycephalum*. The organism is one of a group of saprophytes that plays a role in the decomposition of organic material in soil and damp places. *Physarum* microplasmodia (small multinucleate masses of protoplasm) were maintained in liquid suspension shake cultures in the laboratory under carefully controlled environmental conditions. Each microplasmodium, containing perhaps 1000-10,000 nuclei, undergoes synchronous nuclear division without the formation of a new microplasmodium. The microplasmodia in a suspension culture do not, as a group, undergo synchronous division.

Macroplasmodia can be formed by allowing the coalescence of microplasmodia, and they can achieve extraordinary dimensions (e.g., 2-4 cm in diameter, or even larger). The nuclei of macroplasmodia undergo a series of synchronized mitoses, which can then eventually lead to sporulation and the production of more microplasmodia. Sporulation in plasmodia is induced by starvation in the presence of light.

The Goodman *et al.*[4] research, which involved continuous exposure of microplasmodia to electromagnetic fields, was followed by a number of assays concerning characteristics of cell growth and division. Microscope slides were prepared to evaluate the mitotic interval durations (coalescence to M_1, M_1 to M_2, M_2 to M_3) of macroplasmodia and duration of the protoplasm (in this organism, the cytoplasm flows back and forth at regular intervals in channels in the plasmodium). Oxygen consumption (a measure of respiration) was determined by both carbon dioxide evolution and by direct measurement of oxygen consumed.

Differences in mitotic intervals between ELF-exposed and control cultures were reported. These effects are listed in Table 12. For the mitotic delay experiments, microplasmodia were exposed in tanks for up to 1,100 days, then coalesced in specially designed Petri dishes in the presence of the electromagnetic field. No effects were reported on DNA, RNA, and protein macromolecular syntheses; on sporulation; or on spherulation.

In general, the authors reported that the mitotic delay observed in their cultures depended on field frequency, as shown in Table 13. With a decrease in frequency or in the presence of frequency modulation (± 4 Hz), the effect (delay) occurs sooner. Seafarer is expected to use modulation. If a culture displaying the mitotic delay is exposed to a lower-intensity field or to control conditions, the delay dissipates slowly (in 30-50 days).

DNA, RNA, and protein syntheses were also examined (75 Hz, 2 G, 0.7 V/m), and no significant differences were observed between control and exposed cultures.

In examining these reports, several factors were considered that have some potential for influencing the experimental results: the absence of blind scoring by the investigators, a possible electrolytic effect of the medium, and inherent variability within the system.

TABLE 12

Summary of ELF Effects on Physarum polycephalum (October 1976)

	ELF Fields (uniaxial)		Effect of Exposure[a]		
Frequency	Magnetic G	Electric V/m	Mitotic Delay	Streaming Slowed	Decreased QO_2
75 Hz	2.0	0.7	A-7 + B-66 C-6 D-534	C-8 + D-537	C-9 + E[b]
	2.0	--	+ N.R.	+ N.R.	+ N.R.
	--	0.7	+ F-297	+ F-277	‡
60 Hz	2.0	0.7	A-9 + B-66 C-8 D-536	+ C-8 D-537	‡
45 Hz	2.0	0.7	+ C-8 D-536	+ C-8 D-537	+ N.R.
76 Hz (MSK MOD)[c]	2.0	0.7	+ C-11	+ C-11	‡
	0.4	0.14	+ C-11	+ C-11	+ C-11
	0.1	0.035	+ N.R.	+ N.R.	+ N.R.
76 Hz + 60 Hz, 0.1 V/m	2.0	0.7	+ N.R.	+ N.R.	+ N.R.

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[a] + = positive effect. ‡ = experiment not done. Letters and numbers refer to literature citations and page numbers:

- A. Technical Report Phase I, September 15, 1971-June 30, 1974. Report Date: April 1, 1975.
- B. Marron, M. T., E. M. Goodman, B. Greenebaum, 1975 Nature 254: 66-67.
- C. Technical Report, September 15, 1971-December 31, 1975. Report Date: February 1, 1976.
- D. Goodman, E. M., B. Greenebaum, M. T. Marron, 1976 Radiat. Res. 66: 531-40.
- E. Marron, M. T., E. M. Goodman, B. Greenebaum, manuscript submitted for publication.
- F. Goodman, E. M., M. T. Marron, B. Greenebaum, 1975 J. Cell Biol. 67: 139a.
- N.R. Not reported in any report or article; experiment performed, but results not reported. Per communication from E. M. Goodman.

[b] Carbon dioxide evolution decreased.

[c] MSK MOD = mean shift key modulation; carrier deviation, ± 4 Hz; all other frequencies continuous wave.

TABLE 13

Relationship of ELF Electric- and Magnetic-Field Frequencies to Onset of Mitotic Delay in Physarum Polycephalum

Frequency[a]	Electromagnetic Field	When Mitotic Delay Apparent
75 Hz CW	2 G, 0.7 V/m	120 days
60 Hz CW	2 G, 0.7 V/m	50 days
45 Hz CW	2 G, 0.7 V/m	14 days
76 Hz, MSK Mod	0.4 G, 0.14 V/m	10 days
75 Hz, CW	0.4 G, 0.15 V/m	No effect
75 Hz, CW	0.05 G, 0.017 V/m	No effect

[a] CW = continuous wave

MSK= frequency modulated; carrier deviation, ± 4 Hz

Absence of blind scoring. Measurements of mitotic interval and shuttle streaming involve microscopic determinations. Neither was determined by blind scoring. Blind scoring seeks to ensure an absence of unconscious investigator bias and is generally used in cytologic studies. It is especially necessary in this specific case, because subjective determinations of the state of the nuclei were used to estimate when mitosis would occur or had occurred (see Mohberg and Rusch[12] for cellular stages and duration).

The variability of mitotic intervals is unknown in this system. For example, eukaryotic cell systems have widely divergent cell-cycle durations; values differing by factors of 3-5 (ratio of time for slow vs. fast cells within the same system to complete passage from one stage to another) have been reported. Thus, morphologic-anatomic identification of a cell stage does not take into account the "speed" of a cell through the cell cycle. The importance of blind scoring cannot be overemphasized; there appears to be a consensus among researchers that it should be used where possible. However, the assertion that the effects reported by Goodman *et al*. are bona fide and not due to investigator bias is supported by observations of two types: mitotic delays were not observed in all regimens, and the determinations of oxygen consumption were made by machines.

Electrolytic effects. There is a possibility that the energized electrodes underwent some chemical decomposition by galvanic action and released potentially toxic ions into the culture medium. Biologic systems are very sensitive to metal ions. There have been many studies that used a variety of metals for relatively short periods and showed toxic effects on cells.[8] Metal ions are capable of binding to proteins on cell surfaces.[8] Goodman *et al*.[4] attempted to check for such electrolytic effects by exposing the medium for 48 h (75 Hz, 2 G, 0.7 V/m) and then using it for cultures (for 115 days), substituting new exposed media every 48 h. No mitotic-interval differences were reported in this experiment. However, the experiment entailed only nine mitotic-interval determinations (examination for effects began on day 52), whereas the experiment with which it was compared (75 Hz, 2 G, 0.7 V/m) entailed about 150 mitotic--interval determinations. Because the mitotic delay of previous experiments in this electromagnetic environment occurred only at approximately day 125, it cannot be established, from the data available, whether the ELF effects were due to the electrodes.

Inherent Variability of the System. The data that support the Goodman *et al*.[4] conclusion of mitotic delay induced by exposure to the electromagnetic fields is generally characterized by a difference in mitotic intervals (control *vs.* exposed), followed in some instances by an apparent dissipation of the effect. In one instance (75 Hz, 2 G, 0.7 V/m), the data were lumped into 25-day groups over a 120-day exposure period. The vast majority of the mitotic interval points are in the positive (longer) half of the graph. The points indicate considerable variability, with a maximal range of about 4 h (days 725-750, + 2.5 h; days 775-800, -1.8 h). The variability of transit times from one mitotic interval to another is not known. In general, there is reasonably well-documented synchrony for nuclei within a plasmodial region or between comparable regions of the same plasmodium. However, for other eukaryotic systems, a minimal variability (cell:cell) appears to be a factor of about 3 (ratio of long to short duration) for G_2;[14] a ratio of 5 has been reported for proliferating *Vicia* root meristem cells.[11] Thus, there is a reasonable possibility of similarly appearing interphase stages being biologically different, owing to slower or faster cycling.

It is possible that each culture is its own "universe," that "genetic drift" occurs, and that variations in mitotic intervals occur naturally or irregularly. That Goodman and co-workers recognized the possibility is reflected in their statements "that mitosis time differences might include a cyclic factor of unknown nature,"[5 (p. 12)] that "that mitosis time differences may be cyclic in nature with a period of about six months,"[4 (p. 11)] and that "the effect on the cell cycle has either been mitigated or alternatively that the culture may be in the trough of a cyclic period."[4 (p. 12)]

General comment. The experiments were interesting, of long duration, reasonably complex, and worth pursuing. The effects, if real, were small. Hence, the protocol must be scrutinized for subtleties that might cause the differences, other than the electromagnetic fields themselves.

The microplasmodia are considerably larger (by at least a factor of ten) than most eukaryotic cells; this could account for the sensitivity (effects at 0.035 mA/cm^2 or less). It is also important to appreciate the long-term nature of this research. On the average, one mitotic interval in this organism occurs every 8 h; thus, there are three cycles in a day, and about 550 in 6 months. One must also consider the current densities used. In all the experiments, electrodes were placed in the medium that contained the organisms. Thus, for the four field strengths used, various current densities resulted in the medium surrounding the cells, as shown in Table 14.[12]

TABLE 14

Relationship of ELF Current Densities to Effects on Mitotic Intervals in *Physarum Polycephalum*

Characteristic	Frequency				
	75 Hz and 60 Hz	76 Hz (MSK)	75 Hz	45 Hz	
Field strength	0.7 V/m	0.035 V/m	0.15 V/m	0.14 V/m	0.017 V/m
Current density [a]	350 mA/m^2 [b]	17.5 mA/m^2 [b]	75 mA/m^2	70 mA/m^2 [b]	8.5 mA/m^2

[a] $\text{Current density} = \dfrac{\text{voltage gradient}}{\text{resistivity (200 ohm-cm)}}$

[b] Effects observed at this current density.

The results indicate that, at field strengths (0.035 V/m) and frequencies (76 Hz MSK) along the Seafarer antenna, field effects on *Physarum* may occur; at field strengths twice or about one-fifth that of Seafarer, they do not occur (within the experimental period).

The stationary cultures, which result from a coalescence of microplasmodia (each about 0.1-0.2 mm in diameter) used to study mitotic-cycle duration are, on the average, 2-4 cm in diameter. This is an abnormally large "cell." Human cells, for example, have diameters of about 10-100 μm. For larger cells, fairly small fields are able to generate substantial changes (Δ) in potentials (V) across the cellular membrane (m), as stated by the equation: $\Delta Vm = 1.5ER$, in which E = field and R = radius (see Appendix D). For example, for a cell radius of 10 mm, a field of 1 V/m would generate a membrane potential of 15 mV, which could be a significant increase above the normal membrane potential. It is also possible that field-generated forces are important in such large cells. It must be kept in mind, however, that Goodman et al.[14] reported effects of ELF fields on microplasmodia, which are only 0.1-0.2 mm in diameter.

In classical axonal types of excitation, at least a few millivolts of potential difference must be applied across the cell membrane to bring about excitation. This fact accounts for the often-found 1-mA/cm^2 threshold for excitation when currents are applied grossly to tissue systems. However, some fish have specialized anatomic structures that "funnel" current through specialized membranes that detect voltages much less than a few millivolts. With Physarum, a response is reported to occur at current densities that indicate a sensitivity that is high in relation to most tissues, but low in relation to fish.

Other Cell Systems: Higher ELF Intensities

Mammalian cell culture. Gann and La France[3] exposed some colonies of mammalian cells in culture to 60-Hz electric fields at 200 and 600 kV/m; other colonies served as controls. There were three colonies per culture tube, four tubes per regimen. No effects were observed at 200 kV/m; at 600 kV/m, all cells were dead by 7 days (discussed earlier in this section). At higher field strengths (2 million times greater than those of Seafarer), no effects on cell growth are anticipated.

Mamontov and Ivanova[7] reported an effect of 50-Hz electric fields at 20 kV/m on the mitotic index of cells in the eye and liver of mice. Mice (apparently unrestrained) were placed for 4 h between electrodes that were only 3 cm apart; the mice were then given a mitotic spindle inhibitor by injection and sacrificed 4 h later. Mitotic indexes were made for corneal, epithelial, liver, and tubular cells of the nephron. The nominal field strength was 20 kV/m (50 Hz). Statistically significant differences in mitotic indexes between exposed and control groups for liver and epithelial cells were reported.

This study should be discounted as indicating any biologic effect of the ELF field itself. First, there were no sham control animals; the exposed animals were kept for 4 h in a very small chamber, apparently without water and food, and with severe limitations on movement. Six "control" animals were kept in animal cages. Second, the mice (when exposed) took up most, if not all, of the distance between the electrodes, thereby drastically increasing the field strength and raising the probability of repeated electric shocks by contact with the electrode surface. Third, the number of exposed animals was very small. Fourth, statistical treatment in the paper was not adequate to validate the reported differences.

Chicken cells. Yates et al.[15] studied cell numbers and RNA synthesis of chicken embryo cells exposed to AC electric and magnetic fields (electric, 75 and 60 Hz and 1 and 10 V/m; magnetic, 60 Hz and 1, 5, and 8 G). The cultures were grown in Jamesway egg incubators.[1] After exposure to 1, 5, or 8 G

(60-Hz fields), all experimental cultures had either fewer cells or decreased uptake of RNA synthesis, compared with controls; the differences were usually significant at *p* = 0.01. No dose-effect relationship was observed. The consistent differences between control and magnetic-field cultures can probably be attributed to differences in temperature between the energized and control incubators. The energized coils represented a large input of heat to the incubator; such energized coils are quite warm to the hand. Cultures grown at 1 V/m (60 and 75 Hz) and 10 V/m (60 Hz) showed significant decreases in cell numbers and ^{3}[H]uridine uptake; cultures grown at 10 V/m (75 Hz) had significantly increased cell numbers and ^{3}[H]uridine uptake; cultures grown at 10 V/m (75 Hz) had significantly increased cell numbers and ^{3}[H]uridine uptake. This apparent inconsistency could be resolved if one assumed a frequency effect (60 Hz *vs*. 75 Hz) or the involvement of some other environmental characteristic (e.g., temperature). What seems reasonable is that small differences in temperature[6] in different areas in the incubators were responsible for the differences in observed growth responses.

Ameba. Friend *et al*.[2] studied the perpendicular elongation (directional pseudopod formation) of the giant ameba (*Chaos chaos*) in alternating electric fields. The frequencies (1-10 MHz) and field strengths varied with the experiment, and "the character of the effects is ... a function of field strength." The first observable effect (at a few volts/per centimeter) in the middle range of frequencies (about 10-1,000 Hz) was an inward drift of the cytoplasm parallel to the field, which did not affect the orientation of the ameba in fields up to about 10 V/cm (1,000 V/m). The ratio of sol to gel did not appear to change. Above about 10 V/cm, the perpendicular forms occurred; this form of elongation could be repeated many times without apparent damage to the ameba up to 15 V/cm (1500 V/m). When field-exposed amebae were removed from the field, they became indistinguishable from normals within 5-10 min.

These effects occurred at very high current densities (2 mA/cm^2) at field strengths that were high relative to Seafarer; the fields were applied through electrodes in a conducting medium. At about 0.6 mA/cm^2 (a current density greater than that associated with the soil in the vicinity of the antenna), the effects did not occur.

Flatworms. Marsh[9] reported that the normal regeneration pattern of flatworms (Dugesia) was altered by 60-Hz electric fields of 310-420 V/m. Center sections (head and tail cut off) of two species (D. dorotocephala, and D. tigrina) were placed in agar to regenerate, and some were exposed to 60-Hz electric fields by electrodes in conducting media. The decapitated, de-tailed piece normally regenerates a head at the "head" end and a tail at the "tail" end. In the presence of a 60-Hz electric field (310-420 V/m), this normal regenerative pattern was altered, so that "bipolars" were produced (heads at both ends). The current density to achieve this effect was 0.6-0.8 mA/cm^2 -- considerably greater than that associated with Seafarer. No abnormal regenerates were produced at lower field strengths (250-300 V/m) and corresponding lower current densities ($\leq$0.5 mA/cm^2), which are also considerably greater than those associated with Seafarer.

Organelles. Brain and liver mitochondria and brain synaptosomes were isolated from rats by Riesen et al.[13] The mitochondria were exposed to 60-Hz electric fields of 6.3 or 155 V/m from electrodes in conducting medium, and the synaptosomes were exposed to 60-Hz magnetic fields of 50 and 100 G. The respiratory function of the particles and their uptake of norepinephrine were determined. At a current density of 1.8 mA/cm^2 (the 155-V/m field), some loss of respiratory function was noted. No effects were observed, however, at a current density of 0.07 mA/cm^2 (the 6.3-V/m field). For the magnetic-field exposures (at incubation temperatures of 37, 25, 10, and 0°C), no effects were reported for the 50- and 100-G fields except at 0°C.

Miller *et al*.[10] exposed roots of *Vicia faba* for up to 6 days to 75-Hz magnetic fields of up to 17 G and to 75-Hz electric fields of 10 V/m. (This report is reviewed elsewhere in this section.) No statistically significant differences were noted in mitotic indexes between control and exposed roots; the exposures lasted 1 h, 24 h, and 6 days.

Conclusions

Seafarer electric and magnetic fields would not be expected to have perceptible effects on cell growth and division. Such effects generally occur at field strengths considerably higher than those associated with Seafarer. The perturbations reportedly induced in *Physarum polycephalum* by fields comparable with those of Seafarer have not been confirmed and are questionable.

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Triglycerides

The appearance of two reports in 1973 caused some concern about whether the electric or magnetic fields associated with Seafarer cause increases in human triglyceride concentration.[1,2] One paper reported on men and women at the Wisconsin Test Facility, and another on men at an experimental facility at the Naval Aerospace Medical Laboratory in Florida.

Background

Triglycerides constitute one of the three major lipid groups found in the plasma. Dietary fat is predominantly triglycerides. Approximately 1-2 g of triglyceride per kilogram of body weight is consumed daily by the average person. These triglycerides undergo partial hydrolysis in the intestinal lumen and are taken up with other lipids into the mucosal cells, where they are reformed and assembled into particles called chylomicrons. The chylomicrons enter the systemic circulation via the lymphatic system and are removed from the blood by the action of lipoprotein lipases. Chylomicron triglycerides are described as exogenous in origin.

Triglyceride may also be of endogenous origin, in the form of very-low-density lipoproteins (VLDL). These are synthesized mainly in the liver from such precursors as free fatty acids and excess carbohydrate. VLDL are also removed from the circulation through lipoprotein lipase activity. This process is associated with the formation of low-density lipoproteins (LDL).

Plasma triglyceride concentrations reflect the concentrations of chylomicrons and VLDL in the plasma. Normal fasting plasma does not contain chylomicrons, and disorders resulting in fasting chylomicronemia are rare and easily recognized. Hypertriglyceridemia due to VLDL increase, the most common cause of hypertriglyceridemia, is called type IV hyperlipoproteinemia.

A rarer form of hypertriglyceridemia, type III, results from abnormal VLDL. Type V hyperlipoproteinemia involves a combination of chylomicronemia and increased VLDL and is rarer than type IV. In type IIb hyperlipoproteinemia, LDL, VLDL, cholesterol, and triglycerides are all increased; it is not frequent.

Sampling for Hypertriglyceridemia. Because of the influence of fat ingestion, it is necessary to standardize sampling for triglyceride evaluation. It is customary to sample after a 12- 16-h fast, by which time a normal postprandial chylomicronemia will have disappeared. Many factors influence triglyceride concentrations, such as pregnancy and medications. The status of the subject with respect to these should be taken into account in evaluating triglyceride concentrations.

Significance of Hypertriglyceridemia. Hypertriglyceridemia due to severe chylomicronemia is associated with distinct clinical phenomena that are uncommon and sometimes dangerous, but easily recognized. The more common types of hypertriglyceridemia, such as type IV hyperlipoproteinemia, are not unequivocally proved to be associated with coronary heart disease. In contrast with increased cholesterol, for which prospective studies have demonstrated an increased risk of coronary heart disease, corresponding studies of triglyceride have yielded contradictory and inconclusive results, so increased triglyceride content is not currently an established risk factor for coronary heart disease. Hypertriglyceridemia is thought to be undesirable in general terms, often reflecting such factors as dietary excess and alcohol consumption.

Normal Limits for Triglyceride. Conventionally, the 95th percentile for triglyceride is usually selected to define abnormality. Age-specific National Heart, Lung, and Blood Institute (NHLBI) cutpoints ranging from 150 to 190 mg/100 ml are now used. However, data about to be published from the Lipid Research Clinics Program, NHLBI, indicate that the 95th percentile varies from 250 to over 300 mg/100 ml in men and from 200 to 250 mg/100 ml in women. Application of the currently used NHLBI cutpoints thus tends to overdiagnose type IV hyperlipoproteinemia.

Problems in Evaluating Hypertriglyceridemia. Triglyceride concentrations are much less stable than cholesterol concentrations. They are subject to a variety of common influences such as diet, caloric intake, alcohol intake, stressors, medication, and menstrual status. Considerable fluctuations may occur in evaluating a subject from day to day. It is generally recommended that at least two baseline measures be made in evaluating a person's triglyceride status.

This instability is also reflected in the difficulty in conducting studies of the impact of agents on triglyceride content. Ideally, such studies should be carried out in a metabolic ward with strict dietary control, so that the variable under evaluation can be assumed to be the factor responsible for any observed differences. In practice, for these reasons, triglycerides have been studied much less frequently than cholesterol, e.g., in examining drug effects.

Mechanisms of Hypertriglyceridemia. Although hypertriglyceridemia is common and has been subject to a great deal of investigation, there is no consensus regarding the mechanisms of hypertriglyceridemia in the majority of subjects. There is evidence of increased production, decreased utilization, and both. The problems in this field are related to methodologic difficulties and the difficulty in obtaining a steady state.

Studies

Three experiments were undertaken by Beischer et al.[2] In the first, two subjects were confined to a chamber together for 3 days. A 1-G (45-Hz) field was applied during day 2 for about 10 h. Preexposure triglyceride values were obtained 9 days before confinement; both subjects' triglyceride values were higher after the exposure. One subject was a type IV hyperlipidemic. There was no dietary control. There were no control (sham) subjects.

In the second experiment, two persons were confined and exposed; an additional subject served as a sham control. One experimental subject and the sham control were hyperlipidemic; the second experimental subject was apparently normal. Diet was restricted to a choice of meals prepared by a Navy hospital. Confinement was for 7 days, with a 22.5 h 1-G (45-Hz) exposure halfway through. Preconfinement triglyceride values were minimal in number (one or two). One exposed subject showed a large "spike" in triglyceride values 24 h after exposure amid otherwise normal values.

The third experiment (7 days long with a 1-G exposure for 22.5 h halfway through) involved several sets of participants. In the first exposure set, two subjects' triglyceride values were ascending before the field was turned on and continued to rise until 48 h after field application, placing them above the "normal" range. The next pair of exposed subjects had increased triglyceride 48 h after exposure (with one above "normal"); both subjects had relatively stable values before field exposure. However, the two subjects had an argument during the fourth evening, and their increases could be attributed to the stress of the argument and confinement. Two subjects served both as controls and as experimental subjects, and their values show no consistent pattern with respect to whether the field was on; there was considerable and comparable variability in their triglyceride values. None of the control subjects had any "abnormal" values, but there was considerable variability.

Beischer's experiments suffered from several design deficiencies: the diet was not controlled, the subjects were not matched, there was an absence of critical preexposure (fasting) baseline data for all subjects, there was an absence of specific information on dietary compliance, and, except for two subjects, there was no determination of the effect of confinement itself. The exposed men consisted solely of various categories of aviation officer "dropouts"; Navy corpsmen served only in the control group. Beischer stated that "no effects were seen that could definitely be linked with the magnetic field; however, serum triglycerides in most subjects appeared to be affected by some factor or combination of factors associated with the experimental protocol.... The number of subjects is too small however, to exclude statistically other factors such as psychophysiological reactions to forced changes in personal living habits, modified activities, restricted diet and confinement." We believe that this report does not support an effect of a magnetic field on human triglyceride concentrations.

In another study, Beischer and Brehl[3] used 140 8-week-old virgin female white mice; 70 mice were exposed for 24 h to a 1-G 45-Hz field, and the other 70 served as sham controls. After exposure, each day for 7 days, 10 mice from each group were sacrificed, their livers were removed, and the amount of triglyceride (as indicated by glycerol) was determined. There was no statistically significant difference in triglyceride content between the two groups.

All these experiments[2,3] used determinations of endogenously produced triglycerides. In the human experiments, fasting blood values represented what was produced endogenously and was circulating in the blood. In the mouse experiment, the liver triglycerides represented endogenous production. The mouse experiment was the better controlled, and thus more reliable, experiment. None of them supported a causal relationship.

Grissett and Kupper[4] exposed rhesus monkeys to ELF electric and magnetic fields for more than a year in an extremely well-controlled experiment. In exposures lasting 22 h/day, field strengths of 2 G and 20 V/m were used at a frequency that shifted at pseudorandom intervals between 72 and 80 Hz. There were 28 animals in each of the exposed and control groups paired on the basis of sex, weight, approximate age, triglyceride content, and other factors. Which group was which was not known to those involved in the immediate conduct of the study. Triglyceride contents were determined weekly. There was no significant difference between the exposed and control groups.

Rupilius[5] found no differences in triglyceride values up to 24 h after exposure between control and experimental humans exposed for 3 h to a 50-Hz, 3-G magnetic field in combination with a 20,000-V/m electric field.

Mathewson[6] exposed 180-g male rats (48 experimental and 48 control) to a 20-V/m, 45-Hz electric field for 28 days. No statistical difference in triglyceride values was observed between the two groups.

The Wisconsin Test Facility (WTF) studies, which also gave rise to concern about possible Seafarer effects on triglyceride content, began in 1970. The "exposed" group consisted of 24 people at the facility. A control (unexposed) group was established at the Midwest Naval Electronic Systems Command at Great Lakes, Illinois. The control group also consisted of 24 people, each matched for sex and age with a member of the exposed group. All 48 people were examined during the period from late 1970 to early 1971. Examinations were repeated a year later. However, only 12 test subjects and 21 control subjects reported for the followup examination. Only nine of the matched pairs were left intact.

One report indicated that the exposed group had increased triglyceride values.[1] (This statement was later discussed in Congress and in the press.) However, another report indicated that increased triglyceride was found in both the exposed and the control groups.[7] In the most recent report on this research, Houk[8] concluded that continued medical surveillance had not provided any evidence that exposure to the ELF electric and magnetic fields of the antenna bore any causal relationship to increased serum triglyceride.

The Committee believes that, although the WTF studies provided no evidence of an effect of ELF fields on triglyceride content, these studies would be able to demonstrate only an overwhelming effect, because of the following deficiencies:

- The sample was too small to provide significant results after many members of the original groups dropped out.
- As the investigators noted, one laboratory method of determining triglyceride content was used in the first examination, and a second method was used a year later.

- Of the 18 people in the final matched pairs, five had diabetes, 10 were overweight, and six had an "alcohol excess" problem. These conditions were nearly evenly divided between groups. They further confounded the results, because all three conditions can affect triglyceride content and its variability.
- Proper steps were not taken to ensure that subjects actually did not eat during "fasting" periods before examination. Comparison of triglyceride contents is meaningless if the fasting status is uncertain.

Conclusion

We believe that the studies that reported triglyceride increases associated with ELF fields had serious control deficiencies and that the well-controlled studies did not show any such association. Therefore, we believe that Seafarer fields will not have an effect on human triglyceride concentration. We believe that there is abundant evidence, as cited here, to support this conclusion, so that additional research in the field is not necessary.

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Circadian Rhythms

Many biologic functions—such as sleep, wakefulness, and body temperature—exhibit a 24-h cyclic variation. These cycles are often referred to as circadian (circa = about; dies = day). Although the mechanism of circadian rhythmicity remains obscure, there appears to be rather general agreement that they are endogenous to living organisms, rather than the results of influences from the external environment.[1,2] Furthermore, there is some evidence that alteration of these internal timing systems may be associated with deterioration in psychologic and physiologic function.[3-6]

Effects on Humans

Under conditions where humans lived in electromagnetically shielded and unshielded underground isolation bunkers where such environmental time cues as the normal day-night cycle were eliminated, Wever[7] has demonstrated a so-called "free-running" rhythmic period of approximately 25 h for activity, rest, and body temperature. The rhythms were considered to be free-running because they were not synchronized by any recognized environmental cue. Wever reported that, under conditions where persons were shielded from the natural electromagnetic field, there was an increased tendency for the circadian rhythms to desynchronize from each other—so-called "internal desynchronization." Such desynchronization increases the normal cyclic period from approximately 25 h to perhaps twice as long. The desynchronizations also produce considerable differences in the length of the activity period, in contrast with such physiologic rhythms as body temperature, which maintain their periods at approximately 25 h.

According to Wever,[8-16] subjecting human subjects to "natural radiation fields" or to an ELF field (10 Hz, 2.5 V/m), will shorten the average duration of activity-rest and body-temperature cycles (e.g., from 25.26 h to 24.87 h), reduce or eliminate "internal desynchronization," and reduce interindividual differences in the rhythm periods, compared with results obtained in subjects who were shielded from these fields. He asserted that the presence of natural and artificial ELF fields apparently strengthened the internal coupling of biologic timing mechanisms. Although it is possible to conclude that it is the absence of natural or artificial fields that produces undesirable desynchronization effects, Wever has recently commented to the Committee about some unpublished studies in which he concluded that the objectively measured performance and subjectively scored well-being of human subjects may actually be improved during periods of internal desynchronization. Thus, it is not possible to predict whether imposed fields are desirable, undesirable, or even neutral. The imposition of electric and magnetic fields (2.5 V/m, 0.4 G) that exceeded the intensity of those proposed for the Seafarer system (0.07 V/m, 0.2 G) produced internal synchronization of the circadian timing mechanisms. However, a frequency different from Seafarer was used (10 Hz vs. 76 Hz for Seafarer), and the signal was not frequency-modulated, as would be the case with Seafarer.

Because Wever's tests eliminated all environmental and social cues by placing human subjects in specially constructed isolation bunkers (a condition that would not be encountered in the vicinity of Seafarer), and because the tests did not use the Seafarer frequency (76 Hz) or modulation of signal frequency, it must be concluded that the work is not relevant to evaluation of Seafarer conditions. Furthermore, a number of issues seem to need resolution before conclusions may be drawn about Wever's reported effects of other ELF fields on circadian rhythms:

- There is a need for measurement data on the electric field existing in the test environments (bunkers), to determine the extent to which the shielded and unshielded bunkers differed in attenuation of the natural 10-Hz field.
- There is a need to examine the spontaneous drifts in the period of circadian oscillation. Linear fitting of the data may be significantly influenced by the choice of the number of cycles included in control and test phases of each experiment. These effects may be as large as the mean difference reported by Wever between periods with and without the electric field.
- There is a need for clarification of the difference between "naps" and "rest periods," especially because the two were differentiated on the basis of subjective statements of the subjects. This is important for determining the true duration of the circadian periods.

Static fields (DC electric and DC magnetic) appear to have no measurable effect on internally synchronized human circadian rhythms.[7-14]

Effects on Plants and Animals

Halberg *et al*.[17] undertook a series of investigations of ELF radiation effects on silk tree leaflets, flour beetles, and mice. Field conditions ranged from 45 to 75 Hz, 0.4 to 2 G, and 1 to 180 V/m, with duration of exposure varying from a few days to several months.

Magnetic fields (60 Hz, 1 G) and electromagnetic fields (60 Hz, 0.4 G, 100 V/m and 60 Hz, 1 G, 100 V/m) either had no effects on the circadian rhythms of silk tree leaflets or were inconclusive. A gradual increase in the 24 h average pinnule angle and a gradual decrease in the amplitude of the rhythmic movement were observed in the case of pinnules exposed *in vitro* to the lower of two magnetic fields (0.4 G) in a 100-V/m electric field. This effect was observed in excised-leaf preparation and not in the intact silk tree plants; therefore, the results are not necessarily applicable to natural plant populations that would be found in the vicinity of Seafarer. However, there is some suggestion of the ability of plant tissue to be stimulated.

Halberg *et al.*[17] demonstrated the absence of any effect of exposure to 60- to 70-Hz 1-G fields on an assumed circadian susceptibility of the flour beetle to the toxic effects of an insecticide (Dichlorvos).

Similarly, exposure of mice to a 45-Hz 136-V/m electric field continuously for a week before and after ouabain injection did not increase susceptibility to the drug. No significant difference in mortality appeared to exist between controls and experimental groups exposed to 75-Hz 25-V/m electric fields. Body weight was found to be unchanged between control animals and those continuously exposed to a 75-Hz 1-G field for several months. Likewise, fields ranging from 1 to 10 V/m and 0.5 to 2 G, singly and in combination, had no effect on circadian rhythm, body temperature, food consumption, estrus, and survival rate. The interpretation given by Halberg and associates to their own work—namely, that the data presented no persuasive evidence of adverse effects of ELF fields—seems entirely appropriate.

No effects of ELF radiation on a plant (silk tree), an invertebrate (flour beetle), and a vertebrate (mouse) have been found. The reported effects on human circadian rhythms occur almost exclusively in the absence of ELF fields. In the presence of such fields, greater synchronization of weakly coupled bio-oscillators is achieved. However, even where ELF fields are reported to increase the synchronization of biorhythms, such results must be considered suggestive, rather than conclusive.

Summary

Circadian rhythmicity is related to the daily physiologic cycles exhibited by man and other organisms—cycles that pertain, for example, to sleep and wakefulness and to daily temperature cycles. In experiments with human subjects reported by one laboratory, very slight effects were found when subjects were shielded from natural background fields. The proposed Seafarer antenna is very different, and those experiments are not considered applicable. In experiments performed by another laboratory with silk tree leaflets, flour beetles, and mice under natural conditions simulating Seafarer conditions, no alterations in circadian rhythmic phenomena were found.

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Electrosensitive Fish

Some fishes rely on electric fields in detecting prey and in sensing their orientation in space. These are the sorts of animals that one would expect to be most susceptible to man-made electric fields.

The Electric Sense of Marine Elasmobranchs

Marine sharks, skates, and rays show biologically relevant responses to DC and low-frequency electric fields of either dipole or uniform configuration at voltage gradients as low as 1.0 μV/m.[1,2] At 8 Hz, their sensitivity is less than to a DC field by a factor of 2; at higher frequencies, falloff is 12 dB/octave or faster. If this falloff of 12 dB/octave is used to extrapolate to the Seafarer frequency of 76 Hz, the sensitivity at 76 Hz is found to be lower by a factor of about 200, compared with DC.

The fields are detected by the ampullae of Lorenzini, which are mainly in the protruding snout of the animals.[2,6] The electric characteristics of the ampullae are responsible for the unique sensory capabilities of the elasmobranch fishes, and denervation of these sense organs renders the animals insensitive to weak electric fields. The electric sense plays an important part in predation: sharks, skates, and rays cue in on the bioelectric fields of their prey. They may also orient to the electric fields generated by ocean currents flowing through the earth's magnetic field, to follow ocean streams during migration or to compensate for passive drift. In addition, they may sense the magnetic compass direction in which they are heading by the electric fields that they induce when actively swimming in the earth's magnetic field. Drift and swimming speeds of only 2 cm/s suffice to generate electric fields of threshold magnitude. Obviously, great insight into the animals' electromagnetic sensory world is required to understand and predict their behavioral responses.

The Electric Sense of Catfish and Lower Bony Fishes

On the North American continent, representatives of the freshwater electrosensitive fishes are the catfish (Ictalurus), the paddlefish (Polyodon), and probably the sturgeon (Acipenser), the garpike (Lepisosteus), and the bowfin (Amia). Although freshwater catfish are not quite as sensitive as marine elasmobranchs, they still respond to electric fields of about 0.05–0.1 mV/m.[3,4] Again, their sensitivity decreases steeply at frequencies over 8 Hz. But little work has been done at frequencies around 75 Hz. On the basis of the factor of 200, which is also applicable here, these fish are expected to respond to electric fields as small as about 10–20 mV/m at 76 Hz.

The electroreceptors of catfish are the microscopic pit organs, which are distributed all over the skin. The small size of the receptors is related to the high resistivity of freshwater. Catfish, too, use their electric sense in predation and also orient to inanimate electric fields in their natural habitat.[2,3,4] In freshwater, the prevailing inanimate fields are of electrochemical, rather than electromagnetic, origin and are appreciably stronger than those produced by motion through the earth's magnetic field. That is, in freshwater fish, the electric sense works at higher voltage gradients than in marine elasmobranchs. Studies on the older, lower bony fishes (Polyodon, Acipenser, Lepisosteus, and Amia) have hardly begun, although the electric sense of these ancient species may have been crucial to their survival and certainly is of great interest from an evolutionary point of view.

ELF Susceptibility of Marine Elasmobranchs

Near the North American coastline, a Seafarer communication system as now envisioned is expected to produce voltage gradients of 0.01 μV/m at the surface of the ocean and 0.0001 μV/m at a depth of 100 m (private communication, Naval Electronic Systems Command, June 3, 1976). Slowly decreasing with distance, the fields will be only one-tenth as strong after traveling one-fourth of the way around the world. The system will operate with 76 Hz as the carrier frequency. Thus, the antenna fields will be weaker by at least two orders of magnitude than the DC and low-frequency threshold gradients of marine sharks, skates, and rays and lower by four orders of magnitude than the animals' sensitivity within the antenna's frequency band. Therefore, we may conclude that the proposed communication system is unlikely to have any effects on the behavior of marine elasmobranchs. Submarines would be able to detect electric signals far below the sensitivity range of the elasmobranch fishes, because of the great antenna length and the technique of coherent demodulation used at the receiving end of the Seafarer system.

ELF Susceptibility of Freshwater Electrosensitive Fish

In the vicinity of the land-based transmitting antenna, the electric fields in local freshwater would be much stronger than in the ocean. Unfortunately, only a few studies have been carried out at frequencies comparable with those of Seafarer.

In studies conducted by McCleave *et al.*,[6] possible effects of the proposed Seafarer system on American eels (*Anguilla rostrata*) and Atlantic salmon (*Salmo salar*) were investigated in three ways. Conditioned cardiac deceleration techniques demonstrated that both species are marginally sensitive to Seafarer

ELF (60-75 Hz) electric fields (7-70 mV/m), but not magnetic fields (0.5 G). Locomotor activity and diel patterns of the fishes were not affected by alternating 24-h periods of exposure and nonexposure to the ELF electric or magnetic fields. Activity rhythms were not synchronized by 1-h exposures every 23 h to ELF electric or magnetic fields. It is concluded that, although at least these two species could probably perceive Seafarer fields, there is no experimental evidence that their normal behavior would be affected by such fields. Higher frequencies would probably result in less effect than lower frequencies.

Gardella and co-workers[7] have investigated the sensitivity of 17 black bullhead and four carp to 60-Hz alternating electric fields at up to 64 mV/m. Spontaneous (nonconditioned) heart-rate decrease was used as the test response, with each fish being exposed 10 or 12 times to five or six intensities (0, 2, 8, 16, 32, and 64 mV/m rms). Nine bullhead had statistically significant ($p \leq 0.05$) responses to 64 mV/m, and three of these fish were also responsive to 32 mV/m. Results from the carp were inconclusive, owing to the highly variable heart rate. Additional evidence suggested that the sensitivity threshold of bullhead may be as low as 16 mV/m.

In both cases,[6,7] the electrode systems used may have injected local cardiac currents. These currents could affect the results reported, even though the weak fields used suggested otherwise. The sensitivities reported by the two investigative teams were comparable and also of the same order of magnitude as extrapolated from lower-frequency data and DC data indicated above.[1,2]

It therefore appears likely that, in the area of the antenna grid, electrosensitive fish would detect the emanating electric fields, even in locations away from the antenna ground terminals. However, there is no solid basis for judging whether the fields would interfere with the animals' normal behavior or if so, whether compensatory adaptation may ensue. Near the ground terminals, the fields would be much greater. In the absence of more definitive information, it would be prudent to take care in the installation of ground terminals as now designed, that they be as far away as possible, at least 500 m, from bodies of water.

