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This is one of a series of Resource Letters on different topics intended to guide college physicists, astronomers, and other scientists to some of the literature and other teaching aids that may help improve course content in specified fields. [The letter E after an item indicates elementary level or material of general interest to persons becoming informed in the field. The letter I, for intermediate level, indicates material of somewhat more specialized nature; and the letter A, indicates rather specialized or advanced material.] No Resource letter is meant to be exhaustive and complete; in time there may be more than one letter on some of the main subjects of interest. Comments on these materials as well as suggestions for future topics will be welcomed. Please send such communications to Professor Roger H. Stuewer, Editor, AAPT Resource Letters, School of Physics and Astronomy, 116 Church Street SE, University of Minnesota, Minneapolis, MN 55455.

Resource Letter BELFEF-1: Biological Effects of Low-Frequency Electromagnetic Fields

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This Resource Letter provides a guide to the literature on the interaction of extremely low-frequency electromagnetic field (ELF/EMF) interactions with biological matter, and on the possibility that such interactions could have a harmful effect on human health. Journal articles and books are cited for the following topics: ELF/EMF theoretical interactions with biological cells, organs and organisms, magnetic dipole interactions, sensing by animals, biomedical–biophysical experiments, epidemiology, and litigation–mitigation risk issues.

I. INTRODUCTION

The interaction of electric and magnetic (EM) fields with matter has been studied by physicists for over a century. Calculations based on the classical equations of Maxwell and the equations of quantum mechanics have long been used to estimate the strengths and characteristics of the EM interactions with condensed matter, molecules, atoms, and particles. Experiments have shown that these equations successfully represent the interactions, thus allowing physicists to use these interactions to investigate the basic properties of matter. The bibliography in this Resource Letter will extend this subject matter into the region of 50 Hz (European) and 60 Hz (U.S.), the extremely low-frequency electromagnetic fields (ELF/EMF) interacting with biological matter.

Physicists are often asked about the potential health hazards of ELF/EMF. In 1979, an epidemiology study by N. Wertheimer and E. Leeper reported an enhanced rate of leukemia for children living near 60-Hz electrical power lines in Denver, CO. This study catalyzed the wide-spread opinion that it is dangerous to live near electrical power lines. However, this study has been widely criticized inasmuch as the assignments of wire configurations (type of nearby power lines) to residences were made subjectively and with the investigators' knowledge as to whether an afflicted child or control had lived there. Furthermore, cumulative data on childhood leukemia has been inconsistent and inconclusive, considered by some to suggest only a weak association with ELF/EMF. By late 1995 there were well over 100 published epidemiological studies in the general scientific literature. These studies fueled public concerns about the possibility that ELF/EMF can promote cancer. In response to this concern, many disciplines are carrying out wide-ranging research programs to determine if there is a positive linkage between ELF/EMF and cancer. In 1991, Congress asked the National Academy of Sciences/National Research Council (NAS/NRC) to evaluate the literature on possible health effects of ELF/EMF. The Academy is expected to report its results in 1996. In addition, the 1992 Energy Policy Act established a $65 M 5-year program on ELF/EMF research, which is being reviewed by the NAS/NRC. A much longer version of this paper can be obtained at http://www.calpoly.edu/~dhafemen.

A. ELF/EMF source terms

Since the 5000-km wavelength of 60-Hz radiation is much larger than the relevant distances from power lines and appliances, the nonradiative, near-field terms are considerably larger than the radiative terms. In practice, only 1 mW is radiated from a 10-km section of a 60-Hz, 500-MW power line which is only 10^{-12} of the transmitted power. To a very good approximation the electric field from a power line is determined from its charge distribution (or its voltage) from Gauss's law while the magnetic field is determined from the current flow with Ampere's law. Since power lines have op-

posing, separated currents, the electric and magnetic dipole moments per unit length produce EM fields that diminish as the inverse square of the distance.

Several state regulations limit the fields from transmission lines to about 10 kV/m for the E fields and about 200 mG for B fields. (The mG unit is the standard unit for most U.S. regulations and publications in this area. For SI units, 1 μT=10 mG, 1 T=10^4 Gauss.) Some city regulations seek to constrain B fields to less than 2 mG, a direction that is supported at the national level by those who believe there are harmful biological effects. There are public guidelines for ELF/EMF at 1000 mG because pacemakers can exhibit abnormal pacing characteristics in 60-Hz fields above that threshold and because of induced body currents.

A typical U.S. home has the Earth's constant magnetic field of about 450 mG and a 60-Hz background magnetic field level (primarily not from power lines) that ranges from 0.5 to 4 mG with an average value of 0.9 mG. Five percent of the homes have fields above 2.9 mG, and 1% are above 6.6 mG. For comparison sake, one study reports that electrical powerline workers experience an average field of 11 mG. Typical transmission power lines produce average fields at distances of 30 and 60 m as follows:

	E (V/m at 30/60 m)	B (mG at 30/60 m)
115 kV	0.07/0.01	1.7/0.4
230 kV	0.3/0.05	7.1/1.8
500 kV	1.0/0.3	12.6/3.2

As a simple example, a two wire 500 MW transmission line at 500 kV draws 500 A in opposing directions in the two wires. From Ampere's law a single wire of 500 A produces a field of 33 mG at a distance of 30 m. If two opposing currents of 500 A are separated by 4 m, the field will be 4.4 mG (in the plane of the wires). By reducing the separation to 1 m, the field falls to 1.1 mG. At a doubled distance of 60 m, the field from the single conductor is 17 mG and the fields from the paired conductors are 1.1 mG for a 4-m separation and 0.3 mG for 1-m separation. Motor and appliance electrical coils produce either magnetic dipole or quadrupole fields that diminish as the inverse square or cube of the distance, respectively. Average fields at a distance of 30 cm are: color television (7 mG), microwave (4 mG), analog clocks (15 mG), electric razors (20 mG, 100 mG at 15 cm) and hair driers (1 mG, 300 mG at 15 cm).

