Background Paper on "Power Line Fields and Public Health

March 29, 1996

To: Panel on Public Affairs, American Physical Society

From: David Hafemeister
Physics Department
California Polytechnic State University
San Luis Obispo, CA 93407
805-544-5096, dhafemei@oboe.calpoly.edu
http://www.calpoly.edu/~dhafemei

Re: Background Paper on "Power Line Fields and Public Health"
(an update of the May 8 and Dec. 15, 1995 papers)
(Sec. I and VIII published, Amer. J. Physics 64, 974-981 (1996)

I. Introduction.

This paper has been reviewed in draft by ELF/EMF researchers, by POPA, by the American Journal of Physics (Sec. I and VIII) and by others, but its contents are the sole responsibility of the author. Comments appreciated.

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, Colorado. 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 five-year program on ELF/EMF research, which is being reviewed by the NAS/NRC. A much lonnger version of this paper can be obtained at http://www.calpoly.edu/~dhafemei.

ELF/EMF Source Terms

Since the 5,000 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 milliwatt 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 opposing, 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 microT = 10 mG, 1 T = 10,000 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 mG 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 meters 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 amperes 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 meters, 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-meter separation and 0.3 mG for 1-meter 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).

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 x 10^+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 x 10^-2 V/m within the electrolyte of a 20 micron 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 millivolts. 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 microV, 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.

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 msec pulses of one ampere at 500 volts, for a peak power of almost 500 watts 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 microV/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.

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 microV/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 doe 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 microV/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 microV/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 microV/m, corresponding to a 60-Hz field of 2 mG. A fast nod in 0.16 seconds creates an electric field of 40 mV/m, corresponding to a 60-Hz field of 40 mG.

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 second 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.

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.

Radon Near Power Lines

Henshaw, et al. (reference 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 towards 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. Lastly, one would expect the radioactive aerosols to plate out on the power lines or on the skin in comparison to lung deposition.

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 process 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 x 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.

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 Hz 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 non-smoking 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), the direction and magnitudes between ELF and Earth B fields, or the harmonic content, or a frequency window.

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 moleules) 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.

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."

I would like to thank Robert Adair, David Bodansky, Aviva Brecher, Richard Frankel, Edward Gerjuoy, Robert Goldberg, John Moulder, Brian Rasnow and the AJP Reviewers for comments on the draft manuscript.

II. Conclusions.

II.1. General Conclusion: The scientific literature and the reports of review panels show no consistent, significant link between cancer and the 60-Hz ELF fields. This literature includes epidemiology studies, research on biological systems, and the analyses of theoretical mechanisms. This result is consistent with those that have advanced arguments that there can be no such link. The preponderance of the epidemiology and biophysical/biological research findings have failed to substantiate those studies that have reported specific adverse health effects from the exposure to 60-Hz ELFs. It is always possible that some minor carcinogenic connection might be found, but the present data do not establish that connection. For expenditures for mitigation to be justified, there should be some consistent, meaningful combination of the following factors: (a) A plausible coupling mechanism at the cellular level exists, (b) the coupling must produce consistent biochemical changes, (c) the biochemical changes must be detrimental, (d) meaningful epidemiology data should determine the degree of danger, and finally, (e) upper-bound ELF mitigation costs should be comparable to those for other dangers mitigated in society. For cases where the epidemiolgy association is very strong, then clearly the other criteria are less important. For cases where the epidemiology association is weak, then clearly the other criteria must be considered. The current cost of ELF is more than a billion dollars a year, an amount which clearly cannot be justified on the basis of applying the above criteria to the data. This cost has been driven by the combination of unlimited "prudent avoidance" in a fearful society.

II.2. Reviews of the ELF Data (Sec. III). None of the approximately dozen scientific panels that have carried out comprehensive reviews of the data has concluded that there is an established link ELF and cancer.

II.3. Epidemiology (Sec. IV): The scientific panels that have reviewed

the ELF epidemiology data have found them inconsistent and inconclusive. It is necessary when comparing the data to separate the results by cancer type. For example, consider the recent case of three studies of electrical workers and a fourth study of non-electrical workers in Sweden. The 1993 California study reported no association of EMF with either leukemia or brain cancer while the 1993 Canadian-French study reported an increase in leukemia, and a modest association of ELF with brain cancer. The 1995 Savitz/Loomis study reported no association of ELF with leukemia, but they did report an association with brain cancer. The 1993 Swedish study reported an association of ELF with leukemia, but they did not report an association with brain cancer. Thus, these four "best studies" report very contradictory results. One has to look at the Savitz/Loomis data in Sec. IV.4 to gain some understanding for the statistics involved in making these judgments. It is very difficult to statistically determine relative risk factors of less than two for rare modes of death because of the many confounding factors.

II.4. Biology and Biophysics Experiments (Sec. V): The scientific review panels, the review articles, and the research papers that we have investigated do not claim a causal link between ELF and cancer. In addition, the review panels and review articles have pointed out that there is a large problem with replicating the experimental results.

II.5. Theoretical Mechanisms (Sec. VI): No plausible biophysical mechanism for the systematic initiation or promotion of cancer by these extremely weak ELF's has been identified. The lack of epidemiology evidence and experimental evidence establishing a link between ELF and cancer is consistent with the biophysical calculations that rule out the carcinogenic effects because the thermal noise fields are larger than the fields from ELF. Since quantum mechanics, thermal noise fluctuations, and cancer promotion are all statistical effects, it is difficult to derive a proof that is a necessary and sufficient condition to preclude all cancer promotion. However, these fundamental calculations are a significant guide post to conclude that the ELF-cancer link, if any, should be extremely difficult to detect because of its small, if any, magnitude.

II.6. Prudent Avoidance (Sec. VII.1): Spending considerable funding to mitigate ELF under the guidance of "Prudent avoidance" would make sense if the ELF risk was documented and some measure of cost-effectiveness could be determined. This is not the case for the alleged adverse effects from ELF/EMF. Since prudent avoidance does not place a limit on mitigation costs, it allows fear to propel society's institutions to spend more than $1 billion per year (Florig. Bromley states a $23 billion total by 1993). Prudent avoidance runs counter to the prioritization of spending on a cost-effectiveness basis. In normal courtroom practice, the plaintiff has the burden to prove damages or risks in order to obtain action from the society, and it should be in the ELF case as well. The misused, quasi-legalistic, prudent avoidance concept essentially states to the public that there is a likely possibility of danger to them and that we should begin to spend money to mitigate the risk, if any.

II.7. Who will speak on the ELF issue? The study of ELF has become a multidisciplinary effort and therefore many different professional voices are needed to comment on this issue. Thus, the National Academy of Sciences (NAS/NRC) is examining the ELF issue. Unfortunately, the NAS/NRC will only assess whether there is a health risk from ELF without consideration of economics. If the conclusions of this paper are correct, one would assume that the NAS/NRC will conclude that the ELF risk has not been proven. However, because one cannot prove there is no risk, there will be uncertainties and the final answer can only establish an upper limit, D, on risk. Since the NAS will not address the cost for mitigation, the upper bound error bar (D) can be used as an argument for mitigation funding. Clearly, a broader approach is needed. Because

physicists have worked on many aspects of this multidisciplinary topic, our views are relevant, and consistent with those of the American Medical Association and others. In exploring this issue, I have learned that many ELF-researchers would not be troubled if we had a statement that stated the simple concepts of (1) don't scare society with ELF, (2) don't spend billions to mitigate. On April 22, the American Physical Society passed on "Power Line Fields and Public Health" (available at this www site).

II.8. Journalism: The number of newspaper stories on ELF rose from 233 in 1992 to 548 in 1993 (S. Friedman, Quill, Jan. 1995). The number of magazine stories rose from 101 in 1992 to 216 in 1993. The writings of P. Brodeur have been followed with headlines of "Is My Electric Blanket Killing Me" to "Chilling Possibility: That A Power That Has Improved Life Could Also Destroy It" to "Warning: Electricity Can be Hazardous to Your Health." Even when an article is even-handed, the caption at the top read, "Steps to Protect Yourself from Danger -- Real and Potential."