Similar fields exist under high-voltage powerlines and are of comparable strength in the water. An anecdotal report[8] suggested that sturgeon perceive such fields. Future research should incorporate studies of the possible use of electrosensing for migratory navigation.

Summary

It is conceivable that, in the area of the antenna grid, electrosensitive fish will be affected by the emanating electric fields, especially in the regions of the antenna ground terminals. It is not known whether the fields would interfere with the animals' normal behavior or, if so, to what extent the animals might be able to compensate or adapt.

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Insect Behavior

Honeybees have a very elaborate and well known social behavior. They have also been the subject of a vast number of studies of orientation behavior and sensory physiology. As a result, they are the most practical animals with which to assay the potential effects of electric and magnetic fields like those associated with the proposed Seafarer antenna.

Electric Fields

Nineteen papers dealing with the effects of electrical fields on insects have been examined.[1-3,7,12-15,20-24,27-31,33] Of these, four dealt with beetles, 13 with honeybees, and one with flies. Three others were general or mentioned insects only in passing.

The static electric field of the earth varies, but values of 300-500 V/m near the earth's surface are typical. Many investigators have looked into the question of whether high-voltage AC fields have any effects on bees. Altmann[1] used 50-Hz fields of about 10 times the strength of the static field and found that colonies so treated had higher metabolic rates. Hence, their food consumption and activity were high, and the life span of workers decreased. Hüsing[14] repeated the work and found that AC fields induced "great restlessness." Wellenstein[33] found that colonies under 220-V 50-Hz powerlines were "restless and aggressive." Lecomte[15a] repeated this work under 380-V 50-Hz lines and found no effect. Altmann[1] and Warnke[30] found that bees were more aggressive on days during which the atmosphere was high in negative ions. They also found that, in a high static electric field, bees in a plastic hive sealed themselves in and died. Presumably, the plastic hive accumulated a high static charge. Warnke[30] went on to "measure" the potentials on the bodies of worker bees in a very qualitative way and speculated that bees might communicate by electric fields. Es'kov[12a] claimed that they do just that.

The above reports were published in nonrefereed journals, in semi-popular journals, or as short summary reports. Some of the work could not be confirmed. Warnke's reports contained no data, no values, no measurements, and no controls. The reports were anecdotal. Polystyrene hives were used, and they hold charges; so there was no evidence to connect the results with the fields encountered. When wooden hives were used, there were no observed effects.

Thus, there is no acceptable evidence that electric fields of the kind mentioned above affect insects. In any case, the results of this work are inconclusive because there were no rigorously controlled experiments. Inasmuch as the Seafarer antenna would produce a field strength of only 0.07 V/m, there is no reason to believe that its electric field would have any effect of the type reported above.

Magnetic Fields

We have found nineteen papers dealing with the effects of magnetic fields on insects.[4-11,15-18,20,21,23-26,32] Four papers dealt with termites, one with cockroaches, five with beetles, six with flies, and four with honeybees.

The magnetic field of the earth has a strength of about 0.4 G. It is oriented roughly north-south in the horizontal plane. In the vertical plane, its orientation depends on latitude, being horizontal at the equator and increasingly vertical toward the poles.

Two effects on the behavior of honeybees were noted. The first was related to the angle of the communication dance, the second to the compass direction in which combs are aligned in the hive. Honeybee foragers perform dances that indicate the locations of food sources in the field. The angle of the dance on a vertical surface with respect to vertical is approximately the same as the angle of the food in the field from the sun. The deviations of dance angle from food angle depend on the orientation of the hive with respect to the compass direction and the time of day.[15-17] If the earth's magnetic field is canceled in the hive, the compass deviation in the dances disappears after about 30 min.[15-17] Clearly, the earth's field affects the bees' measurement of gravity. Bees are also able to orient directly to the earth's magnetic field. As with birds, this capability may be redundant to some extent. When bees are forced to dance on a horizontal surface, they begin, after about 3 weeks, to dance parallel or perpendicular to the field. When the earth's field is compensated for, this orientation disappears. More impressively, in the absence of other cues, bees orient the sheets of comb in their hives to the earth's magnetic field. Stronger or unusual fields cause bees to build combs never before seen in nature.[15-17]

Lindauer and Martin[15,16] stated that bees are sensitive to changes of field strength of 0-0.003 G, and that only "dynamic" changes are important. They said that, with changes of more than 2.5×10^{-6} G/min, bees lag behind in reorientation, displaying only 10% of the normal response. It is not clear where the empirical basis for these statements lies in the data. They also hinted that diurnal fluctuations in the strength of the earth's magnetic field are used by bees, in the absence of other cues to set their circadian rhythms. Again, no data were presented.

We have not found any work dealing with honeybees in alternating magnetic fields. Predicting the effect of such fields on bees from the static-field data is difficult, because no one knows how the bees detect magnetic fields. They might have little "lodestones," or they might depend on charge displacement induced by movement through the field. The 30 min required by bees to adjust to a new field is most confusing. In principle, neither type of detector ought to be so slow.

An alternating field (e.g., 76 Hz) might affect bees in one of two ways: because of the very long adaptation time, such relatively rapid variations might simply be canceled, leaving only the static field of the earth to be detected; or the alternating field might block the detection of the earth's field.

With regard to any practical effects on bees and other insects from the proposed Seafarer antenna, we believe that there would be none, beyond the disruption related to the digging up of the ground to install the wires. Magnetic fields elicit behavioral responses in the instances in nature when no visual cues are available. The uses of the field seem relatively minor in the overall behavior of insects.

Summary

It is not expected that Seafarer electric fields will have adverse effects on bees or other insects. Honeybees are known to use magnetic fields for orientation and comb-building. These electric fields are steady (DC) fields, and what effect an alternating (AC) field would have (as would occur with Seafarer) cannot be predicted with certainty.

It might be ignored because of the long adaptation time; or it might block some piece of orientation behavior. Only direct experiments can determine this point. One should note, however, that honeybee colonies need not be placed on the proposed rights-of-way; wild colonies are not likely to be within range of any magnetic field that would disturb behavior; and bees are sufficiently mobile so that any location that is for any reason unsatisfactory will be abandoned.

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Magnetotactic Bacteria

Magnetotaxis in bacteria (i.e., bacterial motility related to magnetic fields) was first reported in 1975.[1] Bacteria responded to weak magnetic fields by orienting so as to align themselves with the field and then swam in the direction in which they had oriented. Such cells were first found in marine marsh muds and in surface layers of muds collected at a depth of 15 m in Buzzard's Bay, Massachusetts. Similar forms were later found in the sediments of the Baltic Sea (R. S. Wolfe, personal communication). Magnetotactic bacteria also occur in freshwater pools and acid bogs on Cape Cod at population densities of 200-1000 cells/ml. Moreover, a surprising variety of morphologically different forms of these bacteria was observed in each environment. These observations suggest that magnetotactic bacteria are cosmopolitan, include a variety of species, and live in environments conspicuously different in salinity, pH, and other important characteristics.

By reversing the local geomagnetic field with Helmholtz coils, Blakemore[1] demonstrated that the bacteria respond to both the horizontal and the vertical components of the earth's magnetic field. In more recent (unpublished) experiments, Blakemore and Kalmijn have studied the orientation capability of these bacteria as a function of the strength of applied uniform magnetic fields up to 10 times as strong as that of the horizontal component of the local geomagnetic field. They also found that magnetotactic bacteria behave in a manner expected of permanent magnetic dipoles. Cells immediately turned and moved in the opposite direction when a strong (300-G) remagnetizing pulse (1-μs duration) was applied. This response was assumed to reflect a change in the polarity of permanent magnetic domains associated with each cell. Thus, magnetotactic bacteria are, in reality, magnetic bacteria.

The instantaneous turning response of an entire cell by a change in the direction of a weak applied magnetic field (0.1 G or less) suggests that ferromagnetism is involved, and not diamagnetic or paramagnetic forces. Consistently with this, magnetic bacteria from both freshwater and marine environments were found to possess unusually large amounts of iron. This iron was contained in previously undescribed, structured particles in each cell.[1] The particles have not been purified; consequently, their chemical composition and physical properties remain unknown.

Although the magnetotactic bacteria respond to constant magnetic fields as low as those associated with the proposed Seafarer antenna, the effects of alternating, 75-Hz, 0.13-G fields have not been studied. Thus, the possible effect on these bacteria of magnetic fields associated with the Seafarer antenna is impossible to assess from existing data. There might be interference with normal cell motility and cell distribution in the vicinity of the antenna or its terminals.

Blakemore[1] speculated that magnetotaxis might direct these bacteria downward to anaerobic areas more favorable to their growth. In the absence of evidence of important ecologic changes associated with test environments, there may be no great cause for concern with respect to Seafarer. However, the need for answers to some questions, including the effects of altered and imposed small fields on the survival and behavior of magnetotactic bacteria, invites continued experimentation.

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Bird Orientation and Navigation

Many species of birds migrate from a nesting range to an overwintering area and back again--in some cases, a total of several thousand kilometers. Successful migratory movement requires a mechanism for the timing of onset and behavior that permits judgment of distance, direction, and appropriateness of habitat, as well as arrival at the appropriate end point, which is often very specific. Indeed, for some species, it has been demonstrated that individuals return to specific woodlots and trees for breeding. Bird migration and the related process of homing have been summarized in a series of books and papers that bring together physiologic, ecologic, and behavioral evidence contributing to an understanding of the migratory abilities of many birds.[3,5,9,13,16,17,23]

The observations and experiments discussed here dealt with homing, as well as orientation during migration, and it must be emphasized that the problems confronted by the birds appear somewhat different in the two cases. In homing, the animal can be at a great distance from home in any direction; it must, within a short time, make a judgment as to the home direction and head off. More information is required than can be obtained from a simple compass. This set of decisions is thus somewhat more complicated than some migratory movements, wherein a given compass direction may be maintained for a long distance. It is thus possible to contrast true "goal orientation" with simple "compass orientation." However, detailed tracking of songbirds along the Atlantic coast now suggests that simple compass orientation may not explain, for example, the long circuitous routes taken by some birds in their intercontinental flights. It is the opinion of Keeton and others that, during some part of such migratory flights, the birds must be "goal-orienting"

(Keeton, presentation to Committee). Larkin (personal communication) has emphasized that we do not know whether migration and homing use the same or different mechanisms for orientation.

We are interested here in examining whether birds, in the course of oriented migratory movement or homing, are able to sense the presence of the ELF magnetic fields associated with the proposed Seafarer system. If birds are able to detect the presence of these magnetic fields, what are the limits of detection, and, more importantly, adverse or beneficial behavioral or ecologic consequences of such exposure?

There is now increasingly reliable evidence that, on a migratory flight, birds may use a variety of cues. Such redundancy provides an improvement in performance, as measured by successful arrival at the appropriate geographic end point.[20] The homing and navigational studies of Griffin, Kramer, Matthews, Sauer, and Keeton, to mention but a few (for entry to the literature, see Galler _et al_.;[13] Keeton;[23] and Emlen[9]), have shown the importance, to some birds, of landmark recognition and orientation; the sun and its qualities of altitude and azimuth, along with a precise time sense; the star pattern of parts of the night sky; and the position and movement of weather fronts and the resulting wind patterns.

At least since 1855 (Middendorf, cited in Keeton[21]), it has been suggested that qualities of the earth's magnetic field may provide useful orientative information to birds moving through it. Polarity, lines of equal intensity, and contours of equivalent dip angle are some properties that have been offered as possibly useful to birds. A number of types of experiments or observations have been undertaken to test the hypothesis that birds can perceive a magnetic field, compare field intensities, travel along a magnetic contour, and move up or down a gradient. The evidence has been conflicting, owing in part to the difficulty of designing experiments that unequivocally evaluate sensory perception of and response to signals that humans cannot detect (see, for example, Appendix E).

Emlen[9] has reviewed conditioning, Zugunruhe (migratory restlessness), and homing experiments. In addition, radar-tracking observations of night-flying migrants passing over the operating antenna at the Wisconsin Test Facility have recently been undertaken.[28,47] Some of these are reviewed in the following sections.

Conditioning Experiments

Attempts have been made with conditioning experiments to demonstrate the ability of birds to detect static or oscillating magnetic fields. Emlen[9] summarized a variety of experiments, including the early pioneering studies.

Meyer and Lambe[30] reported negative results in experiments on four pigeons, wherein the birds were to discriminate between a field of 0.582 G and, separately, one of 0.560, 0.567, 0.579, 0.585, 0.588, 0.591, 0.600, and 1.000 G. In no case was discrimination shown. It must be noted that differences in field strength were very small in this set of tests.

Reille[36] reported on a series of conditioning experiments in which change in heart rate was used as a measure of perception of a magnetic stimulus. Maximal positive response was reported to oscillating fields of 0.8 G (calculated by Kreithen and Keeton[26] to have been inaccurately reported), and 300-500 Hz; positive, although more feeble, results were noted with a continuous field of 0.8 G, oriented 120° from the earth's field and a very slowly oscillating field of 0.5 Hz. Perception of the field, at least, was suggested.

In an effort to verify the experiments of Reille,[36] Kreithen and Keeton[26] attempted to train 97 homing pigeons. They used birds that had shown homing delay or disruption when released with magnets attached to their wings in an earlier experiment. The authors were unable to duplicate the discrimination described by Reille. An apparently significant difference between oscillating- and steady-field animals in an early test series was not confirmed in a second and more sensitive set of tests. It was suggested by Kreithen and Keeton (op. cit., p. 361) that, "if . . . a conditioned response to magnetic stimuli is to be achieved in the laboratory, it seems likely that a technique utilizing long-duration stimuli combined with motion must be developed." Beaugrand,[2] in another laboratory, also attempted to confirm magnetic sensitivity to static fields of intensity near that of the earth's field, with methods similar to those of Kreithen and Keeton.[26] He also failed to discern cardiac response to magnetic-field stimulus and concluded that, under his experimental conditions, "homing pigeons did not respond to small changes in the ambiant [sic] magnetic field with changes in autonomic functioning."

Experiments of Marr, Rivers, and Burns[29] were designed to test temporal discrimination, detection, and preference of pigeons (and rats) in various combinations of 45, 60, and 70 Hz, up to 2 G and 100 V/m. In no combination of the characteristics studied could field detection be validated for these species. Preference studies confirmed that the ELF stimuli failed to act as reliable reinforcement or punishment with these species. No effects were found with temporal-discrimination procedures. If, however, the transduction of magnetic information is a slow process requiring many seconds or minutes, rather than fractions of a second,[23] then these experiments were so designed that clear positive results would not be expected.

To confirm sensitivity to the earth's magnetic field, Bookman[4] designed a flight tunnel in which unrestrained pigeons could be trained to discriminate between a simulated field of 0.5 G and a strongly reduced field of 0.02 ± 0.01 G. The flight tunnel, about 3 m long and built inside a Faraday cage, terminated at paired feeding stations with concealed food bins. Birds were trained to travel the length of the tunnel and enter one feeding box in the presence of the 0.5-G field and the other in the presence of the reduced (0.02 G) field. Mated pairs showed greater activity in the chamber than single birds, so they were used as test subjects; three pairs were tested. After 2 weeks to permit stimulus-reward association, a trial was initiated by release of the birds at the tunnel entry; they were observed with closed-circuit television. The first entry of the first bird into a feeding box was recorded as the datum. Incorrect response was punished by retaining the bird in the box for 30 s before permitting entry to the correct feeding box. The trial ended when both birds had entered and fed and were removed from the correct box. Birds were recorded as either walking ("no flutter") the length of the cage or "fluttering" (more than 3 s jumping, hovering, or in flight).

Records for all performances suggested significant discrimination between coil states. With trials separated into "flutter" and "no flutter" sets, in "all cases, the 'with flutter' trials were statistically non-random while the 'no flutter' trials were obviously random." Thus, discrimination appeared to have been enhanced by flutter activity. It was asserted that, although "attempts were made to eliminate any inadvertent cues such as coil hum, their expected influence on discrimination would be largely independent of flutter activity," thus arguing for the absence of cuing or other bias. Whether the operator knew the magnetic-field mode when scoring the birds as "fluttering" or "nonfluttering" was unclear in the manuscript.

In view of the long history of negative results in training experiments, it is desirable that this experiment be duplicated and confirmed. Testing with an AC field for training would also be desirable.

A useful caution was provided by Emlen[9] when he stressed the necessity of pairing a particular conditioned stimulus with an appropriate behavioral response. Unless both elements of a stimulus-response pair are known, it is not always possible to predict the missing one correctly. Association of stimulus with later response does not always follow an expected pattern. For example, the experiments described by Garcia, Hankins, and Rusimiak[14] demonstrated the association of an illness or bout of nausea (induced by a variety of agents, such as radiation, ingested toxins, and injected drugs) with the taste of food consumed sometime previously. The stronger the taste, the greater the aversion; the more severe the illness, the greater the aversion to the taste; strength of aversion was inversely related to the span of time between consumption and illness. As pointed out by the author (*op. cit.*, p. 825), these relationships would be expected in standard studies of conditioning, except that the time scale was expanded from seconds to hours and the food taste was the only cue among several (size and shape of food, characteristics of container, and environment of feeding) that rats would associate with the illness occurring later. Thus, in this example, the punishing (or rewarding) stimuli did not immediately follow the initial gustatory signal. Furthermore, it was not necessarily the last food tested before illness that was later avoided, but may have been an earlier food with novel or stronger flavor. And not all visual and auditory stimuli associated with the act of feeding could signal the impending illness. Only taste appeared to be so associated, thus apparently violating the Pavlovian rule of the equipotentiality of conditioned stimuli.

It is very difficult to predict what might best constitute "appropriate" association with the experimental presentation of a magnetic field. One must use great care in the interpretation of negative (or positive) training experiments. Beaugrand,[2 (p. 353)] having failed to condition pigeons to the static magnetic fields presented, concluded as follows:

> . . . While it is difficult to interpret negative results, the repeated failure of laboratory experiments to develop an experimental model of magnetic detection suggests that the pertinence of the classical conception and methodology used to study magnetic sensitivity is questionable. A laboratory model presenting greater external validity must be sought and new experiments must be conducted taking into account the notion of the biological limits of the organism under study. Finally, many more negative results must be gathered before it is concluded that birds are insensitive to magnetic fields.

Zugunruhe Experiments

Nocturnal migratory birds, under natural conditions of increased daylength in spring or decreased daylength in fall, come into the condition of migratory restlessness, or Zugunruhe (see review of Berthold[3]). At this time, a captive bird demonstrates highly increased nightly locomotor activity, concentrated in the direction of the impending migratory flight. Thus, using this tendency to move directionally in a cage, one may present a controlled physical and visual environment to measure the cues that establish the information required to permit successful attainment of a distant end point.

At the time of spring migratory restlessness, several species of passerine birds, exposed to artificially induced magnetic fields (0.6-1.7 G), have shown significant increases in activity (2-4 times in 85% of all cases among five species, according to El'Darov and Kholodov[7]). Shumakov[37] undertook somewhat complementary experiments, wherein the behavior of birds under the influence of a strong natural magnetic anomaly was investigated. Individuals of several passerine species were placed in circular activity cages; activity level and directional preferences were determined in an area on the Baltic characterized by normal field intensity and direction. The apparatus and experimental birds were transported from the Baltic test site to the center of the Kursk magnetic anomaly (near Gubkin). When tested at that site (with increased magnetic intensity, and a 60° change in field orientation) under overcast skies, the test birds failed to show orientation; they did, however, demonstrate activity 2-3 times that shown at the Baltic site. As Emlen[9 (p. 194)] has observed, the "biological significance of these findings is unclear, but they could suggest a sensitivity and responsiveness to magnetic information."

An interesting set of experiments has been carried out by Southern with the ring-billed gull (Larus delawarensis), a gregarious species in which adults and young were available in large numbers at a Lake Huron site near Rogers City, Michigan. Banding studies[39] had shown generally southeasterly fall migratory movement of adult birds from that colony. Juveniles on their first flight showed a preference for east-southeast (mean angle, 112°; Southern[38,41]), suggesting an innate approximate directional preference determined by the requirements of a future migration. Indeed, in work with younger and younger birds back to chicks 2-3 days old, a directional preference for southeast (walking or flying) continued to be demonstrable statistically. With a non-magnetic 8-ft (2.4-m) orientation cage at the Michigan site, but away from the colony, single chicks were released at the center of the cage; after 2 min, or at the perimeter, the direction of the bird relative to the release point was measured. Means for performance clusters were used to indicate preference direction. Southeasterly headings (mean angles) were selected to a statistically significant extent by chicks tested under both clear and overcast skies and during periods of moderate stability of the earth's magnetic field (K, value 3 or lower; $< 4 \times 10^{6}$ G deviation; Southern[39,40]). At greater magnetic disturbance (K value, 4-7, 4×10^{6} G to over 20×10^{6} G), increased dispersion and randomness of headings were noted, the Rayleigh test being used to demonstrate the absence of statistically significant directional heading.

Experiments with a magnetically shielded room,[43] despite acknowledged design problems, appeared to confirm the disruption of the southeast tendency when the earth's magnetic field was artificially deformed. Experiments with fledgling ring-billed gulls, which had not previously migrated, appear to have demonstrated[41] that, in free flight from a release point 18 miles (29 km) west of the home colony, control birds (with non-magnetic nylon disks glued to their heads) headed approximately 154° ("mean" direction all controls; releases under clear sky, "mean" bearing 142°; releases under overcast sky, "mean" bearing 184°). This was a directional heading roughly approximating the prospective fall migration direction. Experimental birds, with small magnets glued to the tops of their heads (1 oersted at magnet poles, 0.3 oersted measured at ventral surface of head), dispersed randomly from the release site. Thus, it appeared that in the free-flying young gulls, directional orientation may have been disrupted by the application of a weak static field across the head.

Taking advantage of the operating antenna at the Wisconsin Test Facililty, Southern[42,44] tested orientation of a sample of Michigan ring-billed gull chicks under conditions of actual antenna use. The "Southern orientation apparatus" was set up directly over the buried north-south antenna, thereby subjecting test animals to the maximal (except at ground terminals) fields to be associated with an operating system. The trials were conducted under diurnal clear-sky conditions. During four control-trial days (antenna off), gull chicks in 255 trials were found to move in a similar mean direction (145.9° - 154.3°) as had been shown by fledglings tested on their home site in Michigan (Southern[41] --154°); but in a somewhat different direction from the Michigan chicks (Southern[38,41] —112°).

The 642 test trials were undertaken on 8 days of similar sky conditions and low-intensity natural magnetic disturbance ($K < 3$) with the antenna energized (260 or 300 A and 45 or 76 Hz). Under these conditions, the birds dispersed randomly (Rayleigh z test and V Test; Batschelet[1]). Subgroups representing the various antenna states (frequency and amperage) were not significantly different from each other. Southern[44 (p. 144)] concluded that "from these data it appears likely that the electromagnetic field encountered by gulls at ground level above the [Seafarer] antenna is sufficient to disrupt their orientation." He emphasized that, after a "worst-case" test, it would be desirable to test at increasing distance from the active antenna, because field falloff is rapid. Furthermore, it should be noted that data suggesting disruption of behavior in chicks cannot, *a priori*, be extended or extrapolated to demonstrate disruption of migrating adults.

A smaller number of tests on overcast days provided dissimilar results. Both experimental and control groups appeared to maintain significant directional movement (138° and 146°, respectively). These results were not clearly interpretable.[42,44 (p. 145)]

On the basis of the data presented by Southern[42] covering the entire series of tests run under all conditions of the Wisconsin Test Facility antenna and a recalculation of the Rayleigh z values, it is clear that the orientation (clustering of angular headings) of control birds (antenna off) on clear days was significantly better than that of birds under any other antenna configuration (E-W, N-S, or both) under clear skies. Rayleigh z values for all other groups suggested but feeble clustering, if any. High significance values presented for some z and V measures were due to very large samples for some test conditions; it is questionable whether biologic significance can be assigned to them.

An important series of experiments, mostly using the European robin (Erithacus rubecula), has been conducted by Merkel, Fromme, and the Wiltschkos (summarized by Emlen[9]), with the hypothesis that the earth's natural geomagnetic characteristics are used by this species as orientative cues determining direction for migration in spring and fall. Single birds were tested by using an octagonal cage with radially extending recording perches; change of position of a bird moving from perch to perch was recorded on tape or electronically by Merkel and Fromme.[32] The mean direction of movement for the night was determined from the tapes and did not require the observational interpretation used by some previous investigators of bird orientation. After accumulating data from many bird-nights, one could calculate a mean of nightly means, to provide a measure of directional tendency under a given test treatment. As a visual presentation on a circular plot, the direction of the vector arrow showed mean direction; the length of the arrow was a measure of the concentration of individual vectors.[31]

The earliest experiments[12,32,34] showed that in an enclosed room, the visually cueless European robin nonetheless demonstrated spontaneous orientation of nocturnal activity in the direction of incipient migration. Placing the apparatus in a steel chamber, thus reducing the magnitude of the magnetic field (from 0.41 G to 0.14 G) but not changing its direction, removed the directional tendency of the Zugunruhe, and the movements became random.[12,33,48]

The field around the cage was modified in direction and intensity with Helmholz coils. In an artificial magnetic field whose intensity was approximately equivalent to that of the earth (0.41 G), a change in the direction of magnetic north resulted in an equivalent change in the mean direction of the nocturnal activity.[31,48] Interestingly, in these later experiments, when the magnetic field was reduced to 0.14 G or when it was approximately doubled, the test birds were disoriented. However, if the birds were permitted to live under the test conditions (0.14 G) for 3 days or longer, they were then able to orient in the proper experimental magnetic direction when tested at 0.14, 0.30, or 0.41 G. They have also been shown to become accustomed to increased fields.[53] (See also the discussion of directional failure of the white-throated warbler, Sylvia communis, in magnetic fields of reduced intensity in Wiltschko and Merkel.[52])

The experiments have more recently been elaborated[9,49,53] by manipulation of the vertical component of the field independent of the horizontal. In an artificial field with a normal horizontal component, but zero vertical component, the birds were disoriented. In the presence of a normal horizontal field, if the polarity of the vertical component were reversed (e.g., -66^{o} to

+66°), the robin reversed the preferred direction. A sequence of experiments varying the polarity and coupling of the components led Wiltschko and Wiltschko[53 (p. 62)] to conclude:

> The magnetic compass of European robins does not use the polarity of the magnetic field for detecting the north direction. The birds derive their north direction from interpreting the inclination of the axial direction of the magnetic field lines in space, and they take the direction on the magnetic north-south axis for "north" where field lines and gravity vector form the smaller angle.

They further pointed out that the magnetic compass as postulated is very flexible, being adjustable to naturally occurring intensity variations. The birds appeared not to depend on the polarity of the horizontal component of the field; that suggested that the migratory process would not have been totally disrupted by polarity reversals of the earth's field.

Experiments undertaken at the same time with the European garden warbler (*Sylvia borin*) have shown apparently similar use of the angle of inclination of the earth's field, rather than its horizontal component, in setting direction in the apparatus during the fall migration period.[50] Most individuals of this transequatorial migrant species pass across the magnetic equator, thus experiencing a reversal of the dip angle as they fly over central and southern Africa. Species that face such problems in migrating may well require additional orientative cues, especially while crossing the zone of zero or very low dip angle.

Emlen, working with the Wiltschkos, attempted to duplicate these experiments with the indigo bunting (*Passerina cyanea*) in a different laboratory (Cornell University) and with different equipment and technical help. A preliminary summary[9] showed buntings in early spring to orient toward north under control conditions; when the horizontal component of an artificial static magnetic field was shifted clockwise by 120°, the statistically derived preferred direction likewise changed to east-southeast. The second-order statistical pooling demonstrated a significant tendency for southward autumnal orientation, and the opposite in spring, as measured under conditions that were visually cueless. Experimental deflection of the magnetic field resulted in a predictable shift of preferred direction.

These experiments were continued[11] with the simultaneous testing of the indigo bunting in two separate Wiltschko cages and two funnel cages,[10] each surrounded by a Helmholz coil. The funnel cage enclosed a small conic funnel with central inkpad; the hopping bird registered its direction by ink streaks on the liner of blotting paper. Each of the four setups was housed separately. Pooled directional data from the two tests continued to show that birds chose the proper northward migratory direction in the normal geomagnetic field and the predicted shifted direction as the horizontal component of the magnetic field was artificially rotated 120° to east-southeast. Experiments run from spring (April 24) into early summer (June 16) showed deterioration of directionality to random as the migratory tendency was reduced. The evidence has become persuasive that at least some migratory birds are able to detect magnetic fields whose strength is similar to that of the earth's field. Furthermore, these experiments suggested strongly that the indigo bunting "can use this information to help finalize the appropriate seasonal direction for migration" (Emlen _et_ _al_., _op_. _cit_., p. 507).

Duplicating the experiments with the European robin outdoors under the night sky, but in an artificial field, Wiltschko, Höck, and Merkel[51] found a tendency to orient in the proper magnetic direction rather than the true migratory direction, as discernible from stars or other features of the night sky. Directional tendency was especially concentrated under overcast skies, but still significant under clear skies. They postulated from these results, in light of other workers' evidence validating the use of the star compass, that the magnetic compass provides calibration for the star pattern and is therefore primary. The stars may be recognized rapidly while the birds move through the sky, whereas evaluation of magnetic information appears to be much slower.[54] Under changing conditions of star pattern through time or space, recalibration would enable its continued use.[55] In similar outdoor experiments with the European robin, Wiltschko and Wiltschko[56] showed equivalent deviation of northward trend to east-southeast when the magnetic field was rotated to that direction. Unlike the European warbler, the robin was slow in reacting and changed directional selection to the experimental magnetic north direction after two clear test nights. The results with robins appeared to confirm the orientation model described for the European warbler.[55]

If, indeed, it can be fully verified that the natural magnetic field of the earth "serves as the directional basis for the learning process establishing the star compass,"[57 (p. 385)] the importance of the introduction of large magnetic anomalies, even within the range of variation of those found naturally elsewhere on earth, should not be underestimated. There is no evidence to allow prediction of the difficulties, if any, that could arise for birds coming into a condition of seasonal migratory restlessness under such newly imposed aberrant magnetic fields.

Some attempts to repeat the Merkel-Wiltschko experiments have failed, in part because of modified experimental design. For example, Howland[19] described orientation direction of European robins as being determined by asymmetries of the Kramer cage, as well as significant orientation based on a failure of experimental protocol in using the cages (see also Perdeck[35] and the response by Merkel, Fromme, and Wiltschko,[34] as well as the discussion of Wallraff,[46] who himself successfully duplicated the robin experiments in Seewiesen, Germany).

Radar Tracking

Operation of the ELF antenna at the Wisconsin Test Facility has made possible direct observation, by use of scanning and tracking radar, of bird movement over and near this source of artificial electromagnetic anomaly. The brief experiments of Williams and Williams[47] and Larkin and Sutherland[28] in 1974 and 1975 provide a tantalizing view of possible perception of the ELF magnetic field. A long argument is available[6] to support the position that flying birds are not significantly influenced in their normal flight path by the impinging high-frequency radar impulses.

It is possible that the radar signal may be detected, especially by low-flying birds, but there is ample evidence that birds may be tracked for long distances without deviating from a flight path. In the following observations, there is no indication that the birds react at the time of contact by the low-power radars used. The results of the observations at the Wisconsin Test Facility cannot be accounted for as an artifact of the radar observation technique.

Williams and Williams (op. cit.) conducted observations at the Wisconsin Test Facility during the fall migration seasons of 1974 and 1975. The "Ornithar," a low-power high-resolution radar widely used in the study of bird migration, operates only at relatively short range (up to 1 km), but provides information on targets down to an altitude of 10 m. An obvious difficulty in the tracking of nocturnal migrants is that the specific identification of a given target is open to question. Relative size (strength of echo), rate of travel, and altitude provide possibility for some discrimination. Daily counts of birds on a test transect, plus additional observations, provide a species list and a qualitative measure of abundance. In the fall of 1974, the heavy migration was declining during the time of observation. The peak of the 1975 fall migration was observed; during this period, the goose migration was documented, and 23 smaller migrant species were observed in the area during the day. The radar tracks were observed on a screen, but, in most cases, were also preserved by time-lapse cinematography for later frame-by-frame analysis.

Williams and Williams[47] found no evidence of either aggregation near or avoidance of the antenna in any mode of operation. Furthermore, the radar tracks showed no indication of disorientation. Dead birds were not found under the antenna wires. Several variables (e.g., size of target, length of time in view, and number of targets together) were not significantly related to antenna mode (off or on).

During the (probable) goose migration in the fall of 1974 (one night only), the active antenna was significantly associated with change in average flight direction of the birds (relative to the controls, flying during the off mode). Data from large targets (only) on four nights of the fall of 1975 similarly showed significant deviation from the nightly controls. When small targets were added to large, the difference of experimental animals from controls lost significance. On the basis of these very small samples, the Williamses suggested that "the North-South antenna tended to deviate birds from the mean of the control condition, and the East-West antenna did not do so [$\underline{p} < 0.01$]." Such deviation might reflect a process equivalent to that noted by Keeton in his homing pigeons, wherein there appeared to be a slight but systematic change of bearing with prevailing K value.[25,27]

The associated study of Larkin and Sutherland,[28] and in extended form in Williams and Williams,[47] used a low-power tracking radar that automatically followed the target with a nutating, 30-Hz pulse stream, recording X, Y, and Z coordinates to an accuracy of within 5-10 m. Birds flying between 80 and 300 m in altitude were tracked as they approached, crossed, and moved away from the crossed antenna array. Each track was blindly termed linear (straight and level) or nonlinear (turns in the X-Y plane, change of altitude, marked change of speed) by a technician without knowledge of antenna mode. Tracks were later sorted according to antenna mode. Over 11 nights of observation, 469 tracks of more than 15 s in length and without apparent artifact were accumulated.

In examining mean angular direction and speed of the 414 tracks classed as linear, the investigators found that variation within antenna conditions (on, off, both) was greater than that between antenna conditions. Nonlinear tracks, however, occurred with significantly greater frequency under "on" (12%; n = 232) than under "off" conditions (4%; n = 163), and even more often (28%, n = 74) if the mode was changing during the course of the tracked flight. Larkin and Sutherland stressed that, whereas statistical effect was clear and significant, it had not yet been possible to show, for individual birds, an instantaneous response to an "antenna-related stimulus." (In no experiments so far reported could it be shown that an individual bird will respond predictably and reliably to a magnetic field pattern; all the effects noted have been statistical.) Other environmental variables (cloud cover, wind, transmitter noise, and light) seemed not to be statistically related to the effects noted (but see Larkin and Sutherland,[28] (p. 779, note 16) regarding possible X-Y nonlinearities caused by wind gusting).

The nonlinearities noted varied from moderate and corrected changes in flight-path direction to extended changes of direction, altitude, or rate climb persisting to the point of contact loss (up to 80 s). Larkin and Sutherland (*op. cit.*) concluded that their "data are inadequate to permit an evaluation of the long-term environmental effects of the proposed Project Seafarer on resident or transient migrant birds" and that their results "imply that some birds can detect low-intensity magnetic changes within a few seconds and that orientation involving the use of magnetic cues may be used during flight."

Williams and Williams stressed that results from their radar studies were preliminary. They concluded, however (*op. cit.*, p. 24), that the ELF field seems to have a real and measurable effect on some migrant birds, but that "there is no large-scale disturbance to migration near the Wisconsin Test Facility." There was a suggestion in some tracks observed by Larkin and Sutherland of correction of a deviant nonlinear course as the bird moved away from the antenna. However, other tracks suggested that, for some large fall migrants (probably geese), the nonlinearity was not corrected within the range (1 km) of the Ornithar. Repetition and extension of these observations is exceedingly important, because they provide some of the very few data resulting from exposure of receptive organisms to modulated fields.

Homing Experiments

Hypothesizing that homing pigeons can navigate by sensing motion through the vertical components of the earth's magnetic field and, separately, sensing the work required to withstand or counteract the deformation of flight path due to Coriolis force, Yeagley[58,59] attached small bar magnets to the undersides of the wings and noted the effect on homing ability. This was not the first attempt to disrupt homing by this method, but the alleged positive results obtained in an early set of experiments excited the biologists then working on problems of animal navigation, migration, and homing. Numerous workers, and even Yeagley in the later sets of experiments, failed to confirm the results.

It has been recognized more recently[20] that experienced adult pigeons can use a variety of redundant cues to aid their return and that earlier experiments had failed to separate clearly single sets of cues for experimental disruption. Keeton (op. cit.) released pigeons whose internal clocks had been shifted by 6 h, as controlled by birds on local time. Under sunny skies, the time-shifted birds headed away from the release point in a direction that was predictable on the basis of use of the simple "sun compass." The nonshifted birds returned on the appropriate heading to the loft. Under complete overcast, however, and at a completely unfamiliar launch site, both classes of birds headed correctly toward the loft. This suggested that, with deprivation of sun-arc information, the cues facilitating orientation in the experiments did not require time compensation and that use of the sun compass alone could not explain the test results.

In later experiments, Keeton[21] attached a small bar magnet (weighing about 3 g)* to the back at the base of the neck of each pigeon in the experimental groups. Controls had brass bars of similar size and weight. The "magnet" and "brass" birds had been raised and maintained in the same enclosures and were exercised together; the bars were attached just before

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*Magnetic field strengths: at poles, about 250 G; at birds's head, about 0.5 G.

testing. The birds were moved in closed vehicles from the loft to the release site, where they were tossed singly into the air in random directions. Compass bearing of the vanishing point, time to vanishing point (10 x 50 binoculars were used), and homing speed were recorded.

In a group of tests, experienced birds were released under sunny skies, some at familiar sites, others at unfamiliar sites. Within each group, the experimental birds carried magnets; the controls, brass bars. Both experimental birds and controls took appropriate homeward bearings, homing at similar speeds, although in one test the magnet birds took longer to reach the vanishing point. Thus, magnets failed to disrupt homing. Under conditions of heavily overcast skies, in five of seven tests, the magnet birds scattered randomly (or nearly so), and the controls took the proper home bearing. Emlen[9 (p. 205)] has provided a summary recalculation of data from one group of tests, clearly comparing the pooled departure bearings of experienced pigeons released under overcast skies. The oriented control group, in contrast with the highly distributed experimental birds provided "some of the clearest evidence to date of a magnetic effect upon bird orientation."[9 (p. 204)]

Keeton has provided further experimental refinement with young, first-flight birds. It had been shown[24] that untrained pigeons under sunny conditions successfully oriented in the homeward direction, whereas, under total overcast, they vanished randomly. In later experiments,[25] magnets and brasses were attached to young, first-flight birds. Under sunny conditions, birds with brasses oriented homeward, and the magnet birds were totally disoriented. It therefore appears that, in earliest stages in the behavioral ontogeny of pigeon orientation, both sun and an undistorted magnetic environment are required.

Complementary results were obtained by Walcott and Green.[45] In their experiments, small Helmholz coils enclosing the head were substituted for the bar magnets of Keeton. When they were attached to a battery, a magnetic field (0.6 G) was induced through the bird's head. The field pointed up ("north up" condition) or down ("south up"), depending on the direction of current flow in the device. In releases of "south up" and "north up" birds under sunny skies, the vanishing directions of both groups, although not identical, were very close to the home direction. Under overcast skies, the "south up" birds oriented in the homeward direction, but the "north up" birds oriented away from the home direction. The two groups demonstrated similar homing performance, however, because the short battery life terminated the imposed magnetic field in 2-3 h.

As Emlen pointed out,[9 (p. 206)] these results of Walcott and Green appeared to be in agreement with the Wiltschko model which suggested that north is determined as the direction in which the gravity and magnetic-field vectors intersect at the smallest angle. Reversal of the magnetic-field vector by changing the polarity of the battery and direction of current flow would reverse the apparent northward direction as seen in the Walcott and Green results.[45]

As an attempt specifically to test the influence of the Wisconsin Test Facility antenna on the behavior of homing pigeons, the U.S. Navy supported preliminary experiments.[15] In this study, 161 pigeons raised in Bowling Green, Ohio, were released to their home loft near the crossing of the test antenna under conditions of north-south antenna on, east-west antenna on, and full off. He recorded direction from release point at 20 s, 40 s, and vanishing, as well as the vanishing time. A second group of observations was made with a loft of 60 birds near the antenna crossing; the young birds experienced the electromagnetic environment of the functioning antenna for about 75 days. Releases of these birds at three points on the antenna configuration were similarly monitored. These experiments suffered from small samples of experimental birds in the several test states and from design difficulties, in part described by the author. Though Graue stated that his results "do not provide strong evidence that there is any effect of the ELF fields on pigeon orientation," we feel that these experiments cannot be analyzed with sufficient confidence to provide any conclusion.