B. Electric fields in biological matter

E fields are greatly reduced in biological matter from their values in air external to the body. Since the boundary conditions on Maxwell's equations require the real current density in the body to almost equal the displacement current density outside the body, the 60-Hz electric field from a power line is diminished by seven to eight orders of magnitude inside the human body. This factor reduces the maximum allowable E field of 10 000 V/m at the edge of the right-of-way of a power line to an internal electrical field of only 10^{-3} to 10^{-4} V/m. A smaller 60-Hz E field of 100 V/m, the same magnitude as the earth's surface field, will produce an E field in the body of about 10^{-5} to 10^{-6} V/m. These values of internal E fields should be compared to the internal field in the human body from thermally driven charge-density fluctuations in the human body. Since the E field from the charge of a proton at ten Bohr radii is a very considerable $6\times10^{+9}$ V/m, it is not surprising that fluctuations in the electric dipolar fields from Brownian motion can contribute meaningfully. Thermal fluctuations in the electrolyte of the biological resistors cause E-field fluctuations that appear as voltage fluctuations. Estimates of the Johnson–Nyquist noise voltages give root-mean-square average E-field fluctuations of about 2×10^{-2} V/m within the electrolyte of a 20-μ cell. The fluctuating E fields in the electrolyte are considerably larger than the internal fields of 10^{-6} to 10^{-3} V/m from power lines.

Since cellular membranes have a much higher electrical resistance than the electrolyte between the cells, there is considerably less current flow through the cellular membranes from external sources. The potential across a cellular membrane is about 50 mV. Since the thickness of a cellular membrane is only 5–10 nm, very large E fields of about 10^7 V/m are produced in the membrane. Thermal fluctuations in the membrane are of the order of a μV, considerably less than the potentials of 50 mV across the membrane. As in the case of the cellular electrolyte, the noise fields in the cellular membranes are considerably larger than the ELF E fields induced in the membranes.

If there were any health problems from EM fields, it is generally believed that the B fields, and not the E fields, would be the cause of health problems because the E field is effectively shielded by the human body while the B field is not shielded.

C. Electric fish

Some animals have specialized organs to sense weak EM fields, a fact that is not relevant to potential health effects. Electric rays and electric eels produce very large electric discharges. The freshwater electric eel whose body is mostly an electric organ generates stunning 2 ms pulses of one ampere at 500 V, for a peak power of almost 500 W and an energy of one Joule per pulse. Whereas these pulsed fields have a low duty cycle, some freshwater fish produce continuous electric fields with amplitudes on the order of 10 V/m, frequencies from dc to 10 kHz, and power on the order of 10 mW. These so called weakly electric fish sense their environment and communicate by modulating and detecting modulations in the electric current through their skin.

Sharks can detect external fields of less than 1 μV/m at frequencies of the order of 1 Hz with their long electric sensing organs, the Ampullae of Lorenzini. As the shark crosses the earth's B field lines, the Lorentz force induces electric fields in the amupulae that the shark detects and uses for navigation. Sharks also locate prey by sensing electric fields emanating from the prey's muscles and nerves during respiration and movement. Some amphibians, salamanders, and even a mammal, the duck-billed platypus, possess low-frequency electric sensory systems used for detecting weak electric fields generated by their prey's muscle activity. Electrosensory systems are not found in terrestrial animals because the high impedance of air attenuates the electric current and power in the electrostatic field to below detectable levels. At the other end of the spectrum, it takes strong E fields of the order of 10 000 V/m to give humans a tactile sensation, by torquing body hairs that become polarized as they attract static electric charges.

D. Magnetic fields in biological matter

Power line magnetic fields are often constrained by "prudent avoidance" to about 200 mG at the edge of a right-of-

way, but in practice they are usually less than 2 mG for those living near power lines. By applying Faraday's law to this range of 2–200 mG, one obtains E fields of between 4–400 μV/m. These values are considerably less than the natural Johnson–Nyquist E fields of 0.02 V/m.

Walking in the earth's magnetic field of about 400 mG produces "electromotive force" voltages from Faraday's law. Walking in a constant magnetic field does not generate currents, but it is interesting to calculate the E fields generated by walking. By moving very slowly at the rate of 0.1 m/s, an internal E field of 4 μV/m is developed (corresponding to 2 mG of ELF/EMF). It one runs very fast at 8 m/s (18 mph), an internal E field of 400 μV/m is developed (corresponding to 200 mG).

Rotations (or twirling) of the human body in the Earth's magnetic field of about 400 mG creates radial electric fields, giving rise to currents in the human body. A tilt of the head of 45 degrees in the slow time of 1.6 seconds will create an electrical field of 4 μV/m, corresponding to a 60-Hz field of 2 mG. A fast nod in 0.16 seconds creates an electric field of 40 μV/m, corresponding to a 60-Hz field of 40 mG.

E. Biogenic magnetic materials

Some bacteria have tightly coupled chains of single domain, superparamagnetic magnetosomes, magnetite (Fe_3O_4) or greigite (Fe_3S_4) particles, that allow them to magnetically navigate vertically to find food. Chains of many magnetite grains, 50 nm on a side, have been observed in these bacteria. Because the magnetic interaction of these bacterial magnetic chains in the Earth's magnetic field is many times the thermal energy, the bacteria maintain their orientation with respect to the Earth's magnetic field. Since the magnetosome dipole relaxation times are much longer than 1/60 s in water in the earth's magnetic field, the bacteria do not oscillate significantly in 60-Hz fields.

Honey bees navigate by observing changes as small as 0.6% in the Earth's magnetic field (2.5 mG out of 400 mG). Other studies have shown that other animals, such as sea turtles and homing pigeons, can navigate using the Earth's magnetic field as a guide. In order to navigate to precision, it is necessary to have many magnetosomes with a permanent dipole moment which are able to maintain their direction in the Earth's magnetic field while being buffeted by Brownian thermal fluctuations.

Small magnetite crystals with average diameters of 33 nm, in some cases 200 nm, have been reported (but the work has not yet been replicated) in the human brain by using transmission electron microscopy. The level of magnetite is very low, of the order of one part in 10^9 of the mass of the brain, much less than the magnetite fraction in magnetic bacteria of about 1%. It has not been shown that these magnetic particles are relevant for ELF/EMF and public health. If the magnetosomes are too small, they lack the ability to strongly torque in a weak magnetic field at 60 Hz. If the magnetosomes are large, the magnetite becomes multidomained, and the increased viscous torques dominate. In order to enhance this magnetic interaction it would be necessary to have very long chains of magnetosomes within a cell (which has not been observed) acting coherently. Calculations show that for fields less than 50 mG, viscosity damps out the induced oscillations to amplitudes less than those from thermal fluctuations. It has been conjectured that the large magnetic fields of a magnetosome next to a cell might affect the flux of calcium ions through its membrane, but this should not be influenced significantly by weak 60-Hz magnetic fields.