"Epidemiology, the Press and the EMF Controversy" by D. Wartenberg and M. Greenberg (Public Understanding Sci 1, 382-394, 1992) conclude that the press has not evaluated investigators claims, nor have they put risks in context. My conclusion is that the science and relative risk methodology of ELF/EMF often undercut the quality of journalism in a free and fear-prone society.

III. Review of ELF Reviews and Government/Industry Responses.

III.1. The Oak Ridge Associated Universities (ORAU) panel (Health Effects of Low Frequency Electric and Magnetic fields, June 1992) prepared its report at the request of the Presidential Committee on Interagency Radiation Research and Policy Coordination (CIRRPC). The panel was made up of scientists from the following disciplines; 5 biologists, 3 epidemiologists, 2 physicists, 1 electrical engineer. Over a period of 1.5 years, the panel examined 1,000 journal articles. The ORAU panel concluded the following:

"From the published studies, evidence is lacking to demonstrate that electric or magnetic fields act as cancer initiators, by altering structural properties of DNA, function as cancer promoters by inducing or accelerating cell growth, or influence tumor progression."

"If a rapidly increasing widespread exposure were indeed strongly associated with childhood cancers, and if no strong countervailing trends in other risk factors were occurring, we should be witnessing an observable epidemic of childhood cancers. However, there is little, if any evidence of such an epidemic of childhood cancer."

"The suggested reproductive risks of electric and magnetic fields are not supported by the totality of the basic science and human studies that pertain to reproduction. However, the fact that a reproductive effect may not seem biologically plausible and that adequate documentation of an increased risk has not been demonstrated in human studies does not mean that these concerns should be summarily dismissed."

"This review indicates there is no convincing evidence in the published literature to support the contention that exposures to extremely low frequency electric and magnetic fields (ELF-EMF) generated by such sources as household appliances, video display terminals, and local power lines are demonstrable health hazards."

"The lack of converging epidemiological and biological support for the occasionally reported adverse health effects is consistent with calculations of quantities based on fundamental laws of physics for describing electric or magnetic fields."

"Although exposure to ELF-EMF does not appear to constitute a public health problem, there is evidence that these fields may produce some biological effects, such as changes in the pattern of secretion of the hormone melatonin and enhancement of healing of bone fractures." [DH: There is some disagreement on the melatonin and bone healing data, and much of it is at higher B fields.]

"This review does not provide justification for a major expansion of the national research effort to investigate the health effects of ELF-EMF. In the broad scope of research needs in basic science and health research, any health concerns over exposures to ELF-EMF should not receive a high priority."

III.2. UK Report; Report of an Advisory Group on Non-ionizing Radiation, National Radiological Protection Board, Electromagnetic Fields and the Risk of Cancer 3 (1992):

"In summary, the epidemiological findings that have been reviewed provide no firm evidence of the existence of a carcinogenic hazard from the exposure of paternal gonads, the fetus, children, or adults to the extremely; low frequency electromagnetic fields that might be associated with residence near major sources of electricity supply, the use of electrical appliances, or work in the electrical, electronic, and telecommunications industries. Much of the evidence that has been cited is inconsistent, or derives from studies that have been inadequately controlled and some is likely to have been distorted by bias against the reporting or publishing of negative results. The only finding that is at all notable is the consistency with which the least weak evidence relates to a small risk of brain tumors. This consistency is, however, less impressive than might appear, as brain tumors in childhood and adult are different in origin, arising from different types of cells."

"In the absence of any unambiguous experimental evidence to suggest that exposure to these electromagnetic fields is likely to be carcinogenic, in the broadest sense of the term, the findings to date can be regarded only as sufficient to justify formulating a hypothesis for testing by further investigation."

III.3 Battelle Conference; B. Wilson, R. Steven. L. Anderson, ed,
Extremely Low Frequency Electromagnetic Fields: The Question of Cancer, Battelle Press, Columbus, Ohio, 1990):

The editors state: "The first tenet of our discussion is that cancer induction is a stochastic process. That is to say, it is probabilistic in nature..... At this time, there are insufficient data to judge whether or not ELF fields influence cancer rates... To date, no convincing laboratory evidence has been obtained indicating that ELF fields cause damage to DNA... However, a recent report offers evidence that ELF exposure can increase micronuclei formation in mouse polychromatic erythrocytes, suggesting possible chromosomal loss. Effects on calcium may increase oxidative stress to cells, and tumor promoters have been found to increase oxidative stress as well. Thus experiments designed specifically to identify possible tumor-promoter activity such as initiation-promotion are suggested..... It is not our intent to argue that ELF exposure increases cancer risk; rather, we wish to suggest areas wherein future experiments may be carried out. Whether or not ELF electric and magnetic fields contribute to increased cancer risk, it is important to conduct scientific studies that will reduce the uncertainty currently associated with the question of cancer."

"Although experimental studies have shown that electromagnetic fields can, in some circumstance, affect the physiology and biochemistry of cells, they do not appear to damage directly the genetic material, DNA, in cells and therefore are unlikely to act as an initiator of cancer."

[DH: There is disagreement over the reportings of some of the biological effects, particularly at the 10 mG level.]

III.4. K. Foster, "Weak Magnetic Fields: A Cancer Connection?" in Phantom Risk, Ed. by K. Foster, D. Bernstein and P. Huber, MIT Press, 1993. Foster's study covers epidemiology and bio-medical data up to November 1992, including the Swedish data. Foster's analysis and data do not support the EMF cancer connection: "In science one can draw no conclusions from unexplained phenomena or inconclusive studies. But in the courtroom it is sometimes enough just to raise questions. And these studies have done that very well." And in Physics and Society 21, 5 (1993): "The epidemiologic data does not directly point to "fields" as causative agents... The bioeffects literature is very noisy, with many unexplained or nonreproducible phenomena, and often speculative.... The most relevant data comes from epidemiology, followed by certain kinds of animal screening studies." (See Sec. IV.)

III.5. Institute of Electrical and Electronic Engineers (1988, 1991) analyzed six major reports (WHO-1984, WHO-1987, AIBioSci-1985, FloridaEMFSciAdComm-1985, WestAssoc-1986, NYPwrLSciAdPanel-1987):

"(1988): In response to the public interest in this subject, we have made an analysis of six recent major scientific committee reports relating to power-frequency electric and magnetic fields. All of these reports concluded that there is insufficient information to define safe and unsafe field levels. In general, there is not enough relevant scientific data to establish whether common exposure to power-frequency fields should be considered a health hazard."

"(1988): At present there is no consensus expressed in any of the published reports as to which factor, the electric or magnetic field is biologically important. Similarly, the roles of field strength, duration of exposure, and intermittent versus continuous exposure are also unknown."

"(1991): "The associations between exposure to power-frequency magnetic fields and cancer reported in epidemiological literature thus far are not conclusive, because the degree of association has often been low, because exposure characterization and dose response information have been limited, and because the possibility of confounding factors has been only partially investigated. The laboratory studies themselves have not indicated a health hazard."

III.6. National Academy of Sciences/National Research Council (NAS/NRC): In 1991, The Congress asked the NAS/NRC to determine the possible effects of EMFs on biological systems. It is expected to be completed in late 1995. The 1992 Energy Policy Act established a $65 M/five year program on ELF research, which is being reviewed by the NAS/NRC. The Electric and Magnetic Fields Interagency Committee shall prepare a final report on the possible health effects on this research on EMF by March 31, 1997. The GAO stated (GAO/RCED-94-115): "Because of the delays, many research projects that are to be implemented under the act will not begin until fiscal year 1995, thus reducing the amount of information that can be obtained and reported to the Congress by March 31, 1997."

[DH: Neither of these studies were studies were asked to consider the costs of mitigation in reaching their conclusions and recommendations. They were asked only to determine if there is, or is not, a health effect, without economic factors. If the NAS/NRC concludes that their are no health effects, but there is an upper bound uncertainty, D, then the political momentum of prudent avoidance can be used as an argument to mitigate on the basis of the upper bound, D, of risk.]