Conclusion

The evidence is now convincing that some birds are able to sense the presence of magnetic fields whose strength approximates the strength of the earth's field. The lower limits of detection have not been established; the initial finding that systematic deviation of mean orientation bearing in homing pigeons is an inverse function of the K value of the earth's magnetic activity suggests sensitivity to some small fraction of the natural earth field. On the basis of present knowledge, the effect of Seafarer operation on birds cannot be predicted safely, for the following reasons:

- The Seafarer field would be alternating, whereas most experiments and observations have concerned static, DC fields.
- The extent to which birds may be able to use nonmagnetic environmental cues to compensate for magnetic anomalies encountered when flying is not known.
- The functional significance to a bird of passing over a large number of anomalous magnetic peaks (repeated brief field-intensity changes) cannot be predicted from experience with avian overflight at the Wisconsin Test Facility or from investigations of flight behavior near natural magnetic anomalies. For example, if a given individual bird were deflected systematically, even though slightly, while

passing over individual antenna lines of the grid, the cumulative effect could be a considerable directional deviation. If deflection were equally slight, but of random direction, the resulting deviation in most cases would probably be slight. This information is not available.

- The natural geomagnetic topography has very recently been suggested as a set of orientative cues by which the star compass of some birds is learned and, in migratory flight, recalibrated. If this is confirmed, the hypothesis might be offered that birds raised outside the influence of the Seafarer grid, but flying through it, could treat the Seafarer magnetic anomaly as they would a naturally occurring geomagnetic anomaly and duly compensate. An important question arises, however, as to whether young birds raised within the influence of the peculiar magnetic contours of Seafarer could successfully use visual cues of the night sky as they moved away from the anomaly to the much more gentle contours of the natural magnetic field. Neither of these points, raised by recent experimentation, has been verified.
- Construction of the grid near a major migratory flyway would present more opportunities for harm to birds at lower altitudes, if harmful effects exist, than building it away from a major flyway.

Recommendation

The Committee recommends further research on the basic biology of bird navigation and orientation designed to verify recent highly suggestive experiments and to address the questions noted above.

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Mammalian Neurophysiology and Behavior

At our present state of knowledge, there is no reason to believe that environmental electromagnetic fields at the magnitudes associated with the proposed Seafarer transmitter sites would elicit disruptions of cerebral processes in higher organisms. This view is based on long experience with power and lighting systems that use frequencies not significantly different from those of the proposed system and on a limited amount of well-controlled but short-term experimentation. There is no evidence that ELF fields cause subjective perceptual distortions, modifications of motor function, or interference with higher nervous activity essential for judgment and decision-making.

In part, we may attribute this absence of strong interactions to the structuring of central nervous tissue, wherein each of numerous cellular elements has separate and complexly related electric activities, including the generation of an electric field by each cell in its own immediate environment. Therefore, an electric field originating outside the nervous system in the typical monopolar or bipolar configuration of a powerline or ELF transmission antenna, with interpolar distances vastly exceeding the dimensions of brain cells, would not be expected to perturb sharply the essential character of the intrinsic electric fields in brain tissue. Ocean waves might provide a close analogy. Within a single cubic meter of water at the ocean surface, there are numerous local pressure gradients producing highly complex focal motions. Passage of a tidal wave, with its long wavelength, through the same region has relatively little effect on the major fluid movements within this small volume. Environmental low-frequency electric fields, even those at the brain's own dominant frequencies, have relatively small effects, even in comparison with the brain's own processes of electric field generation.

It has also been argued, on the basis of indisputable information about the firing of impulses in nerve cells and nerve fibers, that the intrinsic field surrounding brain cells is far too weak to influence those processes directly. This intrinsic field has been called "the noise of the brain's motor." Recent research increasingly favors a direct role of slow, wave-like electric events in the passage of information between brain cells.

It is not that classical research on the genesis of nerve impulses and the transmission of information by volleys of impulses has been found incorrect. Rather, it is now believed by some workers that brain nerve cells may be susceptible to electric influences far weaker than those which directly elicit firing of nerve impulses.

Evaluation of subtle influences of weak electric fields on nervous functions of higher organisms is inherently difficult. Given the complex behavioral repertoire of the organism, the search for altered behavioral states must take full account of equally subtle environmental influences unrelated to the imposed field, which also constitute part of the total sensory influence and could be responsible for effects that are found. Also, the innate variability of mammalian and avian behavior makes the system extremely "noisy."

Despite these difficulties, there are reports of effects of weak ELF fields on central nervous functions in higher organisms. These effects, none of which have been clearly established, are in three main categories:

- Behavioral: Although direct effects on cognition and decision-making have not been detected, alterations in subjective estimates of the passage of time, in reaction time, and in feeding behavior have been reported.

- Neurophysiologic: Changes in brain electric rhythms (EEG) have been described.
- Neurochemical: Changes in calcium ion flux in isolated brain tissue samples have been reported as having been caused by environmental fields at frequencies of 6-20 Hz and intensities of 10-56 V/m.

In evaluating these reports, a special problem for the Committee is the fact that most reported effects have not been independently confirmed. Indeed, the frequent occurrence of conflicting findings and the numerous experiments with negative findings are disconcerting. It is clearly necessary that negative experiments, as well as positive ones, be specifically evaluated for their adequacy in design and care in observations. Selection of appropriate behavioral, physiologic, and neurochemical variables is clearly of the utmost importance.

Behavioral Effects

Behavioral correlates have been sought with both natural and artificial ELF fields. König[15] has reviewed some of the major components of natural electric fields at frequencies of 1-25 Hz. Peaks occur as electromagnetic waves at 10-11 Hz that are components of a Schumann-resonance phenomenon. Other peaks at 5 Hz and below 1 Hz have been noted. For comparison with effects of artificial fields discussed below, the amplitude of these natural fields is typically 1-2 V/m. The resonance described by Schumann[19] is believed to arise as a nonradiating self-oscillatory wave at the surface of a large conducting sphere surrounded by a thin layer of air and an ionosphere.

Reaction Times. Reaction times were measured in man and monkeys. The subjects were required to press or release a button or key when given a simple light or tone stimulus. König[14] reported slowed responses in man at times of high natural signal frequencies between 3 and 6 Hz and a converse effect at times of 10-Hz peaks. König[15] has pointed out that these studies were incomplete and lacked statistical significance. Further studies by König[15] and König and Ankermüller[16] with artificial fields at frequencies of 5-10 Hz and strengths of 0.3-5.0 V/m again showed trends consistent with the effects of natural fields, but these trends were not amenable to statistical analysis. König has also studied effects of these fields (3 Hz and 2 V/m) on human galvanic skin responses. Only five of 10 subjects reacted positively, and statistical evaluation of these data is not possible. Hamer[10,11,12] also tested human reaction times in ELF fields of 1-20 Hz and concluded that the reaction time was related inversely to the frequency of the applied field. The statistical significance of these results may be questioned. Grissett and de Lorge[9] examined reaction times in squirrel monkeys exposed to 45-Hz, 10-G magnetic fields for 42 days. Three monkeys were tested for one hour daily before, during, and after field exposure. No effects were seen. Grissett and de Lorge's study used Helmholtz coils to produce combined electric (E) and magnetic (H) fields. Resulting tissue interactions would not necessarily be identical with effects of E or H fields applied separately (Grissett and de Lorge[9]).

There have been several other studies in which no effects were seen. In reaction-time experiments where positive effects were reported, only very small changes, typically less than 5% were seen. Because of the experimental designs, statistical validation in the human experiments from the published data is difficult. Grissett and de Lorge[9] pointed out regarding their monkey experiments, that, "if a psychophysiological effect exists, it is probably quite subtle, and will therefore require a broad range of very sensitive experiments to evaluate properly the long-term effects of the ELF environment." It seems doubtful that "paced" or cued responses inherent in reaction-time measurements are optimal test procedures in the search for subtle interactions.

Subjective Estimates of the Passage of Time in Subhuman Primates. These estimates have been examined by two laboratories. They measured the effects of ELF fields on the ability of monkeys to estimate a time interval of 5.0 s in the absence of behavioral cues. The results were conflicting, but the differences emphasize the importance of seemingly minor differences in test procedures.

In two separate studies, Gavalas-Medici and colleagues[6,7] studied subjective time estimating in pigtail macaque monkeys exposed to fields of 7-75 Hz, at intensities of 1-100 V/m. At 7 Hz and 10 V/m, a shortening of the mean time estimate was 5-10% compared with no-field conditions. At 45 and 75 Hz, fields of 56 V/m were reported to produce smaller changes; with fields of 100 V/m, the effect was not as apparent. No effects were observed in tests at 60 Hz.

Monkeys in the experiments of Gavalas-Medici *et al.*[6,7] included animals with and without implanted cerebral electrodes. Similar sensitivities were noted during field exposure, but the presence of metal electrodes in cerebral structures raised questions of induced electric gradients at bare electrode tips that would be greater than those elsewhere in the tissue. Measurements by Valentino[20] in a phantom monkey head in the exposure facility of the Gavalas-Medici experiments indicated a total current of 0.9 nA with a 10-V/m field at 7 Hz. On the basis of a specific resistance for brain tissue of 300 ohm-cm, the expected extracellular electric gradient would be 10^{-7} V/cm. For the exposed areas of electrode tips used in these experiments, an increase in this gradient at the electrode tips by a factor of 1,000 would be expected, or a gradient of 10^{-4} V/cm. This is still far below the transmembrane gradient of 10^{3} V/cm associated with synaptic depolarization in classical transmembrane excitatory processes. Thus, the presence of the implanted electrodes was not believed to be associated with significant "antenna" effects.

A similar study on rhesus monkeys was performed by de Lorge,[3,4] who used weak 15- and 45-Hz magnetic fields with intensities of 8.2-9.3 G. The findings were interpreted by the investigator as equivocal. Three of four subjects showed shorter interresponse times with the first series of exposures to 45 Hz, but not to the second. A Kolmogorov-Smirnov test of the distributions was highly significant ($p < 0.001$). However, means of the interresponse times (IRTs) were not significantly altered by field exposure. One monkey had shorter IRTs with both 45-Hz exposures ($p < 0.001$). In the 15-Hz fields, one monkey was significantly faster ($p < 0.05$), one was significantly slower ($p < 0.001$), and two were unaltered.

These differing conclusions in studies that appear closely related emphasize the probable importance of details of test procedures. Gavalas-Medici used a daily exposure schedule of 4 h and monkeys with implanted electrodes. It was noted in some subjects that larger field/no field differences in IRTs occurred in the third and fourth hours than in the second hour of exposure. DeLorge used situations with either one or two different behavioral tasks. The IRT schedule was imposed three or six times in a 2-h session, but for only 15 min for each task. If the findings by Gavalas-Medici are valid in showing a gradual onset of altered subjective time estimation over several hours, they emphasize the importance of further studies of long-term exposure. This need is underlined by the fact that, in the later hours of the experiments, investigator intervention were sometimes required to stimulate task performance. Altered subjective time estimates may reflect broader changes in biologic rhythms, including endocrine cycling, about whose sensitivity to environmental electromagnetic fields very little is known.

A relatively slow onset of altered reaction times has been reported by Hauf and Wiesinger[13] in preliminary studies of 20 human subjects exposed to 50-Hz electric fields at strengths far higher than planned for Seafarer--1,000 V/m and 15,000 V/m. An attempt to replicate these results was not successful.[5]

Effects of Weak Oscillating Fields on Feeding Behavior. These effects have been studies by Persinger and his associates[18] in considering the possible consequences in adult rats of exposure to low-frequency magnetic fields before or shortly after birth. Pregnant animals were exposed to rotating magnetic fields of 0.5-30 G at 0.5-Hz.

Continuous prenatal exposure (and absence of fields thereafter) was reported to lead to reduced ambulation but more frequent defecation, at the age of 21 to 25 days. When the field exposure was confined to fetal days 13-16 or postnatal days 1-4, changes were noted later in a conditioned delayed-approach test. The sensitivity of this test was increased by the use of reward schedules with step, impulse, and ramp signal procedures. In this way, transient behaviors were induced that might have sensitively reflected subtle differences in behavioral states. Rats deprived of water were tested during a 10-s imposed delay in a water reward schedule. The authors concluded that rats exposed during the first 3 postnatal days responded significantly more frequently during this delay period than either control animals or those exposed before birth. However, statistical evaluation is difficult in most of these studies, which presented mainly derived data. In addition, no independent confirmation of these results has been reported.

Neurophysiologic Effects

Brain electric rhythms (EEG) have been recorded in the presence of a wide range of steady and oscillating electric fields. Although there are major technical difficulties in securing EEG records free from artifacts attributable to environmental ELF fields, careful and painstaking techniques have now provided some adequate records on animals. No comparable data appear to have been gathered on man, but some of the experiments at ELF frequencies have shown slowly induced changes in ongoing or background brainwave patterns. Related studies with ELF modulated radiofrequency fields that produced stronger tissue components have shown alterations in brief conditioned or "learned" EEG responses.

Gradual entrainment of electric rhythms in some deep brain structures of the monkey by 7-Hz, 10-V/m fields has been reported (Gavalas, Walter, Hamer, and Adey[6]). These entrained rhythms appeared slowly during a 4-h field exposure as a statistically significant modification of records from hippocampal regions of the temporal lobe and thalamus. They were absent in spectral analyses of EEG records at the onset of an exposure, but presented clear spectral peaks in the third and fourth hours of exposure. Their appearance in the hippocampus is consistent with what is known of its functions in the temporal sequencing of behavior.

In related studies, modulation of VHF radio carrier waves (147 MHz) at ELF frequencies has been reported to alter brain electric rhythms in cats and to increase the occurrence of brief EEG rhythm "signatures" that occur in many deep structures of mammals, including man (Bawin, Gavalas-Medici and Adey[2]). These relatively major modifications in brain rhythms have not been reported for ELF fields, however, and occurred only when the ELF modulation of the radio carrier wave was at the same frequency as the intrinsic brain rhythm "signature."

Rats exposed to 10-kV/m DC fields showed increased electric activity in the cerebral cortex and decreased activity in deep centers of the hypothalamus (Lott and McCain[17]). However, the use of those very high field strengths raises questions concerning effects on fur, etc., as a source of peripheral sensory stimulation. The same authors reported that a much weaker pulsed field (20 V/m, 640 pulses/s) significantly increased hypothalamic activity. Because these studies were performed under barbiturate anesthesia, the findings cannot be extrapolated directly to possible interactions in unanesthetized subjects. Furthermore, in acquiring electrophysiologic data with wire electrodes in the presence of large oscillating environmental fields, extreme care must be exercised in interpreting the results.

Neurochemical Effects

Release of calcium ions from cat and chicken cerebral cortex has been reported to be reduced by environmental fields at frequencies of 6-20 Hz and amplitudes of 10-56 V/m, but similar fields at 75 Hz were without effect (Bawin and Adey[1]). In other studies,[21] 60- and 76-Hz fields were reported to have no effect on calcium efflux from the chick brain. Confirmation of these results will be of importance because calcium ions are essential in nerve-cell excitation.

Conclusions

Extrapolations from these laboratory experiments to field conditions proposed for Seafarer suggest that the behavioral, neurophysiologic, and neurochemical effects reported for fields in air occur only at field strengths well above those expected even in the immediate vicinity of the antenna and only at lower frequencies. For earth currents that may enter the body through bare feet in the vicinity of ground terminals, cerebral components are a small part of the total current passing from one foot to another. Limits of subject acceptance would be determined by painful shock stimulation long before direct modification of cerebral functions would occur.

As described above, many of the observations are preliminary and need confirmation in further research. The character and magnitude of the effects, even if confirmed, do not appear to be a cause for concern, especially considering the intensity and frequency of the Seafarer fields.

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Plants

One of the major concerns about the proposed Seafarer system is that it may have serious effects on the vegetation near the antenna and, in an extreme, may cause a "wasteland" throughout an area of several square miles. Agricultural and forestry industries depend on plants, and plants are an important aspect of scenic quality. In addition, plants form the framework for an ecosystem, and an influence on plants could have indirect but important effects on all other organisms in the system. Thus, possible effects of Seafarer on plants may be of concern second only to possible effects on the human population.

Although there have not been many experiments investigating the effects of ELF electric and magnetic fields on plants, several papers in the literature on Seafarer should be discussed. A paper in 1960 by Audus[1] has been cited as an example of a magnetic-field effect on plants. Young seedlings of the herb *Lepidium* were placed between the poles of an industrial magnet that produced a constant magnetic field of 4,000 G. Data and photographs suggested a bending of the roots in response to this magnetic field. There are some difficulties in this experiment, particularly with regard to the applicability of the results to Seafarer. First, the magnetic field was greatly in excess of that proposed for Seafarer—4,000 G, compared with 0.2 G. Second, no safeguards were mentioned in the paper for eliminating other possible effects of the equipment, such as an electric field, on roots. Third, the roots were photographed by using a flash of light; although Audus stated that this alone had no effect, plants respond to flashes of light and it is possible that there was a light effect. Fourth, although the magnetic field was very strong, the plant response was very small. Fifth, the statistics, numbers of roots measured, and temperature control are questionable. Therefore, although these effects of electric and magnetic fields, if real, would be very interesting from the scientific standpoint, the conditions used did not duplicate, or even approximate, those of Seafarer and need not be considered further.

Ecologic studies are desirable in analyzing the possible effect of an ELF antenna on plant growth. At a Seafarer-prototype antenna in North Carolina, McCormick _et al_.[3] measured pine bud mortality, which has been shown to be a relatively sensitive indicator of ionizing radiation. In addition, they looked for changes in species diversity in the experimental area—a standard ecologic procedure, because species diversity is relatively finely balanced, and an advantage or disadvantage to a given species will very quickly become evident. By their methods, the authors were unable to detect any changes in vegetation patterns or in pine bud mortality that could be related to the ELF antenna. They did find changes in species diversity and pine bud mortality along the route of the antenna, which was cut through the vegetation, and attributed these to an "edge effect." This would surely have obscured smaller effects that had other causes. When a swath is cut through vegetation, the microclimate and other factors in the immediate area are changed, causing effects in the vegetation immediately adjacent.

Greenberg[2] surveyed plant species as part of a procedure for matching test plots in a field study of possible ELF effects on soil arthropods over a period of several years. Species counts varied among both control and experimental plots, the variations were not consistent, and no conclusions could be reached on the basis of this study.

Two studies examined directly the effect of exposure to ELF fields similar to those of Seafarer. Miller *et al.*[4] used *Vicia faba*, the broad bean, and measured root growth and the mitotic index in root meristems and looked for chromosomal abnormalities in root cells. The experimental system involved an electric field of 10 V/m in air and magnetic fields of 0.5, 5, and 17 G. They were unable to observe any effects, even when the electric and magnetic fields were greater than those proposed for Seafarer. In this experiment, indexes of growth that might be expected to be affected by subtle changes in the environment were examined, with appropriate controls and statistics. Thus, although it was necessarily limited in scope to a relatively few measurements with one plant, it was a valid experiment.

Gardner *et al.*[6] measured several plant phenomena that might be sensitive to ELF effects--growth, stomatal resistance, and transpiration of snap beans grown in controlled environments in the biotron at the University of Wisconsin-Madison. These authors noted some effects of the experimental treatment on plants, but were unable to separate those effects from the effects of other factors, even in well-designed experiments in carefully controlled environmental facilities.

Rosenthal[5] germinated and grew sunflower seeds in greenhouse and growth--chamber environments exposed to an electromagnetic field of 1 G and 10 V/m in air at 75 Hz. Measurements were made on many indexes of growth, such as percentage of germination and length and weight of roots and stems. The author concluded that there were small, but statistically significant, differences in seedling mortality, stem, and root length brought about by the ELF field. There are some problems with this experiment that make the results inconclusive. In the seedling germination tests, when genetically uniform seeds from a commercial seed-producer were used, no effect of the ELF field could be noted; when nonuniform seeds produced by the author were used, effects attributed to the ELF field were noted. The total number of seeds that failed to germinate was not large and the results were not repeated in other similar experiments. Furthermore, it is well known that germination experiments with any kind of seed can be extremely variable.

In length measurements, Rosenthal[5] noted a difference in one of eight experiments. The difference in stem length was extremely small (approximately 2 mm) and not convincing for a tall, fast-growing plant like sunflower. Furthermore, there are experimental problems in moving plants from one location in a growth chamber or greenhouse to another, and some statements in the article lead a reader to wonder whether the statistical problems of experiments in such controlled environments are fully appreciated. Therefore, the results are not convincing, owing to problems in the experimental setup, in the control of experimental procedure, in plant material, and in some of the measurements themselves.

The available data on effects on plants of electric and magnetic fields similar to those associated with the proposed Seafarer antenna are sparse. However, on the basis of the data that are available, it is our judgment that the ELF fields generated by the proposed Seafarer antenna (0.01 V/m, 0.13 G) would not have any effect on plants growing along the antenna.

Construction paths through vegetation for installation of the antenna will, of course, have ecologic effects.

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Soil Organisms

Despite the pervasiveness of 50- and 60-Hz fields, no long-term study of the ecologic consequences of such fields has been found. The absence of any known impacts suggests that ecologic effects, if they exist, would be readily masked by responses to variations in physical factors, such as soil temperature, soil water content, and soil aeration. Detailed calculations of variations in such physical factors have been made by Baughn (Appendix A). Because of their close coupling with the Seafarer fields, soil organisms might serve as indicators of the biologic importance of ELF ground currents.

To provide information in this regard, several studies have been commissioned by the Navy. In a laboratory under carefully controlled conditions, Meilinger[14] studied nutrient uptake in *Citrobacter freundii*, bacteria commonly found in the soil at the Wisconsin Test Facility. At both 10 and 50 V/m, no effect of the field was found in the metabolism of the organisms. The results were significant at the 5% level. Similar results were obtained with the indigenous bacterial population of a Miami silt loam soil.

Ecologic studies were initiated at the Wisconsin Test Facility in 1969. As part of the original Hazleton study, single soil core samples were taken from paired plots in 1969 and 1970. No conclusions could be drawn from the limited data obtained. Greenberg and associates[6,7,8,10,11] established new pairs of field plots and took soil cores four or five times each summer in 1971, 1972, 1973, and 1975. Fourteen plots were marked off, in addition to the two original Hazleton plots. The original plots were 10-ft (3-m) squares, and the new plots were 4-ft (1.2-m) squares. Two plots (considered to be the main test pair) were further subdivided into three subplots each. A new plot was selected to replace the old Hazleton test plot, which was deemed to be poorly paired with its control. Pairing was based on soil type, vegetation, and general topography. The distance between the two members of a pair varied from 8 to 15 miles (12.8 to 24 km). The test plots were situated at various points along the antenna right of way. The two legs of the antenna were mounted overhead on poles, except where they were grounded. In addition, a third cable was buried at a depth of about 30 in (76 cm) along the north-south right of way, to permit comparison of overhead with buried installation. One additional plot was situated at the ground terminal of an electric power substation, to permit comparison with 60-Hz fields. The antenna was first turned on in July 1969 at a low current, which was increased by steps over the next 2 years. A maximal current of 300 A was achieved by March 1971. From then on, the antenna was activated on a nominal schedule of 5 days/week, 6 h/day. However, the three sections of the antenna were not necessarily all active at the same time. During May and June 1974, the antenna was not on at all. The total on time during the critical summer growth periods, June-August 1973 and 1974, was about 500 h, or 9% of the time. Altogether, over the 5-year period of the experiment, the time of exposure to the ELF fields was less than 20%.

The field strength (horizontal) just below the soil surface for the main test plot averaged about 150 mV/m. Field strengths for the other test plots ranged from 0.096 to 2.63 V/m, for a current of 300 A. At the 100-A current specified for Seafarer, this range would be 0.032 to 0.88 V/m. The variation in the fields is not unexpected, owing to the highly variable soil conductivity. The magnetic field was much more uniform; at the surface of the test plots, it varied from 0.011 to 0.88 G.

Four to 14 cores were taken from each plot at each sampling date. These cores were 7 in (17.8 cm) long and 2 in (5.1 cm) in diameter. The locations of the cores were randomized within each plot and, with few exceptions, taken to a depth of 7 in (17.8 cm). Cores were then assayed for soil arthropods. In particular, springtails (Collembola) and three groups of mites were identified and counted (Prostigmata, Cryptostigmata, and Mesostigmata). These organisms are relatively mobile and are extracted from a soil sample by drying the soil from one end of the sample. The organisms migrate to the other end and drop out into an alcohol solution. This extraction was done at the test facility immediately after sampling.

Current concepts of the roles of arthropods in soil-litter systems emphasize regulation of the general decomposition process. The decomposition of dead organic matter results from bacterial and fungal attack. Soil invertebrates may regulate this process by direct and indirect means. Some direct digestion of dead organic matter occurs, but currently more importance is given to indirect effects of arthropods: fragmenting organic material, mixing it with mineral soil, altering substrate quality, disseminating microbes, selectively cropping microbial populations, and so forth.

Soil microarthropods—primarily mites and springtails—belong to the so-called mesofauna of soil, being intermediate in size between the true microfauna (protozoans) and the macrofauna (millipedes, earthworms, etc.). The classification is based essentially on size and convenience of collecting. Soil microarthropods are usually numerous and easily sampled. They are usually found in the top 15-20 cm of the soil profile, and there may be as many as 10^6 in an area of 1 m^2. Macrofauna require much more sampling effort; and microfauna are difficult to study.

Experimental results have demonstrated that the microarthropods influence litter decomposition rate. Weight lost by decomposing litter can be monitored by enclosing it in mesh bags. If the mesh size allows only microfauna and microflora to enter, decomposition is slow. With a slightly larger mesh, the mites and springtails can enter the bags, and decomposition will proceed rapidly. Coarse-meshed bags allow macrofauna to enter as well, but they may contribute little more to the decomposition rate.[5,13] Use of selective chemical treatment to reduce microarthropod populations has also shown that they have a significant effect on decomposition rate.[12,16] Thus, there is some rationale for selecting microarthropods, as a segment of the soil fauna, for examining system response to perturbation. Rapid increases in springtail populations have been observed after different sorts of perturbations, such as insecticide treatments and irradiation.

It is not known how these various microarthropods subdivide their resources, or how their niches differ. Collembolans may graze upon rapidly growing fungal hyphae, maximizing their growth rate to take advantage of sudden food abundances; cryptostigmatids appear to utilize senescent microflora, maximizing stable population, instead of growth rate.

Results

Greenberg observed variations in numbers that he attributed to natural causes. Such variations occurred between plots in control and experimental areas in his main series. It occurred between test and control plots and between years. Greenberg[7,8] showed several cases in which the analysis-of-variance models indicated significant differences in size of microarthropod populations between experimental and control plots. These were not a feature of any one arthropod group, nor was an experimental population always lower than a control one. The 1974 paper[11] reported mainly on year-to-year comparisons in population size and failed to indicate significance (if any) in population-size differences between experimental and control plots.

In the 1974 paper,[11] Greenberg and Ash attached more importance to ratios of groups than to population sizes. Proportions of predators (defined by Greenberg as Mesostigmata and Prostigmata) were found to be the same in collections from paired experimental and control plots, at least in seven of nine cases. For comparison, between years (1972 vs. 1973), only six of 19 plots had significant shifts in proportion of predators, and those were divided evenly between increases and decreases.

Greenberg concluded that he had not detected any effects of ELF radiation on the microarthropod populations. In the 1973 papers,[7,8] analyses of variance demonstrated some differences between experimental and control plots, especially in the "clover" series. Some of these differences diminished in the additional year's data reported in the 1974 paper.[11] Large year-to-year differences appeared in adjacent replicate plots; this argues against attributing much significance to shifts in numbers. Greenberg used the ratios Cryptostigmata:Collembola and Cryptostigmata:Mesostigmata and the fraction of predators (Mesostigmata + Prostigmata) as indexes of community structure. Ratios in experimental and control plots behaved similarly over the 1969-1973 period. Greenberg thus concluded that the ELF radiation had not altered the microarthropod community significantly.

Evaluation

It was on the basis of this study that the Navy stated[15] that: "Even long term (7 year) studies of soil animals have failed to show as much as a subtle influence from the field produced at the Wisconsin Test Facility." Thus, this study was deemed to have significance, and close scrutiny is in order.

It is axiomatic in statistics that the magnitude of differences detectable by a given sampling program is directly determined by the magnitude of uncontrolled variability in the data. The sources of extrinsic variability in density of animal populations under field conditions are many, ranging from food availability and predation to physical factors, such as soil type, exposure to light, and moisture. In addition to spatial variation, the data demonstrate (as one might have expected) large temporal variability, on both an intraseasonal scale and a year-to-year scale, in the density of soil arthropods. To complicate the problem further, one has every right to expect interactions--i.e., nonlinearities--that greatly weaken, if not invalidate, most ordinary statistical testing. For example, in a given season, high temperature may be favorable at a moist site and unfavorable at a dry site.

In the framework of the small numbers of samples taken, Greenberg's sampling design was a reasonable attempt to deal with such sources of variability: test areas were paired with presumably comparable control areas; the samples were spaced at intervals throughout the summer; and sampling was continued at several sites for 3 years or longer. Nevertheless, the residual variability in the data is such that only a truly massive, consistent average difference in abundances, upward or downward, due to the antenna could have been detected. The fact that the animal identification was not carried to the species or genus level implies, in addition, that ecologic replacement of one species or genus by another would not have been detected.

The basic approach underlying such a study, then, is that one must accept, a priori, that it cannot be a sensitive test; it will detect an ecologic catastrophe, but probably overlook other less obvious, but conceivably important, effects. Thus, the Navy's statement[15] that not even a subtle effect was found is subject to criticism, in that the procedure was not designed to find subtle effects, and any effect observed could hardly have been classed as subtle.

Field-plot experiments have a long and honorable history in biologic research, and they have been a powerful tool in ecologic studies. A difficulty with the Greenberg studies is that the "paired plots" were not sufficiently comparable. Plots were paired on the basis of general similarity of plant cover and similarity of the top 2-3 ft (0.6-0.9 m) of the soil profile. The soil-profile descriptions were sufficiently different to suggest some differences in hydrologic properties. These could have led to differences in both the thermal and moisture regimes. In addition, the vegetation was changing over the several years of sampling. Although this is to be expected after any drastic change associated with clearing rights of way, paired plots were not changing at identical rates in identical ways. Whether such differences were significant in the function of the ecosystem is arguable.

There are at least two ways to deal with the variability of the system. The first is to use a much larger number of sites--say, 50-100. This avoids the necessity of trying to find nearly identical plots. Reduction of the deviation for both the exposed and control plots reduces the limits for any effect that is present but undetected. The second approach is to use more rigorous criteria for the pairing of plots and to monitor the factors (temperature, water, light, etc.) known to be of first-order importance in ecosystem performance. One then analyzes to determine whether observed differences are explained by these variables. A proper ecologic study designed to find subtle effects that are difficult to demonstrate even under very carefully controlled laboratory conditions is a major undertaking and requires the planning and participation of experienced scientists from several disciplines. No such study has been carried out at the Wisconsin Test Facility.

Summary

As in the case of plants, there has been considerable interest in whether soil organisms might be affected by ELF.

Such organisms would be more strongly coupled with the fields produced by Seafarer than above-ground organisms. If there are effects on soil organisms, they might be expected to occur at a fundamental cellular level and thus be important quite generally. A laboratory experiment on soil bacteria at 10 and 50 V/m showed no effect on metabolic activity. Studies at the Wisconsin Test Facility designed to detect ecologic changes that might provide evidence of ELF effects failed to reveal any changes that could be correlated with exposure to Seafarer fields. The Committee does note that, as in the case of plant studies, only major effects would have been detected in the field surveys of soil organisms undertaken, in part because of inherent difficulties in separating possible small effects from effects due to other perturbing factors, such as soil water, soil temperature, and soil aeration.

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Small Mammals

A 2-year survey of small mammal populations in the Chequamegon National Forest was conducted in the vicinity of the Wisconsin Test Facility during the summers of 1971 and 1972 by Seale, Gauger, and Damberger.[1] This study can be considered as a baseline inventory of some areas in the forest. Although some plots were exposed to ELF fields, and others were not, the study cannot be considered to represent a controlled experiment in ELF exposure. This was recognized by the authors, who stated:

> Because this study was not made in rigorously controlled circumstances, and because no previous data exists which could be used to establish a set of controls, no statement can be made on whether or not the ELF electromagnetic fields from the test antenna affect small mammals in subtle ways. However, the data gathered during this study could be of use in assessing any possible long term effects of the antenna and in structuring any future work of this kind.

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Epidemiology and Standards

A variety of approaches are available for identifying possible biologic effects on man associated with electric and magnetic fields. One approach is to extrapolate to man from data generated in animal experiments. Although this may be of value, it has limitations, as described elsewhere in this report. A second approach is to study the effects of electric and magnetic fields _in vitro_ in either tissue or cell culture. Again, there are major limitations to generalizing from the _in vitro_ situation to the _in vivo_ situation. Although it might be desirable, therefore, to carry out randomized trials of human exposure to these fields, this is generally not feasible, because of practical and ethical considerations. Another possible method for assessing the effect of such fields in man is to utilize natural or unplanned experiments in which groups of people have been exposed to such fields and to compare those people with appropriate comparison or control groups. This is the rationale that underlies prospective epidemiologic investigations of electric and magnetic fields.

Such fields have been present, especially in urban and industrial areas, for many decades, so the epidemiologic approach is potentially very valuable for studying the effects. But there are numerous problems. (Even if these problems could be overcome, it might involve an inordinate--even astronomic--cost.) One problem is the selection of paired populations that are not systematically loaded with some other bias. The control or comparison group should be comparable with the case or exposed group in all relevant characteristics, except for the exposure itself. The report of the study should provide the data needed to assess whether the study has met these requirements. The paper should also outline potential biases in selection of subjects, in measurements, and in followup that may affect the inferences being derived regarding the effects of the fields. Another problem is that the sample must be large enough to make it possible to detect an increased risk. It is often necessary to study a population of many thousands to get significant results. Perhaps the main limitation of epidemiologic studies in this subject is the lack of sufficient knowledge with which to select appropriate biologic outcomes for measuring the effects of the fields on man. This very problem would also apply to another type of epidemiologic study: the case-control or retrospective study, in which people with a disease are compared with a group of disease-free people. Both are then examined for history of specific exposure. Again, because the type of disease or pathologic condition one might anticipate is not known in this case, a retrospective study of the effects of electric and magnetic fields is very difficult to design.

Relatively few epidemiologic studies are available regarding electric and magnetic fields, and most are from eastern European and Soviet investigators.

On the basis of these studies, there is little reason to be concerned that these fields have had adverse effects. However, eastern European and Soviet reports have suggested that there are biologic effects when animals are exposed to stationary and low-frequency electric fields. Field strengths reputedly causing effects are mostly between 20 and 200 kV/m; in some reports, field strengths were not specified. Such symptoms as listlessness, excitability, headache, drowsiness, and fatigue were described in persons occupationally exposed to high electric fields. Because these symptoms are also caused by many other occupational and psychosocial factors, it is not possible to establish a cause-effect relationship.

Literature Review

Asanova and Rakov[2] reported clinical studies on 45 employees of a Soviet 400- 500-kV electric power substation. The group included "maintenance personnel," whose average daily exposure to the electric field was 5 h; "attending personnel," whose average daily exposure was 2 h; and "to a lesser number, signalmen and secondary personnel," who "were not in the field constantly, nor for prolonged periods." The number of workers in each of the above categories was not stated. The major part of the report was a description of the various disorders found among the 45 workers. The most common complaints were subjective—headache, fatigue, disrupted activity of the digestive tract, etc.—in 41 of the 45 examinees. A variety of other ailments were reported—"arteriosclerotic cardiosclerosis" in three examinees over the age of 50, hypotension in seven people, hypertension in four, and diseases of the digestive tract (chronic gastritis and "coliccystitis") in six. A few statements related disorders to ELF radiation exposure—e.g., "more marked neurodynamic changes were seen in maintenance people who had the greatest daily exposure to the electric field," and "the impression is created that changes in the cardiovascular system are encountered more frequently and are more marked in persons systematically subjected to the influence of electric fields (maintenance personnel), than those exposed sporadically (signalmen, attendants)." None of these statements was supported by quantitative data. Furthermore, the authors stated that "it must be noted that we were not successful in establishing increased neurologic complaints and neuropathology with increased work experience under the influence of high voltage electric fields." No breakdown was given of the incidence of disorders according to the type of work (i.e., according to the degree of ELF exposure) or according to the duration of work in electric fields, nor was there any indication of the incidence of disorders in a "normal" population of workers (not exposed to high-intensity ELF). Thus, there was no objective basis for concluding that the observed disorders were in any way related to exposure to ELF radiation.

In a report by Sazonova,[21] 54 people working in open switchyards were studied. Two groups were compared: "operation" personnel, who were exposed for not more than 2 h daily (29 persons); and "maintenance" personnel, who were exposed at least 5 h daily (25 persons). A series of tests were carried out on both groups, before and after work, daily for 6 days. Measurements included temperature, pulse, blood pressure, reaction time and quantitative error, critical flicker frequency, and reaction of the adductor muscle of the thumb to electric stimulation. Data were presented for one day's measurements. No significant changes were seen in temperature or critical flicker frequency. Small differences were seen in heart rate at the end of the day; they appeared to be due to increases in rate from the beginning of the day in the operating personnel, rather than to an effect in the maintenance personnel, whose rates were essentially unchanged. The average blood pressure of the maintenance personnel was significantly lower than that of the operating personnel, at both the beginning and the end of the day. To attribute the above differences to the effects of electric fields, two conditions should be met: the two groups should be similar in age, sex, physical condition, and other pertinent characteristics; and the work and work environment for the two groups should be similar in all respects, except for the presence or absence of the electric field. The information provided by Sazanova did not indicate that either of these conditions was met. Data were presented on the age distribution and work experience of the personnel taken as a single group (maintenance and operating personnel), but not on sex, age distribution, or work experience of the personnel in each group. Thus, the difference in blood pressure between the two groups could be due solely to differences in age and/or sex and have no relationship to the work environment.

In summary, a number of physiologic differences were seen between "operating personnel" with "low" ELF exposure and "maintenance personnel" with "high" ELF exposure. However, it was difficult to exclude factors other than electric-field exposure as the cause of the observed differences.

The difficulty in establishing the relationship of ELF to cardiovascular changes was cogently described by Guskova and Kochanova[9] of the Institute of Industrial Hygiene and Occupational Pathology (Moscow), USSR Academy of Medical Sciences, who disputed earlier Soviet reports of the relationship of occupational diseases to electromagnetic radiation. These authors stated that it is very difficult to determine etiology of pathologic conditions of the circulatory system in groups of workers exposed to superhigh-frequency (SHF) radiation, because such work involves nervous and emotional tension, as well as other deleterious factors. The incidence of hypertension previously associated with chronic exposure to SHF fields is comparable with that of the general population of Moscow. Guskova and Kochanova[9] suggested, that when diagnosing pathologic cardiovascular conditions in people exposed to ultrahigh-frequency (UHF) radiation, in addition to assessing working conditions, it is also imperative consider other causes of cardiopathy, such as smoking, obesity, and genetic factors (emotional, psychologic, and personality) that are accepted risk factors in the development of cardiac ischemia.

According to Korobkova *et al.*,[13] after several months of operation of the first 500-kV substations, some of the personnel began to complain of headaches and malaise associated with prolonged stays in the electric field (5-25 kV/m). After examination of about 250 subjects, the authors reported that prolonged work in 500-750 kV switchyards without protective measures had an "unfavorable effect upon the human organism resulting from the direct field influence." They also attributed some of the findings to "the influence of electrical discharges." The authors did note, however, that 5 kV/m did not influence people.

Studies were carried out by Krivova *et al.*[14] on 319 men up to the age of 50 in 220-, 330-, and 500-kV switchyards. A variety of medical examinations were carried out, and it was concluded that the electric field caused an "unfavorable" influence, with nonspecific disturbances of the central nervous system.