F. Stochastic resonance and squared dependence

Under certain circumstances, the addition of a small amount of input noise to a larger input signal can greatly increase the output signal and the output signal-to-noise ratio. The phenomena has been labeled "stochastic resonance" though the process does not involve ordinary resonance. Such stochastic-resonance enhancements have been observed in the mechanoreceptor hair cells of cray fish. It is highly speculative to connect stochastic resonance to predict enhanced ELF/EMF sensitivity in biological matter. Since the addition of a small input signal to a larger input noise does not result in an increased output signal-to-noise ratio, it would not seem that the stochastic resonance phenomena would enhance ELF/EMF sensitivity in biological matter.

Both the EM torque and force are proportional to the first power of the oscillating EM fields. Since the time average of a sine wave is zero, the average energy imparted to a system over many oscillations cannot be proportional to the first power of E or B. Since the time average of the sine squared is nonzero, the projected biological effects would be expected to be proportional to the square of the oscillating fields (E^2 or B^2). This does not rule out a linear dependence for the case of constant or quasi-dc fields as observed at 1–2 Hz for sharks and bees. Since human epidemiology data do not show consistent, meaningful associations with cancer for those living in very high field regions, such as sleeping under electric blankets, working on electrical power lines, or working on electric railways, a squared dependent relationship has not been demonstrated.

G. Radon near power lines

Henshaw *et al.*[38] report that naturally occurring radioactive daughters of radon are enhanced near power lines. After the daughters attach themselves to aerosols, the neutral aerosols are attracted by the gradient of the E field toward the power line. Because the contaminated aerosols oscillate with the power frequency, they would tend to plate out more frequently on the skin. The aerosols containing the radioactive radon daughters would also be inhaled into the lungs in a strong enough concentration to cause cancer.

Detractors of this theory respond as follows: Radon concentrations in open air near power lines are very slight. The half-lives of the radon daughters are relatively short, thus making the transition to humans at a distance problematical. Some epidemiology data shows an association with magnetic fields, but essentially none show an association with electric fields. Residences beyond the right-of-way of power lines do not have considerable elevated electric fields. One would expect enhanced lung cancer which is not reported in excess near power lines, rather than the usual suspects of leukemia and brain cancer. Last, one would expect the radioactive aerosols to plate out on the power lines or on the skin in comparison to lung deposition.

H. Cancer mechanisms

Chemicals, such as unburned carbon, and EM radiation at frequencies above the visible region have sufficient energy to directly initiate cancer. Visible light breaks bonds in the pro-

cess of photosynthesis but is not usually suspected of causing cancer. The energy of a hydrogen bond is about 0.1 eV and that of a carbon–carbon single covalent bond is 3.6 eV. The photon energy from 60-Hz radiation of 2.5×10^{-13} eV is, of course, insufficient to directly break chemical bonds. Thus, new interaction mechanisms would have to be proposed to predict possible health problems from ELF/EMF. It is known that very large EM fields affect membrane permeability and the recombination of ion radicals.

Cancer can be initiated by direct damage to the genetic material of cells (genotoxicity), or it can be promoted by increasing the probability that a genotoxic exposure will cause cancer (epigenetic activity or promotion). Direct cancer effects are exemplified by the breaking of chemical bonds in DNA, while indirect effects could promote the likelihood, severity or speed that cancer might be caused once the DNA bonds had been broken. It is conjectured that ELF/EMF could supply currents, torques, or forces in the body that could enhance the risk of cancer, such as the reduction of melatonin from the pineal gland from the action of ELF/EMF on magnetite in the brain. Or, ELF/EMF could be part of a multistep biological process. In order to clearly establish these conjectures, it is necessary to demonstrate a meaningful combination of positive findings from epidemiology and biomedical–biophysical experiments, which are consistent with a theoretical biophysical mechanism. The stronger the evidence from epidemiology, the lesser the requirement to have a consistent theoretical mechanism in order to take a public policy position, but conversely, weak epidemiology evidence should be treated with great caution.

I. Epidemiology

By 1995 over 100 additional epidemiological studies have examined various possible associations between public health and ELF/EMF from power lines, appliances and other devices. Most of this literature is concerned with the power-line frequencies of 50 and 60 Hz and magnetic fields in the region of 1–10 mG. Scientific review panels have generally concluded that the combined data show at best a weak association with ELF/EMF and at worst that the findings are mutually inconsistent and inconclusive. Epidemiology examines disease and health in human populations by identifying associations between the occurrence of human diseases and the possible causes of those disease. Because epidemiology searches for correlations between a particular disease and environmental or other factors, it does not directly prove causality because there can be other explanations for correlations. However, when there is, for example, a very strong association between cancer and exposure, such as a strong linear correlation between the amount of additional cancer and the rate of smoking, the epidemiology data and the fact that the smoke contains known carcinogens are considered as the proof of causality. On the other hand, the association between cancers for nonsmoking family members and the rate of smoking in the home is quite weak. This epidemiology data has been accepted by the regulatory process as significant because of the strength of the other evidence (experiments and mechanisms). The tobacco industry and others consider this conclusion as political, based on weak data.

Because less than robust epidemiology data can be misinterpreted, Sir Austin Bradford Hill in his Presidential Address to the Section of Occupational Medicine at the Royal Society of Medicine (U.K.) presented a list of suggested criteria by which to judge whether an association was indeed causal. The criteria list is not necessarily all-encompassing, but it gives very useful benchmarks.

(1) Strength: Is there a strong correlation between disease and ELF/EMF fields?
(2) Consistency: Have the same results been obtained by different researchers in different locations?
(3) Specificity: Does ELF/EMF produce the same types of cancer in similar proportions to other groups similarly exposed?
(4) Temporality: Since there is a latency period for cancer, are the measurements of ELF/EMF in the present the same as in the past?
(5) Biological gradient: Do higher "doses" of ELF/EMF cause more cancer than lower doses? Is there an approximate proportionality of risk and dose, as in the case of the probability of additional lung cancer and the number of cigarettes smoked per day?
(6) Plausibility: Does the biological data on conjectured cancer promotion by ELF/EMF converge on a plausible, consistent biological–biophysical mechanism?
(7) Coherence: One should expect coherence between the data and the mechanism. In general, most mechanisms that attempt to connect ELF/EMF and cancer would predict that enhanced exposures of ELF/EMF would enhance cancer rates.
(8) Experiment: Are the various *in vitro* (cells in culture) and *in vivo* (complete living systems) experiments consistent among themselves and with a theoretical mechanism?
(9) Analogy: Is the connection between ELF/EMF and cancer analogous to situations where the proof is more substantial. Does one have to have "new" physics to understand this connection?