III.7. National Cancer Institute (NCI, http://www.os.dhhs.gov): "A small number of cell culture studies have indicated that ELF fields may

cause biological effects in living tissues, such as interference with protein synthesis. However, these biological effects have not been proven hazardous. There is still no evidence that ELF fields cause or promote cancerous transformation of normal cells. Studies of laboratory animals exposed to ELF radiation have not shown any increased risk of cancer. Occupational studies of electrical workers have suggested an association with cancers, particularly leukemia and brain tumors. However, these studies are difficult to interpret because electrical workers are often exposed to chemicals, solvents, and other carcinogens.... Human epidemiologic studies of ELF fields and cancer have been inconsistent and inconclusive." (Dec. 1992) [DH: Note the use of the word "may" before "cause biological effects." Note that the Savitz 1995 study reverses the electrical worker data.]

III.8. Environmental Protection Agency. The 1990 EPA Draft report that stated EMF was a carcinogen was reversed in September 1991 by the EPA Science Advisory Board, Radiation Advisory Committee of the Nonionizing Electric and Magnetic Fields Subcommittee.

EPA's Report "Q&A about EMFs," (1992) states that "We are not sure if EMF exposure adversely affects human health." A call to the EPA-EMF hot line (1-800-363-2383) gets the same answer. The EPA ("Electric Power Lines: Q&A on Research into Health Effects") states: "Governmental reviews have concluded that existing scientific evidence, although suggestive, does not show that EMF cause cancer. These include national reviews by: an Advisory Board to the U.S. EPA, Advisory Panel to the Australian Minister of Health, National Radiological Protection Board of the UK, Danish Ministry of Health, French National Institute of Health and Medical Research, and reviews by the states of California, Texas, Connecticut, Illinois, Maryland and Colorado."

III.9. The Department of Transportation, in a series of reports on "Potential Health Effects... of ELF .... to Maglev and other Electric Rail Systems" (DOT/FRA/ORD-93-31, plus others) does not make a connection between ELF and cancer, but cautiously says the knowledge is inadequate. Similarly, the Final Environmental Impact Statement, Vol. II on the Northeast Corridor Improvement Project Electrification - New Haven, CT to Boston, MA (Oct. 1994) concludes, "Few of the recent studies were able to estimate and control for other occupational exposures or personal factors that may affect the occurrence of cancer. Some of the studies were limited in their ability to assess an individual's lifetime exposures. None of the studies, including these recent studies using improved measures of EMF exposure, indicates an overall increase in total cancers, that is, all types considered together in electrical workers, or other exposed populations Consistent associations have not been reported for any specific type of cancer and exposure to magnetic fields."

The DOT EIS states that EMF mitigation is part of their NE Corridor proposal (Vol. 1, p. 5-5): "The overhead catenary system and power transfer facilities design has been shown to minimize environmental EMF along the right-of-way in over a decade of operation powering the TGV system in France. The out-of-phase currents in the catenary and return feeder provide a partial magnetic field cancellation (except for the passengers in the current loop). At 30 feet from the track, the EMF due to this design is about half that produced by each overhead wire's current. In addition to EMF field reduction, this design offers EMF minimization at the source. As a consequence, no specific changes are recommended in the overhead catenary design." Considerable expense was added to the NE Corridor system to make these design changes and to change the locations of stations.

III.10. The Electric Power Research Institute states that $40 M was spent in 1993 from all sources on EMF research, its budget is about $10 M/yr. DOE and industry will spend $65M/5y. See Electrical and Magnetic Fields Research Abstracts (EPRI TR-104359, August 1994) for research

projects.

III.11. P. Buffler, Dean, School of Public Health, University of California-Berkeley (UC-Berkeley Wellness Letter 11, 1, Nov. 1994): "In April, in a paper presented to the National Council for Radiation Protection, ... Buffler... highlighted the serious weaknesses of this [93-Sweden] and similar studies and pointed out how the results have been overblown and misrepresented.... Some scientists have proposed various sketchy theories to explain the dangers of EMF's, but none of these hypotheses has widespread support... the evidence so far certainly does not justify inordinate concern, let alone hysteria.... Some call this 'prudent avoidance,' but others say it is waffling. Carried to an extreme this policy could result in spending millions of dollars (passed on to us in higher energy rates and appliance prices) to avoid an unidentified or 'phantom' hazard, according to Buffler."

III.12. The Council on Scientific Affairs of the American Medical Association 1994 report, "Effects of Electric and Magnetic Fields:" "Most studies of magnetic field effects in children, workers, and other populations do not meet accepted scientific criteria in terms of accurately measuring past exposure, identifying comparable test and control groups, and accounting for potentially confounding factors. Findings of studies are inconsistent in terms of whether a risk exists, what conditions might be related to exposures, and risk magnitude. Positive studies indicate, for the most part, that the associated relative risks are low."

III.13. In 1995, three biomedical Nobel laureates joined an amicus brief to the California State Supreme Court stating, "The physics and cellular biology combined strongly indicate that it is not scientifically reasonable to believe that 60-Hz magnetic fields increase the incidence or cancer."

III.14. National Council on Radiation Protection and Measurements (NCRP) leaked draft report calling for a 2 mG standard has been declared "improperly disseminated" (leaked) and unfinalized by NCRP management.

IV. Epidemiology and Cancer Data: (See Sec. III for panel reviews.)

IV.1. Recent Compilation of the Data: The December 1994 issue of IEEE Spectrum lists the references and results for 15 epidemiology studies before the recent 1995 Savitz/Loomis study. Unfortunately, this summary does not analyze the data with respect to the different types of cancer. The first major study by N. Wertheimer and E. Leeper in 1979 triggered journalism that then created a large public response. These results are greatly discredited by the totality of the 16 studies. The early results also were plagued by the fact that they reported an association with power lines (wire codes) but they did not report an association with measured spot fields. It is necessary when comparing the data to separate the results of these study by cancer type. For example, consider the case of three studies of electrical workers. The 1993 California study reported no association with either leukemia or brain cancer. The 1993 Canadian-French study reported an association with leukemia, and a modest association with brain cancer (based on only five cases) of the 32 types of cancer studied. Thus, it is statistically possible to find a few positive associations if looking among many possibilities. In addition, the authors have stated that there was "a discrepancy in the results between the three utilties." The 1995 Savitz/Loomis study reported no association with leukemia, but they did report an association with brain cancer. One has to look at the Savitz/Loomis data in Sec. IV.3 to gain some understanding for the statistics of the relatively few extra deaths involved in making these judgments. [DH: The inconsistency in the results of these 16 studies is evidence of either a truly small or nonexistent risk, or else a measure of the confounders of different lifestyles, chemical exposures, etc.]

IV.2. Confounders and Causality: Epidemiological data can be biased by other factors, called confounders, for example data (Sci. Amer. 271 , 26, Dec. 1994) showing that "People of color -- defined by the report as the total population less non-Hispanic whites -- are currently 47 percent more likely than are whites to live near a commercial toxic waste facility." Other data (Science 267, 1269, 1995): "... social instability, as indicated by parental divorce, which correlates with a loss of 4 years from a person's life span." Since each epidemiology study will have different confounders, these effects, such as the socio-economic factor of living near a power line must be removed from the data. It is clear that a correlation and associations between epidemiology variables can be meaningful, but it does not prove causality.

[DH: These kinds of confounders are very important when one is examining relative risks of less than two for rarer death causes. The ELF epidemiology is further complicated by the fact that the dosimetry is usually not directly measured, and when dosimeters are used they usually do not determine the harmonic components as a function of time so important for Faraday's law of induction. Some ELF workers have stated that it makes little sense to establish larger epidemiological studies beyond the "best" study of Savitz/Loomis because the lack of real dosimetry will make the studies of limited utility.]

IV.3. University of North Carolina Study on Electrical Workers Mortality (D. Savitz and D. Loomis, Amer. J. of Epidemiology 141, 123-134, 1995): "Reports of leukemia and brain cancer among men in electrical occupations suggest a small increase in risk, but most previous studies have failed to classify magnetic field exposure accurately or to consider potential confounders. The authors conducted an historic cohort mortality study of 138,905 men employed at five large electric power companies in the U.S. between 1950-86 with at least 6-months of work experience. Exposure was estimated by linking individual work histories to data from 2,842 workshift magnetic field measurements. Mortality follow-up identified 20,733 deaths based on 2,656,436 person-years of experience. Death rates were analyzed in relation to magnetic field exposure history with Poisson regression. Total mortality and cancer mortality rose slightly with increasing magnetic field exposure. Leukemia mortality however, was not associated with indices of magnetic field exposure except for work as an electrician. Brain cancer mortality was modestly elevated in relation to duration of work in exposed jobs and much more strongly associated with magnetic field exposure indices. Brain cancer risk increased by an estimated 1.94 per microtesla-year of magnetic field exposure in the previous 2-10 years, with a mortality rate ratio of 2.6 in the highest exposure category. In contrast to other studies, these data do not support an association between occupational magnetic field exposure and leukemia but do suggest a link to brain cancer."