Criteria, Methods, and Interpretations

The Soviet and eastern European publications reviewed lack descriptions of study methods and of selection and characteristics of controls in the detail that is standard for the West. Evaluation by the reader is often difficult where an idiosyncratic vocabulary mixes empirical observations with hypothetical processes. Few epidemiologic studies provide the incidence of abnormalities in exposed populations. The central nervous system symptoms and signs commonly described are called the "neurasthenic" or "asthenic" syndrome. The term "neurasthenia" originated a century ago, but has been obsolescent in the United States for some decades.[4] Labile functional cardiovascular changes involve neurocirculatory asthenia or vagotonic reaction, known as the "vegetative dystonia" or "autonomic dystonia" syndrome, attributed to neural influence, mainly from the parasympathetic division of the autonomic nervous system. A third rubric, designated the "diencephalic" syndrome, includes hallucinations, insomnia, syncope, and inhibition of visceral functions and is said to be associated with exposure to electromagnetic radiation in general. In the clinical appraisal, routine neurologic examination appears to add little to the history and general physical findings beyond descriptions of hand tremors, dermographism, and rare ataxia. Correlations between EEG changes and other clinical observations and subjective complaints have been made, but do not appear consistent.

Studies of exposed working groups that report clinical effects of ELF lack important information, and the data are inconsistent. Many investigations do not describe how controls were selected for the exposed subjects. Some do not even mention controls.[13,16] The reports by Asanova and Rakov[2] and Sazonova[21] do not provide adequate field measurement and exposure data.

It is also possible that conditions other than the electric field in switchyards may be responsible for some of the observed effects. For example, there is a low-frequency (100-120 Hz) noise in switchyards. Such noise has been shown to produce headaches, nausea, coughing, visual blurring, and fatigue (Ades <u>et al.</u>,[1] Hale,[10] Halsted,[11] Lockett,[15] Mohr <u>et al.</u>[18]). These effects are similar to those attributed to the electric field.

Environmental factors related to the general lifestyle of the occupation, which may or may not be distinct from that of other occupations have to be considered. Exposure to the "elements" in what is essentially an outdoor, all-weather, year-round job--in some cases in exposed or mountainous locations--is a characteristic of the occupation of linemen and to a lesser extent of transformer substation workers. Purely psychologic and psychosomatic factors associated with apprehension over receiving unpleasant microshocks, or even direct conductor-contact shocks, have been invoked to explain some of the reported symptoms of the Soviet switchyard workers, and these should be considered further.

The importance of psychosocial factors in assessing the effects of environmental insults is revealed in a report by Weintraub,[22] who studied 954 male and 325 female workers in 21 U.S. industrial plants. He found a significant overall relationship between job dissatisfaction and psychosomatic complaints. Weintraub emphasized that his study could not show whether the ailment or the disgruntlement with the job came first, but only that the two were associated in the people he studied.

Standards

The publication by Glass[7] is a valuable reference for background information on protection guides and standards in the USSR. Soviet standards are generally more stringent than American practices. This reflects differences in the concept of an environmental standard and in the research applied to setting this norm.

Although Goldman[8] has noted that "Soviet philosophy dictates [that] a healthy environment can be preserved apart from the interest of individual polluters" and that "regulatory control over government enterprise should be easier to exercise," Glass[7] has reported that, in practice, these ideals are difficult to achieve. There appears to be some resistance to environmental controls among the public and plant managers.[8]

Protection guides (standards) for 400-, 500-, and 750-kV electric installations in the USSR have established limits for maximal exposure, in 24-h periods, to electric fields greater than 5 kV/m without protective devices.[3] For fields equal to or less than 5 kV/m, personnel are permitted to remain in the field for an unlimited time (Lyskov _et_ _al_.[16]).

According to Lyskov _et_ _al_.,[16] infrequent and nonsystematic exposure of the local population and agricultural workers can practically be disregarded. Thus, the following standards are accepted as permissible values:

20 kV/m for difficult terrain,

15-20 kV/m for nonpopulated regions, and

10-12 kV/m for road crossings.

The permissible field strength must not be exceeded at the center of the span at a height of 1.8 m above ground and at the lowest sag (at the maximal 15-year temperature).

Lyskov _et_ _al_.,[16] also noted that the USSR experience with its 500-kV system, amounting to some 150,000 km-years of operation (as of February 1975), indicated no problems in regard to health or safety, although the field intensity at ground level from such lines may range from 10-14 kV/m.

The Ministry of Health of the USSR is responsible for planning and promoting research on pollutants and translating the results into national standards.[2] If an effect is reported, it may constitute a basis for standard setting, even though it may be reversible or innocuous and even though a cause-effect relationship may not have been demonstrated for the agent in question. This attitude extends to all environmental considerations.[7,20]

Much Soviet research on environmental standards may not be applicable to the West, because the Soviet interest is in determining only the lowest concentrations that produce a measurable biologic change, regardless of its importance.[7,11] Full enforcement of present standards in the USSR has not been attained, for economic reasons[6] and because the standards are numerous and in most cases extraordinarily stringent.[7] For example, Magnuson *et al.*[17] noted that Soviet air standards are not in fact rigid ceiling values and that excursions above these values "within reasonable limits" are permitted.

Conclusion

Our review of the epidemiologic literature reveals concern for ELF fields in eastern European countries and the USSR in connection with electric power installations. Although the data are difficult to evaluate, they provide no indication that adverse effects would result from the fields associated with the proposed Seafarer system.

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APPENDIX A

SAFETY IN THE VICINITY OF SEAFARER ANTENNA GROUND TERMINALS: ITS RELATION TO SOIL ELECTRICAL CONDUCTIVITY IN THE TOP TWO METERS OF EARTH

John W. Baughn

EXECUTIVE SUMMARY

A review of the soil science literature shows that the electrical conductivity of the types of soils at the proposed Michigan, New Mexico, and Nevada Seafarer sites varies widely as a function of water content, soil temperature, and salinity of the soil solution. Seasonal variations cause water content and temperature to change radically throughout the year in the top one meter of soil, and these variables can cause soil conductivity to change by factors of 10 to 100 at a given location.

At the Michigan site, soil conductivity is expected to range from 10 to 100 millimhos/meter, but low values of 0.1 to 10 mmho/m might occur in extremes of dry soil of summer or frozen soils in mid-winter; high values of 100 to 200 mmho/m might occur under extremely high water content or salt content.

At the Nevada and New Mexico sites, soil conductivity is expected to range from 10 to 300 mmho/m, with high values possibly reaching 400 to 600 mmho/m in saline areas at high water content. Experiments on artificially-salinized soil cores suggest that soils of these arid regions might exhibit surface conductivity effects that prevent the soil conductivity from dropping below 20 to 40 mmho/m, no matter how low the soil water content becomes.

It is to be emphasized that the above values are estimates based on scientific work at locations other than the Seafarer sites and performed for purposes other than evaluating the environmental impact of electrical fields from antenna ground wires. To date there has been no program in the Seafarer project aimed at measuring soil electrical conductivity in the top one meter of earth at any of the proposed ground terminal sites.

A theoretical investigation of the effect of soil inhomogeneities on a uniform electric field shows that horizontal variations in local terrain or soil composition can cause significant amplifications of the electric field in the vicinity of the inhomogeneity. Calculations suggest that the electric field could be multiplied by factors of five or ten in worst-case situations of inhomogeneity. To date, there appears to have been no appreciation of this type of field enhancement, in either official calculations of step potential and body currents, or in any planned program of measuring step potentials at antenna sites.

Thus far in the Seafarer program, official conclusions about antenna ground safety have been based on two approaches: calculations of step potential and body currents using a homogeneous-earth model and a two-layer earth model, and site measurements of step potential and load currents at the Bravo Test Facility. Homogeneous-earth models are not applicable to the top one meter of earth, however, because climatic variations make that layer of earth extremely inhomogeneous as an electrical conductor; assigning a single value of electrical conductivity to the soil for the purposes of calculating antenna safety is a meaningless exercise. The two-layer earth model is applicable to the soil surface, however, and does permit valid conclusions to be drawn, provided that correct values are used for soil conductivity. The most recent Navy-sponsored two-layer calculations suffer only from the fact that although a range of conductivities was assumed for the two layers, there has been no experimental work to show that soil conductivity at the three Seafarer sites actually falls within that range at all times of the year and under all climatic conditions. On-site measurements made in 1968-1970 at the BTL were a step in the right direction, but that series suffered from being insufficiently broad in scope; measurements must encompass worst-case climatic and terrain conditions in order for conclusions about safety to be validly drawn.

On the basis of offical Navy documents and other literature, we judge that present understanding of soil electrical conductivity at the ground terminal sites is not sufficient to allow judgments to be made about the safety of the antenna grounds. A range of conductivities has been assumed in theoretical calculations of body currents and step potentials, but no measurements have been made to corroborate the assumed range, and no concerted experimental effort has been made to find worst-case conditions at the site and to measure step potentials and body currents under worst-case climatic and terrain conditions.

In order for valid conclusions to be drawn about the safety of Seafarer ground terminals, the following types of information would have to be obtained by site-specific measurements:

(1) <u>Soil electrical conductivity</u> as a function of depth in the top two meters of earth, and as a function of time of year and time of day. The aim of these measurements would not be to obtain a single average value of conductivity, but would rather be to obtain the typical range and extreme values so that worst-case conductivities would be known. Seasonal extremes such as spring thaw and summer rainstorm (and others listed in Table 5) should be sought out and included in the program of measurement.

(2) Step potentials and body currents as a function of local terrain, time of year, and time of day. The aim here should be to find typical ranges and extreme values so that worst-case conditions would be known (see Table 6). Times and places of measurement should be planned so that the worst-case climatic conditions and the worst-case horizontal variations in conductivity are encompassed.

PART I. INTRODUCTION

Environmental impact and safety of the Navy's proposed Seafarer Communication System has been a major concern since design and planning on the ELF antenna was begun years ago under the name Project Sanguine. The antenna ground terminals will directly expose the surrounding environment to an oscillating electric field and current of significant magnitude, hence questions about the strength of the field and the probability of electric shock to persons in the area have been raised. Recent information about the antenna design and environmental electric fields provided in the Kruger presentation (10 January 1977) and the SPECOM report on Seafarer electromagnetic fields at the Michigan site (22 December 1976) give the following antenna design specifications for assuring that the ground terminals will be environmentally compatible (i.e., safe in regard to electric shock):

1. The electric field at the surface of the earth near the antenna ground terminals shall not exceed 15 volts/meter, when averaged over any one meter span.
2. Ground terminals will be constructed so as to limit the maximum possible body current to less than 1.0 milliampere for a (biped's) one-meter step. Maximum body current is to be calculated from the equation $I_b = \frac{E_{max}}{R}$ [1]

   where: I_b = maximum possible body current for 1-meter step (amps),

   E_{max} = maximum surface voltage gradient average over a 1-meter step (volts/meter), and

   R = worst case current path electrical resistance (ohms).

The worst case path resistance shall be calculated from the following equation: $R = 1000 + \frac{5}{\sigma}$ [2]

where:

σ = soil conductivity (mhos/meter) at the site in question,

1000 = approximate resistance (ohms) of a human body along the current path: extremity-torso-extremity, and

$5/\sigma$ = contact resistance of the two feet in contact with the soil (each foot considered to be in series between body and soil).

3. Soil conductivity measurements shall be made to evaluate for the site under consideration, and due consideration shall be given to seasonal variations in its value.
4. Bodies of water will be avoided in laying the antenna grounds, and the distance between ground wire and water shall be such that the electric field in the water shall be limited to 1.0 volt/meter.

These design specifications require that site measurements be made of surface voltage gradients and soil electrical conductivity so that E_{max} and I_b can be calculated and terminal construction can be initiated or modified to reduce any dangerously high values in either step potential or body current.

Two questions can be immediately raised about the four specifications listed above. The first, which is the subject of study by other scientists and will not be treated in this report, is whether or not the

15 volts/meter value for the step potential and 1.0 milliampere value for body current will actually ensure safety of humans in the vicinity of a ground terminal.

The second question, which is the subject of this report, is when, where, and how should site measurements of E_{max} and soil conductivity be made in order to ensure that the true maxima of E and I_b have been identified for each and every dangerous spot on each ground terminal.

It is certainly appreciated by Seafarer system designers that the antenna return path electrical resistance depends on the nature and composition of substrata materials underlying the antenna grid, and that the ground terminal resistance depends on the electrical resistivity of the top few hundred meters of earth in which the ground terminal is embedded. Resistivity measurements to date have aimed at ascertaining average values for these deep-layer resistivities. System designers have also appreciated that the environmental safety and impact of the antenna ground terminals depend sensitively on the electrical resistivity of the top several meters of soil, and that the gross operational efficiency of the system or grounds does not depend sensitively on the conductivity of the top few meters of earth.

What does not appear to have been realized, however, is that soil electrical conductivity varies strongly as a function of water content, soil texture, temperature, and conductivity of the soil solution. These variables, in turn, are influenced markedly by seasonal variations, by natural variations in terrain, and by vertical stratification of the top two meters of the soil, making it virtually impossible to assign a single average value to soil conductivity , for use in Eq. [2]. In order for worst-case conditions to be identified for both step potentials and body currents, these seasonal and spatial variations must be understood so that conductivity measurements can be made at the optimal places and times. Part II of this paper describes the manner in which soil conductivity varies environmentally and seasonally, and suggests times and locations where extreme conditions might be met.

Local inhomogeneities in the conductivity of the conducting medium can also lead to significant spatial variations in current density near ground terminals, and hence to significant variations in the magnitude of the electric field in the vicinity of the inhomogeneities. Since these variations can amount to an amplification of the electric field by perhaps an order of magnitude, understanding why and where they might occur can lead to optimal choices for measuring worst-case step potentials near a ground terminal. Part III of this paper discusses the effect of inhomogeneities on a uniform electric field, estimates the magnitude of such effects, and suggests environmental situations in which extreme situations might be met.

Part IV discusses two models of antenna ground behavior: the homogeneous earth model and the two-layer earth model. The usefulness and accuracy of these models for predicting ground terminal resistance will be discussed, and the accuracy with which these models can describe the environmental impact at the soil surface will be evaluated. The current status of Navy thinking on Seafarer environmental safety and its dependence on soil conductivity will be summarized, at least to the extent that it can be evaluated from available documents. Values assigned to soil conductivity in Seafarer literature will be presented, along with the models to which these values are applied, and both values and models will be appraised in light of the material presented in Parts II-IV of this paper.

The paper will conclude with a summary of soil conductivities that are likely to be found at the Michigan, Nevada, and New Mexico sites, and an appraisal of their worst-case seasonal and environmental conditions. Recommendations will be made concerning site measurements that should be made in order to ensure that extremes of antenna safety margins have been encompassed in the construction of ground terminals.

PART II: SOIL ELECTRICAL CONDUCTIVITY--REPRESENTATIVE VALUES AND ENVIRONMENTAL/SEASONAL VARIATIONS

Partial results of a literature search on soil electrical conductivity are presented in Table 1. All data except that of Waugh (1968), Dell (1965), and Scott (1971) were obtained with Wenner four-electrode arrays, or variations thereof, and are considered to represent well-designed assessments of soil conductivity for the given conditions of measurement. Methods for the data of Waugh, Dell, and Scott are not known. Alternating-current fields of low frequency were used for the 4-electrode measurements, making the resulting conductivities appropriately measured for the frequencies of the Seafarer system; for example, Rhoades and Ingvalson (1971), and Rhoades, Raats, and Prather (1976) used a Model 63220 Megger Null Balance Earth Tester that operated between 10 and 20 cycles per second.

It is important to note that the various data were obtained under widely different circumstances: some are field measurements on undisturbed and untreated soils, some are field measurements on artificially salinized soil plots, and some are laboratory measurements on soil bodies either artificially packed or removed "undisturbed" from a field site. The "conditions of measurement" and "comments" columns give relevant experimental conditions.

In spite of the varying soil texture, location, and soil use, however, the soil conductivities fall generally in the range of 10 to 100 millimhos/meter for non-frozen, non-saline soils having water contents in the normal moisture range (0.10 to 0.50 cm^3/cm^3). Conductivities below this "general range" were obtained only in the extremes of very low water content, low

TABLE 1

Soil Electrical Conductivities

Soil Electrical Conductivity mmho/m	Soil Name & Texture	Conditions of Measurement	Soil Water Content cm^3/cm^3	Electrical Conductivity of Soil Sol'n mmho/m	Comments	Reference
60 to 0.5	Webster silty clay loam	Field soil in Ames, Iowa; no pretreatment; 25°C; <u>in situ</u> measurement.	.50 to .06	Not Measured	Drying soil; probe spacing = 3 in.	Kirkham & Taylor (1949); Taylor (1950); and Kirkham (personal communication, 1977).
0.5	Webster sicl	Field soil, Iowa	0.10	Not Measured	T = 7°C	Taylor (1950)
5.0	Webster sicl	Field soil, Iowa	0.10	Not Measured	T = 25°C	Taylor (1950)
10.0	Webster sicl	Field soil, Iowa	0.10	Not Measured	T = 35°C	Taylor (1950)
20.0	Webster sicl	Field soil, Iowa	0.29	Not Measured	T = 7°C	Taylor (1950)
27.9	Webster sicl	Field soil, Iowa	0.29	Not Measured	T = 25°C	Taylor (1950)
33.6	Webster sicl	Field soil, Iowa	0.29	Not Measured	T = 35°C	Taylor (1950)
285	Clay loam	Field measurement; no treatment	0.29	1950	Saline seep	Halvorson & Rhoades (1974)

TABLE 1--Continued

Soil Electrical Conductivity mmho/m	Soil Name & Texture	Conditions of Measurement	Soil Water Content cm^3/cm^3	Electrical Conductivity of Soil Sol'n mmho/m	Comments	Reference
20	Clay loam	Field measurement; no treatment.	0.14	40	Recharge area upslope of saline seep	Halvorson & Rhoades (1974)
30	Not given	*In situ* measurement; no treatment.	?	?	Citrus stand; 15 cm depth.	Rhoades & Schilfgaarde (1976)
70	Not given	*In situ* measurement; no treatment.	?	?	Citrus; 100 cm depth.	Rhoades & Schilfgaarde (1976)
25 to 300	Wellton-Mohawk soils of Arizona: ls, sl, sil, and sicl.	Field plots artificially salinized.	Field capacity	200 to 2000	Typical arid region soil conditions	Rhoades & Schilfgaarde (1976)
52	Indio silt loam	Alfalfa field; no salinization	?	?	15 cm depth	Rhoades & Schilfgaarde (1976)
159	Indio silt loam	Alfalfa filed; no salinization	?	?	45 cm depth	Rhoades & Schilfgaarde (1976)
190	Indio silt loam	Alfalfa field; no salinization	?	?	105 cm depth	Rhoades & Schilfgaarde

TABLE 1--Continued

Soil Electrical Conductivity mmho/m	Soil Name & Texture	Conditions of Measurement	Soil Water Content cm^3/cm^3	Electrical Conductivity of Soil Sol'n mmho/m	Comments	Reference
10 to 200	Pachappa fsl	Field plots, artificially salinized	Field capacity, 0.12	100 to 2000	Cotton irrigated with saline water	Rhoades & Ingvalson (1971)
20 to 250	Columbia fsl	Soil packed in tank; salinized	Zero to 125 cm of suction	50 to 1600	Saline soil	Shea & Luthin (1961)
25 to 1200	Indio vfsl	Undisturbed soil cores measured in lab; salinized	.10 to .50	250 to 5600	Soil solution had Sodium Absorption Ratio of 4.0	Rhoades, Raats, & Prather (1976)
18 to 560	Pachappa fsl	Undisturbed soil cores measured in lab; salinized	.10 to .30	250 to 5600	Soil solution had Sodium Absorption Ratio of 4.0	Rhoades, Raats, & Prather (1976)
40 to 420	Waukena loam	Undisturbed soil cores measured in lab; salinized	.20 to .40	250 to 1900	Soil solution had Sodium Absorption Ratio of 4.0	Rhoades, Raats, & Prather (1976)
45 to 520	Domino cl	Undisturbed soil cores measured in lab; salinized	.25 to .40	250 to 1900	Soil solution had Sodium Absorption Ratio of 4.0	Rhoades, Raats, & Prather (1976)

TABLE 1--Continued

Soil Electrical Conductivity mmho/m	Soil Name & Texture	Conditions of Measurement	Soil Water Content cm^3/cm^3	Electrical Conductivity of Soil Sol'n mmho/m	Comments	Reference
14 to 75	Palouse silt	Field soil	.05 to .14	?	Method Unknown	Waugh (1968)
2.0	Clay-shingle mix	Top one foot	?	?	Method Unknown	Dell (1965)
8 to 90	General relation to many soils	Fitted	.10 to .50	?	Method Unknown	Scott (1971) as cited in Longmire & Smith (1975)

Note: s = sand; si = silt; c = clay; l = loam; f = fine; for example, vfsl = very fine sandy loam; sicl = silty clay loam.

temperatures, or unusual soil texture such as the clay-shingle mix of Dell (1965). Conductivities above the general range were obtained in the extreme of high salinity, and were typically 100 to 400 mmho/m for salinities found in the arid region soils of the United States, and could reach values of as high as 1000 mmho/m under extremely high salt conditions.

Having identified a general range of 10 to 100 mmho/m and noted deviations above it (in the 100 to 400 mmho/m range) and below it (in the 1.0 to 10 mmho/m range), we emphasize that the high and low ranges will probably be often met with under field conditions, as a result of natural seasonal and environmental conditions, and that the highs and lows should not be regarded as statistical fluctuations having low probability of occurrence.

The factors governing soil conductivity will now be considered in more detail, and applications to the soils of the Michigan Upper Peninsula will be made in order to estimate conductivities and to identify variations that will probably hold in the various extremes of weather and terrain.

PART II. SOIL ELECTRICAL CONDUCTIVITY--REPRESENTATIVE VALUES AND ENVIRONMENTAL/SEASONAL VARIATIONS

1. DEPENDENCE ON WATER CONTENT

The data of Kirkham and Taylor (1949) and Taylor (1950) in Table 1 show the trend of soil conductivity increasing with an increase in water content. Water contents of .05 to .10 cm^3/cm^3 correspond generally to very dry conditions, while water contents in the range .40 to .50 correspond to very wet (or saturated) conditions, depending on soil texture.

Table 2 below shows the relation between soil conductivity and moisture content in detail for the Webster silty clay loam studied by Taylor (1950). As percent moisture decreased from about 50% down to 6%, soil conductivity decreased by a factor of 100, from roughly 60 millimho/m to 0.5 mmho/m (to convert the numbers in Table 2 to mmho/m, multiply by ten; i.e., 6.00×10^{-4} mho/cm = 60.0 mmho/meter).

Figure 1A. shows the relation between soil conductivity and water content found by Rhoades, Raats, and Prather (1976) on an Indio very fine sandy loam. The curve for $EC_w = 2.5$ (Figure 1A) shows that as water content decreases from 0.45 to 0.08 cm^3/cm^3, soil conductivity decreases from 87.5 mmho/m to 10 mmho/m.

Scott (1971), as cited in Longmire and Smith (1975), measured water content and soil conductivity for a variety of different soils and found that the average electrical conductivity could be correlated with the single parameter, water content. Figure 2 shows Scott's correlation. At 100% water content, corresponding to pure soil solution, conductivity equals 250 mmho/m, which means that the Scott curve should compare somewhat with the data of Rhoades et al. (1976) for their case of soil solution

TABLE 2

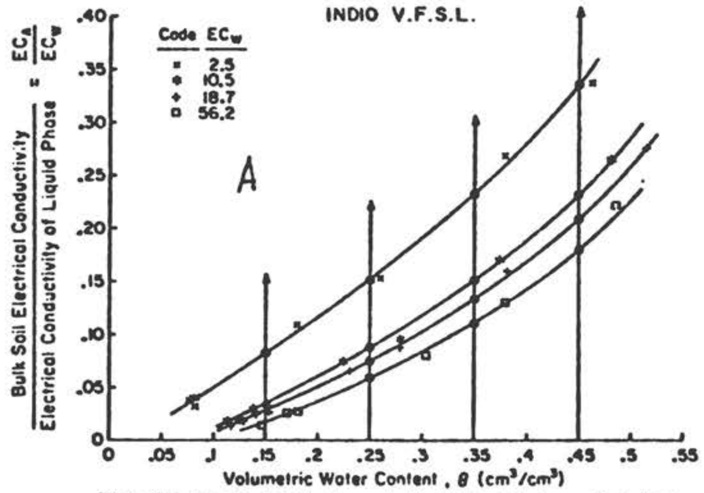
Experimentally Determined Relationship Between Soil Electrical Conductivity σ and Moisture Content, at a Temperature of 25°C

(From Taylor, 1950)

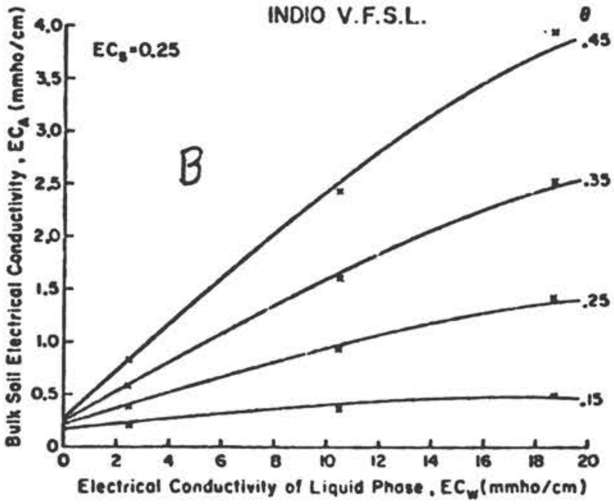
	Webster Silty Clay Loam, Story County, Iowa					
	Unit No. 4		Unit No. 5		Unit No. 9	
Date	x 10^4 (mho/cm)	Percent Moisture	x 10^4 (mho/cm)	Percent Moisture	x 10^4 (mho/cm)	Percent Moisture
8-5	6.00	52.12	5.75	50.02	6.52	51.02
8-7	4.77	46.53	5.12	47.46	4.92	46.91
8-9	4.39	42.28	4.54	42.62	4.34	42.56
8-11	3.68	38.02	3.84	38.26	3.52	36.15
8-12	2.82	31.09	3.37	34.00	3.12	33.86
8-14	2.82	30.42	3.05	31.35	3.04	33.18
8-16	2.47	26.17	2.81	27.96	2.99	31.12
8-18	2.31	20.58	2.44	22.66	2.58	25.40
8-20	2.14	17.67	2.25	20.76	2.40	22.43
8-22	1.73	15.66	1.86	15.74	2.19	19.68
8-24	1.60	14.99	1.07	12.71	1.90	16.02
8-26	1.20	13.65	0.69	10.80	1.65	14.65
8-28	0.32	10.07	0.22	8.69	0.51	10.30
8-30	0.12	8.72	0.04	6.78	0.20	8.92
9-1	0.06	7.38	0.04	6.14	0.12	8.24
9-3	0.05	6.49	--	--	0.09	6.86
9-5	--	--	--	--	0.08	5.95

Moisture equivalent - 24.46.
Fifteen atmosphere percentage - 13.5.

Fig. 1. Relationships between soil electrical conductivity, water content, and soil solution conductivity (from Rhoades et al., 1976).

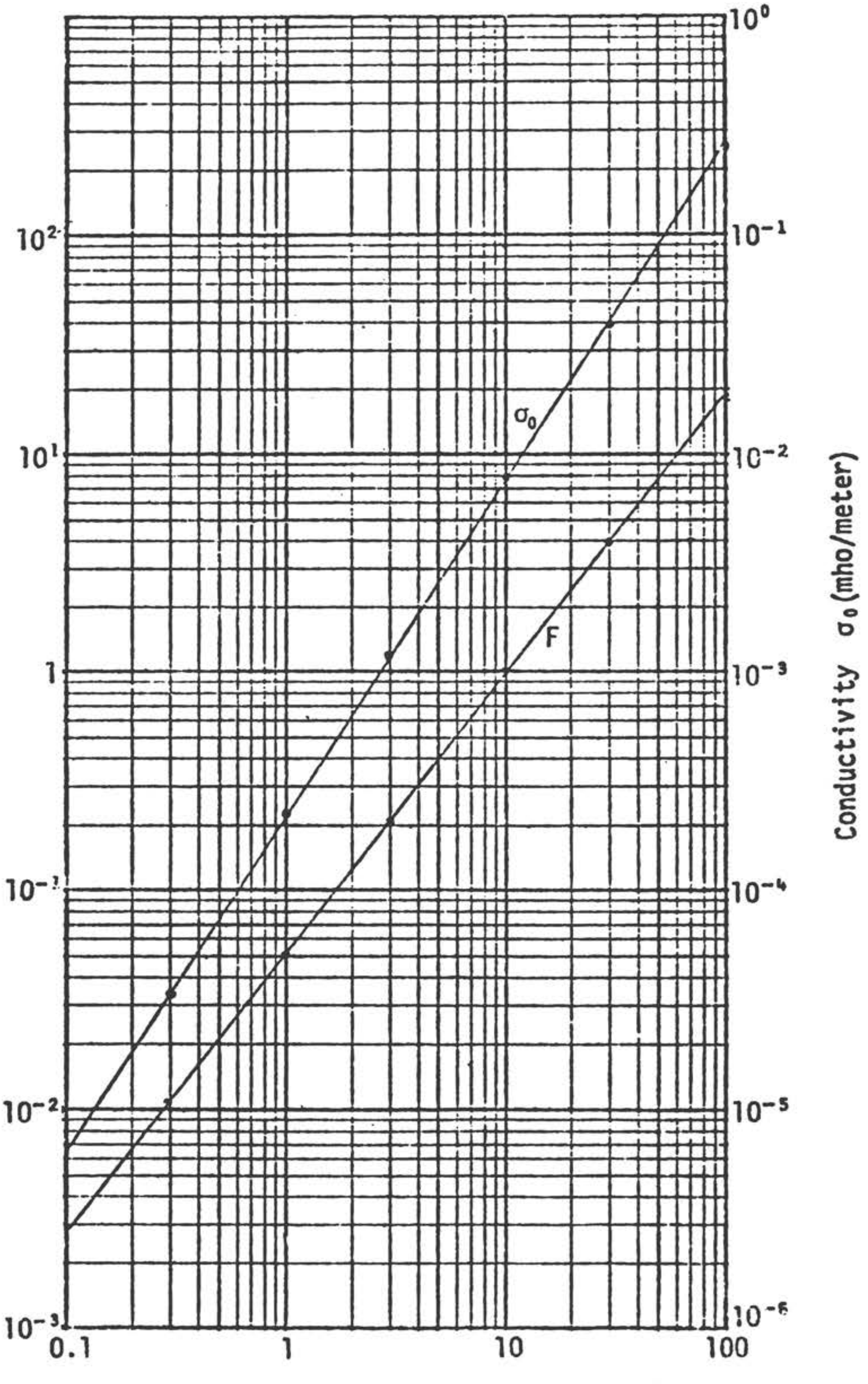


—Plot of bulk soil electrical conductivity/liquid phase electrical conductivity, EC_a/EC_w, vs. volumetric water content, θ, for Indio vfsl.



—Plot of bulk soil electrical conductivity, EC_a, vs. liquid-phase electrical conductivity, EC_w, for various fixed volumetric water contents as interpolated from Fig. 3 for Indio vfsl showing the extrapolated value of surface conductivity, EC_s.

Fig. 2. Relation of soil electrical conductivity to water content (from Scott, 1971, as cited in Longmire & Smith, 1975).



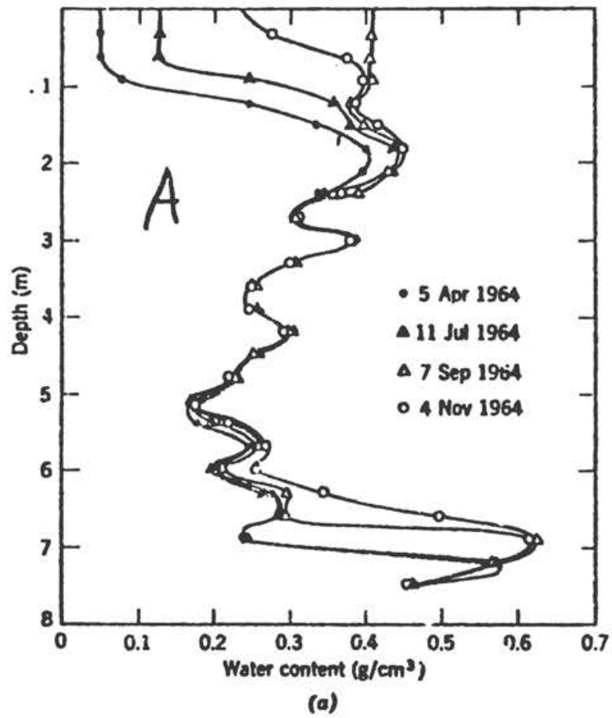
conductivity equal to 250 mmho/m (upper curve of Figure 1A). And indeed the two curves do match very well. For water content = 0.45, Rhoades et al. found a conductivity of 87 mmho/m and Scott's curve gives 80 mmho/m, while for water content = 0.10 Rhoades et al. found a conductivity of 12 and Scott's curve gives 8.

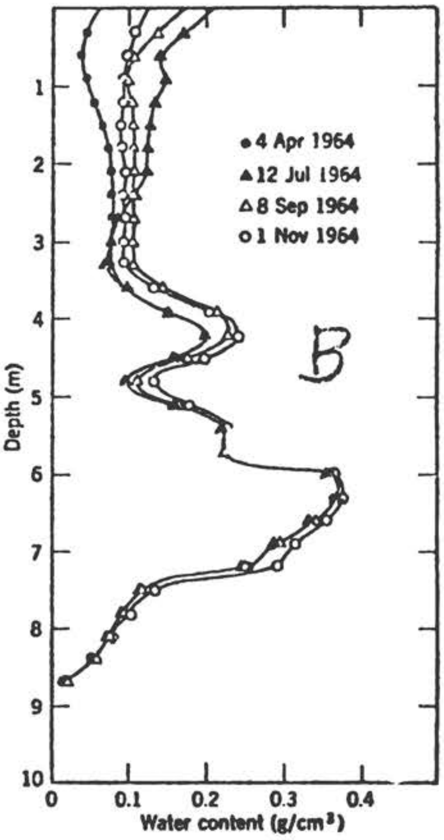
The extremes of water content measured in these three references are not uncommon. Saturated conditions (water content $\simeq$ 0.50) are realized in the top cm or so of field and forest soils after heavy rainfall or during spring thaw in northern climates, while very dry conditions are realized in the top meter of soil during dry periods toward the end of the summer for Wisconsin and Michigan, and during most of the summer in arid regions of the Southwest. Water content of the top meter of soil is perhaps the most unpredictable and variable soil parameter that is subject to seasonal and environmental change.

Yearly seasonal trends cause soil water to increase during the wet season (or spring months) and to decrease during the dry season (summer months) in most of the continental U.S. An example of this annual variation is given in Figure 3 for moisture profiles of sands under forest in the southern hemisphere. Figure 3A shows that the top meter is at high water (0.41 g/cm^3) in September (beginning of the warm season in that hemisphere) and by April (end of the warm season) is almost entirely depleted of water (content down to 0.05 g/cm^3) to a depth of one meter. Figure 3B shows a similar but less extreme yearly variation of a sand forest soil.

Redistribution of water following rainfall or irrigation causes changes of soil water content on a time scale of a few weeks, as shown in

Fig. 3. Variation of soil water content with season (from Holmes & Colville, 1970).





Soil water profiles. (*a*) = Young sand, Mount Gambier Forest; (*b*) Kalangadoo sand, Penola Forest. (Holmes and Colville, 1970.)

Figure 4, in which irrigation saturated the top 17 cm of a profile that was otherwise uniformly dry (moisture content = 0.05) to a depth of 80 cm. In the 40 days following irrigation, the top ten cm of soil decreased from 40% water down to 22%, and the wetting front penetrated to a depth of 40 cm. The soil below 40 cm remained at its initial water content. This trend is expected of field soils following heavy rainfall: the top 10 cm or so will be saturated by the rain and will remain high in water for a few days, during which soil electrical conductivity will be at its maximum value; redistribution will quickly decrease the surface water content after the first few days, and soil conductivity in that layer will drop markedly. After one or two weeks, redistribution takes place at a much slower rate and soil conductivity will show small but steady decreases as the soil water content continues to decrease. This cycle will repeat itself after every major rainfall. Wet summers will lead to high soil conductivity throughout most of the growing season, while a dry year will produce very low soil electrical conductivities.

Water content of the top one or two cm of soil deserves special comment since this thin layer might act as an insulating barrier and provide extra safety margins to persons. The top half centimeter of soil dries quickly after rainfall or irrigation, and undergoes marked daily variations as shown in Figure 5. During and immediately following a rainfall, this layer will be high in water and provide good electrical connection between a person's foot and the deeper reaches of soil, but as it dries out it will serve to insulate a person from the wetter regions below. The top centimeter is driest a few hours before sunset and wettest just at sunrise (Figure 5). The behavior of this layer is relevant to methods of measuring soil conductivity: probes which penetrate a foot into the soil

Fig. 4. Variation of soil water content with depth and time during redistribution after irrigation (from Gardner et al., 1970).

380 SOIL WATER—THE FIELD MOISTURE REGIME

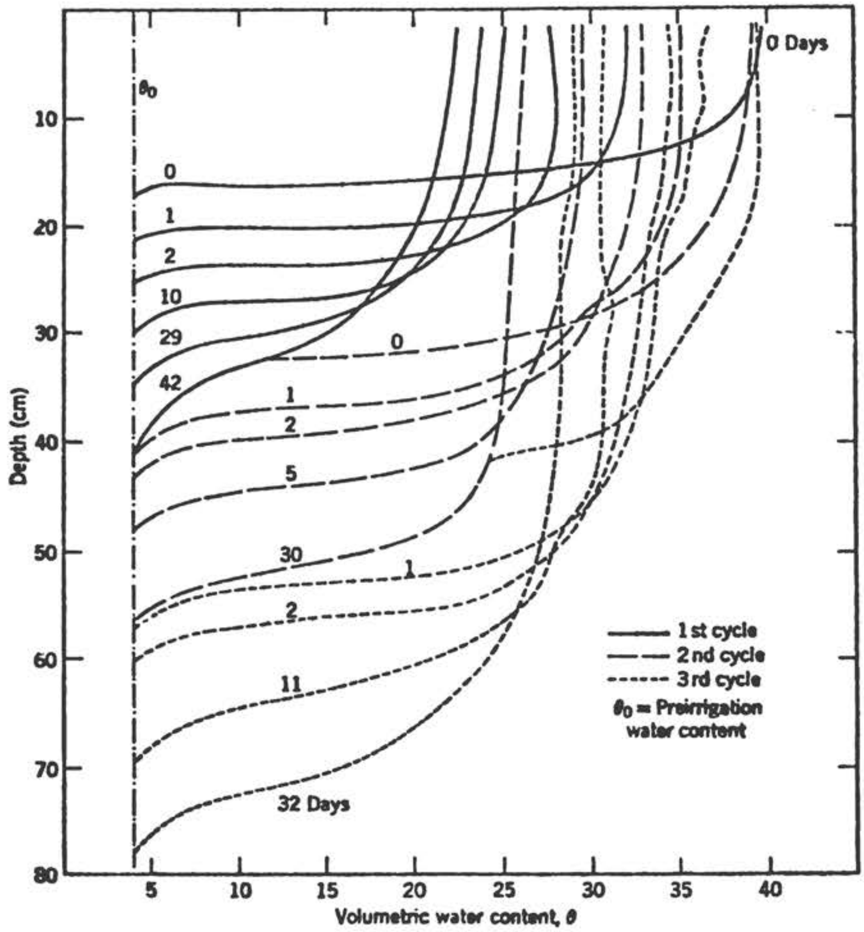


FIG. 10-12. Successive water content profiles during redistribution cycles following one, two, and three irrigations of 5 cm each. (Gardner et al., 1970.)

Fig. 5. Diurnal variation of water content in the top half-centimeter of soil (from Jackson, 1973).