Review panels have concluded that Hill's criteria do not lead to a link between ELF/EMF and cancer. The scientific panels that have reviewed the ELF/EMF epidemiology data have separated the results by the type of cancer. For example, recently three studies of ELF/EMF on electrical workers have appeared. The 1993 California study reported no association with either leukemia or brain cancer. The 1993 Canadian–French study reported an association with leukemia and astrocytoma, out of the 32 cancer types studied. Because these studies do not make corrections for multiple comparisons, one would expect a study of this many different types of cancer to produce 1 or 2 "significant" correlations even if there were no real associations, that is 1 or 2 "false positives." (In addition, this study suffers from internal inconsistencies.) By contrast, the 1995 Savitz/Loomis study reported no association with leukemia, but they reported an association with brain cancer with weak statistics.

For these epidemiology studies, it is necessary to estimate the individual ELF/EMF doses. In the best epidemiological experiments, the magnetic doses have been measured for the electrical workers, but there are limits to these estimates. It is unclear whether the exposure metric should be the product of magnetic field strength times the duration of exposure, or proportional to the square of the field as dictated by basic physics (neglecting nonlinear cellular mechanisms), or the direction and magnitudes between ELF and Earth B fields, or the harmonic content, or a frequency window.

J. Biophysics and medical-physics experiments

Many types of experiments have been carried out to examine the possible interaction of ELF/EMF and biological matter, such as: (a) direct effects (heating, induced electric current, energy of charged molecules, excitation of molecules, changes in membrane potential); (b) direct forces on electric charges or electric moments; (c) resonant interactions (ion cyclotron or paramagnetic resonance); (d) torques on magnetic moments; (e) free-radical chemistry; (f) temporal average or spatial intensification of weak ELF/EMF waves. There have been many positive and negative findings from *in vivo* and *in vitro* experiments with ELF/EMF. Usually the researchers with positive findings do not claim a causal connection between cancer and ELF/EMF, but rather that the data is part of the findings that might make such a connection possible. The scientific review panels and review articles have pointed out the continuing problem with replicating experimental results on cells and animals. This failure to find positive links between ELF/EMF and cancer is consistent with those who say that such health effects should be very unlikely because ELF/EMF forces (10^{-10} pN at 100 mG) are much less than both typical biological forces (5 pN myosin muscle molecule) and background forces from thermal oscillations (10^{-9} pN). Because biological systems are very complex, this argumentation cannot be considered to be a sufficient proof of no health effects, but it is a very strong guideline.

K. Mitigation, litigation, regulation, and cost/benefit

In a rational world, risks to human life would be reduced by prioritized spending on mitigation that ranked all the choices in terms of money per life saved (or money per year of life saved), including estimates for benefits to the natural world. Since the ELF/EMF issue should be joined with other risks in society, it is useful to conclude with some broader topics. Thus, society is concerned with relative rates of risk reduction and costs of mitigation. Cost estimates by the U.S. General Accounting Office for ELF/EMF mitigation from power lines, not covering appliances, have been substantial. Some of GAO's estimates are: $2 million/mile to bury transmission lines in fluid-filled steel pipes to reduce magnetic fields by 99%, $200 billion to bury transmission lines nationwide near homes with fields greater than 1 mG, $250 billion to reduce average exposure to less than 2 mG from all transmission and distribution lines. After an examination of the data described in this review, in 1995 the American Physical Society concluded: "No plausible biophysical mechanisms for the systematic initiation or promotion of cancer by these power line fields have been identified. Furthermore, the preponderance of the epidemiological and biophysical/biological research findings have failed to substantiate those studies which have reported specific adverse health effects from exposure to such fields. While it is impossible to prove that no deleterious health effects occur from exposure to any environmental factor, it is necessary to demonstrate a consistent, significant and causal relationship before one can conclude that such effects do occur. From this standpoint, the conjectures relating cancer to power line fields have not been scientifically substantiated."

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II. JOURNALS

A wide variety of journals, world wide web sites, and internet newsgroups cover ELF/EMF topics.

Advances in Electromagnetic Fields in Living Systems
American Journal of Epidemiology
British Medical Journal
Bioelectromagnetics
Biophysical Journal
Cancer Causes and Control
Epidemiology
EPRI Journal
Health Physics
Journal of Comparative Physiology
Journal of Experimental Biology
Journal of Theoretical Biology
IIIE Transactions on Biomedical Engineering
Mutation Research
Nature
Physical Review
Proceedings of the National Academy of Sciences
Proceedings of the Society of Experimental Biology and Medicine
Radiation Research
Science

A. ELF/EMF periodicals

EMF Keeptrack
EMF Health and Safety Digest
EMF Health Report
EMF News
Microwave News

B. World Wide Web

EMF-Link (http://infoventures.com)

Frequently Asked Questions on Powerlines and Cancer (http://www.cis.ohio/state.edu/hypertext/faq/usenet/static-field-cancer-FAQ/)

National Cancer Institute/National Institute of Health (gopher://gopher.nih.gov/11/clin/cancernet and http://www.os.dhss.gov)

C. Newsgroups

bionet.emf-bio
sci.med.phys
sci.physics.electromag

D. Hot lines

Environmental Protection Agency (1-800-363-2383)

National Institute of Environmental Health Science (1-800-643-4794)

National Institute of Occupational Safety and Health (1-800-356-4674)

III. CONFERENCE PROCEEDINGS

The scientific review panels listed below conclude that ELF/EMF is not a public health problem. Conference proceedings usually do not come to a conclusion nor do they include an economic dimension.