Savitz Data ($5M over 7 years), showing lower mortality rates because of the "healthy worker effect:"

Cause of Death	Observed Deaths	Expected Deaths	Mortality Ratio (+/-95%)
All Causes	20,733	26,779.5	0.77 (0.76-0.78)
All Cancer	4,833	5,515.1	0.86 (0.84-0.89)
Brain/nervous sys	151	158.4	0.95 (0.81-1.12)
Leukemia	164	217.0	0.76 (0.64-0.88)

Leukemia Results: For leukemia, note the relative risk (RR) of 0.76 similar to the overall cancer RR of 0.77, thus no association with emf. The RR (vs. total exposure in microT-yr) from Savitz/Loomis: RR(microT-yr): 1.0(0-0.6), 1.28(0.6-1.2), 0.94(1.2-2.0), 0.72(2.0-4.3), 1.62(>4.3). Thus, Savitz conclusion of no association with leukemia is in agreement with the California study but in disagreement with the Canadian-French and 1993 Swedish studies.

Brain Cancer Results: Savitz quotes an RR of about 1.5-2.5 which is similar to the French-Canadian result of about 1.5, but in disagreement with the California and 1993 Swedish results of no association. Since this mode for death is relatively rare, these conclusions are based on relatively small numbers. Note that there are only 7 "extra" emf brain cancer deaths (158-151), as compared to 20,700 actual total deaths, a very weak association with emf.

Savitz Press Release (1-11-95): "Although the most recent studies had found evidence that magnetic fields were related to leukemia, we did not.... The positive association between magnetic fields and brain cancer that we saw was stronger than had been seen in previous studies of electric utility workers..... It is disappointing that our results do not provide a clearer picture when combined with the previous studies of electrical workers and particularly electrical utility workers."

Washington Post, Jan. 12, 1995: "Savitz stressed yesterday that lethal brain cancers are rare -- occurring at a rate of about 6 per 100,000 persons in the general population -- and thus even a doubling of the risk does not pose a dramatic threat. 'I don't want to downplay the adverse aspects of our findings, but one thing our study does is show once again there is not some public health disaster lurking out there."

IV.4. Sweden (M. Feychting and A. Ahblom, Am. J. Epidemi. 138, 467-481,1993):

The Swedish results should be examined in conjunction with the studies from Denmark and Finland, which do not show an association with ELF. "For childhood leukemia and with cut off points at [average residential exposure] 0.1 and 0.2 microT, the relative risk (RR) increased over the two exposure levels and was estimated at 2.7 (95% c.l.: 1.0-6.3) for 0.2 microT and over.... For brain tumors or for all childhood cancers together there was little support for an association.... In adults and for magnetic fields of 0.2 microT and over, the RR for acute myeloid (AML) and chronic myeloid leukemia (CML) was estimated at 1.7 (0.8-3.5) and 1.7 (0.7-3.8)." The authors have commented that calculated wire codes should be a better predictor of dose than actual field measurements.

R. Wilson and A. Shlyakhter (Amer. J. of Epidemi. 1995) analyze (with humor) the Swedish Results: "... This suggests that there is an unusually large number of cases, leading to a larger risk ratio among the 262 (695-433) homes for which there were no spot measurements. This leads us to speculate that the failure to make a spot measurement might itself be associated with an increase in leukemia."

IV.5. Danish Study (J. Ohlson, Brit. Med. J. 307, 891-95, 1993):

"This study demonstrated that the risk of lymphatic cancer is increased among children with exposure to magnetic fields from high-voltage lines of 0.1 microT (1 mG) or greater. On the other hand, no increase in risk was found at this exposure level for either leukemia or brain tumor. For all three types of cancer combined an increased risk was also found at magnetic field exposures of 0.4 microT (4 mG) or greater, which corresponds to a residential distance of 25-50 meters from the 'most powerful' transmission facilities."

G. Taubes (Science, 262, 649, 1993) quotes P. Buffler, the dean of the School of Public Health, University of California at Berkeley, who attacks the grouping of Danish data. [DH: Study used the crude power line distance parameter, and based on few numbers.]

IV.6. Finland (Bioelectromagnetics 14, 229-36, 1993)

".... 68,300 boys and 66,500 girls aged 0-19 years living....in magnetic

fields calculated to be greater than 0.01 microT (0.1 mG) ... 140 cases of cancer were observed (145 expected; standardized incidence ratio 0.97, 95% confidence interval 0.81 to 1.1). No statistically significant increases in all cancers and in leukemia and lymphoma were found in child at any exposure level. A statistically significant excess of nervous system [brain] tumors was found in boys (but not in girls) who were exposed to magnetic fields greater than 0.2 microT (2 mG) or cumulative exposure of greater than 0.4 microT-years (4 mG-y)."

"Conclusions: Residential magnetic fields of transmission power lines do not constitute a major public health problem regarding childhood cancer. The small numbers do not allow further conclusions about the risk of cancer in stronger magnetic fields."

IV.7. Joint Canada/France Utility Workers (American Journal of Epidemiology, March 15, 1994). [DH: This study combined 3 separate studies and has internal inconsistencies between the three utilities. Of the 32 cancer types examined, only two showed an association, which might be expected when considering so some many statistical linkages.]

"223,000 male utility workers... A significant association between exposure to EMF and leukemia and brain cancer has not been obtained.... Overall, combining all different cancer types, the study did not find any association between the cancer cases analyzed and electric or magnetic fields. Proceeding then to a separate analysis of 25 different cancers and 7 regroupings among these cancers, an association was found in only three. For these three cancer-type/regroupings, a link with cumulative exposure to magnetic fields was observed for acute non-lymphocytic leukemia (60 cases), including 47 cases of acute myeloid leukemia and a type of brain tumor known astrocytoma (41 cases). However, no relation was found between length of exposure and effect; the results were inconclusive for astrocytoma, given the low number of subjects and the imprecision of the findings."

IV.8. "Are the stray 60-Hz electromagnetic fields associated with the distribution and use of electric power a significant cause of cancer?" by J. D. Jackson (Proc. Nat. Acad. Sci 89, 3508-10, 1992). "Total per capita power generation has increased by a factor of 10 since 1940, and per capita residential consumption has increased by a factor of 20 in the same period.... When respiratory cancers (largely caused by tobacco use) are subtracted, the remaining death rate has actually fallen since 1940." The Oak Ridge report points out that electrical power use has increased by nearly three orders of magnitude during this century. Some cancer mortality rates have risen, and others have fallen. Because of changes in cancer detection and medical intervention, it is difficult to make EMF totally blameless on the basis of the data. Nonetheless, because of the marked increase of electricity consumption (factors of 10, 20, 1000), it seems clear that EMF cannot be a significant cause of cancer.

In May 1995, Jackson comments: "My paper has been criticized for not taking into account the changes over the years of delivery systems, especially in residences. The replacement of the old-fashioned pairs of wires, spaced eight or ten inches apart and passing through the floor joists in porcelain insulating tubes, with modern conduit or cable with closely spaced wires, so the argument goes, has greatly reduced the ambient magnetic fields (much smaller effective dipole moment per unit length for the same current) and compensated for the huge growth in per capita consumption. While my paper does not address these changes in detail, I do not think the criticism significant. Before the Second World War, house wiring was of the old-fashioned sort (my own home is still half filled with that kind!), but the cancer incidence data of Fig. 2 are for more recent times. The 20-fold increase in per capita consumption of electric power in the last 50 years has occurred with essentially no change in household wiring in kind, but only in quantity."