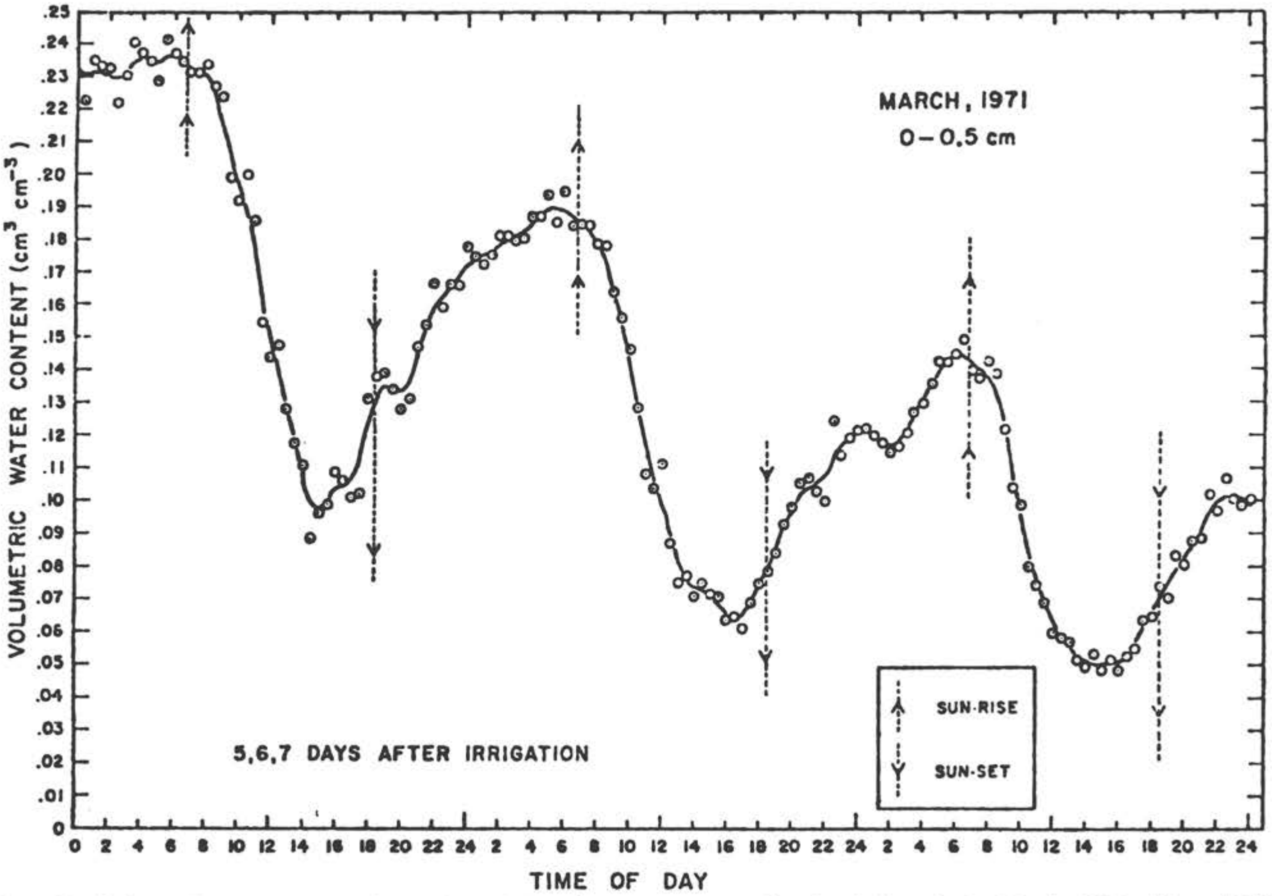


Figure 2. Volumetric water content in the 0- to 0.5-cm increment versus time for 3 days during March 1971. The solid line represents smoothed data and the symbols represent the measured values.

will not "see" the resistance of this top thin layer, whereas probes that go only a few inches deep (as that of Kirkham & Taylor, 1949) will measure conductivity of the upper few inches. A probe with electrodes that press flatly on the soil surface would seem to model a biped's foot contact with the soil more accurately than electrodes that are driven several inches into the soil.

It is reasonable to ask just how low the soil electrical conductivity becomes as the soil becomes very dry. The references cited do not provide consistent answers to this question. Taylor (1950), for example, measured drying soils and repeatedly found conductivities in the range 0.5 to 1.0 mmho/m (See Table 2). Rhoades et al. (1976), on the other hand, extrapolated their data to pure water soil solution and identified what they called the surface electrical conductivity (EC_s) of their soils, which is the conductivity resulting from the exchangeable ions (cations) that reside on the surfaces of the silt and clay fractions of the soil. The surface conductivity, they argue, is independent of water content, and their formulation of the dependency of conductivity on soil water content gives EC_s to be a residual conductivity that holds in the limit of zero water. Importantly, the values they obtained for EC fall in the range 20 to 40 mmho/m for a range of soil textures (sl, vfsl, l, and cl), which is much higher than Taylor found for his silty clay loam in the limit of zero water content.

This discrepancy needs to be resolved because the Rhoades et al. results suggest that there is a minimum conductivity below which soil values will not fall in drying soils, while the Taylor results show soil conductivity falling considerably below the Rhoades et al. minimum. Different soil textures could not explain this problem, because Taylor's silty clay loam is similar in texture to a clay loam measured by Rhoades et al. to have a high EC_s.

Although there is little evidence to help decide this question, I feel that the answer may reside in one of two places in the Rhoades et al. experiment. First of all, they pretreated their soils with a solution having a high sodium salt content, which could have loaded the exchange sites and enhanced the surface conductivity many times over what Taylor's field soil might have had. Secondly, a close inspection of Figure 1A shows that few measurements were made in the water content range below 0.1 cm^3/cm^3, and hence the Rhoades results for surface conductivity were obtained by an extrapolation beyond the range of actual measurements. It could be that water content becomes an important factor in reducing soil conductivity in the low water range, and that they did not see such a factor because of their truncated range of measurement. In fact, a close inspection of Figure 1A shows that for EC_w = 250 mmho/m and water content = 0.08, bulk conductivity was found to equal 12 mmho/m, which is considerably lower than the surface conductivity of 25 mmho/m estimated for the Indio vfsl.

If the salt loading or the extrapolation did lead to spuriously high surface conductivities for the soils measured by Rhoades et al., then field and forest soils of the Michigan site might be expected to behave more like Taylor's Iowa soil than Rhoades' experimental soils. In my opinion the question of minimum soil conductivity at the Michigan site must be answered by experiment. I would not be surprised to find that for extremely dry soil there is a minimum conductivity around the value

10 mmho/m, but I would also not be surprised to find that conductivity dipped a factor of ten below that value.

Soils at the proposed Nevada and New Mexico sites will have higher salt content than the Michigan UP site, on average, and might therefore have a significantly high minimum conductivity during the dry season if the results of Rhoades et al. (1976) hold. Thus soil conductivity might remain at the two southwestern U. S. sites, and might rise to the range 100 to 400 mmho/m during and after rainstorms or melting snowfall. Values approaching 1000 mmho/m might occur under extreme conditions of high salt content.

Summary. Water content in the top meter of soil can be expected to vary widely annually with season changes and on a week-to-week basis depending on local weather The top 10 cm of soil will experience daily changes in water content under the influence of the diurnal cycle of solar heating and evaporation. Contents from 0.05 to 0.50 cm^3/cm^3 are the expected limits to this variation, and for a given soil, these water content fluctuations may lead soil conductivity at the three proposed sites to vary by as much as a factor of 10 to 100 between the extremes of saturation and very dry conditions.

2. DEPENDENCE ON TEMPERATURE

As soil temperature decreases in an unfrozen soil, the viscosity of the soil solution decreases and ion mobility becomes smaller, leading to decreased electrical conductivity. As Table 3 shows, the decline in conductivity is less sharp for high water content than it is for low water content, presumably because viscosity effects are relatively more important when the amount of water in the soil is small and most of it resides as thin films on soil particles. In the high water range, conductivity approximately doubles as temperature increases from 7°C to 45°C, while for low water contents conductivity increases by factors as high as 30 or 40 for the same temperature increases.

As the soil freezes, ion mobility and electrical conductivity decrease sharply, and although we have not obtained data to quantify the exact decreases, we expect conductivity in frozen soil to be two or three orders of magnitude below the value for the same soil at 25°C.

As far as environmental temperature variations go, dry soils will show the greatest relative variability. For example, a dry soil at the end of the warm season, subject to frost temperatures nearing 0°C will show the lowest conductivity, while that same soil may show a conductivity thirty times higher a few days later when temperatures have risen back up to the 25°C range.

The depth to which soil freezes in the upper Midwest depends on the severity of the winter, of course, and also on the depth of the snow cover. A thick cover of snow insulates the soil from the cold air and

TABLE 3

Relation of Soil Electrical Conductivity to Soil Temperature At Constant Water Content (From Taylor, 1950)

Temperature °C	σ in mho/cm x 10^4						
	Clarion Silt Loam						
	Percent Moisture						
	12.33	16.05	18.41	20.10	28.29	29.75	37.47
7	--	0.68	--	0.82	1.22	--	1.81
9	0.52	--	0.76	--	--	1.33	--
15	0.64	0.83	0.89	0.97	1.38	1.47	1.97
20	0.79	0.98	1.04	1.12	1.54	1.63	2.13
25	1.01	1.20	1.26	1.35	1.77	1.86	2.36
30	1.27	1.46	1.52	1.61	2.03	2.12	2.62
35	1.58	1.77	1.83	1.92	2.33	2.42	2.92
40	1.92	2.12	2.19	2.28	2.68	2.77	3.28
45	2.29	--	2.56	--	--	3.15	3.66
	Webster Silty Clay Loam						
	Percent Moisture						
	10.52	14.81	19.09	21.47	29.47	35.44	41.22
6	--	0.76	1.37	--	--	2.44	3.28
7	0.05	--	--	1.67	2.08	--	--
9	0.05	0.89	1.45	--	--	2.65	3.49
15	0.08	1.09	1.60	1.88	2.30	2.87	3.72
20	0.26	1.31	1.76	2.10	2.54	3.11	3.97
25	0.48	1.55	2.21	2.35	2.79	3.37	4.23
30	0.72	1.81	2.48	2.62	3.07	3.65	4.51
35	0.98	2.09	2.76	2.90	3.36	3.95	4.81
40	1.28	2.40	3.08	3.23	3.68	4.27	5.15
45	1.60	2.73	3.41	3.57	4.02	4.61	5.50

prevents deep freezing. Thorud and Duncan (1972) found that for a Minnesota oak stand, a layer of snow as thin as 13 cm was significant in decreasing depth of freezing: frozen soil averaged 38 cm deeper in snowless plots than in snow-covered control plots, and the control plots froze to depths of 60 to 80 cm.

According to Dr. S. G. Shetron of the Ford Forestry Center, Michigan Tech. University, snowfall in the Upper Peninsula averages three to four feet a winter, and if the snow is early the soil rarely freezes more than a few inches deep (personal communication, 1977). In such cases, snowmelt continues throughout the winter and constantly supplies a small flux of water to the unfrozen soil.

Soil electrical conductivity in the winter at the Michigan site is therefore expected to vary greatly from year to year, depending on snowdepth and depth of soil freezing. A heavy snowfall early in the winter will probably lead in general to unfrozen soils and a conductivity represenative of unfrozen soils at 0°C, while sparse snow will allow deep freezing soils and marked decreases in conductivity below the value of unfrozen soils. It should not be overlooked that even when snow is plentiful, its spatial distribution is not always uniform, and that deeply frozen and unfrozen patches of soils might be found in the same vicinity, depending on local terrain.

3. DEPENDENCE ON SOIL SOLUTION

Since electrical current in the soil is the motion of ionic species, conductivity depends on the electrolyte concentration of the solution that surrounds soil particles. For a given water content, the relation between soil conductivity and the electrical conductivity of the soil solution is approximately linear, as shown in Figure 1B, Figure 6, and Figure 7. These figures show that soil conductivity generally has a value that is 5 to 30% of the soil solution conductivity, depending on water content.

The data of these three figures also show that soil conductivity does not extrapolate to zero when the conductivity of the soil solution becomes zero. This phenomenon is taken to indicate that interchangeable cations on the soil particle surface can migrate under an applied electric field and contribute to soil conductivity even when the soil solution is pure water. Rhoades et al. (1976) argue that the surface conductivity is approximately independent of water content. The three experiments reported in these figures give similar values for surface conductivity, showing it to be in the range 20 to 45 mmho/m. As discussed above, the existence of such high values of surface conductivity would imply a minimum soil conductivity in the field, yet the data of Taylor (1950), and of Scott (1971) show soil conductivities below the 20 mmho/m value. Thus while the question of minimum soil conductivity is still somewhat open, there is no question that when the liquid phase conductivity reaches values of 50 mmho/m and higher, the soil conductivity begins to increase and follow the soil solution in a linear fashion.

Fig. 6. Relation of soil electrical conductivity to conductivity of the soil solution (from Shea & Luthin, 1961).

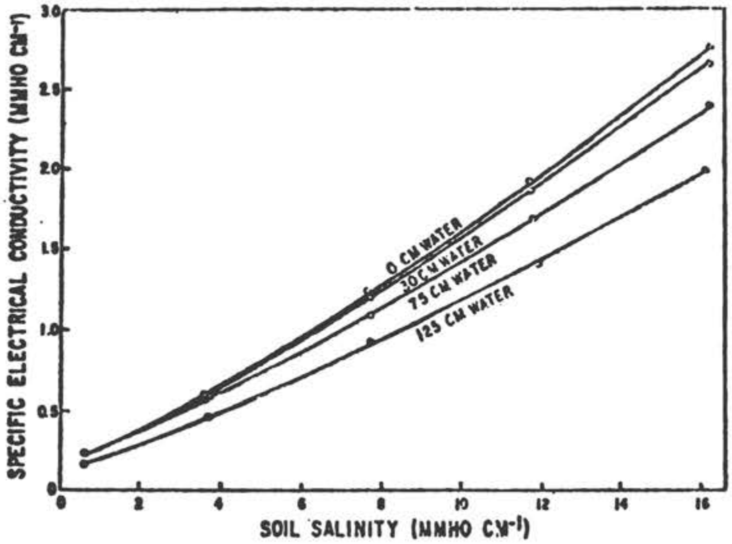


Fig. 5. Specific electrical conductivity as a function of soil salinity at specified soil-moisture suctions with the electrodes 1 foot below the soil surface.

Fig. 7. Relation of soil electrical conductivity (EC_e) to conductivity of the soil solution (EC_a) (from Rhoades & Schilfgaarde, 1976).

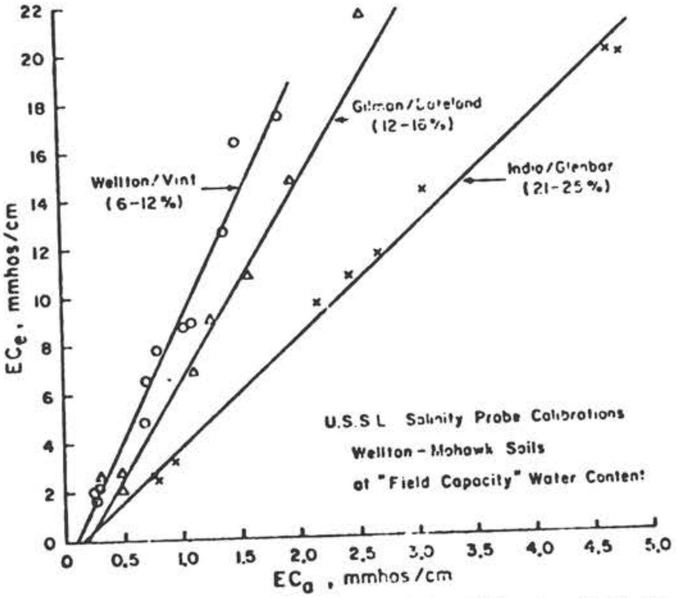


Fig. 3—EC_a − EC_e calibrations for Wellton-Mohawk soils as obtained with the soil-salinity probe.

Surface and subsurface waters in the Michigan Upper Peninsula are relatively pure and would not generally contribute to high soil conductivities. While water from some wells in the region reached values as high as 100 mmho/m, most were in the range 10 to 50 mmho/m (EDAW, Inc., 1974A). Most surface waters had conductivities in the range 10 to 30 mmho/m (EDAW, Inc., 1974B). Most of the data reported by EDAW, Inc., was obtained by water monitoring programs of the U.S. Geological Survey, the Michigan Department of Natural Resources Geological Survey, and the Michigan Department of Health.

Corroboration of these values is found in measurements made by Wilde, Trach, and Peterson (1949) and by Pierce (1953) on groundwater underlying Wisconsin forest soils and organic soils. Pierce found groundwater electrical conductivity to range from 5 to 20 mmho/m beneath moss peat bog supporting black spruce and woody peat swamp supporting white cedar and balsam fir, and he found values in the range 30 to 70 mmho/m under a sedge peat marsh. Wilde et al. found groundwater in organic soils to have conductivities in the range 10 to 70 mmho/m. Table 4 summarizes these data on well water and groundwater conductivity in Wisconsin and Michigan.

Highly saline soils are not a problem in the Michigan Upper Peninsula, yet in considering the soil conductivity near an antenna ground it would be well to remember that local microrelief and accumulations of biological materials might concentrate soluble species to the extent of giving high soil solution conductivities. Wadleigh and Fireman (1948) showed that evaporating irrigation water in plowed land carried salt up

TABLE 4

Electrical Conductivity of Waters in the Wisconsin-Michigan Upper Peninsula Area

Water Location	Electrical Conductivity (mmho/m)			Reference
	Low	Typical	High	
Subsurface	Below 10	10 to 50	100	EDAW, 1974A
Surface		10 to 30		EDAW, 1974B
Groundwater Under Organic Soils		10 to 70		Wilde et al., 1949
Groundwater Under Organic Soils	5	20 to 30	70	Pierce, 1953

into the ridges and out of the furrows (evaporation from ridges predominated), giving a saturated extract conductivity of 5000 mmho/m for the ridges compared to a conductivity of less than 100 mmho/m for the furrows between the ridges. Sandoval et al. (1964) studied cropland located on an ancient, saline lake and found that the soil of ridges had conductivities up to 10 times higher than the soil of depressions, even though the ridges and depressions differed in height by only one foot and were separated by 100 to 200 feet. While these two examples admittedly dealt with saline soils, they show that topography is important in determining where salts will be deposited during evaporation. High spots are likely to be higher in salt than low spots, no matter what the prevailing level of salinity.

Evaporation from pond and wetland shorelines can concentrate soluble electrolytes near the waters' edges, making for high soil conductivity. Biological compounds such as amino acids, proteins, and other cellular constituents are also likely to accumulate near the edges of bodies of water due to decomposition of aquatic plant and animal remains and contribute significantly to soil electrical conductivity.

Soil solution is likely to be saline in soils of the Nevada and New Mexico sites, and soil electrical conductivity is therefore expected to be higher at those sites than in Michigan. The extreme variability of local conditions makes accurate prediction of salinity and conductivity impossible, so on-site measurements are necessary for soil conductivity to be quantitatively assessed.

4. SUGGESTIONS CONCERNING THE MICHIGAN SITE

Although detailed soil electrical conductivity measurements have not been made on the top meter of earth in the proposed Michigan Upper Peninsula Seafarer site, soil data indicates that the soil textures are similar to those which have been studied. The soil data map prepared by GTE Sylvania (Map 11 of ELF Communications Seafarer Program Site Survey Final Report Michigan Region, 1976) shows that approximately 50% of the site is covered with silt loam soils, 20% with sandy loam, 20% with sand, and 10% with mucky peat (wetlands soils). The mineral soils that cover 90% of the site fall into the general textural range of the soils that were studied in the experiments reported elsewhere in this paper, hence the data collected here is applicable to the Michigan site. Although measurements of conductivity of wetland soils have not been found and reported here, conductivity of groundwater in Wisconsin organic soils has been collected, and does allow estimates of how the mucky peats of the site might behave.

Site-specific measurements are necessary to ascertain the normal range and extremes (high and low) of soil conductivity, but in the absence of such we can estimate from the results of our literature search that for mineral soils the normal range of soil conductivity will be 10 to 100 millimhos/meter. Conditions of high water, high soluble salts, or high concentrations of decomposing organic matter will lead to values above this range, while it would require low water content, low salt, or freezing soils to give conductivities in the 1 to 10 mmho/m range or below. Frozen soils in winter will give very low conductivities (probably less than 0.1 mmho/m), but it will require a snowfree winter for soil freezing to progress to more than a few inches.

Organic soils will be very high in water throughout the entire year, and their conductivity will depend on the nature of the organic colloids and soluble salts that they contain. A rough order of magnitude estimation of conductivity would be to put it at the conductivity of the water which permeates the soil, which would indicate soil conductivities in the range 10 to 70 mmho/m for organic wetland soils.

From the point of view of safety, the worst-case soil conditions to have are a dry subsoil (or low conductivity basement underlying the top meter of soil) and a wet (highly conductive) layer of surface soil. The resistive lower layer would allow the antenna ground step potentials to reach high values at the surface, and the conductive top layer would put humans in good electrical contact with the earth, thus maximizing the possibility of shock. Two types of seasonal situations suggest themselves as being conducive to this dangerous condition: spring thaw, and times of heavy rain at the end of the summer. A deeply frozen soil thaws from the surface downwards and from the bottom upwards, sandwiching a very resistive layer of frozen soil between a wet subsurface stratum and a very wet topsoil with high conductivity. Dry conditions at the end of summer will establish a soil profile of low water content and low conductivity to a depth of one or two meters, and a rain will saturate the top 10 or 20 cm of soil and give it a relatively high conductivity.

Soil conductivity measurements aimed at covering the seasonal extremes of Michigan will have to be carefully made at specific times of the year. Table 5 gives suggested times for conductivity assessments of

TABLE 5

Suggested Times for Measuring Soil Conductivity at the Michigan Seafarer Site, and Qualitative Estimates of the Conductivities at Two Soil Depths

Time of Year and Climatic Condition	Expected Soil Conductivity (Millimhos/meter) At Indicated Depth	
	Top 10 cm	1.5 Meter Depth
Mid-winter (unfrozen soil)	low	low
Mid-winter (frozen soil)	very low	very low
Spring thaw (subsoil frozen)	medium	very low
Early summer, late spring	high	high
Summer (during drought)	very low	medium to low
Summer (after drought-ending rain)	high	low
Late fall (frost on dry soil)	low	low
Late fall (frost on wet soil)	low	medium

<u>**Note**</u>: For constant temperature, the daily solar and evaporation cycle would indicate that highest conductivities at the soil surface would be found at sunrise and lowest in late afternoon, due to the diurnal variation in water content of the surface. However, the diurnal temperature trend is generally opposite to the dryness, being highest in afternoon and lowest in early morning, so it is not clear exactly what hour of a given day will give the highest soil conductivity.

the topsoil and subsoil at 1.5 meter and lists conductivities expected to be found at those times.

Conditions of terrain that might lead to high soil conductivity are listed in Table 6, along with the factors that lead such sites to have high conductivity. Field measurements to identify worst-case situations should be made with these factors in mind.

In concluding, we point out that insofar as it relates to antenna safety, the treatment of soil conductivity in the official Navy literature seems to be in error on the values that soil conductivity might have at the antenna site. Recent documents assign a single value to soil conductivity and do not allow for seasonal and topographical variations (Genge, 1976; SPECOM, 22 Dec 1976; Kruger, 10 Jan 1977). In view of the literature presented in this Part, it is clear that soil conductivity at the site cannot be assigned a single value that will hold for all times of the year and for all locations along the ground terminal. The Navy's models for earth conductivity will be discussed in more detail in Part IV of this paper.

Assuming that a single value of soil conductivity could be assigned for the sake of calculating safety factors such as step potentials and body currents, we find the value 1.0 mmho/m used in the SPECOM report of 22 Dec 1976 (page 30) for the Michigan site to be unrealistically low by one or two orders of magnitude. For conductivity equal to 1.0 millimho/meter, the foot contact resistance $5/\sigma$ equals 5000 ohms and the total path resistance (Eq [2]) is 6000 ohms, leading to body currents of about 0.7 milliampere if the step potential is 4.0 volts. If the more realistic

TABLE 6

Terrain and Factors that Might Lead to High Soil Conductivity

Terrain of Special Concern for Measuring Soil Conductivity	Factors that Might Contribute to High Conductivity
Highland soil near water	High water content, high salts, high decomposing biomass
Lowland soil near water (swamps, bogs, wetlands)	High water content, high salts, high concentration of decomposing biomass
Soil with near-surface water table	High water content, high salts from evaporation
Soil near artesian wells with saline groundwater	High water, possible high salt concentration from passage of groundwater through geologic strata that are high in soluble salts
Organic soils; wetlands soils	High water content, high concentration of salts and organic electrolytes

value 50 mmho/m is used for conductivity, however, foot contact resistance drops to 100 ohms and total path resistance is 1100 ohms, giving body currents in the range of 4.0 milliamperes.

The importance of accurate assessment of soil electrical conductivity in the top meter of earth is clear, and subsequent parts of this paper will consider how adequately soil conductivity has been measured in the Seafarer environmental impact assessment studies.

5. SUGGESTIONS CONCERNING THE NEVADA AND NEW MEXICO SITES

Reports of soil electrical conductivity measurements in the states of New Mexico and Nevada have not been found in the official Navy literature on Project Seafarer, nor have such reports been found in the soil science literature. In the absence of direct measurement, the best predictors of soil conductivity appear to be the laboratory studies in which high-salt soil solutions were used (see Table 1). The range of soil types encompassed in the table probably includes the types of soil to be found in the southwestern United States, and the environmental conditions that will predominantly govern soil conductivity in the arid Southwest are soil water content and soil salt content. Low salt and low water content will probably give conductivities in the range of 10 to 100 mmho/m, while high water and salt may lead to conductivities in the range of 100 to 400 mmho/m.

The worst case shock hazard would probably exist immediately following a rain, when the surface ten or 20 centimeters of soil would be saturated and highly conductive (giving a low contact resistance), while the subsurface soil would be dry and cause the ground terminal step potentials to reach high levels.

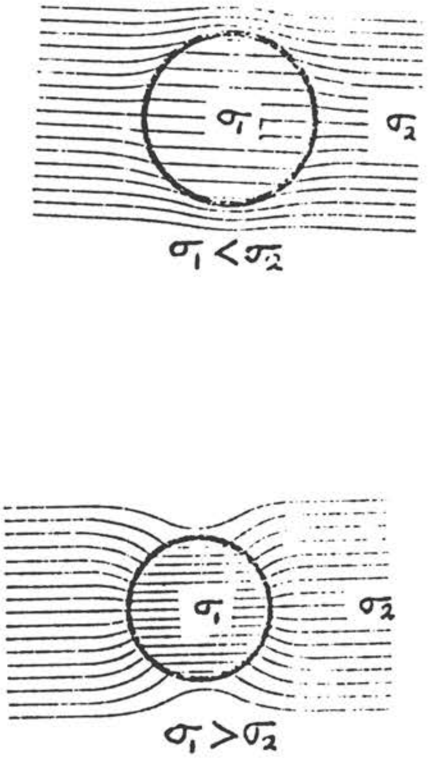
Site-specific measurements to ascertain seasonal and geographical extremes of conductivity should be designed to encompass extremes of soil water content and soil salinity.

PART III. EFFECT OF SOIL INHOMOGENEITIES ON SEAFARER ANTENNA GROUND ELECTRIC FIELDS

The electric field and current density near a Seafarer ground wire will depend on the electrical conductivity of the earth in that region. The actual spatial inhomogeneity of the earth is so great, however, that exact calculations of the field and current density are precluded, and various simplified models of the earth medium must be used to estimate them. For example, the homogeneous-earth model, although too simple to be realistic, allows explicit calculation of the field and current density (Martin, 17 April 1969; Genge, 1976; Kruger, 1977), and allows the surface step potential to be derived, as a function of the soil conductivity and antenna parameters. A two-layer earth model (surface layer overlying a basement) has been used (Martin, 17 April 1969; Heppe, 1977) to provide a realistic model of the effect of vertical stratification on step potentials and biped body currents.

However, neither of these models shows the effect that local inhomogeneities such as buried metal objects or small bodies of water may have on the magnitude of the electric field. For example, a metal object placed in an otherwise uniform conducting medium with a superimposed uniform electric field will provide a low-resistance pathway for current flow, and the local current density will converge on the object; a larger current will flow through the object than will flow through an equal volume of the surrounding medium (see Figure 8). Importantly, this convergence of current is associated with an increased electric field in the vicinity of the object. Similarly, a body of water having a greater

Fig. 8. Lines of current density around a conducting sphere of conductivity σ_1, in a uniform electric field in a medium of conductivity σ_2 (adapted from Bleaney & Bleaney, 1976, p. 45).



electrical conductivity than the surrounding soil will be a region of convergence for current density, and the electric field will be enhanced near the shoreline.

The purpose of this Part is to quantify these descriptive ideas about soil inhomogeneities and to give a quantitative treatment of certain situations that might occur in the vicinity of a ground wire.

1. THEORETICAL APPROACH TO AN INHOMOGENEITY OF CONDUCTIVITY σ_1 IN A MEDIUM OF CONDUCTIVITY σ_2, WITH A UNIFORM SUPERIMPOSED ELECTRIC FIELD

Suppose that a uniform electric field $\vec{E}_0$ exists in a conducting medium of conductivity σ_2, and that an inhomogeneous region with conductivity σ_1 exists within the medium. The electric field and current density inside each region are obtained by using the appropriate Maxwell equations and the boundary conditions:

1. the tangential component of the electric field is continuous at the boundary of the two media, and
2. the normal component of the current density is continuous at the boundary of the two media.

If $\vec{E}_1$ and $\vec{J}_1$ represent the electric field and current density, respectively, inside the inhomogeneity, and $\vec{E}_2$ and $\vec{J}_2$ represent the field and current density outside, respectively, then the boundary conditions can be written:

$$\begin{aligned} &1.\ \vec{E}_{1\text{tang.}} = \vec{E}_{2\text{tang.}} \\ &2.\ \vec{J}_{1\text{normal}} = \vec{J}_{2\text{normal}}. \end{aligned} \qquad [3]$$

Morecver, since $\vec{J} = \sigma\vec{E}$, the second boundary condition can be rewritten as $\sigma_1\vec{E}_{1\text{normal}} = \sigma_2\vec{E}_{2\text{normal}}$.

The field and current density could be found from basic principles, but a shorter method is to make use of a mathematical isomorphism between density $\vec{J} = \sigma\vec{E}$ and electric displacement $\vec{D} = \varepsilon\vec{E}$. $\vec{D}$ and $\vec{J}$ have the same boundary conditions at an interface, namely, continuous normal components, and each has similar relations to $\vec{E}$, namely, each is a constant times $\vec{E}$ in a given medium. $\vec{D}$ relates to dielectric media of given permittivity, and $\vec{J}$ relates to conductive media of given conductivity, but in both cases the electric field satisfies the condition of having zero divergence:

$$\text{div } \vec{E} = 0 \qquad [4]$$

and of being the gradient of a scalar potential:

$$\vec{E} = -\text{grad } V. \qquad [5]$$

The electrostatic potential V and the electric field, will be the same for both the static case of dielectrics and the steady-state case of conducting media, provided the geometry and boundary conditions are the same (Bleaney & Bleaney, 1976, p. 67). Lines of displacement and lines of current density will coincide, and displacement and current density will be obtained from $\vec{E}$ by multiplying by ε or by σ, respectively.

The utility of this isomorphism between $\vec{J}$ and $\vec{D}$ is that many cases of dielectrics in electrostatic fields have been worked out and presented in physics textbooks, and solutions for conducting media of the same geometry and boundary conditions can be obtained merely by replacing ε_1 by σ_1 in the equations for electric fields, where the subscript *1* refers to each homogeneous region of space.

2. CONDUCTING SPHERE IN A UNIFORM MEDIUM WITH A UNIFORM APPLIED ELECTRIC FIELD

For this case we are interested in the electric field and current density inside the sphere, and at representative points immediately outside the sphere, such as points P_1, P_2, and P_3 in Figure 9. The electric field and current density inside can be written (Bleaney & Bleaney, pp. 44-46):

$$\vec{E}_1 = \left(\frac{3\sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o \qquad [6]$$

$$\vec{J}_1 = \sigma_1\vec{E}_1 = \left(\frac{3\sigma_1\sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o = \frac{3\sigma_1}{\sigma_1 + 2\sigma_2}\vec{J}_o \qquad [7]$$

where $\vec{E}_1$ = electric field inside the sphere,

$\vec{E}_o$ = electric field applied to the medium,

$\vec{J}_1$ = current density inside sphere,

$\vec{J}_o = \sigma_2\vec{E}_o$ = current density at great distance from sphere.

The electric field and current density at points P_1 and P_2 outside the sphere but very close to it are given by

$$\vec{E}_2 = \left(1 + 2\,\frac{\sigma_1 - \sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o = \left(\frac{3\sigma_1}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o \qquad [8]$$

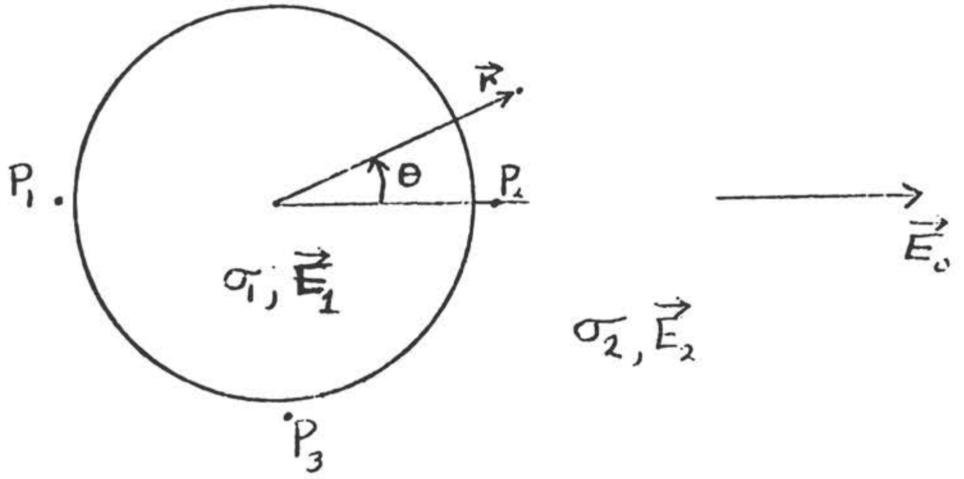
$$\vec{J}_2 = \sigma_2\vec{E}_2 = \left(\frac{3\sigma_1\sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o = \frac{3\sigma_1}{\sigma_1 + 2\sigma_2}\vec{J}_o \qquad [9]$$

The electric field and current density at point P_3 outside the sphere but very close to it are given by

$$\vec{E}_2 = \left(1 - \frac{\sigma_1 - \sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o = \left(\frac{3\sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{E}_o \qquad [10]$$

$$\vec{J}_2 = \sigma_2\vec{E}_2 = \left(\frac{3\sigma_2}{\sigma_1 + 2\sigma_2}\right)\sigma_2\vec{E}_o = \left(\frac{3\sigma_2}{\sigma_1 + 2\sigma_2}\right)\vec{J}_o. \qquad [11]$$

Fig. 9. Conducting sphere in a uniform conducting medium with a uniform superimposed electric field. P_1 and P_2 are points immediately upstream and downstream from the sphere, in relation to the direction of the applied field E_o.



Metallic Sphere

If the sphere is metallic, then σ_1 becomes infinitely large compared to σ_2, and E_1 inside the sphere vanishes (Eq. 6). The current density inside the sphere becomes three times as large as the current density at large distances outside the sphere (Eq. 7). The electric field immediately upstream and downstream of the sphere, at points P_1 and P_2, becomes three times as large as the applied field E_o that exists at large distances from the sphere (Eq. 8). Thus a buried metallic object of roughly spherical shape will amplify the electric field by a factor of three in the regions immediately upstream and downstream of it. This result is independent of the size of the object, and represents the worst-case field amplification by a spherical inhomogeneity in the conducting medium.

The amplification in step. potential can be obtained by integrating the electric field along a 1-meter path upstream from the sphere. Although the equations are not presented here, a one-meter diameter metallic sphere is found to produce a step potential that is 13/9 larger than the distant-field step potential, when the step path is taken radially from the edge of the sphere (point P_1) to a point 1 meter upstream.

Insulating (non-conducting) Sphere

If the sphere is non-conducting ($\sigma_1 = 0$), then the electric field upstream and downstream vanishes (Eq.8), and the equation shows that electric field at point P_3 becomes 3/2 times as large as the applied distant field E_o (Eq. 10). Thus even an insulating sphere in the soil, such as a block of frozen water or frozen soil, or a large rock can lead to amplifications of the electric field.

3. CONDUCTING PROLATE SPHEROID IN A UNIFORM FIELD

Figure 10 shows the geometry of a prolate spheroid in a conducting medium, oriented with its principal axis a parallel to the applied distant field E_o. The electric field inside the spheroid is given by (Bleaney & Bleaney, 1976, p. 752):

$$\vec{E}_1 = \vec{E}_o \frac{\sigma_2}{\sigma_2 + D_a(\sigma_1 - \sigma_2)} \qquad [12]$$

where $\vec{E}_1$ = field inside the spheroid,

$\vec{E}_o$ = applied field, distant from spheroid,

σ_2 = conductivity of the surrounding medium,

σ_1 = conductivity of the spheroidal region, and

D_a = the number given by the integral in Table 7.

The ellipsoid of revolution can be used to model many cases of interest for a conducting body embedded in a uniform conducting medium. When the length of principal axis a equals the length of principal axis b, for example, the ellipsoid is a sphere and can represent a buried spherical object, or a hemisphere whose flat side is coplanar with the surface of the soil. When the length of a is larger than the length of b, the ellipsoid is an elongated (prolate) object which can represent long, thin objects such as circular cylinders or pipes buried in the soil; the prolate ellipsoid can also represent a long, narrow shallow body of water lying on the earth's surface.

The electric field at points P_1 and P_2 immediately outside of the spheroid and upstream and downstream from it (See Figure 10) is obtained from the boundary condition that the current density is continuous across

Fig. 10. Conducting prolate spheroid in a uniform electric field E_0.

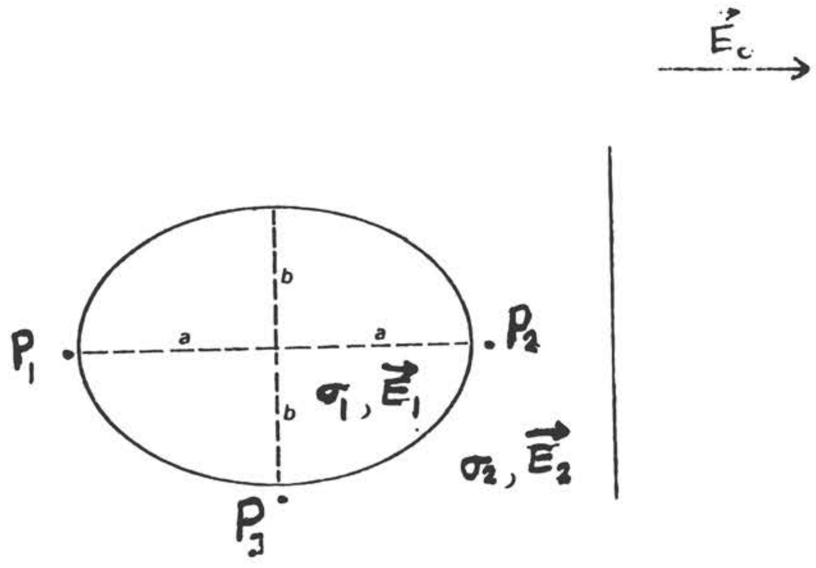


TABLE 7

Tabulated Values for the Integral D_a for Prolate Spheroids (Taken from Stoner, 1945)

$$D_a = \frac{ab^2}{2} \int_0^{\infty} \frac{ds}{(s+a^2)^{3/2}\,(s+b^2)}$$

D_a	a/b
.333	1.0
.233	1.5
.174	2.0
.135	2.5
.109	3.0
.075	4.0
.056	5.0
.020	10.0
.0107	15.0
.0067	20
.00144	50
.00043	100
.000007	1000

Note: For very slender prolate spheroids (a/b much larger than 1.0), D_a is given by

$$D_a = \frac{1}{m^2}\ \ln(2m-1)$$

where $m = a/b$ (Osborn, 1945).

the interface near P_1 and P_2:

$$\sigma_1\vec{E}_1 = \sigma_2\vec{E}_2 \qquad [13]$$

or

$$\vec{E}_w = \frac{\sigma_1}{\sigma_2}\,\vec{E}_1 = \vec{E}_o\,\frac{\sigma_1}{\sigma_2 + D_a(\sigma_1 - \sigma_2)} \text{ at } P_1,\ P_2. \qquad [14]$$

For a highly conducting spheroid, σ_1 becomes much larger than σ_2; Figure 10 shows that the field inside the spheroid becomes small; and Eq. 14 shows that the field at points P_1 and P_2 is

$$\vec{E}_2 = \frac{}{(\sigma_2/\sigma_1) + D_a}\,\vec{E}_o \qquad [15]$$

For the case of a metal object having axis <u>a</u> equal to axis <u>b</u> in length, the spheroid is a sphere, $\sigma_2/\sigma_1 = 0$, and $D_a = 1/3$, giving $E_2 = 3\ E_o$ as was found above for a metallic sphere.