1. Health Effects of Low Frequency Electric and Magnetic Fields, Presidential Committee on Interagency Radiation Research and Policy Coordination (Oak Ridge Associated Universities, Oak Ridge, TN, June 1992). (I)
2. Report of an Advisory Group on Non-ionizing Radiation, National Radiological Protection Board (United Kingdom), Electromagnetic Fields and the Risk of Cancer Vol. 3 (1992). (I)
3. Electromagnetic Fields: Biological Interactions and Mechanisms, edited by M. Blank, Adv. Chem. **250** (1995). (I)
4. Biological Effects of Electric and Magnetic Fields (Vol. 1. Sources and Mechanisms: Vol. 2, Beneficial and Harmful Effects), D. O. Carpenter and S. Ayrapatyan (Academic, San Diego, CA, 1994). (I)
5. Extremely Low Frequency Electromagnetic Fields: The Question of Cancer, edited by B. W. Wilson, R. G. Stevens, and L. E. Anderson (Battelle, Columbus, OH, 1990). (I)

IV. TEXTBOOKS AND EXPOSITIONS

The following is a wide-ranging collection of summaries of ELF/EMF issues.

6. Health and Low-Frequency Electromagnetic Fields, W. R. Bennett (Yale U. Pr., New Haven, CT, 1994). A discussion of the ELF/EMF issues that were considered by the Oak Ridge interdisciplinary panel of scientists. (I)
7. CRC Handbook of Biological Effects of Electromagnetic Fields, 2nd ed., edited by C. Polk and E. Postow (CRC, Boca Raton, FL, 1996), Review chapters on ELF/EMF. (I)
8. Phantom Risk: Scientific Inference and the Law, edited by K. R. Foster, D. E. Bernstein, and P. W. Huber (MIT, Cambridge, MA, 1993). A summary of the various risks that society is concerned about. (I)
9. Power Frequency Magnetic Fields and Public Health, edited by W. F. Horton and S. Goldberg (CRC, Boca Raton, FL, 1995). Discusses in detail the ELF fields from power lines and appliances and the approaches that would be needed to mitigate them if ELF/EMF were a serious problem. (I)
10. Radio-Frequency and ELF Electromagnetic Energies: A Handbook for Health Professionals, edited by R. T. Hitchcock (Van Nostrand Reinhold, NY, 1995). (I)
11. "Cancer and Power Lines," W. R. Bennett, Phys. Today **47**, 23–29 (April 1994), and letters, Phys. Today **48**, 13–15, 71–73 (January 1995). A good discussion of the basic physics involved with ELF/EMF. (I)
12. "Biological Effects of Power-Frequency Fields as They Relate to Carcinogenesis," J. E. Moulder and K. R. Foster, Proc. Soc. Exp. Biol. Med. **209**, 309–324 (1995). An excellent survey and interpretation of the totality of the biomedical–biophysical data. (I)
13. "Electromagnetic Fields and Power Lines," W. R. Bennett, Science Med. **1**, 68–77 (July/August 1995). (I)
14. "Today's View of Magnetic Fields," T. S. Perry, IEEE Spectrum **31**, 14–23 (December 1994). A compilation of epidemiology data, but it fails to subdivide the data by the types of cancer involved. (E)

Two booklets give a great deal of information on ELF/EMF:

15. Fields from Electric Power, M. G. Morgan (Dept. Engineering and Public Policy, Carnegie Mellon, Pittsburgh, PA, 1995). (E)
16. Questions and Answers About EMF: Electric and Magnetic Fields Associated with the Use of Electric Power (Nat. Instit. Envir. Health Sci. and U.S. Dept. Energy, 1995). (E)

Three journalists, Paul Brodeur, who sensationalized ELF/EMF, and Gary Taubes and Jon Palfreman, who respond, give differing views on ELF/EMF.

17. The Great Power-Line Cover-Up: How the Utilities and the Government Are Trying to Hide the Cancer Hazard Posed by Electromagnetic Fields, P. Brodeur (Little Brown, Boston, MA, 1995). (E)
18. "Fields of Fear," G. Taubes, Atl. Mon. **274**, 94–108 (November 1994). (E)
19. "Apocalypse Not," J. Palfreman, Tech. Rev. **99** (3), 24–33 (April 1996). (E)

V. CURRENT RESEARCH TOPICS

A. Theory of ELF/EMF interactions with biological matter

The basic physics of ELF/EMF is discussed in this set of papers with the general conclusion from the physics community that the ELF/EMF interaction energies and forces are less than those from thermal fluctuations in the body.

20. "Catalogue of Electromagnetic Environment Measurements, 30–300 Hz," J. Randa *et al.*, IEEE Trans. Electromagn. Compat. **37** (1), 26–33 (February 1995). (A)
21. "Constraints on Biological Effects of Weak Extremely-Low-Frequency Electromagnetic Fields," R. K. Adair, Phys. Rev. A **43**, 1039–1049 (1991). (A)
22. "Comment on 'Constraints on Biological Effects of Weak Extremely-Low-Frequency Electromagnetic Fields,'" J. L. Kirschvink, Phys. Rev. A **46**, 2178–2184 (1992). (A)
23. "Reply to 'Comment on 'Constraints on Biological Effects of Weak Extremely-Low-Frequency Electromagnetic Fields'" R. K. Adair, Phys. Rev. A **46**, 2185–2187 (1992). (A)
24. "The Response of Living Cells to Very Weak Electric Fields: The Thermal Noise Limit," J. C. Weaver and R. D. Astumian, Science **247**, 459–462 (1990). (A)
25. "Some Engineering Models for Interactions of Electric and Magnetic Fields with Biological Systems," F. S. Barnes, Bioelectromagnetics Supplement **1**, 67–85 (1992). (A)
26. "Biological response to Weak 60-Hz Electric and Magnetic Fields Must Vary as the Square of the Field Strength," R. K. Adair, Proc. Nat. Acad. Sci. **91**, 9422–9425 (1995). (A)
27. "A model for the acute electrosensitivity of cartilaginous fishes," W. F. Pickard, IEEE Trans. Biomed. Eng. **35**, 243–249 (1988). (A)
28. "Rectification and signal averaging of weak electric fields by biological cells," R. D. Austumian, J. C. Weaver, and R. K. Adair, Proc. Nat. Acad. Sci. **92**, 3740–3743 (1995).

B. Magnetic dipole interactions

The discovery of chains of magnetosomes in bacteria has stimulated interest in searching for magnetic structures in higher animals.