IV.9. Brain Cancer Data: The NCI Surveillance, Epidemiology, and End Results (SEER) report of November 1994 and Science 267, 1414 (1995) give the changes in cancer rates between 1973 and 1991. For mortality rates, of the eight types that increased, brain cancer was ranked 6th with an increase of 0.7%/year, for incidence rates, brain cancer was ranked 7th at 1.2%/year. The rate of increase in the incidence in brain cancer is about the same as the rate of cancer incidence at all-sites. The total incidence and mortality rates for all forms of cancer are 390.4 and 172.8 per 100,000 persons, respectively. The leukemia and brain mortality rates are 7.6 and 4.8 respectively.

The NCI comments (May 1994): "Scientists believe a substantial part of the increase in brain cancer rates, especially in the older groups, is due to the advent of sophisticated scanning and imaging equipment, which are better able to detect brain tumors.... Factors shown to have a link to brain tumors, such as certain heritable conditions and childhood radiotherapy to the head, are uncommon and account for only a small percentage of the total number of cases."

IV.10. E. Washburn, et al (Cancer Causes 5, 299-309. 1994) examine 13 epidemiology studies related to childhood cancer and power lines. They conclude: "We found no statistically significant relation between combined relative risk estimates and 15 indicators of epidemiology quality. Assessment of EMF exposure in the primary studies was found to be imperfect and imprecise."

V. Biology and Biophysics Experiments (see Section III for panel reviews):

V.1. Comments: In general these experiments use magnetic fields to "stimulate" a biological response, and not the electric field which is reduced by a factor of 108 in the human body. The views of biomedical-biophysics panels (Sec. III) and the research below do not show a link between ELF and cancer. [DH: I have asked the researchers that I called for evidence of such a link and they said there was no evidence. The review panels and others have pointed out that there is a problem with replicating the experimental results described below. Two of the main researchers I called stated that their work had only been "partially replicated."]

V.2. T. Teneforde (Ann. Rev. Publ. Health, 13, 173-196, (1992)) concludes the following: "Various different effects of ELF magnetic fields have been reported to occur at the cellular, tissue, and animal levels. Certain effects, such as the induction of magnetophosphenes in the visual system, have been established through replication in several laboratories. Many other effects, however, have not been independently verified or, in some cases, replication efforts have led to conflicting results. A substantial amount of experimental evidence indicates that the effects of ELF magnetic fields on cellular biochemistry, structure, and function can be related to the induced current density, with a majority of the reported effects occurring at current density levels in excess of 10 mA/m2. These effects, therefore, occur at induced current-density levels that exceed the endogenous currents normally present in living tissues. From this perspective, it is extremely difficult to interpret the results of recent epidemiological studies that have reported a correlation between cancer incidence and exposure to 50-Hz or 60-Hz magnetic fields with very low flux densities. The levels of current density induced in tissue by occupational or residential exposure to these fields are, in nearly all circumstances, significantly lower than the levels found in laboratory studies to produce measurable perturbations in biological functions. There is a clear need for additional epidemiological research to clarify whether exposure to ELF magnetic fields is, in fact, causally linked to cancer risk. Laboratory animal studies conducted under controlled conditions are also needed to determine whether ELF magnetic fields can initiate or promote tumors. In addition, more studies of both a theoretical and experimental nature are

needed to elucidate the molecular and cellular mechanisms through which low-intensity magnetic fields can influence living systems. A growing body of evidence indicates that cell membranes play a key role in the transduction and amplification of ELF field signals. Elucidation of the physical and biochemical pathways that mediate these transmembrane signaling events will represent a major advance in our understanding of the molecular basis of magnetic field effects on biological systems."

Foster (Sec. III.4) concludes on the melatonin work: "..... Most employed fields far above environmental levels... In short, the health significance of these effects is unclear, and in several cases there is reason to question their existence. Given the dismal record for reproducibility of bioeffects...."

J. Stather of the UK National Radiological Protection Board comments (Science 267, 451, 1995): "Although laboratory studies have suggested that electromagnetic fields can influence growth in both plant and animal cultures, the effects of such studies, 'when properly controlled,' have usually turned out to be inconclusive."

EPA ("Electric Power Lines" Q/A on Research into Health Effects, Bonneville, May 1994): "Some reported effects of 60-Hz EMF in laboratory studies: Increase in bone fracture-healing, avoidance of strong fields, decrease in the hormone melatonin, changes in stress hormones, field detection, slowing of human heart rate, changes in human brain activity, changes in tumor development, changes in white blood cell counts, temporary effect on growth, changes in behavior tests, changes in biorhythms, changes in functions of cells and tissues." [DH: Note the verb reported means often unconfirmed, some disputed, and some are not replicated. Also, many of these experiments have been carried out at fields well above 10 mG.]

V.3. Animals: Honey bees follow B fields (Walker/Bitterman, J. Comp. Physiol. 157, 67-73, 1995, and Science 265, 95, 1994) down to a few mG DC accuracy and sea turtles turn when B varies at earth's locations (Science 264, 661 (1994). [DH: Note that detection of DC fields is not detection of AC fields, and it certainly is not cancer promotion. The honey bees are insensitive to AC fields. See introduction and Sec. VIII., Bibliography for more data on animals.]

V.4. Montrose and Litovitz (Phys./Society 21, 7, 1992) report changes in ornitine decarboxylase (ODC) enhancement in chick embryos with ELF. Adey in Battelle book discusses communication between cells through gap-junctions which are sensitive to low-frequency EMF. "We hypothesize that cancer promotion with tumor formation may involve dysfunction at cell membranes, disrupting inward and outward signal streams."

V.5. Magnetite in the Brain (J. Kirschvink et al, Proc. of Nat. Acad. Sci. 89, 7683, 1992): "These magnetic and high-resolution transmission electron microscopy measurements imply the presence of a minimum of 5 million single-domain crystals per gram for most tissues in the brain..... indicate the crystals are in clumps of between 50 and 100 particles.... Samples from seven brains were obtained from patients whose ages averaged 65 years... Subsamples for magnetic measurements were removed form the tissues by using similar tools in a magnetically shielded dust-free clean laboratory. Measurements of the ferromagnetic materials were made using a magnetometer employing Rf-biased SQUIDS.... 3-100 ng/g of magnetite.."

[DH: This work has not yet been replicated. J.R. Dunn, et al (Brain Research 36, 149-153, 1995) gives some data at a lesser resolution from magnetic force microscopy. See Sec. VI.3 for a discussion of the results. Kirschvink (Nature 374, 123, March, 1995) appeals for researchers to have very clean rooms to avoid adding magnetic particles from the environment, thus nullifying their experiments.]

V.6. P. Valberg, "Designing EMF Experiments: What's Required to Characterize Exposure?," Bioelectromagnetics, 1995. "Anyone who has attempted to organize and synthesize the results of research on biological effects of electric and magnetic fields (EMF) has experienced frustration when trying to evaluate the comparability of EMF exposures among separate studies.... To this end, a numerical listing of 18 separate parameters important to EMF exposure characterization is proposed... (1) Intensity of the magnetic field, (2) timing and duration of each EMF exposure, (3) repetition of exposure periods, (4) Circadian time of exposure, (5) frequency of field oscillation, (6) harmonic content, (7) intermittency, (8) turn-on and turn-off transients, (9) coherence in time, (10) circular and linear polarization, (11) relative orientation and magnitude of AC and DC magnetic fields, (12) spatial homogeneity, (13) superimposed electric fields, (14) Earth's magnetic field, (15) incidental, unplanned EMF exposure, (16) geometry of cell culture system, (17) size, number and movement of exposed animals, (18) accessory non-EMF exposure.

V.7. Bone Healing from EMF (C. Polk, Advances in Electromagnetic Fields in Living Systems, 1, 129-153 (1994)): Pulsed electromagnetic fields (PEMF) typically "consist of 15 pulse bursts per second. Each burst is 4.5 ms long and contains 20 magnetic field pulses. In each pulse the magnetic field increases from 0 to approximately 2 mT [20 G] during 200 ms, decrease to 0 again during 23 ms and is equal to 0 for 2 ms before the next 225 ms sequence begins." Also, see the Bioelectric Repair and Growth Society, PO Box 64, Dresher, PA 19025 for more details. [DH: The fast rise times enhance the dB/dt by about a million with respect to 10 mG ELFs, to some 50 V/meter. The healing properties are not agreed to by all. Some have commented that the transients from switching should be more relevant than steady-state power.]