For the case of <u>a</u> much larger than <u>b</u>, however, the field amplification by metallic objects can be much larger. For example, a rod that is two inches in diameter (b = 1 inch) and 17 feet long (a = 100 inches) has a/b = 100, and $D_a = .00043$, hence the field at P_1 and P_2 is roughly 2000 times larger than the applied field E_o. Although we have not obtained the step potential for this case, the remarkable amplification of the field shows that large effects can be expected when long metallic objects are oriented perpendicular to the ground wire.

<u>Bodies of Water</u>

Another application of the spheroid calculation is to model the effect of a body of water that is longer than it is wide, with its longer axis perpendicular to the ground wire, and hence parallel to the wire's electric field. The electrical conductivity of a body of water can be estimated to be ten times as high as the conductivity of the soil nearby which is saturated by water of the same quality (See Figure 7), which means that $\sigma_1 = 10\sigma_2$. If the body of water is three times as long as it is wide, then $a/b = 3.0$, $D_a = .109$, and the electric field near the upstream shore will be

$$\vec{E}_2 = \vec{E}_o \frac{10\sigma_2}{\sigma_2 + .11(9\sigma_2)} = \vec{E}_o \frac{10\sigma_2}{2\sigma_2} = 5\vec{E}_o \qquad [16]$$

On the basis of the above calculation, it might be expected that ground wires near ponds or wetlands will have greatly enhanced step potentials at the shoreline closest to the ground, with the exact enhancement depending on the narrowness of the pond (ratio of dimension a to dimension b) and its conductivity relative to that of the soil.

4. SUMMARY AND RECOMMENDATIONS

The results of the preceding sections indicate that a uniform electric field will be significantly distorted by the existence of inhomogeneities in the conducting medium, and that sizable amplifications of the field can result. Inhomogeneities having higher conductivity than the soil medium will cause convergence of the current density and lead to enhanced electric fields in the regions upstream and downstream from the object or region in question. Inhomogeneities having conductivity lower than the soil will cause divergence of the current density and lead to enhanced fields in the regions tangential to the region in question. Quantitative estimates show that the field can be multiplied by factors of up to three for spherical inhomogeneities, and by factors of from five to hundreds for regions shaped like prolate spheroids with the longest axis parallel to the applied electric field.

In view of these results, it is suggested that worst-case step potentials will probably be found near regions in which soil conductivity changes sharply because of horizontal changes in the medium. Regions near bodies of water or near buried conducting objects will show significant variations in step potential, with long narrow ponds or buried metal rods giving extreme enhancements of the electric field.

Measurements made with the intent of discovering worst-case situations should probe regions in which conductivity or the makeup of the soil shows radical horizontal variations.

PART IV. MODELS OF SEAFARER GROUND TERMINAL ELECTRIC FIELDS

Attempts to understand the environmental impact of the Seafarer system have been both experimental and theoretical. Step potentials and body currents have been measured at the Wisconsin Test Facility with the aim of identifying "hot spots" of high potential gradient or high body current, so that the ground terminal could be modified as needed to correct the situations discovered. Calculations have been made with homogeneous-earth and two-layer earth models to predict the surface electric fields and body currents in the vicinity of the ground wire.

Earth resistivity measurements have been focused on the deep basement or the top hundred meters of earth, with the aim of assessing the resistance of the ground terminal. Early resistivity measurements gave estimates of the conductivity of earth in the top ten feet, but did not apply to the top meter of soil. To date, there does not appear to have been any program for measuring the electrical conductivity of the soil in the top one meter of earth.

1. THE HOMOGENEOUS-EARTH MODEL

A ground wire of length l buried at depth d in a homogeneous medium of conductivity σ will produce a surface electric field with components given in Figure 11 (taken from Genge, 1976). At the surface near the wire, but away from either end of the terminal, E_x is much smaller than E_y (where x and y are the axes of Figure 11), and the primary component of the electric field is the y component:

$$E_y = \frac{I}{\pi\sigma l}\,\frac{y}{y^2 + d^2} \qquad [17]$$

where I = antenna current, amps

sigma = medium conductivity, mhos/meter

l = length of ground wire, meters

d = depth of wire, meters

y = horizontal distance away from ground wire, meters

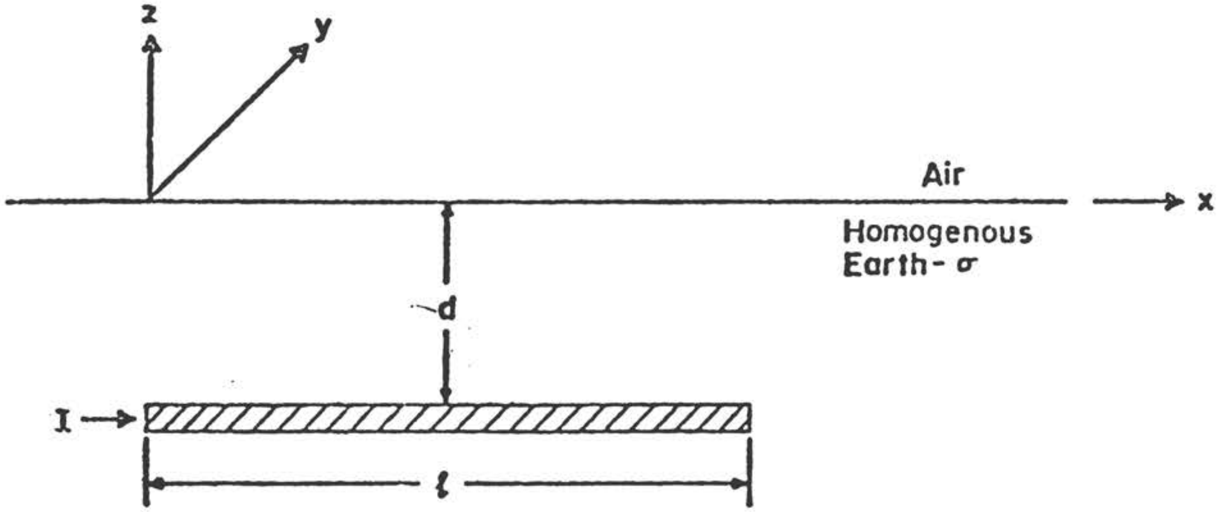
E_y = electric field in y direction, volts/meter.

The maximum of this electric field occurs at a distance away from the wire equal to its burial depth (i.e., at y = d), and is given by

$$E_y\ \frac{I}{2\pi\sigma l d} \qquad [18]$$

Eq. [18] shows that for fixed antenna parameters (I,l,d), the surface maximum in the electric field will vary inversely with soil conductivity in a homogeneous earth. An early Naval document suggested that safe values of the step potential would obtain if soil conductivity were sufficiently high (Martin, 17 April 1969). (That same author recognized the inadequacy of the homogeneous-earth model, and discussed the two-layer model in the same document.)

Fig. 11. Electrical field components for a horizontal buried ground terminal wire (from Genge, 1976),



$$\left.\begin{aligned}
E_x &= \frac{I}{2\pi\sigma\ell}\left[\frac{1}{\sqrt{(x-\ell)^2+d^2+y^2}}-\frac{1}{\sqrt{x^2+d^2+y^2}}\right]\\
E_y &= \frac{I\,y}{2\pi\sigma\ell}\left\{\frac{1}{\left[(x-\ell)+\sqrt{(x-\ell)^2+y^2+d^2}\right]\left[\sqrt{(x-\ell)^2+y^2+d^2}\right]}\right.\\
&\qquad\left.-\frac{1}{\left[x+\sqrt{x^2+y^2+d^2}\right]\left[\sqrt{x^2+y^2+d^2}\right]}\right\}
\end{aligned}\right\}$$

The surface electric field is only one aspect of a safe antenna ground. It must also be ascertained that body currents generated in humans and wildlife are harmless in the vicinity of the ground. The danger of shock exists because extremities can be in contact with points of different electric potential. A biped taking one-meter steps, for example, will have feet in contact with earth at a potential difference of

$$E_{step} = E_y \cdot 1 \text{ meter}. \qquad [19]$$

It should be noted that artificial extensions of more than one meter are easily realized. A person touching the front-end of a tractor might be in electrical contact with earth ten feet away if the tractor is grounded by having a plow touching the earth. A person in contact with a metal object grounded a distance <u>L</u> away will experience a voltage

$$V = E_y \cdot L \qquad [20]$$

between the extremity touching the earth and the extremity touching the metal object.

Such voltages will drive a current through the body, of course, but the magnitude of the body current will depend on the electrical resistance of the contacts and the resistance of the pathway of current flow. For a person walking, the voltage will be imposed across a total resistance of foot, leg, torso, leg, and foot, all in series, and the current will flow mostly through the legs and lower torso. The total path resistance (R_t) for a walking person is

$$R_t = R_b + 2R_f \qquad [21]$$

where R_b = body resistance, ohms

R_f = resistance of foot in contact with earth, ohms.

For the situation where a person with both feet together in contact with earth lays a hand on an object at different potential, the pathway for current is a series of hand, arm, torso, legs, and feet. The total path resistance is

$$R_t = R_b + (R_f/2) \qquad [22]$$

where $R_f/2$ is the resistance of both feet in parallel.

In the above, the body resistance R_b includes the torso and extremities and is difficult to measure realistically. Estimates of R_b range from 500 to 1000 ohms (AIEE, #80, 1961, p. 9), and a value of 1000 ohms was used in a recent Navy summary (SPECOM Report, 22 December 1976, p. A-1).

Contact resistance of a foot resting on earth can be approximated as the resistance of a hemisphere embedded in earth (AIEE, #80, 1961, p. 45), giving the formula:

$$R_f = \frac{1}{2\pi\sigma b} \qquad [23]$$

where R_f = contact resistance of foot-earth, ohms

sigma = conductivity of the earth, mhos/meter

b = radius of hemisphere, meters.

Electrolytic trough experiments show that a person's foot is equivalent to a hemisphere of radius 0.07 meter, on average, hence the foot resistance formula becomes

$$R_f = \frac{2.5}{\sigma} \qquad [24]$$

This equivalency has been used for foot resistance in recent reports (SPECOM, 22 December 1976; Kruger, 10 January 1977), along with a 1000 ohm body resistance, giving the following formula for body resistance

$$R_t = 1000 + (5/\sigma) \qquad [25]$$

where sigma is soil conductivity in mhos/meter.

The body current for a walking biped is calculated by dividing the step potential E_{max} by the total path resistance R_t:

$$I_b = \frac{E_{max}}{R_t} = \frac{I}{2\pi l d\sigma} \; \frac{1}{1000 + 5/\sigma} \qquad [26]$$

where I_b = body current, amps

E_{max} = step potential maximum, volts

R_b = body resistance, ohms

R_f = contact resistance of foot with earth, ohms.

Eq. [25] has been used in recent official presentations (SPECOM Report, 22 December 1976; Kruger, 10 January 1977) to estimate maximum body currents for a walking person that will occur with specified antenna parameters and the soil characterized by a single conductivity. Table 8 summarizes the homogeneous earth model's predictions of body currents for a range of soil conductivities.

It can be seen from Table 8 that in a homogeneous medium, the body current will be maximal for low values of the conductivity, and will decrease monotonically as sigma increases. The maximum body current predicted, 0.87 mamp, is within what is considered to be the safe range.

It should be noted, however, that if a person is reaching over and touching the earth one meter away, then the feet are in parallel and

TABLE 8

Electric Field and Body Current for a Walking Biped Around Seafarer Ground Wires, Calculated in the Homogeneous Earth Model

Soil Electrical Conductivity millimhos/meter	Maximum Electric Field volts/m	Total Resistance To Current (R_t) ohms	Body Current milliamps
0.001	4340	5×10^6	0.87
0.01	434	5×10^5	0.87
0.1	43	5.1×10^4	0.85
1.0	4.3	6000	0.72
10.0	0.43	1500	0.29
100	0.044	1050	0.042
1000	0.0043	1005	0.004

Note: Antenna parameters for the above are:

Length = 1985 meters

Current = 99.0 amps

Burial Depth = 6 feet = 1.83 meter

E. [22] applies instead of [23] for the total path resistance, and the body current becomes larger. The maximum body current for such a situation is 3.4 mamp, which is considerably larger than the 0.87 mamp in the above situation.

Applicability of the Homogeneous-Earth Model

It is common experience that the earth is not homogeneous, so its electrical behavior might be expected to be radically different from that of such a uniform medium. Indications of the complexity of the actual soil medium are contained in the data of Report #5177 (Dewald, 1970--Sanguine Ground System Navy Step Gradient Measurements, 7 April 1970 to 20 April 1970) in Table 1 of Attachment 1. Measurements of step potential and current through a 1500 ohm resistance were made, and several cases were found in which the step potential and load current diverged in opposite directions. For example, sites N24 and N26 of the North Ground both had step gradients of about 6 volts/meter, but the load currents at the sites differed by a factor of four (0.48 mA compared to 2.2 mA). The South Ground sites S1, S50, and S51 also show very different load currents for roughly the same step gradient, as did sites W25 and W42 of the West Ground. If the earth were homogeneous, maximum step potential and load current would be uniquely related and there would not be any cases of similar potential differences giving dissimilar load (body) currents.

We feel that the conductivity of the earth is sufficiently non-uniform for the homogeneous-earth model to be inapplicable, and data such as the above support this belief. The discussions of Parts II and III of this paper also showed the types of variations that hold in the top meter of soil at different times and under different conditions of local terrain.

In spite of the seeming inapplicability of the homogeneous earth model, it has been used recently (SPECOM, 22 December 1976; Kruger, 10 January 1977) for calculations of body currents, in order to argue that safety margins of the antenna design are adequate.

2. THE TWO-LAYER EARTH MODEL

The two-layer earth model, which has been used to calculate body currents for a walking biped (Martin, 17 April 1969; Heppe, 1977) represents a realistic model of the vertical stratification in the top few meters of earth. Foot-to-foot current flow through the body of a person walking near the ground wire has been calculated by Heppe for the range of soil (top layer) conductivities from 0.1 to 100 mmho/m, which encompasses the soil conductivities expected to be found at the Michigan site.

The worst-case body current calculated by Heppe was 2.0 mA, which occurred when a 10 cm upper layer of conductivity 10 mmho/m existed above a bottom layer having conductivity 0.1 mmho/m. Heppe thought that the lower layer conductivity was unrealistically low, but we feel that a frozen soil would have conductivity this low. Heppe's worst case seems very close to conditions that would hold during spring thaw in Michigan, when the top 10 cm have thawed but the lower several feet just beneath the surface layer are still frozen. Thus the 2.0 mA body current does seem realistic to us.

In considering again the case of a person touching the earth one meter away with a hand, while standing with feet together, we note that for Heppe's worst-case situation a body current larger than 2.0 mA might be expected.

Heppe's calculations will apply also to two-layer situations in the Nevada and New Mexico sites, but we suggest that conductivities larger than 100 mmho/m may be encountered in the Southwest.

PART V. SUMMARY AND RECOMMENDATIONS

A review of the soil science literature shows that the electrical conductivity of the types of soils at the proposed Michigan, New Mexico, and Nevada Seafarer sites varies widely as a function of water content, soil temperature, and salinity of the soil solution. Seasonal variations cause water content and temperature to change radically throughout the year in the top one meter of soil, and these variables can cause soil conductivity to change by factors of 10 to 100 at a given location.

At the Michigan site, soil conductivity is expected to range from 10 to 100 millimhos/meter, but low values of 0.1 to 10 mmho/m might occur in extremes of dry soil of summer or frozen soils in mid-winter; high values of 100 to 200 mmho/m might occur under extremely high water content or salt content.

At the Nevada and New Mexico sites, soil conductivity is expected to range from 10 to 300 mmho/m, with high values possibly reaching 400 to 600 mmho/m in saline areas at high water content. Experiments on artificially salinized soil cores suggest that soils of these arid regions might exhibit surface conductivity effects that prevent the soil conductivity from dropping below 20 to 40 mmho/m, no matter how low the soil water content becomes.

It is to be emphasized that the above values are estimates based on scientific work at locations other than the SEAFARER sites and performed for purposes other than evaluating the environmental impact of electrical fields from antenna ground wires. To date there has been no program in the Seafarer project aimed at measuring soil electrical conductivity in the top one meter of earth at any of the proposed ground terminal sites.

A theoretical investigation of the effect of soil inhomogeneities on a uniform electric field shows that horizontal variations in local terrain or soil composition can cause significant amplifications of the electric field in the vicinity of the inhomogeneity. Calculations suggest that the electric field could be multiplied by factors of five or ten in worst-case situations of inhomogeneity. To date, there appears to have been no appreciation of this type of field enhancement, in either official calculations of step potential and body currents, or in any planned program of measuring step potentials at antenna sites.

Thus far in the Seafarer program, official conclusions about antenna ground safety have been based on two approaches: calculations of step potential and body currents using a homogeneous-earth model and a two-layer earth model, and site measurements of step potential and load currents at the Bravo Test Facility. Homogeneous-earth models are not applicable to the top one meter of earth, however, because climatic variations make that layer of earth extremely inhomogeneous as an electrical conductor, and assigning a single value of electrical conductivity to the soil for the purposes of calculating antenna safety is a meaningless exercise. The two-layer earth model is applicable to the soil surface, however, and does permit valid conclusions to be drawn, provided that correct values are used for soil conductivity. The most recent Navy-sponsored two-layer calculations suffer only from the fact that although a range of conductivities was assumed for the two layers, there has been no experimental work to show that soil conductivity at the three Seafarer sites actually falls within that range at all times of the year and under all climatic conditions. On-site measurements made in 1968-1970 at the BTL (Martin, 1969A, 1969B, 1969C) were a step in the right direction, but that series suffered from being insufficiently broad in scope; measurements must encompass worst-case climatic and terrain conditions in order for conclusions about safety to be validly drawn.

On the basis of official Navy documents and other literature, we judge that present understanding of soil electrical conductivity at the ground terminal sites is not sufficient to allow judgments to be made about the safety of the antenna grounds. A range of conductivities has been assumed in theoretical calculations of body currents and step potentials, but no measurements have been made to corroborate the assumed range, and no concerted experimental effort has been made to find worst-case conditions at the site and to measure step potentials and body currents under worst-case climatic and terrain conditions.

In order for valid conclusions to be drawn about the safety of Seafarer ground terminals, the following types of information would have to be obtained by site-specific measurements:

(1) <u>Soil electrical conductivity</u> as a function of depth in the top two meters of earth, and as a function of time of year and time of day. The aim of these measurements would not be to obtain a single average value of conductivity, but would rather be to obtain the typical range and extreme values so that worst-case conductivities would be known. Seasonal extremes such as spring thaw and summer rainstorm (and others listed in Table 5) should be sought out and included in the program of measurement.

(2) Step potentials and body currents as a function of local terrain, time of year, and time of day. The aim here should be to find typical ranges and extreme values so that worst-case conditions would be known (see Table 6). Times and places of measurement should be planned so that the worst-case climatic conditions and the worst-case horizontal variations in conductivity are encompassed.

In view of the scientific expertise available to the Navy, a final recommendation is made about testing the validity of conclusions concerning ground terminal safety. If the data in (1) and (2) above is collected, it should be possible to use the soil conductivity data to calculate step potentials and body currents in the worst-case conditions actually found at the site. Comparison of the calculated and measured step potentials and body currents under worst-case conditions would provide a test of our understanding of the antenna ground behavior, and good agreement between calculation and measurement would validate conclusions about ground terminal safety.

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APPENDIX B

BEHAVIORAL ASSAYS OF POSSIBLE WEAK ELF EFFECTS: COMMENTS AND RECOMMENDATIONS

Rochelle Gavalas-Medici

and

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Studies have been presented at these meetings which suggest strongly that weak electric fields play a role in the detection of prey by some fishes with specialized receptors, and in the navigation of some birds. However, a broader question may be raised about whether or not these examples simply represent curiosities of nature or whether there is a more pervasive sensitivity to fields across species which may, in turn, point to a fundamental property of nervous systems. If such a widespread sensitivity may exist then it is important that standards for adequate behavioral testing begin to be formulated. For example, the ubiquity of weak ELF fields in our environment strongly suggests that catastrophic or dramatic behavioral changes do not take place, yet some studies appear to be designed so that only gross changes in behavior could be detected.

Even if the ultimate concern of such research is the question of hazard, it seems clear that one must have some notion of potentially important field parameters and appropriateness of behavioral assays in order to determine where, or in what way, hazardous effects could conceivably occur. Apart from the possible ecological questions involved in such things as bird migration, it would seem that one cannot adequately evaluate hazard except through hypothesis directed research, rather than through a "shot gun" approach. Subjecting a variety of species to electric fields most handily generated in a variety of laboratories and watching to see which animals, if any, behave "bizarrely" will not produce any answers that will satisfy either the scientific community or the population at large.

Even more credible experiments may be unlikely to furnish adequate answers. For example, suppose an experiment is done in which one searches for weak ELF field interference in a discrimination learning task with frequency of the field set at 76 Hz and voltage at 1000 V/m. Evidence suggesting that voltage windows may exist implies that one may not be able to extrapolate findings at this level to lower voltage levels that are of interest. Similarly the frequency used may be totally irrelevant to brain wave activity of the performing animal so that the results cannot be extrapolated across frequencies. Furthermore discrimination learning may be in principle impervious to any field effects because of the extensive external stimulus control inherent in the task. Indeed our own research suggests that rather long term exposure to weak fields (less than 56 V/m p-p) of very low frequency may only be detected by studies of temporally scheduled responding.

A review of other ELF behavioral studies written in the context of our own findings has been undertaken to offer some possible explanation for apparent inconsistencies that exist in the present "data base" (Gavalas-Medici & Magdaleno, 1975). Although counting up studies on the basis of positive or negative findings seems to be a credible way to take a first look at the data, a more intensive review reveals this to be intrinsically unsatisfactory. Careful studies receive the same weight as sketchy ones or pilot efforts and more importantly, possibly major differences in field parameters or behavioral tasks are masked.

Very briefly, our own studies in behavior of monkeys exposed to weak (1-100 V/m) ELF fields (7 Hz to 75 Hz) indicated that minor but systematic perturbations of behavior (shortening of interresponse times, IRTs) could be reliably measured. Furthermore, there was some indication of dose-dependency within a limited range of voltages (0-56 V/m p-p). The lowest threshold appeared for a field frequency of 7 Hz; other (higher) frequencies that were tested appeared to have substantially higher voltage thresholds. It was suggested that this reflected the biological relevance of the 7 Hz field, since 7 Hz is in the range of hippocampal theta for alert monkeys performing this kind of task. An anomaly in the data was the absence of an effect for 60 Hz on the one occasion when that field was tested. A second point of ambiguity was the lack of a systematic effect at 100 V/m; this may be explained by a 24h "carry over" effect at that level.

Recent evidence for subtle but reliable behavioral perturbation as a function of ELF exposure comes from the work of Williams, Williams, Larkin and Sutherland (1977). They have observed that migratory birds near the test facility antenna showed a deviation in flight direction of 5° to 25° when the N-S axis of the antenna was energized. The field was estimated to be .17 V/m rms. at 10 meters, perpendicular to the antenna. Indications were that flight direction was rapidly corrected after the birds passed the immediate area of the antenna. These results appear to be very compatible with the monkey ELF studies. In both cases, rather small but reliably measured behavioral changes could be discovered and in both cases the effects seem to be short-lived.

Many of the other studies that have been done on mammals have revealed only negative results (de Lorge, 1972, 1973; Marr *et al.*, 1973; etc.). However a careful review of these studies in the light of some of the information available within the past few years suggests that some of these inconsistencies may be readily resolved if two major methodological issues are considered. The first of these is simply 1) the differences in field parameters involved in the different studies and the second centers on 2) the precise nature of the behavioral assay used.

1) Optimizing Field Parameters For Behavioral Detection Of Weak Electric Fields

Field parameters may be readily subdivided into frequency (modulation frequency and carrier frequency), voltage or power, and duration of exposure. The data from the ELF monkey experiments suggest that behavior may be especially susceptible to EEG range frequencies. Results presented elsewhere suggest that there is a "tuning curve" of modulation frequencies for VHF fields used in elicitation of significant changes in calcium efflux from *in vivo* chick brains. Similar studies with ELF fields again implicate frequency-specificity in the interaction.

Thus, the background research to date suggests that frequency may be critical in assessing possible behavioral changes. A feasible working hypothesis is that the lowest threshold for behavioral change will be observed with frequency set at a level which is biologically relevant, e.g. within the EEG range of a given animal during performance of the specified task. Note that this cautions, for example, that dominant EEG frequencies observed in sleep may be without effect for an animal in training for a particular behavioral task.

Voltage levels are a second primary parameter. In this case, the evidence is not clear-cut. In the monkey ELF behavioral studies, there was some evidence for dose-dependency with a larger IRT shift being observed as voltage was increased. In the calcium efflux studies on neonatal chicks, on the other hand, there appeared to be a voltage window; no effect was observed at 1 V/m or 100 V/m but statistically significant changes were seen at 10 and 56 V/m p-p. In the shark studies of Kalmijn (1971), data were also presented that implicated a voltage window. These findings suggest that not only is voltage level critical but that one cannot assume that a negative result with relatively high ELF voltages implies no effect at lower levels.

Duration of exposure is an obvious variable that has often been overlooked in ELF studies. In view of the pervasiveness of weak ELF fields in human environments and the absence of catastrophic behavioral changes, it seems to be unreasonable to expect that brief exposure to weak ELF fields might perturb animal behavior. Yet exposure durations as short as one minute have been used in studies cited as negative evidence (Marr et al., 1973). Our ELF studies have maximum exposure durations of four hours. Few studies have used days or weeks of exposure. The short exposure times used in some studies may reflect the fact that they have often been modeled on microwave research -- in which behavioral effects appear to be more immediate.

2) Adequacy Of Behavioral Assays

A. The weak electric field as background stimulation vs the field as contingently linked to behavior.

A major issue regarding the appropriateness of the behavioral assay centers around the question of whether or not the experimental field is merely used as background stimulation during testing or is contingently linked to behavior. Although the second alternative is a much more powerful test, practically every behavioral study of field effects -- with a few exceptions -- has used the first approach. This departs markedly from the usual procedures used to measure sensitivity to stimuli of unknown effect. For example, no one would propose to assay sensitivity to light or sound by training an animal to perform a complex task for primary reinforcement, such as food or water, and then subject the animal to the background presence of a low level of light or sound that is only slightly different than that used in a control session. Clearly, such an experiment could easily fail to measure the animal's ability to detect, and respond to, light or sound. On the other hand, a constraint on the use of contingency paradigms is that they are difficult to implement where long duration of exposure is required -- as in the ELF studies. An exception is the "concurrent chain" paradigm which is discussed later. It might be added that contingency paradigms would appear to be singularly appropriate for VHF and microwave field tests and have not been as widely used in these studies as one would wish.

B. External stimulus control and weak electric field effects

Finally, another major issue may be raised regarding the adequacy of behavioral assays. That is the matter of the degree to which the behavior being measured is under strong external stimulus control. In the monkey studies of weak ELF fields, the orderly results observed were in marked contrast to other behavioral studies which were largely inconclusive (see the review in Gavalas-Medici & Magdaleno, 1975). An analysis of the exact behavioral paradigms used revealed that the protocol followed in this laboratory was distinct from almost all other protocols by virtue of the absence of salient external discriminative stimuli controlling the animal's performance. In the IRT task which was used, the animal was required to press a lever after a lapse of 5 sec. No lights or bells signalled the time when the reinforcer was available. In more commonly used behavioral protocols (e.g. reaction time, match - to - sample, conditioned suppression) lights or bells are used to signal and control the behavior in question.

In recent months a similar interpretation of the role of external stimuli has arisen within the area of behavioral toxicology. Carey & Kritkausky (1972) found that rats trained on a DRL 22 sec schedule had a markedly increased response rate to d-amphetamine. On this schedule animals must respond after a specified time lapse and the timer resets if responses are too early; this is very similar to the IRT task. Carey & Kritkausky performed a second experiment in which the same paradigm was used except that a signal light was added at the end of the 22 sec interval. When this change was introduced, the previously observed sensitivity to d-amphetamine was completely obliterated

Similarly, Laties (1972) observed that d-amphetamine affected the performance of pigeons on an FCN (fixed consecutive number) schedule in which the pigeon was required to press one key 8 times and then shift to a second key. When a signal light was added to the 8-th press, the effects of d-amphetamine disappeared. Ogden Lindsley has used the term "behavioral prosthesis" to describe the use of external environmental control to improve behavior which has been deleteriously affected by brain damage , senility or other "internal" factors. Evans et al. (1975) have shown a "behavioral prosthesis" effect in pigeons on an FCN schedule who have been given long term doses of methyl mercury. The dominant effect of the methyl mercury was to increase the amount of variability and induce shorter response "runs", i.e. switching to the second key before the required 8 presses. When a signal light was introduced at the 8-th press the effect of the methyl mercury vanished and behavior appeared perfectly normal. When the signal light was removed, the behavior soon became perturbed again

These results seem very germane to the interpretation of studies of weak electric fields. For these reasons it is proposed that behavioral assays of weak electric field effects be reviewed in terms of their degree of external stimulus control. It may be reiterated that this point may be of the utmost importance in evaluating and designing adequate experiments. It impies that many of the more conventional behavioral paradigms such as two choice discrimination learning and match-to-sample tasks may be recognized a priori as insensitive tests of either weak drug effects or weak field effects, because of their intrinsic reliance on strong external stimulus control.

In the light of these considerations we would like to present for your consideration, an idealized battery of behavioral tests for assaying possible weak ELF field effects. The results of such a battery of tests should indicate under what conditions, if any, possible effects may be detected and where hazards could, conceivably, exist.

A concern limited to "hazard" would seem to lead to a search for gross behavioral effects in the presence of exaggerated power levels. For example, some microwave studies have been directed at discovering the power level at which the animal is almost totally incapacitated. Such a program of research will certainly tell us nothing about thresholds. A corollary of this may be that only threshold studies -- and not hazard studies -- are likely to supply us with clues to possible subtle central nervous system mediations.

Example of a Recommended Behavioral Test Series

Two rather different tactics might be adopted in the design of such a series. In one case, a set of experiments might be selected where a battery of different unrelated tasks are employed; one would hope that one or more of the diverse tasks would be affected by the presence of the ELF field and thus provide both a general picture of the organism's response to the ELF field and provide a basis for further research. This approach is particularly useful when research is but little advanced and the experimenter has few a priori notions of how the ELF field will affect the organism under study. The primary weakness of such a course is due to the diversity of procedures. The results of the various procedures do not complement or support each other. The success or failure of the individual procedures has to stand as individual, isolated, results. We have seen that this has been the common tactic in ELF research.

The alternative is to perform a series of experiments where each of the procedures is selected so that it is complementary to and so that it will support the other procedures that comprise the experimental series. In designing such a series of experiments it is particularly helpful if one does have some *a priori* notion of how the behavioral effects of low intensity ELF fields might be manifested:

1) Fortunately, a number of experiments have shown that the application of such fields influences *time-dependent behavior* and this seems a reasonable place to begin.

2) It has already been pointed out that the effects of low intensity ELF fields are likely to be rather subtle; this conclusion is supported by the failure to observe clear ELF field effects in a number of conventional experiments. Consequently, *maximally sensitive procedures* must be employed whenever possible.

3) Another experimental requirement has already been mentioned: *External stimuli, whether procedure correlated or not, should be absent or at least held to a minimum*. The effect of the ELF field will be maximized only when it is the most salient, varying external stimulus to which the organism is exposed in the test situation.

4) When exposures have been on the order of seconds (Marr *et al.*, 1973) ELF field effects have not been observed. Consequently, procedures should be selected to *maximize the duration* of ELF field exposure.

With these considerations in mind, we may now examine a set of experiments that would begin to adequately characterize the behavioral effects of exposure to low intensity ELF fields. Some of the experiments have been wholly or in part performed in various laboratories, using various species as subjects; there would be very considerable advantage in performing the entire series in a single laboratory, leaving open the possibility of repeating the entire series in several laboratories.

Experiment I: **A measure of general activity.**

Prior to a systematic examination of the effects of a novel environmental stimulus, it is important to determine the extent to which the stimulation may affect general activity in the test species so as to insure no contamination of more specific behavioral tests and to clarify the mechanisms by which effects are produced in the other experiments. Consider what happens if the stimulus, in this case an ELF field, leads to a change in overall rate and perhaps time-course of general activity in the test species independently of any reinforcement contingency imposed. An increase or decrease in general activity could lead to either an increase or decrease in reinforced responding, depending on the compatibility of the reinforced response and activity in general: If the reinforced response has a topography similar to, i.e. compatible with, general activity, then an increase in general activity will lead to increased responding, but if the two do not have similar topographies, then an increase in general activity would lead to a decrease in the reinforced response. Similar arguments may, of course, be applied to the case where the presence of the ELF field leads to a decrease in general activity; these arguments are left to the reader.

Two sorts of procedure are available for measuring general activity. In the first sort of procedure the subject is placed in the test chamber and left to his own devices; activity is then measured in the presence and absence of the ELF field. In the second and much more powerful procedure, the subject is placed on a fixed time (FT) schedule of reinforcement. The FT schedule is similar to the more familiar fixed interval (FI) schedule in that reinforcements are made available at the end of a constant interval, but whereas in the case of the FI, reinforcement is delivered only if a response is made after the completion of the constant interval, in the case of the FT, reinforcement is delivered independently of the subject's behavior during or after the interval. The use of the FT schedule leads to the appearance of interim activity, reported by Pavlov (1927) in the long-delay trace conditioning procedure and in the "superstition" experiment of Skinner (1948). Interim activity is defined as those behaviors that appear in experimental subjects between the deliveries of non-contingent reinforcements. Interim activities may also appear in the presence of contingent schedules of reinforcement, but the contingency is not necessary to the appearance of the interim behaviors. The periodic delivery of reinforcement is the sufficient condition for the appearance of interim activities.

In the present context the FT has two virtues:

1) The FT schedule is a sufficient condition for the production of interim activities.

2) Unlike other schedules which produce interim activities, such as the FI, the independence of reinforcement delivery from responding insures that all subjects will receive the same number of reinforcements, distributed over time in the same way, in every experimental session. This will assure that the inter- and intra-subject variability due to variations in the number and temporal distribution of reinforcement, which would be expected to affect variables like deprivation, will be held to a minimum.

In recent years, considerable research has been directed at the analysis of these activities (Staddon & Simmelhag, 1971; Killeen, 1975). Interim behaviors have been shown to be an extremely robust phenomenon, easily being produced in all the species tested (including rats, pigeons and chickens). Interim behavior has also been shown to have an extremely regular temporal pattern which may be easily formally described. Interim behaviors have been shown to be sensitive to the presence of drugs; existing formal models handle these changes in a simple and straight-forward manner.

In consideration of the facts outlined above, interim behaviors enjoy considerable advantages over general activity. Among these advantages are: 1) The amount of activity and its rate is determined by the FT schedule; this ensures a minimum amount of intra- and inter-session variability in the amount and rate of activity as well as the time course of the activity. 2) The existence of a quantitative description of these activities provides a ready standard for comparison between (a) different parts of the present experiment and (b) other experiments. 3)The quantitative models available also provide an additional and powerful way of looking at the behavior: its time course, which may be expected to show up particularly subtle field effects.

As in the case of general activity, interim behaviors may be adequately indexed by the use of sensors that record position changes of the subject as it moves about the test chamber. It may be seen that the kinds of activity

by these two procedures are the same; what differs is the degree of control exercised over the amount, temporal distribution and variability of activity.

Experiment II: Performance on an IRT schedule of reinforcement

The IRT schedule of reinforcement is a natural candidate for inclusion in this experimental series in as much as it has shown the greatest sensitivity to ELF fields. Since this schedule has been extensively described elsewhere (Gavalas et al., 1970; Gavalas-Medici and Magdaleno, 1975, 1976) details of its description will not be given here.

Note, however, that the results from these previous experiments become much more powerful in the context of the present experimental series. Standing alone, two hypotheses present themselves to account for the reductions in mean IRT that have been reported:

1) A change in the subject's distribution of responses over time, or

2) A change in the level of the subject's general activity.

With the results of the procedure described in Experiment I in hand, it should be possible to speak to these two hypotheses and thus more precisely specify the nature of the ELF effect.

An important variant on the basic IRT schedule, ELF field experiment follows immediately from the discussion of stimulus control effects in drug research,presented earlier in this memorandum. If the results of those studies are applicable to performance on IRT schedules in the presence of ELF fields, then it follows that if an external discriminative stimulus is presented during the interval during which a response will be reinforced, then the effect of the ELF field should be abolished, providing that the effect of the ELF field is upon the subject's distribution of responses over time. Similarly, removal of the external discriminative stimulus should restore the field effect.

Experiment III: Preference for exposure to an ELF field as measured by means of a concurrent chain

Demonstration of behavioral effects of the ELF field in the earlier experiments leads to the question of whether the subject prefers to have the ELF field present when engaging in the behavior under study and previously shown to be affected by the ELF field.

A test of this question is possible by means of the concurrent chain schedule of reinforcement. This schedule divides the experimental session into a number of cycles. In the first part of each cycle the subject works on a concurrent VI-VI (variable interval - variable interval) schedule. Reinforcement on either of the VI's leads not to a primary reinforcer, but rather it leads to the opportunity to work on another schedule of reinforcement for primary reinforcement. The second part of the cycle continues for a time, after which another cycle begins with a new presentation of the concurrent VI-VI.

In the present experiment, the schedule used in the second part of the cycle is the IRT employed in Experiment II. When the second part of the cycle is entered from one of the alternatives in the first part of the cycle, only the IRT task is presented, but if the second part of the cycle is entered from the first part of the cycle by way of the other alternative, then both the IRT task and the ELF field are presented.

A critical feature in the design of this experiment is the selection of a duration for the second part of each cycle. Marr *et al*. (1973) reported a limited use of the concurrent chain procedure. In their procedure the second part of each cycle lasted about 30 sec; given the considerations previously set forth, here it is very likely that one of the causes contributory to their failure to report an effect was the briefness of their field exposures.

The concurrent chain procedure as described here - (technically conc chain VI; DRL (no field) - chain VI; DRL (field) - is extremely rich and parsimonious. Performance in the first part of each cycle produces the choice data that provides the preference measure. The matching relation tells us that relative rate of responding is equal to relative rate of reinforcement; this is normally expressed as

$$\frac{B_1}{B_1+B_2} = \frac{R_1}{R_1+R_2},$$

where B indicates the behavior measured on each response alternative and R indicates the number of reinforcements/unit time provided by each of two independent VI schedules, 1 and 2 (Herrnstein, 1970). For equal VI's as would be used here, this relationship tells us that if there is no preference for the two alternatives in the second part of the cycle, then the ratio of behaviors should be equal to 0.5. Any departure from 0.5 indicates a preference.

Performance in the second part of the cyle provides a control by showing that the ELF field being used has the anticipated effect on those occasions when it is activated. Performance in the second part of the cyle also provides a replication for Experiment II.

The three experiments described above do not exhaust the list of experiments of interest; they do, however, provide an illustrative example of the method of constructing an integrated series of experiments that will in the most powerful way reveal the effects, if any, of weak ELF fields on behavior. We are of the opinion that the questions of influence and hazard associated with weak ELF fields will receive the clearest and, to the general and scientific communities, most satisfactory answers when data from such an experimental series is available.

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APPENDIX C

ANATOMY AND BIOPHYSICS OF BRAIN CELLS IN WEAK ELF FIELDS

W. Ross Adey

1. Functional organization of nerve membranes during impulse generation

Environmental ELF fields in the amplitude range 10 to 100 V/m produce extremely small tissue electric gradients. They are far below gradients associated with synaptic activation, or with artificial stimulation of nerve fibers. The transmembrane "resting potential" in cerebral neurons is 70 mV and, by extrapolation, involves a potential gradient of 100 kV/cm. Applied transmembrane currents of the order of 1 mA/cm^2 are necessary to abolish this potential during electrical excitation of a nerve fiber (Eccles, 1957).