29. "Magnetic Guidance of Organisms," R. B. Frankel, Annu. Rev. Biophys. Bioeng. **13**, 85–103 (1984). (A)
30. Iron Biominerals, edited by R. B. Frankel and R. P. Blakemore (Plenum, New York, 1991). (A)
31. "Electron Microscopic Studies of Magnetosomes in Magnetotatic Bacteria," D. A. Bazylinski, A. J. Garratt-Reed, and R. B. Frankel, Microsc. Res. Technol. **27**, 389–401 (1994). (A)

Kirschvink's group has reported the discovery of very dilute magnetite in human brains, but this work has yet to be replicated. They also are concerned that some of the "positive" ELF/EMF experiments in unclean facilities might be caused by magnetite impurities in samples.

32. "Magnetite biomineralization in the Human Brain," J. L. Kirschvink, A. Kobayashki-Kirschvink, and B. J. Woodford, Proc. Nat. Acad. Sci. **89**, 7683–7687 (1992). (A)
33. "Magnetic Material in the Human Hippocampus," J. R. Dunn, *et al.*, Brain Res. Bull. **36**, 149–153 (1995). (A)
34. "Ferromagnetism and EMFs," A. K. Kobayashi, J. L. Kirschvink, and M. H. Nesson, Nature **374**, 123 (1995). (I)

Basic physics calculations show that it is very unlikely that ELF/EMF could meaningfully interact with chains of magnetosomes under reasonable conditions.

35. "Constraints of Thermal Noise on the Effects of Weak Fields Acting on Biological Magnetite," R. K. Adair, Proc. Nat. Acad. Sci. **91**, 2925–2929 (1994).
36. "Effects of ELF Magnetic Fields on Biological Magnetite," R. K. Adair, Bioelectromagnetics **14**, 1–4 (1993). (A)
37. "Effects of Extremely-Low-Frequency Magnetic Fields on Biological Magnetite," C. Polk, Bioelectromagnetics **15**, 261–270 (1994). Polk states that it is plausible to expect some biological interactions at the 20 mG level. (A)

C. Radon near power lines

38. "Enhanced Deposition of Radon Daughter Nuclei in the Vicinity of Power Frequency Electromagnetic Fields," D. L. Henshaw, A. N. Ross, A. P. Fews, and A. W. Preece, Int. J. Rad. Biol. **69**, 25–38 (1996). See text for a discussion of the radon issue. (A)

D. Stochastic resonance

It is unlikely that stochastic resonance can significantly entrain the thermal noise of the body, but it has been observed in biological mechanical systems.

39. "Stochastic Resonance and the Benefits of Noise: from Ice Ages to Crayfish to SQUIDS," K. Wiesenfeld and F. Moss, Nature **373**, 33–36 (1995). (I)
40. "Theory of Stochastic Resonance," B. McNamara and K. Wisenfeld, Phys. Rev. A **39**, 4854–4869 (1989). (A)
41. "The Benefits of Background Noise," F. Moss and K. Wiesenfeld, Sci. Am. **273**, 66–69 (August 1995). (E)

E. Animals sensing ELF/EMF

Animals can sense E fields less than 1 μV/m, B field differences of less than 1 mG, and currents from their electrical organs to find food. These unique sensory abilities do not implicate public health from ELF/EMF.

42. "Honeybees Can Be Trained to Respond to Very Small Changes in Geomagnetic Field Intensity," M. M. Walker and M. E. Bitterman, J. Exp. Biol. **145**, 489–494 (1989). (A)
43. "Acquisition of Magnetic Directional Preference in Hatchling Loggerhead Sea Turtles," K. Lohmann, J. Exp. Biol. **190**, 1–8 (1994). (A)
44. "Electroreception and the Compass Sense of Sharks," M. Paulin, J. Theor. Biol. **174**, 325–339 (1995). (A)
45. "Electrosensory Organisms," J. Bastian, Phys. Today **47**, 30–37 (February 1994). (E)
46. "Phase and Amplitude Maps of the Electric Organ Discharge of the Weakly Electric Fish, Apteronotus, Leptorhynchus," B. Rasnow, C. Assad, and J. M. Bower, J. Comp. Physiol. A **172**, 481–491 (1993). (A)
47. "Interactions in the flexible orientation system of a migratory bird," K. P. Able and M. A. Able, Nature **375**, 230–232 (1995). Sparrows have a migratory magnetic compass and a star compass, updating with visual cues from the sky at sunset. (A)
48. "Interaction of apical and basal membrane ion channels underlies electroreception in ampullary epithelia of skates," J. Lu and H. M. Fishman, Biophys. J. **67**, 1525–1533 (1994). (A)

F. Paramagnetic/cyclotron resonance

It is difficult to understand how cyclotron resonance could exist in liquids since they have high collision rates.

49. "Kinematics of Channelized Membrane Ions in Magnetic Fields," A. R. Liboff and B. R. McLeod, Bioelectromagnetics **9**, 39–51 (1988). (A)
50. "On the Cyclotron Resonance Model of Ion Transport," J. Sandweiss, Bioelectromagnetics **11**, 203–205 (1990). (A)

Some interesting, but unreplicated data on paramagnetic resonance follows, along with theoretical articles that disagree with the work.

51. "Clarification and Application of an Ion Parametric Resonance Model for Magnetic Field Interactions with Biological Systems," J. P. Blanchard and C. F. Blackman, Bioelectromagnetics **15**, 217–238 (1994). (A)
52. "Empirical Test of an Ion Parametric Resonance Model for Magnetic Field Interactions with PC-12 Cells," C. F. Blackman, J. P. Blanchard, S. G. Benane, and D. E. House, Bioelectromagnetics **15**, 239–260 (1994). (A)
53. "Criticism of Lednev's Mechanism for the Influence of Weak Magnetic Fields on Biological Systems," R. K. Adair, Bioelectromagnetics **13**, 231–235 (1992). (A)

G. Further biomedical–biophysical experiments

The first reference below by Goodman *et al.*, is a review of the biomedical–biophysical data from those who claim to see an effect from ELF/EMF. In the second paper, Valberg points out that many ELF/EMF experiments have failed replication tests. He suggests experimental procedures to clarify experimental categorizations. This section concludes with 20 biomedical–biophysical experiments using ELF/EMF. Also, see Ref. 12 by Moulder, who discusses these kinds of ELF/EMF experiments.