V.8. Melatonin from the Pineal Gland; EPRI, EMF Laboratory Studies. Melatonin is a hormone produced by the brain's pineal gland and released to circulate in the bloodstream at levels that peak in nighttime darkness and decline in daylight. Laboratory evidence suggest that melatonin can, under some conditions, suppress the growth of hormonally sensitive cancers such as those in mammary tumors.... some studies show that 60 Hz electric fields and AC or rapidly inverting DC magnetic fields suppress nighttime melatonin production in rodents, but others have failed to reproduce these findings." [DH: Some dispute this work.]

V.9. Paramagnetic Resonances; C. Blackman, etal, Bioelectromagnetics 15 239-260 (1994): "Previous studies demonstrated that nerve growth factor (NGF)-stimulated neurite outgrowth (NO) in PC-12 cells can be inhibited by exposure to magnetic fields as a function of either magnetic field flux density or AC magnetic field frequency. The present work examines whether the PC-12 cell response to magnetic fields is consistent with the quasiperiodic, resonance-based predictions of the ion parametric resonance model (IPR).... The first set of tests examined the NO response in cells exposed to 45 Hz BAC from 77 to 468 mG(rms) at a BDC of 366 mG. Next we examined an off-resonance condition using 20 mG BDC with a 45 Hz AC field across a range of BAC between 7.9 and 21 mG(rms). Finally, we changed the AC frequency to 25 Hz, with a corresponding change in BDC to 203 mG (to tune for the same set of ions as in the first test) and BAC range from 78 to 181 mG(rms). In all cases the observed responses were consistent with predictions of the IPR model."

Adair (submitted to Bioelectromagnetics): "The data is far too consistent.... The extraordinary consistency of the data cannot be attributed to chance."

[DH: It is generally agreed Blackman's theoretical model is incorrect. The data are only partially replicated.]

VI. Theoretical Mechanisms

VI.1 Theory I: C. Polk has calculated a variety of EMF situations; (IEEE Transactions 34, 243-249, 1991, and in CRC Handbook of Biological Effects of Electromagnetic Fields, Polk and Postow, eds.) The magnetic fields are determined from the currents, and the E-fields from the voltage:

-- Faraday's Law: E=wBr/2, J=sE. Using SI units, with B in Tesla, E in volts/m, 60 Hz, s=0.1 S/m, r=0.1 m, gives E=18.85 B and J=1.885 B. For a 1 microT field (10 mG), one gets E = 20 microV/m and J = 2 milliA/m2.

-- E fields inside conducting media at 60 Hz, s=0.5, not grounded
E(internal)/E(air) = we0/s = 4 x 10-8, (0.7 x 10-8, Bennett)

Since the body greatly reduces the external E fields, it is generally felt that the B field is more relevant since the E fields produced dB/dt are not reduced because B is not shielded, and also since B might torque magnetic magnetosomes in the body.

Polk (Ch. X in CRC Handbook of Biomedical Engineering, J Bronzio, ed. CRC Press 1995): "Biological tissue and cells are obviously extremely complex media, they are not only extremely inhomogeneous and anisotropic, but also not in thermodynamic equilibrium (unless dead). Thus the application of physics laws to the explanation of field-tissue interactions becomes a very complex problem and the physicist and engineer must be careful not to provide "explanations", or to set limits on what should be "possible" or "impossible", based on physical models that are very far from even an approximate representation of biological conditions..... The experimental evidence existing at the present time is however insufficient to decide whether any of the more promising physical models that are discussed in the given references can provide an adequate explanation for any of the observed biological effects.... Uniform linear motion of an object, such as that of a walking human, in a nearly uniform magnetic field of about 50 microT will produce an induced "Lorentz" electric field proportional to the product of velocity and flux density. However that field cannot produce circulating electric currents as long as the total magnetic flux... does not change. Only tumbling motion,... could produce induced electric currents comparable in magnitude to those induced by a 1 microT [10 mG] 60 Hz field."

VI.2 Theory II: R. Adair has calculated various EM effects in Phys. Rev. A43, 1039-49 (1991), Physics and Society 19, 12-13 (1990) and Phys&Soc. 21, 8-10 (1992). Some of his results are: Thermal fluctuations lead to local electric Johnson--Nyquist "noise" fields from charge oscillations with rms values of

E(rms)2 = 4rkT(df)/d3,

Where r is the resistivity = 2, df is frequency span of 100 Hz, d is the cell size of 20 microns This gives E = 0.02 V/m, 3000 times larger than E from an external field of 300 V/m. J. Weaver (Science 247, 459-462,1990) uses Johnson-Nyquist to estimate 0.1 V/m for broad band detection.

Adair; limits on membrane rectification processes lead to very small currents: "Static magnetic fields smaller than the earth's field of 50 mT and varying fields weaker than 4-mT 60-Hz fields are equivalent in effect to that from walking in the earth's field, cannot be expected to generate significant biological effects. Moreover, the interactions of such weak fields at the cell level are also small compared to thermal noise. These conclusions would be modified by 60-Hz cell resonances. But such resonances are shown to be incompatible with cell characteristics and the requirement from equipartition that the mean resonance energy must be kT. Hence, any biological effects of ELF fields

on the cellular level must be outside the scope of conventional physics." For E fields from time-varying B fields, the Faraday's law approach [with 500 mG] gives E = 0.001 V/m, as compared to a noise field value of 0.02 V/m. Cyclotron Resonance is ruled out for the example of calcium to refute Adey's data, "... the orbit [1 m] of such a resonance must be larger than the size of the cell by five orders of magnitude." (1011 collisions/second, P. Valberg)

T. Tenforde (Ann. Rev. Publ. Health 1992: 13, 173-96) disagrees by stating: "This theoretical treatment, however, neglects the considerable signal amplification that can occur in large arrays of electrically coupled cells in tissue. It also fails to consider nonequilibrium phenomena, such as cooperative transitions, through which extremely weak signals could exert significant effects on cell membrane properties." W. Bennett (Health and Low Frequency Electromagnetic Fields, Yale Univ. Press, 1994) disagrees with Teneforde on degree of signal amplification.

VI.3. Magnetite: Robert Adair (Proc. Nat. Acad. Sci. 91, 2925-29, 1994): "Previous calculations... are extended to consider multiple signals, the possibility of anomalously large magnetosome structures, and the possibility of anomalously small cytoplasm viscosities. The results indicate that the energies transmitted to the magnetite elements by fields less than 5 microT (50 mG).... will be much less than thermal noise energies. Hence, the effects of such weak fields.... cannot be expected to affect biology, or therefore, the health of populations."

Polk (Bioelectromagnetics 15, 261-270, 1994): "The numerical results indicates that predictions of this model depend strongly on the value selected for viscosity of the cytoplasm.....it seems premature to conclude.... 'that 60 Hz magnetic fields weaker than 5 microT (50 mG) cannot generate significant biological effects at the cell level through action on magnetic elements..'"

Kirschvink (Phys. Rev. A 46, 2178-2184, 1992): "A biologically plausible model of the interaction of single-domain magnetosomes with a mechanically activated transmembrane ion channel shows that ELF fields on the order of 0.1 to 1 mT [1-10 G] are capable of perturbing the open-closed state by an energy of kT. As up to several thousand structures could fit within a eukaryotic cell, and the noise should go as the square root of the number of independent channels, much small ELF sensitivities at the cellular level are possible."

Bennett ("Cancer and Power Lines," Physics Today 47, April 1994, p. 23-29) calculates the physical basis for a variety of EM situations and concludes that "the dangers to human health from low-level ELF fields have been exaggerated beyond reason ....." See exchange of letters, Phys. Today 48, 13-15, 71-73, January 1995. Bennett (Phys. Today, p. 72, Jan. 1995) states "Any motion induced by a 60 Hz-field at the cell level will be strongly damped by viscosity effects. Few things are expected to have as large a collective magnetic interaction as a long chain of magnetic domains. For example, Joseph Kirschvink estimated from his model of the problem that it would take more than 1400 mG from 60-Hz field in the presence of cellular protoplasm to open an ion channel with a magnetite particle having a moment as large as 2 x 10-15 A m2 (about 34 domains). Such fields are enormous compared with those from power lines."