However, research on normal excitation of nerve cells, by activity of synapses (or fiber terminals) on cell surfaces has indicated a substantially higher sensitivity. Synaptic terminals in the resting state contain "transmitter substances", stored as small vesicles. Arrival of a nerve impulse at the terminal is associated with release of transmitter substance and depolarization of a small area of underlying neuronal membrane. In most cells, this synaptic depolarizing current must produce an altered transmembrane gradient of about 1 kV/cm for excitation of the cell with propagation of a nerve impulse. This translates into an increment in inward current flow of the order of 0.1 mA/cm^2 and is most obvious in cells already in what may be considered a "metastable" condition, so that the effect is to modify an on-going pattern of recurring discharge of impulses (Eccles, 1957).

None of these mechanisms appears to provide a basis for observed interactions of weak ELF fields with brain tissue. A 10 V/m ELF field induces a current of 0.9 nA in a simulated monkey head (Valentino, 1972) and this would be expected to produce an electric gradient in brain tissue of the order of 10^{-7} V/cm (Adey, 1975) to a first approximation. Even though so small, this gradient modifies calcium efflux from brain tissue by almost 20 percent over a quite narrow range of ELF frequencies between 6 and 20 Hz (Adey and Bawin, 1977). Calcium in brain tissue is predominantly on the surface of cells and in intercellular fluid. It is also concentrated in special structures within the cell but very little is found in the general cell interior. Susceptibility of brain tissue to ELF fields may be attributed to components of the field that pass into channels between cells (the extracellular space). These channels are occupied by highly hydrated, loosely arranged glycoprotein molecules, which are attached to the cell surface and form part of the "greater membrane" (Schmitt and Samson, 1969; Changeux et al., 1967; Singer and Nicholson, 1972). Glycoproteins form cell surface sheets with numerous negative charges. The basis of interaction between these negative charges and calcium ions, has been postulated to be cooperative (Kaczmarek & Adey, 1973; Grodsky, 1976); it may involve long range interactions along the membrane, and could provide a basis for "quantum amplification" of very weak trigger processes. These ionic phenomena associated with ELF field interactions in brain tissue exhibit both amplitude and frequency windows, strongly suggestive of a biological "tunneling" or other form of quantum amplification. Similar amplitude and frequency windows have recently been seen in ELF modulation of VHF (147 MHz) and UHF (450 MHz) radio frequency fields (Adey and Bawin, 1977), suggesting different mechanisms of a more peripheral nature.

Mechanisms underlying these weak field effects are essentially unknown and models to explain them are speculative. Much further research is necessary, and can be expected to focus on these phenomena as essential steps in new concepts of cell-cell communication in brain tissue, with information processing by slow electrotonic processes, rather than through volleys of nerve impulses (Adey, 1961; Schmitt, Dev and Smith, 1976). At this time, it is necessary to set aside classical concepts of transmembrane current levels of the order of 1.0 mA/cm^2 as probable thresholds for central nervous interactions with ELF fields. Emphasis will be on the significance of influences many orders of magnitude lower.

2. Membrane ultrastructure as related to sensing of weak chemical and electrical stimuli

The transductive coupling of weak electrical, chemical, hormonal and immunological events at the membrane surface has elicited an intense search into the structural and functional organization of the membrane surface (Schmitt, Schneider and Crothers, 1975). New knowledge in this field has led to certain unifying concepts between the fields of neurobiology, immunology and cancer research. Awareness of these new concepts in membrane organization is essential in evaluating biological interactions with electromagnetic fields; both in seeking biophysical substrates for previous observations of low level interactions, and even more importantly, in pointing the way to meaningful experiments that might test possible long term effects of low level interactions (Adey, in press). Without such an awareness, much time and effort may well be wasted on fruitless research, not only at the molecular level of membrane biophysics, but equally in the search for behavioral manifestations.

No longer can functions of cell membranes be adequately described simply in terms of lipid bilayer, or plasma membrane. The first electron microscopy of tissues fixed with osmic acid clearly displayed the plasma membrane as the counterpart of the classical cell membrane of light microscopy, and identified its double lamellae of oriented lipid molecules. However, the method failed to disclose the fragile layers of protein now known to cover internal and external surfaces of the lipid bilayer. The deposition of these membrane proteins has progressed through a series of models, beginning with that of Davson and Danielli (1952), which envisaged neatly arranged lamellar closing plates, followed by the Benson (1966) model, with an amorphous intrusion of stranded proteins within the lipid bilayer, to the Singer and Nicholson (1972) fluid mosaic model.

The actual arrangement for nerve cells is consonant with aspects of all three models, but the fluid mosaic model offers certain unifying concepts for both neurobiology and immunology. The model emphasizes the fluid character of the lipid bilayer (McConnell, 1975), and the insertion into it of intramembranous particles (IMPs), which vary markedly in size and chemical structure. Among the smaller molecules lying within the lipid bilayer are the prostaglandins, lipid molecules with molecular weights of only a few hundred. They behave as molecular switches in signaling to the interior of the cell the binding of hormone molecules at receptor sites on the membrane surface. Much larger are the β-microglobulin molecules with molecular weights of the order of 50,000. They signal to the interior of the cell the occurrence of an antigen-antibody reaction on the membrane surface.

These IMPs provide the basis for three important membrane functions. First, as McConnell (1975) pointed out, their presence within the lipid bilayer causes adjoining portions of the lipid bilayer to become more rigid, through long-range interactions between charge sites on the intruding particle and charges on the tails of the lipid molecules. Second, the outer ends of the IMPs protrude from the surface of the lipid bilayer as strands of protein. These strands have terminal carbohydrate (sialic acid) groups which are associated with numerous fixed negative charges. The surface of the membrane thus behaves as a polyanionic sheet with a strong affinity for actions. Third, the IMPs can be caused to move laterally within the lipid bilayer. These movements can be triggered by binding of cationic molecular sites to the protruding strands of the IMPs. Movement of IMPs within the sea of the lipid bilayer requires expenditure of metabolic energy (Yahara and Edleman, 1972).

3. Role of membrane surfaces in handling immunological and neurobiological information

The fluid mosaic model may be evaluated in the context of transaction and storage of information from both immunological and neurobiological experiences. It is not clear that there is any essential relationship between the two, but they may be treated as hierarchical in their utilization of related sensitivities within a single structural framework.

Edelman (1976) has proposed that antigen-antibody interactions at the surface of the lymphocyte are associated with "anchorage modulation" of the membrane surface, with permanent regrouping of the β-microglobulin molecules within the lipid bilayer, as the result of attachment of antibodies to their outer terminal glycoprotein segments protruding from the lipid bilayer. It is further proposed that this rearrangement of the microglobulin molecules is signaled to a microfilament network located on the inner side of the lipid bilayer. Edelman has suggested that this general scheme of immunological information transaction and storage may resemble these processes in the membranes of nerve cells. Coding of the stored information involves structural modification in the length of the membrane. Evidence on interaction of weak extracellular electric fields with cerebral neurons also suggests integration in the long axis of the membrane, with very weak oscillating electrical gradients triggering an altered binding capacity of membrane surface glycoproteins for cations, particularly for calcium ions (Adey, 1975).

Of the divalent cations, calcium and magnesium are the most numerous in the extracellular space. Calcium ions are bound about one thousand times more strongly than any of the monovalent cations except hydrogen (Katchalsky, 1964). Attraction of these ions to the membrane surface creates a cationic atmosphere, the counterion layer, extending 20 to 50 Å from the surface. The initial steps in excitation by an extracellular electric gradient may involve displacement of bound calcium ions to adjacent binding sites, and hydrogen ions may then occupy sites vacated by the calcium ions, producing a "local alkalosis" (Bass and Moore, 1968). Calcium occurs in 2 mM concentrations in extracellular fluid, but is typically in 10^{-7} M concentrations in the general cytoplasm.

Calcium ions are essential in many of the steps in neural excitation. Binding of calcium at membrane surfaces is intimately linked to action of neural transmitters, including amines, amino acids and peptides. Calcium ions regulate membrane leakage currents for monovalent sodium and potassium ions. They play a key role in hormone molecule binding at membrane receptor sites, and in the transmembrane signaling of these events by intramembranous particles (IMPs) described above (Sutherland and Robison, 1966).

It is in similar subtle actions on outer protein layers of the membrane that calcium ions appear involved in field interactions. There is a sharp nonlinearity in the triggered release of calcium ions by other calcium ions, which is presumed to result from their displacement from membrane surface proteins (Kaczmarek and Adey, 1973). Electrical stimulation of cerebral cortex with oscillating electric gradients of 20 to 50 mV/cm, smaller than those recorded in the normal EEG at cellular dimensions (Elul, 1962) and more than four orders of magnitude less than the transmembrane gradient of 10 kV/cm, caused a 25 percent increase in efflux of both calcium and the amino acid transmitter GABA. ELF fields at frequencies below 30 Hz also interact with chicken and cat cerebral tissue. There is evidence for both frequency and amplitude windows (Bawin and Adey, 1976) in the reduced Ca efflux occurring in the frequency range 6 to 16 Hz for fields of 10 to 56 V/m in air. Changes were insignificant at gradients of 5 and 100 V/m. Tissue components of these fields, estimated from measurements in phantoms, would be of the order of 10^{-7} V/cm.

There is a growing body of evidence for direct interactions between weak environmental electromagnetic fields and the vertebrate nervous system. As to the mode of interaction, the phenomena bespeak strange ground rules for which there are no easy explanations. There is evidence for amplitude and frequency "windows", for both electric and magnetic fields, in many of these interactions. These suggest limits established at ionic and molecular levels. The extreme sensitivities noted in some of these experiments would appear to require an extraordinary degree of "cooperativity" in the ordering of charge states across polyanionic sheets of membrane surface glycoproteins (Schwarz, 1967, 1970), if the tissue components of weak environmental fields are to become effective triggers to higher levels in neural excitatory processes. Nevertheless, sharp non-linearities in calcium binding and release, and occurrence of amplitude and frequency windows in sensitivity of this binding to ELF fields, all support the possibility of long range cooperative interactions. At best, these are partial answers. Further painstaking research will be necessary to an understanding of these mechanisms, which lie at the core of cell-cell communication in brain tissue.

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APPENDIX D

ELECTRICAL MEMBRANE POTENTIALS, TISSUE EXCITATION, AND VARIOUS RELEVANT INTERPRETATIONS

H. P. Schwan

The electrical properties of biological membranes, capacitance and conductance, linear and nonlinear have been the subject of extensive investigations for more than half a century.[2,9] A brief summary appears warranted, as it provides some insight into the interaction of electrical fields with membranes.

Membrane Capacitance

Membrane capacitance values are available for many cell types from bulk measurements. Here the applied current to a tissue or cell suspension is varied with frequency and analyzed using appropriate spherical, ellipsodial or cylindrical shape approximations. Measurements are also available with electrode systems impaled into the cells and directly measuring across the membrane. While this technique is restricted to larger cell size it has provided membrane capacitance values in agreement with those obtained from the bulk measurements. Briefly the capacitance is of the order of $1\ \mu F/cm^2$ with a range extending from 0.6 to $1.3\ \mu F/cm^2$ and an accuracy of about 20 or 30% in most cases. This capacitance appears frequency independent for the frequency range from about 1 kHz to 100 MHz. It corresponds to a membrane dielectric constant of about 10 relative to free space and this dielectric constant has been rationalized to reflect a mixture of values from the lipid and protein contributions to the membrane.[9]

The membrane capacitance is polarized by an applied external field with cytoplasmic and extracellular tissue fluids serving as access impendance elements in series with the membrane capacitance. Thus, the evoked membrane potential is given by the applied field sampled over the cell dimension:

$$\Delta V_m = 1.5\ RE \qquad \text{(for spherical shape)} \qquad (1)$$

provided that the applied frequency is low enough to make the membrane impedance large in comparison with that of the access impedance elements, i.e., f must be lower than the characteristic frequency $f_c = 1/2\pi T$ where T is the time constant given by membrane capacitance, cellular size and access impedance. For example, for cellular spherical shape

$$T = RC_m (\rho_i + 1/2\ \rho_a) \qquad (2)$$

It follows then that larger cells are more effective to receive a given membrane potential from an external field than smaller ones. This principle of sampling the field over a distance given by the cellular dimensions explains the sensitivities observed by large cells. It appears also to be used effectively by the receptor organs (ampullae of Lorenzini) of certain electrosensitive fishes.

Membrane Conductance

Membrane conductances cannot be extracted from bulk data of tissues or cell suspensions since very minor variations in the extracellular shunt path correspond to major membrane conductance values. Thus, our knowledge of membrane conductances is limited to larger cells and presently excludes cellular organelles such as nuclei and mitochondria. The data available for large plant cells, nerve cells, and muscle indicate values of the order of 10 mmho/cm^2 but varying over a wide range depending on all sorts of circumstances. However, it can be stated from all available data that the membrane time constant $T = C_m/G_m$ is of the order of a msec, i.e., frequencies below 1 kHz are needed to make the membrane impedance resistive.

Above stated principles have been extensively tested on a large number of membrane systems before the Second World War (Fricke, Cole)[+] and after that war (Schwan, Hanai, Carstensen and many others).[‡] These include all sorts of sea eggs, muscle and most other tissues, erythrocytes, subcellular organelles, bacteria, synaptosomes, a variety of vesicles, PPLO and bilayer membranes. They are responsible for the β-dispersion which terminates at the 10 to 100 MHz frequency range. Clearly at the high frequencies cell membranes are no longer able to sample field strength over cellular dimensions and applied fields result in membrane potentials of the order of R/D times, i.e., 1000 smaller than at low frequencies (R is a measure of cellular size and D membrane thickness).

Nonlinear Properties

Above stated properties are linear, i.e., do not change if the applied external field evokes membrane potentials which are small in comparison to the resting potential of about 70 mV, and maintained by most cells by a mechanism not yet well understood. However, if the membrane becomes depolarized the membrane conductance increases dramatically at least in nerve and muscle cells to values of the order of 100 times those observed in the resting state. In the meantime, the capacitance, as observed at frequencies

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[+] Fricke's and Cole's work is summarized in Cole (1968).[2]

[‡] Early work by Schwan's group is summarized by Schwan (1957),[9] Schwan (1965),[12] and Cole (1968).[2]

well above those given by the "characteristic" frequency f_c remains constant. Extensive investigations of this phenomena resulted in a mathematical model based on physical speculations which envisions a membrane leakage resistance in parallel with the membrane capacitance and two nonlinear resistances, each of them in series with a potential and responsible for sodium and potassium transport. This model of Hodgkins and Huxley (HH)[5] has been exceedingly successful to describe many membrane aspects. For example, extensive computer assisted investigations of the HH model readily confirm the all or nothing nature of membrane response as the membrane is subjected to external fields.[1] It then appears that this model does not leave much room for any possibility that external fields can evoke more subtle membrane responses.

Low Frequency Properties

During the 1950's Schwan reported extraordinarily high dielectric constants on muscle tissue.[8] It appeared that the membrane capacitance increased from 1 $\mu F/cm^2$ to more than 30 $\mu F/cm^2$ as the frequency decreased below 100 Hz. These results were confirmed by Fatt[4] in 1964, and then by many others. Originally, these remarkable results were thought to result from a double layer structure of the membranes in the manner proposed by Davson and Danielli.[3] In 1957, however, Schwan stated that a high surface admittance element parallel to the membrane surface and evoked by counter ion movement might be responsible.[9] Fatt[4] stated that the usual fixed charge concentrations on membrane surfaces are insufficient to provide for enough counter ions and made the attractive proposal that a frequency dependent access to internal cellular organelles connecting with the outer membrane must be considered. However, measurements both with external and internal electrode arrangements were not necessarily supportive of this approach. The proposal of a more extended membrane structure (the greater membrane concept proposed by Adey, Lehninger and Schmitt) might well provide many fold larger fixed charge sites and the counter ion hypothesis as responsible for the α-dispersion may well be worthy of reexamination. The counter ion hypothesis was forcefully reinforced during the early 1960's by a series of investigations on the dielectric properties of colloidal particles. Here also amazingly high dielectric constants were observed largely by Schwan and his group[10,11] with values up to 50,000 for polystyrene particle suspensions which were stabilized in suspensions by a surface coating which provided enough fixed charge sites to create substantial counter ion clouds. Large induced dipole moments are caused by the response of the counter ion cloud to the field. They are equivalent to a frequency dependent surface admittance tangential to the particle surface which is of the order of 10^{-9} mho and may be thousand fold larger at cellular surfaces if the membrane is considered a part of a greater membrane concept with the fuzzy outer regions providing the large number of fixed charge sites necessary to provide for a corresponding large counter ion population. The concept of a frequency dependent surface admittance element was well supported by a mathematical model developed by Schwartz which has predictive value and is in excellent agreement with experimental data.

But several other models can equally well explain the dielectric properties of tissues. The concept of ionic gating currents so prevalent now has been formulated already in the late fifties. It is straightforward to demonstrate from the König-Kramer relationships that such ionic gates which open or close as a field or current step is applied must simulate a time and frequency dependent large capacitance in parallel with the membrane capacitance of 1 μF/cm^2 and representative of the bulk of the lipoprotein membrane matter.[9,12]

Consideration must also be given to the large boundary layer capacitance in the aqueous phase next to the membrane. As the frequency is lowered sufficiently so that the resistive properties of the membrane determine its impedance, this boundary capacitance instead of the membrane capacitance may become dominant and thus explain the low frequency dispersion phenomena of the membrane.

The strong capacitance changes observed at low frequencies are coupled with corresponding membrane conductance changes through the König-Kramer relationships and measured conductance values are entirely in agreement with the theoretical demand. As a consequence it has been speculated that the original concept of constant capacitance but variable conductance upon excitation as originally observed at high frequencies is subject to reexamination. It may well be accompanied by capacitance changes at lower frequencies, with the membrane conductance changing to a lesser extent. Recently, Takashima, Schwan and Cole[15] reported on a change of the squid axon membrane capacitance at low frequencies. It appears to strongly depend on whether the membrane is briefly hyperpolarized or depolarized. These changes are in accord with the König-Kramer relationship. They suggest a reexamination of the HH model and replacement of the constant membrane capacitor by a variable element.

What does this all mean with regard to the possibility of subtle interactions of fields with membranes. There appears little reason to question that very high frequency fields cannot be coupled effectively into membranes. However, the startling membrane characteristics at low frequencies have not been well understood. They can be explained either in terms of inhomogeneous membrane structure or boundary potentials in series with the membrane or connecting organelles or, ionic gates or substantial counter ion movements in a greater membrane complex inducing a frequency dependent surface admittance element tangential to the membrane surface and of substantial magnitude.

If it is assumed that induced membrane potential changes must be a noticeable fraction of the resting potential, bulk membrane current densities needed for excitation can be calculated. Such calculations have been carried out and indicated values ranging from 0.1 to 10 mA/cm^2 depending on cellular size, membrane conductance values and other factors.[13] A value of very approximately 1 mA/cm^2 might be used as indicative of the threshold of excitation with low frequency currents of about 100 Hz or less. More sophisticated models can be based on the cable core conductor approach using either the HH equations for the membrane properties or newer revisions of the model. Some of these models (not reviewed here) appear to explain the strong frequency dependence of excitation threshold with a broad minimum near 100 Hz (Moran, 1976, private communication).

Considerable experimental evidence on current threshold for stimulation exists, including muscle and heart muscle tissues. More recent data have been stimulated by the development of the cardiac pacemaker field.[7] Again, all these data are supportive of the mA/cm^2 threshold for excitation but depend of course in detail on electrode configuration, size, and the mode of excitation.

Considerable experience has also been assembled by those interested in electrical accidents. The extensive body of this knowledge is not summarized here, but supports the above stated threshold figures.[13]

Many data are furthermore available about currents needed to evoke cerebral responses such as sleep, anesthesia and narcosis. Currents are usually in the range between 10 and 100 mA with current densities probably an order of magnitude lower.[6]

All available knowledge from the more basic principles, literature on hazards and more clinically oriented work appears internally consistent. But this internal consistency does not exclude the possibility of more subtle responses, particularly if they are masked by the more strong and readily apparent excitation phenomena discussed above. A perusal of the various mechanisms which may participate in generating the amazing dielectric phenomena at very low frequencies suggests that the lower frequencies below 1 kHz provide for more possibilities of subtle effects if there are any at all. This statement is based on the cutoff frequencies for the effects reviewed, including subcellular connecting structures, large counter ion displacement effects and membrane relazation effects by ionic gates.

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APPENDIX E

TESTS FOR HUMAN PERCEPTION OF 60 Hz MODERATE STRENGTH MAGNETIC FIELDS

Robert D. Tucker and Otto H. Schmitt

Abstract

After preliminary experiments that pointed out the extreme cleverness with which perceptive individuals unintentionally used subtle auxiliary clues to develop impressive records of apparent magnetic field detection, we developed a heavy, tightly sealed subject chamber to provide extreme isolation against such false detection. A large number of individuals were tested in this isolation system with computer randomized sequences of 150 trials to determine whether they could detect when they were, and when they were not, in a moderate (7.5 - 15 gauss rms) alternating magnetic field, or could learn to detect such fields by biofeedback training. In a total of over 30,000 trials on more than 200 persons, no significantly perceptive individuals were found, and the group performance was compatible, at the 0.5 probability level, with the hypothesis that no real perception occurred.

Introduction

Since medieval times there has been a feeling that magnetic phenomena are somehow mysterious and magical and are, therefore, automatically suspect as baleful influences on humans and their domestic animals and crops.

The recent publicity given to the weak electric and magnetic fields associated with extremely low frequency world wide military communication systems such as Seafarer has reminded our population that we all live in such fields and has reawakened these innate fears, especially on the part of those living near power lines and similar installations. In the absence of clear proof that these fields themselves are basically harmless, every anecdotal report of presumed harm or discomfort from fields becomes emotionally magnified and repeated until it is actually believed as fact and used as a basis for legislative or political action.

Hundreds of papers have been written in recent years reporting experimental work or informed opinions with respect to the effects of these fields, but there is still no categorical guarantee that these fields have no significant influence, good or bad, on people or their animals or plants.

Pragmatically we would like to be able to offer assurance that present fields and those to be expected with normal growth of power and communication systems will have no significant adverse effects at a high level of statistical certainty, or to warn of a possible real hazard. Meanwhile we can be thankful that no obviously harmful effects have been established.

Two different kinds of hazards come to mind: one that affects almost everyone slightly so that the total effect could be great without being explicitly demonstrable in any one subject; the other that seriously injures or inconveniences a very few people in the population so that no representative of the class might chance to be in a moderate size test sample. Even within these classes it is exceedingly difficult to determine unambiguously whether a person does or does not suffer a mild psychological shift, a metabolic modification, or a change in mental performance.

Testing a population sufficiently large to be statistically significant for everything imaginable, encompassing both the rare severe effect and the pervasive small effect, is hopelessly expensive. We must concentrate, therefore, on tests that include both types and are sensitive simultaneously to many different classes of effect, expecting to follow, with specifically designed experiments, any significant responses discovered.

We chose conscious perception as a measure that is likely to be coupled to many different kinds of response, yet capable of being evaluated quantitatively by a statistical procedure that is both sensitive and well tested theoretically. Admittedly there could be occult effects, analogous to unfelt x-ray damage, that could exist, but there are, here, no known high energy ionizing radiations or acute toxins. After a century of experience, no specific demonstrable dangers have been established, whereas, in the case of x rays, damage was discovered within months of the development of the generators.

We used an experimental design in which any individual subject to be tested was deprived, to the best of our ability, of all field-related clues other than the presence of a test magnetic field itself. The subject was asked to decide in each of 150 successive trials whether he was or was not in a magetic field, while a small computer, according to a randomization rule, either provided a field or left the field off and recorded the subject's choice of whether a field was or was not present.

With the standardized test series of 150 trials, that can be made within about 15 minutes, one can quickly detect even a small systematic bias or an unusually perceptive subject who can beat "chance" by a substantial margin. Furthermore, this experimental design permits one to pool many individual scores and is insensitive to one individual's biased inclination to say "yes" or "no".

The "Trajectory plot" (figure 1) in which each successive decision advances the trajectory one unit, up or down according to whether it is right or wrong, gives a display in which overall results and short-term trends can be easily recognized. The background curves represent paths enclosing

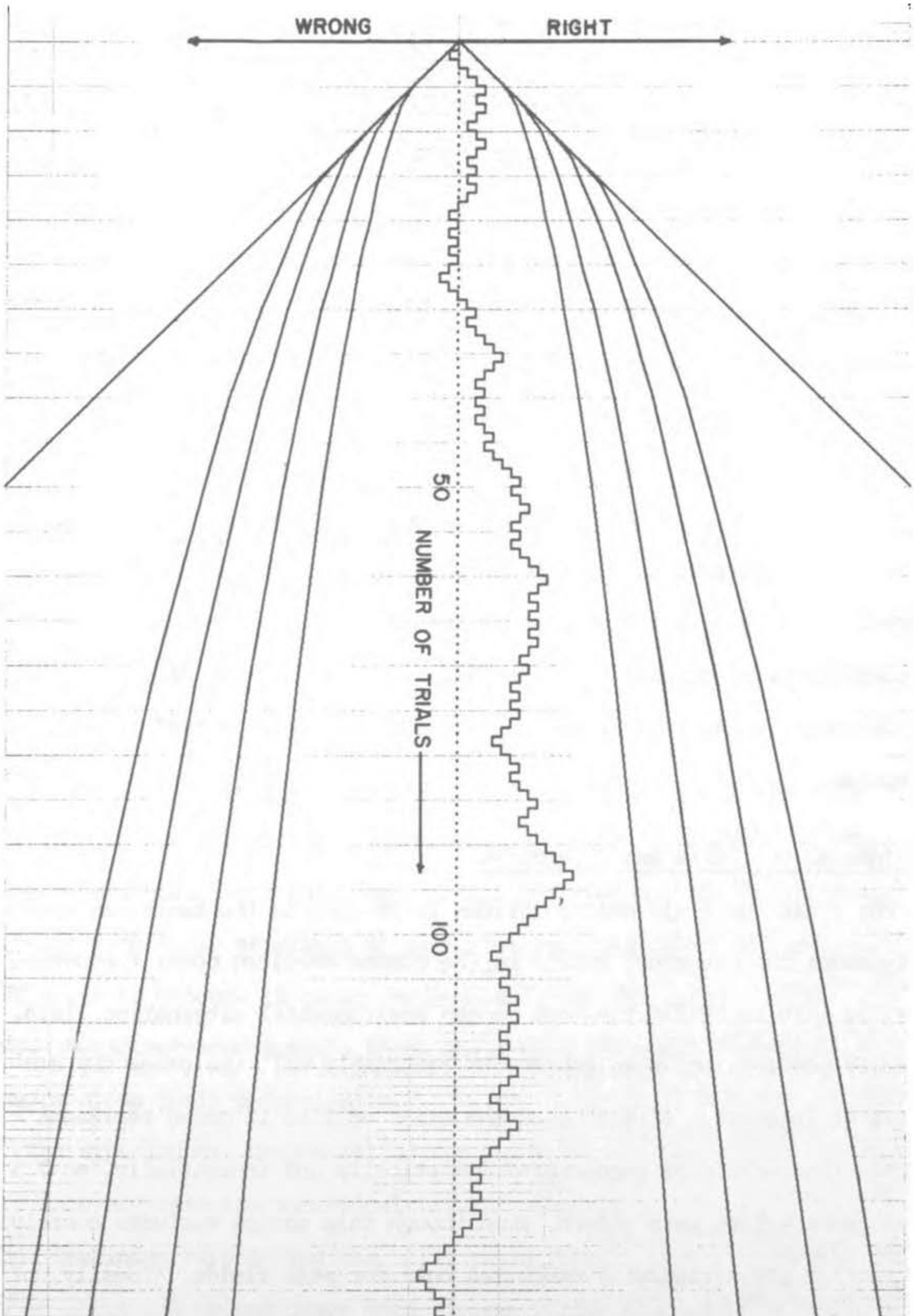
WRONG
RIGHT
50
NUMBER OF TRIALS
100
150
TWO TAILED
"p" VALUES
0.0001
0.001
0.01
0.05
0.05
0.01
0.001
0.0001

Figure 1

successively lower identified levels of positive or negative probability or "p" value. This case, for example, shows a typical null experiment. All experimental runs were routinely monitored by these trajectory plots.

We quickly learned that some individuals are incredibly skillful at sensing auxiliary non-magnetic clues, such as coil hum associated with field, so that some "super perceivers" were found who seemed to sense the fields with a statistical probability as much as 10^{-30} against happening by chance. A vigorous campaign had then to be launched technically to prevent the subject from sensing "false" clues while leaving him completely free to exert any real magnetic perceptiveness he might have. Acoustic "jamming" with white noise or line frequency sound could easily prevent auditory detection of coil hum and similar clues, but this procedure was declared experimentally improper as it might also block "true" field perception.

Experimental Equipment and Procedures

The choice of field configurations to be used in the tests was rather easily made; the frequency should be the common American power frequency, 60 Hz, as this is by far the most common environmental alternating field, is easily powered, and also represents reasonably well the other ELF signatures of interest. Strengths of the order of 1 to 15 gauss represent typical stronger fields encountered domestically and industrially, so 7.5 and 15 gauss values were chosen, even though this choice excludes conceivable effects that are exclusively exhibited only for weak fields. Ideally, of course, one would like to investigate a variety of field strengths, frequencies, and modulation patterns.

These fields are easily produced by "Helmholtz Coil" arrays, even though surprisingly large exciting currents and voltages are required if the coil systems are to be big enough to yield human size work spaces of magnetic uniformity. It is also important that the systems be electrically switchable to produce uniform gradient fields as well as uniform strength fields, because some possible biophysical mechanisms respond selectively to one or the other modality.

Two coil configurations were built. One - the "Large Coil" system - comprised coaxial square coils, 2.8 meters on an edge, separated by about 2.5 meters. These coils, excited with 70 amperes rms at 210 volts, produced 7.5 gauss rms, uniform within 5% in the central cube, 1.5 m on an edge, in which the subject operated. When connected in opposition, these coils produced a central gradient of 13 gauss rms/m.

To test selectively the responses of the head region of the subject, where many of the perceptive processes are presumed to reside, a smaller classical Helmholtz coil pair, the "Small Coil" system, 40 cm in diameter, was built with coils separated 40 cm. These coils require only 6 amperes at 30 volts to produce 15 gauss rms and can be driven safely to over 50 gauss. "Gradient—connected", these coils produce fields changing 0.7 gauss/cm along their central axis.

The experimental design called for 150 trials in each experimental test run. In every case the individual trial included a start at zero field, either remaining zero during the trial for a "no field", or smoothly increasing, in about 1/2 second under motor-driven variac control, to a fixed maximal value for a "field really present" test. This arrangement permitted true "A, B" testing in every case, the field being maintained, if present, until the subject made a decision or "timed out" after 10 seconds, in which case the trial was "discarded" from the standard set of 150 trials and an extra trial incorporated automatically. The number of times that the subject "timed out" was, of course, recorded in all cases, and an occasional experimental run with too many "time outs" was abandoned where, for example, the subject fell asleep or simply could not come to decisions.

The random sequence generator and the detailed scheduling and logging of results were under the automatic control of a DEC PDP5 small computer, with results automatically typed out, tabulated and summarized on a teletype print-out and an accompanying ASCII punched paper tape for data analysis on the PDP8. The actual random decision of "field" or "no field" was based on a least significant digit, 0 or 1, status in a long fast count sequence including the subject's response time, and so was not deterministically preprogrammed and was quite reliably random.

The computer, the subject and the operator all have to signal their readiness to start an experiment. Upon obtaining this concurrence, the sequence is initiated automatically. Provisions are made for the subject or the operator to interrupt the sequence briefly by pressing a "pause" button to permit adjustment to a more comfortable position, nose blowing, etc., from which a "resume" button restarts the sequence where it had left off, always at the end of a trial. An "End" button allows the subject to terminate the experiment before the full sequence is finished if he feels it necessary.

For "biofeedback training" experiments, two additional features were incorporated in the design. One lights an "actual field condition" panel signal lamp above the "correct" selection button on the subject's panel just after a "decision" has been made. A three-digit LED display shows the cumulative percentage performance grade, 500 signifying an equal number of right and wrong choices. From these the subject should be able to improve his performance if an undeveloped but latent ability exists for field sensing.

Early experiments, in which an operator visible to the test subject controlled manually, according to a random number table, whether a field was to be applied or not, alerted us to the necessity for careful isolation of the test subject from unintentional clues from which he could consciously or subconsciously deduce the state of coil excitation. No poker face is good enough to hide, statistically, knowledge of a true answer, and even such feeble clues as changes in building light, hums, vibrations and relay clatter are converted into low but significant statistical biases.

In a first round of efforts to prevent utilization of such clues, the control was taken to a remote room and soon given to a small computer. A "fake" coil system, remotely located but matched in current drains and phase angle to the real large coil system, was introduced as a load in the no-field cases. An acoustically padded cabinet was introduced to house the experimental subject, to isolate him from sound and vibration, and efforts were made to silence the coils by clamping them every few centimeters with plastic ties and by supporting them on air pocket packing material. We tried masking sound and vibrations, but soon realized that this might also mask real perception of magnetic fields.

Even with these precautions, including the isolation cabinet, sensitive subjects still reported that they thought they were faintly hearing hum and were producing extremely high scores. Some scored correct counts that could be credited to chance only at p values in the range of 10^{-10} to 10^{-20}. Feeling that these surely represented some sort of "leakage", we next developed an elaborately sealed heavy wooden isolation cabinet.

This cabinet was fabricated with four layers of 1/2 inch plywood, full contact epoxy glued and surface coated into a monolithic structure with interleaved corners and fillet corner reinforcement to make a very rigid heavy structure weighing, in total, about 300 kg. The structure was made without ferrous metal fastening and only a few slender brass screws were used. The door was of similar epoxyed 4-ply construction but faced with a thin bonded melamine plastic sheet. The door was hung on two multi-tongue bakelite hinges with thin brass pins. The door seals against a thin, closed-cell foam-rubber gasket, and is pressure sealed with over a metric ton of force by pumping a mild vacuum inside the chamber by means of a remote hose-connected large vacuum-cleaner blower. The subject receives fresh air through a small acoustic filter inlet leak that also supplies sufficient air flow to cool the blower. The chosen "cabin altitude" was only about 2500 feet above ambient so it presented no serious health hazard and was fail-safe protected.

With this cabinet, scores dropped dramatically, but a few individuals still made impressively significant scores when, at one point, minor deterioration of acoustic isolation of a field coil occurred, and with biofeedback training, very high scores of 10^{-10} or better were consistently made.

As still more isolation seemed necessary to guarantee practically complete exclusion of auxiliary acoustic and mechanical clues, an extreme effort was made to improve, ever further, the already good isolation. The isolation cabinet was now hung by aircraft shock cord supports through the ceiling to roof timbers. The cabinet was prevented from swinging as a pendulum by four small non-load-bearing lightly inflated automotive type inner tubes placed between the floor and the cabinet base. Coils were very firmly reclamped, the cabinet draped inside with sound absorbing material and the chair for the subject shock-mounted with respect to the cabinet. The final experiments, in which minimal perception was found, were done with this system.

In the "small coil" experiments, there was less difficulty in acoustic and vibrational isolation, as the coils were plastic impregnated to prevent vibration, and were light enough to be suspended on highly compliant elastic cords. Nevertheless, the final small coil experiments were done with the small coil system suspended inside the suspended isolation cabinet.

Results

The initial large coil experiments were all performed with a uniform vertical 7.5 gauss rms field and with the subject seated at the center of the coil system. No very special precautions were taken to isolate the subject from incidental coil hum or vibration beyond clamping the coil turns tightly together and wrapping and mounting them in sheets of foam rubber as no hum was heard at the subject position by an observer listening in the otherwise quiet room. Some tests were also done with the subject lying supine and on the right side at the coil system center to study possible effects of position. As a control, four experiments were done with the test subject seated in the room within hearing range but completely outside the Helmholtz coil system where the field was only a few percent of the central value.

Figure 2 summarizes the results of these 35 experiments within the uniform field and 4 control experiments with the observer outside the coils. The

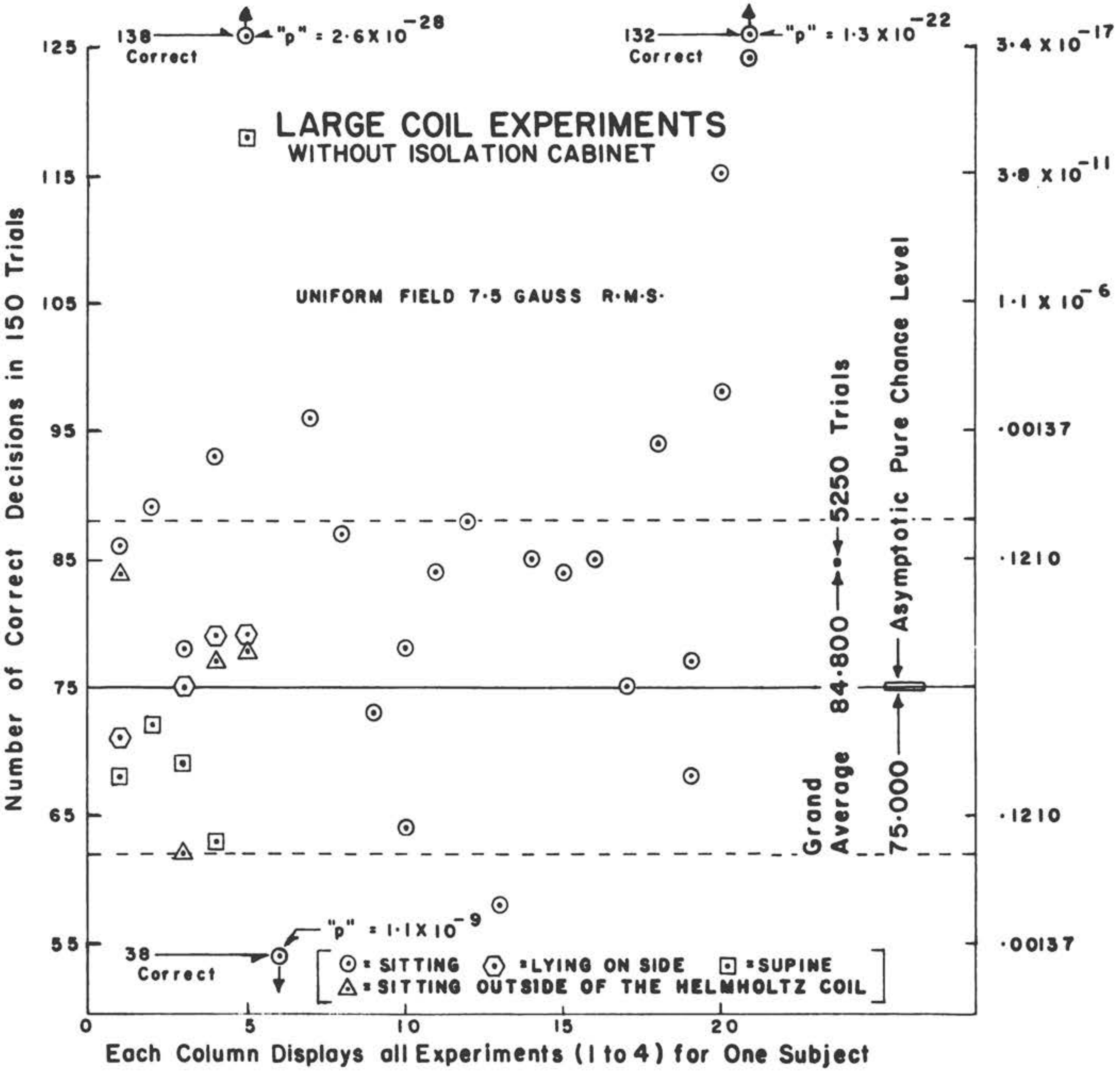
LARGE COIL EXPERIMENTS
WITHOUT ISOLATION CABINET
UNIFORM FIELD 7·5 GAUSS R·M·S·
138 Correct
"p" = 2·6 X 10^{-28}
132 Correct
"p" = 1·3 X 10^{-22}
38 Correct
"p" = 1·1 X 10^{-9}
Number of Correct Decisions in 150 Trials
125
115
105
95
85
75
65
55
0
5
10
15
20
Each Column Displays all Experiments (1 to 4) for One Subject
3·4 X 10^{-17}
3·8 X 10^{-11}
1·1 X 10^{-6}
·00137
·1210
·1210
·00137
Grand Average 84·800 ← 5250 Trials
75·000 ← Asymptotic Pure Chance Level
⊙ = SITTING
⬡ = LYING ON SIDE
⊡ = SUPINE
△ = SITTING OUTSIDE OF THE HELMHOLTZ COIL

Figure 2

central area between the dashed lines represents the region of results expected by chance using a two tailed p value limit of 0.04. One might thus expect on the average, by chance alone, one experiment above this range and one below it in each set of 50 experiments.