54. "Effects of Electromagnetic Fields on Molecules and Cells," E. M. Goodman, B. Greenbaum, and M. T. Marron, Int. Rev. Cytol. **158**, 279–338 (1995).
55. "Designing EMF Experiments: What is Required to Characterize Exposure?," P. A. Valberg, Bioelectromagnetics **16**, 396–401 (1995). (I)
56. "Effect of Low-level, 60-Hz Electromagnetic Fields on Human Lymphoid Cells: I. Mitotic Rate and Chromosome Breakage in Human Peripheral Lymphocytes," M. M. Cohen *et al.*, Bioelectromagnetics **7**, 415–423 (1986). (A)
57. "Exposure of Mammalian Cells to 60-Hz Magnetic or Electric Fields: Analysis for DNA Single-strand Breaks," J. A. Reese *et al.*, Bioelectromagnetics **9**, 237–247 (1988). (A)
58. "Effects of 50-Hertz EM Fields on Proliferation and on Chromosomal Aberrations in Human Peripheral Lymphocytes Untreated and Pretreated with Chemical Mutagens," M. Rosenthal and G. Obe, Mutat. Res. **210**, 329–335 (1989). (A)
59. "Exposure of Mammalian Cells to 60-Hz Magnetic or Electric Fields: Analysis of DNA Repair of Induced, Single-strand Breaks" M. E. Frazier, *et al.*, Bioelectromagnetics **11**, 229–234 (1990). (A)
60. "Reproductive Integrity of Mammalian Cells Exposed to Power-frequency Electromagnetic Fields," G. K. Livingston *et al.*, Environ. Molec. Mutat. **17**, 49–58 (1991). (A)
61. "Effect of 60-Hz Magnetic Fields on Ultraviolet Light-induced Mutation and Mitotic Recombination in Saccharomyces Cerevisiae," D. D. Ager and J. A. Radul, Mutat. Res. **283**, 279–286 (1992). (A)
62. "Electric and/or Magnetic Field Effects on DNA Structure and Function in Cultured Human Cells," M. Fiorani *et al.*, Mutat. Res. **282**, 25–29 (1992). (A)
63. "Effects of Magnetic Fields on Mammary Tumor Development Induced by 7,12-dimethylbenz(a)anthracene in Rats," M. Mevissen *et al.*, Bioelectromagnetics **14**, 131–143 (1993). (A)
64. "Exposure of Rats of a 50-Hz, 30-mT Magnetic Field Influences Neither the Frequencies of Sister-chromatid Exchanges nor Proliferation Characteristics of Cultured Peripheral Lymphocytes," M. Mevissen *et al.*, Mutat. Res. **302**, 39–44 (1993). (A)
65. "Reproductive and Teratologic Effects of Electromagnetic Fields," R. L. Brent *et al.*, Reproduc. Toxicol. **7**, 535–580 (1993). (A)
66. "Tumor Promotion in a Breast Cancer Model by Exposure to a Weak Alternating Magnetic Field," W. Loscher *et al.*, Cancer Lett. **71**, 75–81 (1993). (A)
67. "Intermittent 50-Hz Magnetic Field and Skin Tumor Promotion in Sencar Mice," A. Rannug *et al.*, Carcinogenesis **15**, 153–157 (1994). (A)
68. "Effects of Weak Alternating Magnetic Fields on Nocturnal Melatonin Production and Mammary Carcinogenesis in Rats," W. Loscher *et al.*, Oncology **51**, 288–295 (1994). (A)
69. "Cytological Effects of 50 Hz Electromagnetic Fields on Human Lymphocytes in Vitro," A. Antonopoulos *et al.*, Mutat. Res. **346**, 151–157 (1995). (A)
70. "A Histopathological Study of Alterations in DMBA-induced Mammary Carcinogenesis in Rats with 50 Hz, 100 μT Magnetic Field Exposure," A. Baum *et al.*, Carcinogenesis **16**, 119–125 (1995). (A)
71. "No Effect of 60 Hz Electromagnetic Fields on MYC or Beta-actin Expression in Human Leukemic Cells," A. Lacy-Hulbert *et al.*, Rad. Res. **144**, 9–17 (1995). (A)
72. "Dominant Lethal Studies in Male Mice after Exposure to a 50 Hz Magnetic Field," C. I. Kowalczuk *et al.*, Mutat. Res. **328**, 229–237 (1995). (A)
73. "A 60-Hz Magnetic Field Increases the Incidence of Squamous cell Carcinomas in Mice," J. McLean *et al.*, Cancer Lett. **92**, 121–125 (1995). (A)
74. "Short Exposures to 60 Hz Magnetic Fields Do Not Alter MYC Expression in HL60 or Daudi cells," J. D. Saffer and S. J. Thurston, Rad. Res. **144**, 18–25 (1995). (A)
75. "Melatonin and Puberty in Female Lambs Exposed to EMF: a Replicate Study," J. M. Lee *et al.*, Bioelectromagnetics **16**, 119–123 (1995). (A)
76. "Therapeutic Applications of Low Frequency Electric and Magnetic

Fields," C. Polk, Adv. Electromagn. Fields Living Syst. **1**, 129–153 (1994). Large magnetic fields that change very quickly cause large internal currents that may aid bone growth. (A)
77. "Single Myosin Molecule Mechanics: Piconeutron Forces and Nanometre Steps," J. T. Finer, R. M. Simmons, and J. A. Spudich, Nature **368**, 113–119 (1994). (A)

H. Epidemiology

78. "The Environment and Diseases: Association and Causation," A. B. Hill, Proc. R. Soc. Med., Sec. Occup. Med. **58**, 295–300 (1965). Criteria to base conclusions. (I)
79. **Modern Epidemiology**, K. J. Rothman (Little Brown, Boston, 1986). (A)
80. **Fundamentals of Epidemiology (Parts I and II)** (Electric Power Research Institute, Palo Alto, CA, 1993). Basic facts. (I)
81. "Epidemiology Faces its Limits," G. Taubes, Science **269**, 164–169 (1995). (E)
82. "Weak Magnetic Fields: A Cancer Connection?" K. R. Foster in Ref. 8. A nice discussion on epidemiology associations. (I)
83. "Are Stray 60 Hz Electromagnetic Fields Associated with the Distribution and Uses of Electrical Power a Significant Cause of Cancer," J. D. Jackson, Proc. Nat. Acad. Sci. **89**, 3508–3510 (1992). Electrical use rises considerably while childhood cause cancer remains relatively constant. (I)
84. **Surveillance, Epidemiology, and End Results (SEER)** (National Cancer Institute, Washington, DC, 1995). The cancer facts needed for analysis. (A)