VI.4. Stochastic Resonance (SR) has been shown to be relevant in some electro-optics experiments, and it has been applied in various theories of climate change cycles and in biophysics problems. K. Wiesenfeld and F. Moss (Nature 373, 33-36, Jan. 5, 1995, Sci. Amer. 273, 66-69 (1995) and B. MacNamara and K. Wiesenfeld (Phys. Rev. A39, 4854-69, 1989) state: "But recent research has established that noise can play a constructive role in the detection of weak periodic signals, via a mechanism known as stochastic resonance. In essence, SR is a nonlinear

cooperative effect in which a weak periodic stimulus entrains large-scale environmental fluctuations, with the result that the periodic component is greatly enhanced." These authors have measured SR-like responses of cray fish mechanoreceptors hair cells that follow a SR-like curve. They conclude: "If SR is relevant, the effect of weak, extremely low frequency electromagnetic fields might be greatly amplified. Whether any such enhancement is large enough to have significant biological ramification is at this state purely speculative."

The authors continue: "... the presence of random noise alone is sufficient to induce (irregular switching) between the wells. In the high-friction limit, the dynamics can be modeled by the differential equation

dx/dt = -dU/dx + F(t) + A sin(wt)

where U is the bare potential, A sin(wt) is the signal, and F is the noise..... Remarkably, theories for all three types of SR -- the bistable potential model, the fire and reset excitable system model, and the simple threshold model -- result in the same general formula (apart from some constant factors of order one in both the prefactor and the exponential) for the Signal to Noise Ratio (SNR):

SNRout a (eDU/D)2 exp(-DU/D)

where e is the input signal strength, D is the input noise intensity and DU is a constant related to the barrier height or the threshold."

Adair points out that the SNR above is the output SNR ratio, signal out over noise out. Thus if one divides both sides of the equation by SNRin, (e/D), one obtains

SNRout/SNRin a (eDU2/D) exp(-DU/D).

Adair comments on SR: "However, if the input signal is much smaller than the input noise, the output signal-no-noise ratio will be even much smaller.... where an electromagnetic field signal is much smaller than the thermal noise.... SNRin <<1..... " Adair further points out in a comment on chaos that the flapping of the butterfly in Irkusk might change the day it snowed in New York, but it wouldn't change the average climate.

VI.5. F. Barnes (Bioelectromagnetic Supplement 1, 67-85, 1992): "There have been a number of hypotheses presented (4 ref.), but thus far, it has been difficult to get definitive measurements that either confirm or reject these theories.... Additionally, three models by which a biological system may extract weak signals from noise are presented. The first of these is the injection-locking of oscillating processes where the signal to noise ratio may be less than unity. The second is parametric amplification which allows the external signal and the biological process to be at different frequencies and where stability requirements on the external pump frequency discriminates against the noise. The third approach is to examine a computer model for a neural network which can be trained to identify a 60 Hz field at signal-to-noise ratios much less than one. The key to each of these models for possible interactions of magnetic fields with biological systems is the long-term coherence of the signal with respect to the noise."

VII. Prudent Avoidance and ELF Mitigation Costs.

VII.1 Prudent Avoidance: The vague concept of "Prudent Avoidance" has been used by at least eleven utility commissions to promulgate regulations on ELF because the science connection between EMF and cancer has not demonstrated. G. Morgan defines (Public Utility Fortnightly, March 15, 1992 and EMF Fields from 60 Hz Electrical Power, Carnegie Mellon, 1989) "prudent avoidance" as: "Prudence means exercising sound

judgement in practical matters. It means being cautions, sensible, not rash in conduct." Morgan further states that prudent avoidance "is to try to keep people out of fields when that can be done at modest cost -- but not to go off the deep end with expensive controls which may not be beneficial." This seems reasonable, but from there he moves towards the arbitrary spending without measurable benefits by stating: "Utilities and utility regulators must consider both distribution systems and transmission systems. Activities that may warrant consideration at the distribution level include: paying greater attention to population distributions around facilities; incorporating more consideration of exposure management in maintenance and facility upgrade policies.... making selected use of undergrounding..."

[DH: Thus, prudent avoidance opens the political path for the utilities and other bodies to spend money without a scientific basis for concern. This seems all the more irrational since there is no convergence on the epidemiology data on what to fear, and there is no consensus on whether the concern is (1) the intensity of the fields, (2) the frequency windows which might cause resonance, or (3) the rate of change of the fields (Faraday's law). In our free society, this open-ended, unbounded approach to risk mitigation allows a fearful public to use the threat of litigation to remove the "phantom effect." As long as the rate payers and others will cover the costs, the utilities and others have little incentive to take on litigation in this area. In general EPA requires corrective action when the probability of death to those that are exposed is greater than 1/1,000,000 over a 70 year lifetime, but because of dollar limitations this has often been softened to 1,/0,000.]

[DH: Morgan's approach appears to be driven by his statement that "there is some significant chance that fields pose a modest public health risk, and not much chance that the risk to any one of us will be very big." In my analysis of Morgan's work, he seems to have placed great reliance on well-known discredited work, stating in 1992 that "a series of epidemiological studies, including studies of childhood leukemia by Nancy Wetheimer and Ed Leeper.... have provided a growing basis for concern." In addition, Morgan has failed to examine the risk factors by type of cancer, an approach which shows glaring inconsistences. Lastly, his writings should be updated to take into account the new work of Savitz and others. Philosophically, Morgan alludes to Thomas Kuhn's Structure of Scientific Revolutions, stating that "paradigm shifts" are affecting "scientific thinking about biological effects from electric and magnetic fields." It is premature to talk of paradigm shifts when the preponderance of the data base does not converge on a cancer pathway or on the degree of risk. Morgan's is concerned that public perceptions may drive regulations rather than scientific fact, but yet I conclude that it his own papers which have pushed the ELF-risk process away from science and towards irrationality. I agree with the critics of "prudent avoidance" who have call it "the abandonment of science, "the triumph of fear of the unknown over reason," and "being so vague as to be useless." In the real world of the courts, the public utility commissions, and the city councils, this approach makes for regulation by fear and without substance. Prudent avoidance is a delight for plaintiff lawyers since it is essentially a conclusion that the danger is probable. See "The Imprudence of Prudent Avoidance," by D. Hafemeister, Physics and Society 24, 9-11 (July 1995).]

VII.2 Utility Regulations (GAO Report on EMF, GAO/RCED-94-115): "Regulators in at least 11 states that we contacted have adopted practices for mitigating exposure to EMFs.... Some commercial utilities have also adopted prudent avoidance or other 'low cost/no cost' policies to address the public's concerns about EMFs. Such policies are not based on scientific knowledge about health effects of exposure to EMFs."

VII.3. IRPA/INIRC: The public standards for ELF are driven by the fact that "Twenty of these [pacemaker] units reverted to an asynchronous mode

or exhibited abnormal pacing characteristics in 60-Hz fields with amplitudes ranging from 0.1 to 0.4 mT [1-4 G]." (T. Teneforde, Ann. Rev. Publ. Health 13, 173-196, (1992)). The International Non-Ionizing Radiation Committee of the International Radiation Protection Association developed the following interim guidelines in 1990 for ELF fields which are much higher than the fields from power lines:

Occupational: "Continuous occupational exposure during the working day should be limited to rms magnetic flux densities not greater than 0.5 mT (5 G). Short term occupational whole-body exposure for up to 2 h per workday should not exceed a magnetic flux of 5 mT (50 G). When restricted to the limbs, exposures up to 25 mT (250 G) can be permitted."

General Public: "Members of the general public should not be exposed on a continuous basis to unperturbed rms magnetic flux densities exceeding 0.1 mT (1 G). This restriction applies to areas in which members of the general public might reasonable be expected to spend a substation part of the day. Exposure to magnetic flux densities between 0.1 and 1.0 mT (rms, 1-10 G) should be limited to a few hours per day. When necessary, exposures to magnetic flux densities in excess of 1 mT (10 G) should be limited to a few minutes per day."

VII.4. ELF Mitigation Costs from H. Florig, co-author of prudent avoidance concept ("Containing the Costs of the EMF Problem," Science 257, 468-9, 488, 490, 492 (1992):

"... it seems likely that the total economic cost of the [ELF mitigation] activities described above now exceed $1 billion annually, with the promise of growing costs in the years to come.... If we were to value the reduction of a unit of EMF risk at comparable levels, the most that we could justify spending on EMF mitigation would be something in the neighborhood of $10 billion per year.... Given that the utilities nationwide invest about $13 billion annually in transmission and distribution construction, the cost of these exposure-reduction practices could well exceed $1 billion per year if widely adopted."