As 12 of the 35 experiments appear to show significant detection, there is almost certainly a real effect, direct magnetic or auxiliary clue related. No major evidence appears to point to one position as dramatically more or less sensitive than another. One control in four approaching the 0.04 limit suggests, but by no means proves, that some field clues are active.

The results of the first experimental series, expecially those showing extremely high perceptive sensitivity and even one case of significant perception by a test subject outside the field coils, led us to suspect that non-magnetic perception was involved. The high performance subjects reported that they experienced a vague but definite "hearing" of something or a feeling of vibration. Several subjects complained of mild "magnetic headaches" during the experiment that disappeared shortly thereafter.

In order to determine whether the perception demonstrated beyond reasonable doubt by the first experimental series was assignable to true direct magnetic perception or to indirect perception via auxiliary correlated clues and to examine the "magnetic headache" phenomenon, a second experimental series was conducted. In this series a randomly selected third of the experiments were "no field" control experiments in which the field was <u>never</u> turned on although the subject was allowed to carry out the choice procedure as usual and was never told that such "placebo" experiments were being incorporated.

To eliminate acoustic, tactile and visual clues, the subject was now always seated in the vacuum sealed isolation chamber so mounted above the floor plate of the Helmholtz coil system that he occupied the same central position in the Helmholtz coils as before. The coils themselves were also further isolated by being spaced away from their wooden supports with plastic compliant air cell sheeting.

The results of this second experimental series are displayed in Figure 3. Four subjects among over eighty tested complained of headaches. Headache sufferers usually reported headaches again upon retesting and reported these headaches with about equal frequency for field and no-field "placebo" experiments. Statistical analysis of data for a total of less than a dozen headache reports, including two where headache was reported with no field present, is of doubtful value. We can feel quite sure that some, if not all, of the headaches are unrelated to magnetic fields, as demonstrated by the placebo positives. In no case was the pain so directly related to field as to permit the subject to achieve a significant correlation with field by keying field presence to ache on a trial by trial basis. Taken as a whole, the headache phenomenon seems to be more a result of confinement, repetitive trials and the hard concentration of trying to sense a field. One young lady subject achieved faultless perception trial after trial until it was discovered that she was wearing an electronic hearing aid that responded well to 60 Hz fields.

With three exceptions, the data of Figure 3 is closely in accordance with a chance distribution. In these three experiments, extremely high perception was demonstrated at p values of 5.5×10^{-5}, 4.2×10^{-11} and 1.6×10^{-20}. These were identified as being successive experiments, which aroused our suspicions. In the one where the highest score was achieved, the subject reported that he could almost certainly hear a hum when the field was on. The other high performers confirmed that they seemed to hear something, but

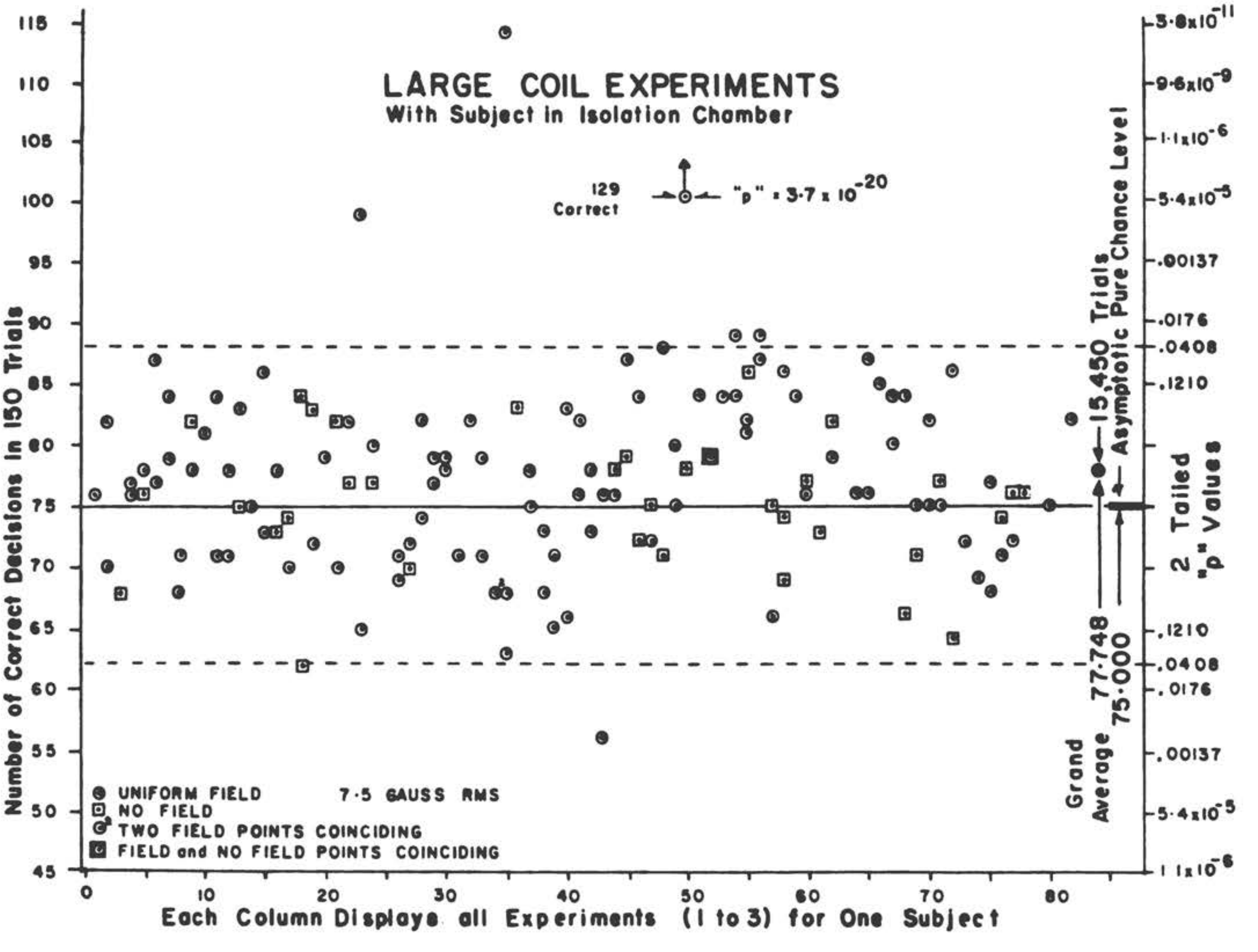LARGE COIL EXPERIMENTS
With Subject in Isolation Chamber
129 Correct
"p" = 3.7 x 10-20
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
Number of Correct Decisions in 150 Trials
0
10
20
30
40
50
60
70
80
Each Column Displays all Experiments (1 to 3) for One Subject
UNIFORM FIELD
7.5 GAUSS RMS
NO FIELD
TWO FIELD POINTS COINCIDING
FIELD and NO FIELD POINTS COINCIDING
Grand Average
77.748
15,450 Trials
75.000
Asymptotic Pure Chance Level
2 Tailed "p" Values
3.8x10-11
9.6x10-9
1.1x10-6
5.4x10-5
.00137
.0176
.0408
.1210
.1210
.0408
.0176
.00137
5.4x10-5
1.1x10-6

Figure 3

were less positive. Upon reexamining the coils at this juncture, we found that one sheet of the bubble plastic had deflated, allowing the coil to rest more directly on its support. After replacement of the defective isolation sheet, two of the high achievers were retested and could no longer get high scores. The third subject was no longer available for retest.

Excluding these three experiments, there were no longer any "star performers". One managed an anti-correlation below $p = 0.01$, and several were near the 0.04 level, as might be expected. Lumped together as a single 15,450 trial experiment, the mean correct count per 150 trials was 76.67, which seems near to the pure chance level of 75.00, but in fact this slight difference still puts the lumped results at a $p = 0.01$ level against pure chance.

Proceeding on the hypothesis that this small but significant deviation might, indeed, represent a finite magnetic or other perception distributed within the group or concentrated in a few of its members, we next examined the possibility of biofeedback enhancement of the effect. Presumably the ability to sense field or its cumulated artifact could be taught to a subject by training with corrective feedback.

Figure 4 summarizes the results for 83 large coil uniform field experiments with feedback. The first four subjects tested showed a remarkable ability to "perceive" magnetic field far beyond chance, achieving levels as significant as $p = 10^{-30}$. As there was now no failure of the coil insulating material, it would appear that the computer assisted learning procedure helped these subjects to utilize effectively clues that were otherwise too faint to sense.

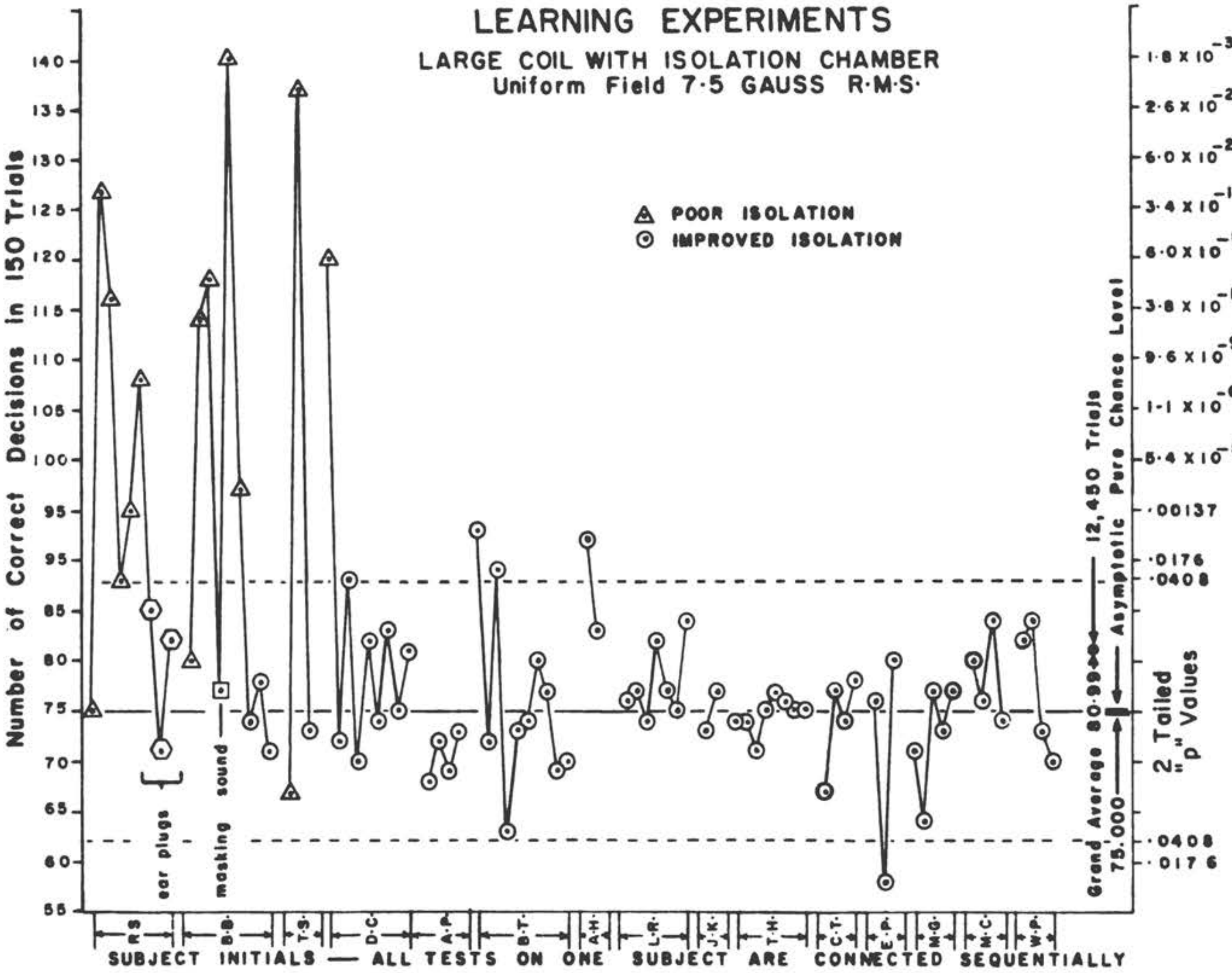
LEARNING EXPERIMENTS
LARGE COIL WITH ISOLATION CHAMBER
Uniform Field 7·5 GAUSS R·M·S·
POOR ISOLATION
IMPROVED ISOLATION
Number of Correct Decisions in 150 Trials
140
135
130
125
120
115
110
105
100
95
95
85
80
75
70
65
60
55
ear plugs
masking sound
1·8 x 10-30
2·6 x 10-25
6·0 x 10-21
3·4 x 10-17
6·0 x 10-14
3·8 x 10-11
9·6 x 10-9
1·1 x 10-6
5·4 x 10-5
·00137
·0176
·0408
·0408
·0176
Grand Average 80·99 — 12,450 Trials
75.000 — Asymptotic Pure Chance Level
2 Tailed "p" Values
R S
B·B·
T·S·
D·C·
A·P·
B·T·
A·H·
L·R·
J·K·
T·H·
C·T·
E·P·
M·G·
M·C·
W·P·
SUBJECT INITIALS — ALL TESTS ON ONE SUBJECT ARE CONNECTED SEQUENTIALLY

Figure 4

To distinguish between field sensing and field associated clue sensing, such as hearing coil hum, we placed ear plugs in one subject's ears during three experiments and employed a 120 Hz masking sound during one experiment on another subject. The scores of these previously high perceivers dropped to values easily explainable by chance. These results led us to believe that our subjects were being "taught" to use subliminal clues incidental to field production, even though the tests were conducted with the subjects in the isolation cabinet.

We now undertook an intensive campaign to isolate the subject from the coil system environment to the very best of our ability. We tightened the coils even more carefully, draped the inside of the isolation cabinet with sound damping material, and placed the subject chair on a foam pad to decrease possible vibration coupling from the chamber to the subject. The chamber was isolated from floor vibrations by suspending it on shock cords from the building roof rafters through the ceiling.

The encircled data points on Figure 4 represent experiments completed after improving the isolation. Here we see no scores, not even those of the "well taught" perceivers, exhibiting the previous extremely high significance. The cumulative mean for all the data is 80.99 correct responses per 150 trials, a very significant $p < 0.0001$. But merely by deleting the pre-improvement isolation data (the triangle marked points), the average becomes 75.93 correct decisions, $p = 0.21$. Thus, it seems that our subjects were indeed sensing subliminal vibration and that the further isolation of the cabinet and subject blocked the perception ability.

In their daily routines, people are seldom subjected to uniform magnetic fields, but more often encounter fields with substantial gradients. Certain categories of possible magnetic field effects depend entirely on these field gradients and are totally absent even in strong uniform fields. We therefore designed a class of experiments around gradient fields with a near zero central value and central coil axis gradient of approximately 13 gauss rms/m, which is representative of fields encountered daily. The biofeedback, or learning mode was chosen for these experiments as it provides a more sensitive test. During the feedback training, the subject can experiment with a variety of sensory modes and can even combine the best features of several.

The results of the gradient field learning experiments using the large coil system are shown in Figure 5. These experiments were interspersed with the uniform field learning experiments and exhibit the same "hearing" artifact phenomenon. If one includes the triangle marked data points, experiments done before final coil tightening and isolation chamber suspension, the composite mean is 77.74 correct responses in 150 trials, which corresponds to a significant p = 0.009. The mean drops to 73.97, however, when only the encircled final isolation data points are used, a negative correlation of p = 0.36. These results again show little evidence for either magnetic field or field associated clue perception.

Because the biofeedback enhanced perception seemed to center around acoustic artifacts, we thought it worthwhile to establish whether ordinary hearing threshold could be significantly lowered by biofeedback methods, utilizing the already available high-isolation chamber. White noise, limited to the ordinary audible spectrum, was used to avoid standing waves and was introduced into the cabinet by a small loud speaker that, presuming low-level linearity, could be directly calibrated at a higher level.

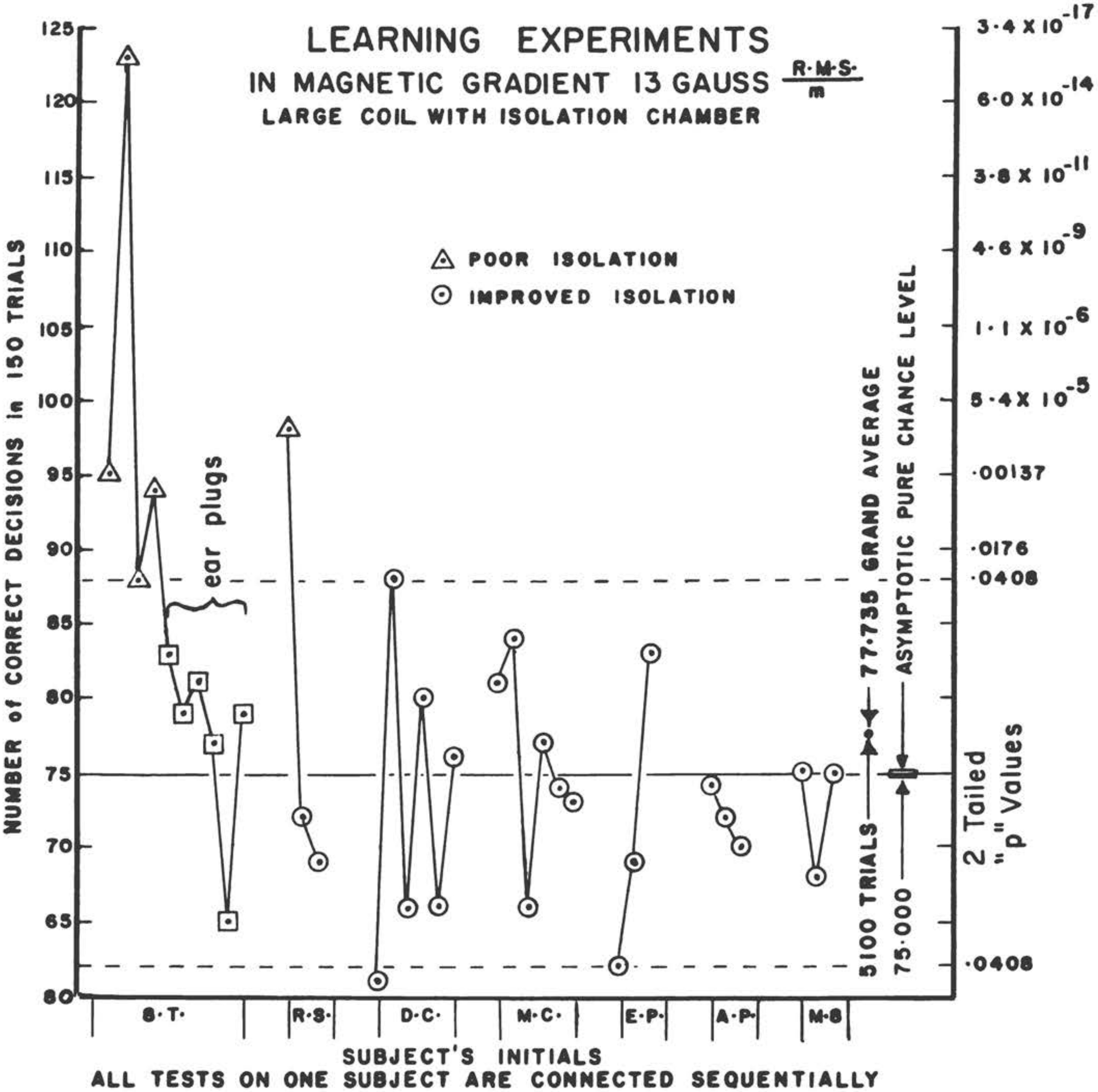
LEARNING EXPERIMENTS
IN MAGNETIC GRADIENT 13 GAUSS $\frac{R \cdot M \cdot S \cdot}{m}$
LARGE COIL WITH ISOLATION CHAMBER
△ POOR ISOLATION
⊙ IMPROVED ISOLATION
NUMBER of CORRECT DECISIONS in 150 TRIALS
125
120
115
110
105
100
95
90
85
80
75
70
65
60
ear plugs
3·4 X 10^-17
6·0 X 10^-14
3·8 X 10^-11
4·6 X 10^-9
1·1 X 10^-6
5·4 X 10^-5
·00137
·0176
·0408
·0408
2 Tailed "p" Values
5100 TRIALS — 77·735 GRAND AVERAGE
75·000 — ASYMPTOTIC PURE CHANCE LEVEL
S·T·
R·S·
D·C·
M·C·
E·P·
A·P·
M·S
SUBJECT'S INITIALS
ALL TESTS ON ONE SUBJECT ARE CONNECTED SEQUENTIALLY

Figure 5

Utilizing a "threshold" defined as a level that could be detected half the time, and guarding against pure guessing by incorporating randomly inserted no-sound tests with an appropriate guessing penalty, we were able to establish an individual's threshold to within 1 dB in single sets of 150 test measurements, each taking only about 15 minutes. The individual's threshold varied by several decibels from day to day, but was reproducible in duplicate test sequences.

Comparing four calibration runs with four feedback training runs on each of two subjects, an average feedback improvement in threshold sensitivity of about 2 dB was achieved. Because of the very small number of experiments, these results are statistically valid only at the 90-95 percentile level.

There has been a continuing theme, largely anecdotal and often poorly substantiated with experimental data in the literature coming especially from Soviet countries (Barnothy, 1964, 1969; Beischer _et al_., 1973; Kholodov, 1971; Mykhaylovsky _et al_., 1969; Vyalov _et al_., 1964), suggesting that ELF fields act selectively on the central nervous system. No tangible transduction sites or mechanisms have been identified but allusion is often made to nerve cell membrane, etc. In our own series of preliminary large coil experiments, several subjects complained of headaches, starting about midway through the experiment and stopping shortly after completion. These we believed might be central nervous system field effects.

In order to separate possible "head" effects from total body effects, we constructed a small Helmholtz coil system for exposing only the subject's head. As we wished to minimize any possible subliminal field associated clues, the coils were plastic impregnated and are virtually noise free up to intensities as high as 50 gauss rms.

The first series of small coil experiments was conducted with uniform field and without biofeedback. The subject was seated at the center of the large coil system with the small coils suspended by elastic shock cord from above. Two different field orientations with respect to the subject's head position were tested; one with the field parallel to the ear-to-ear axis and the other with the field front-to-back through the head. Figure 6 represents the results for these 64 small coil experiments conducted at 15 gauss rms. The data shows no significant difference between the two field-head orientations. Not one subject distinguished himself as a star performer and the combined mean of 74.62 correct responses in 150 trials, $p = 0.62$, offers no evidence for any field perceptual ability.

During our biofeedback learning experiments with the small coil system, we moved the coils inside the isolation cabinet to isolate the subject more completely, thereby allowing him better concentration with fewer distractions. Again, shock cord was used to mount the coils compliantly. The procedure for the small coil and learning experiments was the same as that used previously for the large coils. Both uniform field and gradient field feedback experiments were done at field intensities of 15 gauss rms and gradients of 0.7 gauss rms/cm respectively. The results are shown in Figures 7 and 8. Notice that one subject was able to perform even at the 0.04 level of significance. The uniform field learning experiments have a combined mean of 76.27 correct responses in 150 trials, corresponding to $p = 0.30$, while the gradient field experiment massed mean is 75.58 correct responses, $p = 0.68$. Thus, none of the small coil experiments shows appreciable evidence for any perceptual ability.

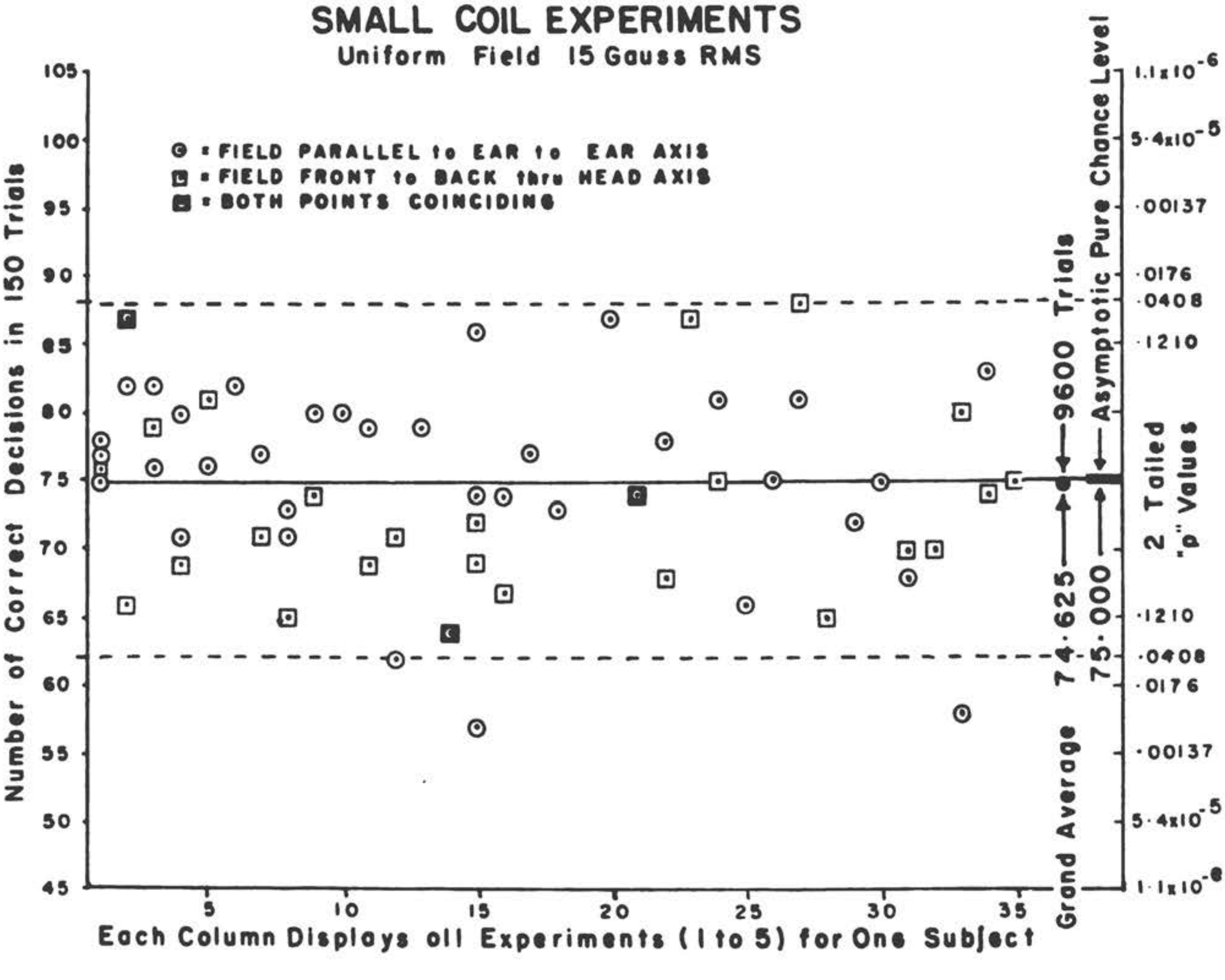
SMALL COIL EXPERIMENTS
Uniform Field 15 Gauss RMS
⊙ = FIELD PARALLEL to EAR to EAR AXIS
⊡ = FIELD FRONT to BACK thru HEAD AXIS
■ = BOTH POINTS COINCIDING
Number of Correct Decisions in 150 Trials
105
100
95
90
85
80
75
70
65
60
55
50
45
5
10
15
20
25
30
35
Each Column Displays all Experiments (1 to 5) for One Subject
Grand Average 74·625 — 9600 Trials
75·000 — Asymptotic Pure Chance Level
2 Tailed "p" Values
1.1x10⁻⁶
5·4x10⁻⁵
·00137
·0176
·0408
·1210
·1210
·0408
·0176
·00137
5·4x10⁻⁵
1·1x10⁻⁶

Figure 6

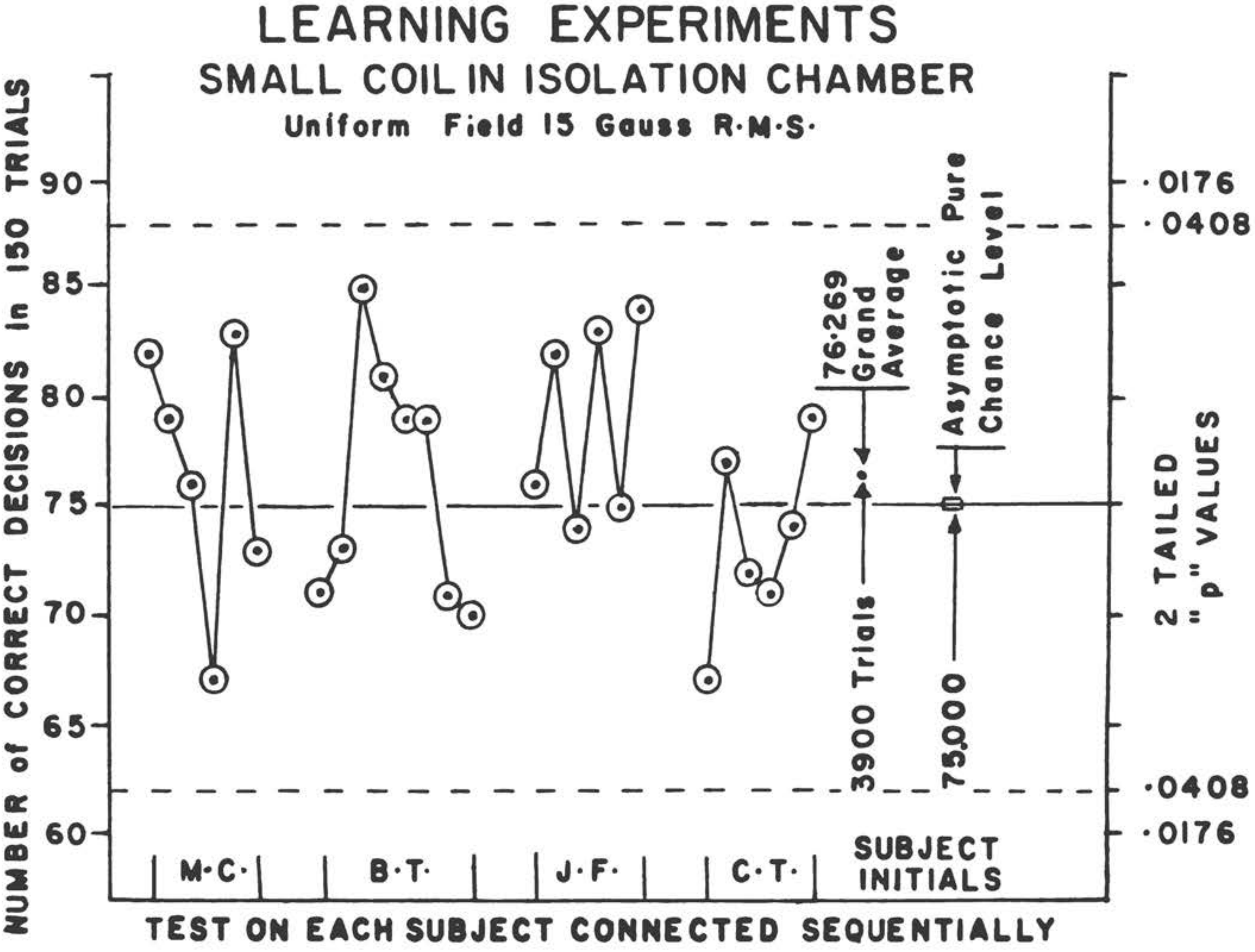
LEARNING EXPERIMENTS
SMALL COIL IN ISOLATION CHAMBER
Uniform Field 15 Gauss R·M·S·
NUMBER of CORRECT DECISIONS in 150 TRIALS
90
85
80
75
70
65
60
·0176
·0408
·0408
·0176
2 TAILED "p" VALUES
76·269 Grand Average
3900 Trials
Asymptotic Pure Chance Level
75,000
M·C·
B·T·
J·F·
C·T·
SUBJECT INITIALS
TEST ON EACH SUBJECT CONNECTED SEQUENTIALLY

Figure 7

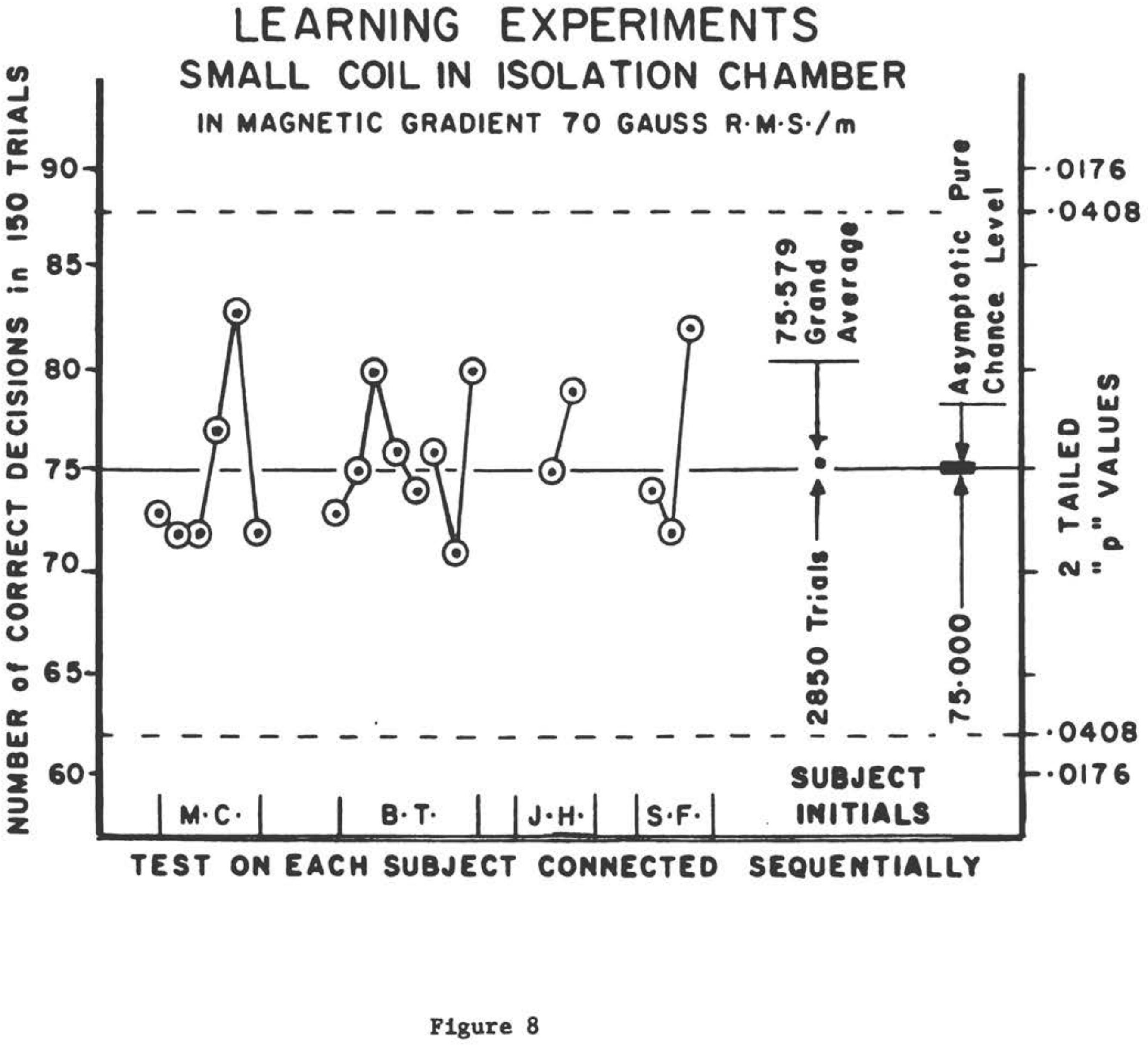
LEARNING EXPERIMENTS
SMALL COIL IN ISOLATION CHAMBER
IN MAGNETIC GRADIENT 70 GAUSS R·M·S·/m
NUMBER of CORRECT DECISIONS in 150 TRIALS
90
85
80
75
70
65
60
·0176
·0408
·0408
·0176
2 TAILED "p" VALUES
75·579 Grand Average
2850 Trials
Asymptotic Pure Chance Level
75·000
M·C·
B·T·
J·H·
S·F·
SUBJECT INITIALS
TEST ON EACH SUBJECT CONNECTED SEQUENTIALLY

Figure 8

Figure 9 summarizes compactly the major results of the whole experimental series. In particular it shows that each successive improvement in isolation from field associated clues resulted in lowered perception, until not even biofeedback learning could produce significant perception. Neither gradient fields nor high strength fields concentrated about the head showed significant perception. The close convergence toward 75.0, the asymptomatic null value, was impressive.

Conclusions

This study was specifically directed at determining whether 60 Hz moderate strength magnetic fields can be perceived consciously by all or even a few normal individuals with or without biofeedback training. It appears to establish that these fields are not normally sensed. It does not address directly the much more nebulous questions of subtle physiological, biochemical or psychological effects that such fields might conceivably have on "alteration of moods", malaise, anorexia, etc., that have been suggested. The "magnetic headaches" experienced by subjects in "placebo" experiments, where the fields were never turned on, suggest that many of these reported discomforts may be iatrogenic, technogenic, or produced by simple fear of the unknown. Only one frequency and range of field strengths was investigated for reasons of experimental economy.

While very strong fields will obviously produce sensations (magnetophosphenes), there was no suggestion of rapidly increasing effects in limited tests up to 50 gauss rms. Were there no limitation of time or money, it would be desirable for scientific completeness to test other frequencies, modulated and lower strength fields to establish that a weak field effect does not exist

SUMMARY OF EXPERIMENTAL DATA

Values given are the number of correct decisions in 150 trials
and their respective "p values"

LARGE COIL DATA	Combined Means	Most Strongly Correlated	Median of Distribution
1. Non Learning Uniform Field (7.5 gauss rms)			
Before Isolation	84.8 p=0.0052	pos: 138 p=2.6x10^{-28} neg: 38 p=1.2x10^{-9}	84 p=0.16
Isolation	76.67 p=0.01	pos: 89 p=0.028 neg: 56 p=2.4x10^{-3}	77 p=0.81
Accidental Isolation Breakdown	114 p<0.0001	pos: 129 p=3.7x10^{-20} neg: none	114 p=6.1x10^{-11}
2. Learning Uniform Field (7.5 gauss rms)			
Isolation	105.86 p<0.0001	pos: 140 p=1.8x10^{-30} neg: 67 p=0.22	111 p=3.9x10^{-9}
Elaborate Isolation (Cabinet suspension)	75.93 p=0.21	pos: 93 p=4.1x10^{-3} neg: 58 p=6.9x10^{-3}	75.5 p=0.97
3. Learning Gradient Field (13 gauss rms/m)			
Isolation	99.60 p<0.0001	pos: 123 p=7.8x10^{-16} neg: none	95 p=1.1x10^{-6}
Elaborate Isolation (Cabinet suspension)	73.97 p=0.36	pos: 88 p=0.04 neg: 61 p=0.028	74 p=0.94
SMALL COIL DATA			
1. Non Learning Uniform Field (15 gauss rms)			
Elaborate Isolation (Cabinet suspension)	74.63 p=0.62	pos: 88 p=0.04 neg: 57 p=4.1x10^{-3}	75 p=1.0
2. Learning Uniform Field (15 gauss rms)			
Elaborate Isolation (Cabinet suspension)	76.27 p=0.30	pos: 85 p=0.12 neg: 67 p=0.22	76 p=0.94
3. Learning Gradient Field (70 gauss rms/m)			
Elaborate Isolation (Cabinet suspension)	75.58 p=0.68	pos: 83 p=0.22 neg: 71 p=0.57	75 p=1.0

Figure 9

which disappears upon presence of moderate environmental strength fields. It would also be desirable to test comparably the complementary family of electric field effects under controlled conditions.

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