I. Childhood Leukemia Studies

85. "Residential Proximity to Electricity Transmission and Distribution Equipment and Risk of Childhood Leukemia, Childhood Lymphoma, and Childhood Nervous System Tumors: Systematic Review, Evaluation, and Meta-Analysis," E. P. Washburn *et al.*, Cancer Causes and Control **5**, 299–309 (1994). A nice summary of the childhood cancer data. (A)
86. "Electrical Wiring Configurations and Childhood Cancer," N. Wertheimer and E. Leeper, Am. J. Epidemiology **109**, 273–284 (1979). (A)
87. "Case-Control Study of Childhood Cancer and Exposure to 60-Hz Magnetic Fields", D. A. Savitz *et al.*, Am. J. Epidemiol. **128**, 21–38 (1988). (A)
88. "Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia," Am. J. Epidemiol. **134**, 923–937 (1991). (A)
89. "Magnetic Fields and Cancer in Children Residing Near Swedish High-Voltage Power Lines," M. Feychting and A. Ahblom, Am J. Epidemiol. **138**, 467–480 (1993). Letter and reply, R. Wilson and A. Shlyakhter, Am. J. Epidemiol. **141**, 378–379 (1995). (A)
90. "Residence near High Voltage Facilities and Risk of Cancer in Children," J. H. Olsen, A. Nielson, and R. Schulgen, Brit. Med. J. **307**, 891–895 (1993). (A)
91. "Risk of Cancer in Finnish Children Living Close to Power Lines," P. K. Verkasalo *et al.*, Brit. Med. J. **307**, 895–899 (1993). (A)
92. "Childhood Cancer in Relation to Indicators of Magnetic Fields from Ground Current Sources," N. Wertheimer, D. A. Savitz, and E. Leeper, Bioelectromagnetics **16**, 86–96 (1995). (A)

J. High field studies

The large fields of the order of 100 mG from older electric blankets (before twisted pair wires) and electrical train workers (30 mG) fail to show effects one would expect if the biological coupling was proportional to either the field or the square of the field (Ref. 26).

93. "Magnetic Field Exposure from Electric Appliances and Childhood Cancer," D. A. Savitz, E. M. John, and R. C. Kleckner, Am. J. Epidemiol. **131**, 763–773 (1990). (A)
94. "Leukemia and Brain Tumors in Norwegian Railway Workers, A Nested Case Control Study," T. Tynes, H. Jynge, and A. I. Vistnes, Am. J. Epidemiol. **137**, 645–653 (1994). (A)

K. Utility employee studies

A study of utility power-line workers reported average fields of about 11 mG. In spite of the higher field values, the epidemiology from the utility studies appears to be inconsistent and inconclusive.

95. "Magnetic Field Exposure in Relation to Leukemia and Brain Cancer Mortality among Electrical Utility Workers," D. Savitz and D. Loomis, Am. J. Epidemiol. **141**, 123–134 (1995). (A)
96. "Cohort and Nested Case-Control Studies of Hematopoietic Cancers and Brain Cancer Among Electrical Utility Workers," J. D. Sahl, M. A. Kelsh, and S. Greenland, Epidemiology **4**, 104–114 (1993). (A)
97. "Cancer risks associated with occupational exposure to magnetic fields among electricity utility workers in Ontario and Quebec, Canada, and France," G. Theriault *et al.*, Am. J. Epidemiol. **139**, 550–572 (1994) and **140**, 805–820 (1994). (A)
98. "Magnetic Field Exposure Among Utility Workers," T. D. Bracken *et al.*, Bioelectromagnetics **16**, 216–226 (1995). (A)
99. "Utility Workers and EMF Health Risks," T. Moore, EPRI J. **20**, 6–17 (March/April 1995). (A)

L. Mitigation, litigation, and prudent avoidance

The diverse costs of ELF/EMF are reported to be over $1 billion/year. Some aspects of these issues are described below.

100. "Containing the Costs of the EMF Problem," H. K. Florig, Science **257**, 468–469, 488, 490, 492 (1992). Present costs of $1 billion/year. (E)
101. **Electromagnetic Fields: Federal Efforts to Determine Health Effects Are Behind Schedule** (General Accounting Office, GAO/RCED-94-115, Washington, DC, 1994). Potential costs of more than $250 billion. (E)
102. "Interim Guidelines on Limits of Exposure to 50/60 Hz Electric and Magnetic Fields" (International Nonionizing Radiation Committee of the International Radiation Protection Association), H. P. Jammet, *et al.*, Health Phys. **58**, 113–122 (1990). Approved in 1993. (E)
103. **Biological Effects of Power Frequency Electric and Magnetic Fields: Background Paper**, I. Nair, M. G. Morgan, and H. K. Florig (Office of Technology Assessment, Washington, D.C., OTA-B1-E53, 1989). (I)
104. "60 Hz Electromagnetic Fields: Problems in Risk Assessment and Policy Response," G. Morgan, Phys. Soc. **19**, 10 (Oct. 1990), and "Prudent Avoidance," Public Utility Fortnightly, March 15, 1992. (E)
105. "The Imprudence of Prudent Avoidance," D. Hafemeister, Phys. Soc. **24** (3), 9–11 (July 1995). (E)
106. "Electromagnetic Fields: Physics, Biology and Law," E. Gerjuoy, Jurimetrics **35**, 55–75 (1994). (E)
107. "Brief of Amici Curiae Robert K. Adair, *et al.*," San Diego Gas & Electric Co. vs. Orange Country Superior Court and Martin Covalt, *et al.*, Supreme Court of California, 1995. (A)

M. Risk in general

The following references would help to prioritize spending for reducing health risks.

108. *Of Acceptable Risk: Science and the Determination of Safety*, W. W. Lowrance (Kaufmann, CA, 1976). (E)
109. "Perception in Risk," P. Slovic, Science **236**, 280–285 (1987). (I)
110. "Risk Analysis and Management," M. G. Morgan, Sci. Am. **269**, 32–42 (July 1993). (E)
111. "Societal Risk versus Technological Risk," C. Starr, Science **165**, 1232–1238 (1969). (E)
112. "Energy Hazards: What to Measure, What to Compare," J. P. Holdren, Tech. Rev. **85**, 33–38, 74–75 (April 1982). (E)