"Recent examples include a town that moved several blocks of distribution lines underground at a cost of $20,000 per exposed person; a utility that rerouted an existing line around a school at a cost of $8.6 million; a new office complex that incorporated EMF exposure in its design at a cost of $100-200 per worker; and a number of firms that have installed ferrous shielding on office walls and floors to reduce magnetic field exposures form nearby power handling equipment at costs ranging up to $400 per square meter of office space."

D. A Bromley, President Bush's Science Advisor, comments on in his book, (The President's Scientists Yale University Press, 1994) on a ELF study done in the Office of Science and Technology Policy: "It is safe, however, to conclude that the EMF risk issue will continue to be contentious and of immense potential economic importance; the current best estimate is that prior to 1993 it has cost the American public more than $23 billion to respond to public worries about EMF -- particularly in connection with the placement of high-voltage power lines."

W. Horton and S. Goldberg (Power Frequency Magnetic Fields and Public Health, CRC Press, 1995) describes the many mitigation measures available. Extra costs of about 10% are allocated for such measures.

VII.5. GAO ELF Mitigation Costs (Electromagnetic Fields, GAO/RCED-94-115), which do not consider the ELF from appliances within the home:

-- $90,000/mile for delta design above-ground transmission lines to reduce magnetic fields by 45%,
-- $2 million/mile to bury transmission lines in fluid-filled

steel pipe to reduce magnetic fields by 99%,
-- $1 billion to limit magnetic fields to 10 mG at edges of rights-of-way for planned new transmission lines,
-- $3-9 billion to reduce magnetic fields at homes where grounding systems are the dominant source,
-- $200 billion to bury transmission lines nationwide near homes with fields greater than 1mG,
-- $250 billion to reduce average exposure to less than 2 mG from all transmission and distribution lines.

VII.6. EMF Litigation: EMF Timeline is a chronology of legal and political EMF battles, such as "San Diego utility SDG&E cancels power plant upgrade and compromises on 69-kV line (May 5, 1994). Recently a law suit was filed against Houston Light and Power and EPRI on behalf of eleven families with children suffering from cancer. The suit charges both the power company and EPRI with "fraudulent concealment of the carcinogenic nature of the fields that secretly and silently invaded their homes." In San Luis Obispo, California, the city planners have used ELF criteria to resite a building.

EMF Heath Report (Vol. 1, 1993, http://infoventures. .com): The utilities "are taking costly preventive measurements to avoid law suits, mindful of the mass-tort assaults against asbestos manufactures. For example one utility, Hawaiian Electric Industries, Inc., spent nearly $5 million to reroute and reconfigure power lines.... At Montague Elementary School in Santa Clara, CA, 13 of the schools' 15 teachers have formally requested to be transferred because of the school's close proximity to power lines. In addition, 4 classrooms, a day care center, and a part of the playground located near power lines have been closed by the Mill Valley School District."

IEEE Spectrum (December 1994); "The World Bank.... is now considered to be a model in this area. The policy of prudent avoidance added about $500,000 to its construction costs.....the California Public Utility Commission required utilities to reduce the existence of EMF.... defined as 4 percent of the total cost of the budgeted project." Also, see E. Gerjuoy, Jurimetrics 35, 55-75,1994.

[DH: Litigation for ELF could be substantial, but probably not as large as the hundreds of thousands of asbestos claims that have been filed. The effects will probably be more subtle than direct litigation in that the public utility commissions, environmental impact statements, companies, city councils, and school districts will respond to the pressure to mitigate and to avoid litigation.]

VIII. Selected Bibliogrophy.

[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 materials.]

VIII.I 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

ELF/EMF Periodicals

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

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)

Newsgroups:

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

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)

II. 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 3 (1992). (I)

3. Electromagnetic Fields: Biological Interactions and Mechanisms, edited by M. Blank, Advances in Chemistry 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 Press, 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 Press, Columbus, OH, 1990). (I)

III. 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 University Press, 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 edition), edited by C. Polk and E. Postow (CRC Press, 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 Press, 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 Press, 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. Bio. 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 and Medicine 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 Univ., 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, Atlantic Monthly 274, 94-108 (November 1994). (E)

19. "Apocalyspse Not," J. Palfreman, Tech. Rev. 99, No. 3, 24-33 (April 1996).

IV. 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 Transactions on Electromagnetic Compatibility 37, No. 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, Ann. Rev. Biophys. Bioeng. 13, 85-103 (1984). (A)

30. Iron Biominerals, edited by R.B. Frankel and R.P. Blakemore (Plenum Press, NY, 1991). (A)

31. "Electron Microscopic Studies of Magnetosomes in Magnetotatic Bacteria," D.A. Bazylinski, A.J. Garratt-Reed and R.B. Frankel, Microsc. Research and Tech. 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, M. Fuller, et al., Brain Research Bulletin 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). (A)

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 mV/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. Biology 145, 489-494 (1989). (A)

43. "Acquisition of Magnetic Directional Preference in Hatchling Loggerhead Sea Turtles," K. Lohmann, J. Exp. Biology 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, 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 that cause 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 reference 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. Cytology 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 Letters 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 mT 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 Letters 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, Advances in Electromagnetic Fields in Living Systems 1, 129-153 (1994). Large magnetic fields that change very quickly cause large internal currents that may aid bone growth. (A)

H. Epidemiology.

77. "The Environment and Diseases: Association and Causation," A.B. Hill, Proc. Royal Soc. Med., Sec. Occup. Med. 58, 295-300 (1965). Criteria to base conclusions. (I)

78. Modern Epidemiology, K. J. Rothman (Little Brown, Boston, 1986). (A)

79. Fundamentals of Epidemiology (Parts I and II), (Electric Power Research Institute, Palo Alto, CA, 1993). Basic facts. (I)

80. "Epidemiology Faces its Limits," G. Taubes, Science 269, 164-169 (1995). (E)

81. "Weak Magnetic Fields: A Cancer Connection?" K. R. Foster in ref. 8. A nice discussion on epidemiology associations. (I)

82. "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)

83. Surveillance, Epidemiology, and End Results (SEER), (National Cancer Institute, Washington, DC, 1995). The cancer facts needed for analysis. (A)

I. Childhood Leukemia Studies

84. "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)

85. "Electrical Wiring Configurations and Childhood Cancer," N. Wertheimer and E. Leeper, Am. J. Epidemiology 109, 273-284 (1979). (A)

86. "Case-Control Study of Childhood Cancer and Exposure to 60-Hz Magnetic Fields", D.A. Savitz, et al., Am. J. Epidemiology 128, 21-38 (1988). (A)

87. "Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia," Am. J. Epidemiology 134, 923-937 (1991). (A)

88. "Magnetic Fields and Cancer in Children Residing Near Swedish High-Voltage Power Lines," M. Feychting and A. Ahblom, Am J. Epidemiology 138, 467-480 (1993). Letter and reply, R. Wilson and A. Shlyakhter, Am.

J. Epidemiology 141, 378-379 (1995). (A)

89. "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)

90. "Risk of Cancer in Finnish Children Living Close to Power Lines," P.K. Verkasalo, et al., Brit. Med. J. 307, 895-899 (1993). (A)

91. "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 the square of the field (ref. 26).

92. "Magnetic Field Exposure from Electric Appliances and Childhood Cancer," D.A. Savitz, E.M. John, R.C. Kleckner, Am. J. Epidemiology 131, 763-773 (1990). (A)

93. "Leukemia and Brain Tumors in Norwegian Railway Workers, A Nested Case Control Study," T. Tynes, H. Jynge, and A.I. Vistnes, Am. J. Epidemiology 137, 645-653 (1994). (A)

K. Utility Employee Studies.

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

94. "Magnetic Field Exposure in Relation to Leukemia and Brain Cancer Mortality among Electrical Utility Workers," D. Savitz and D. Loomis, Am. J. Epidemiology 141, 123-134 (1995). (A)

95. "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)

96. "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. Epidemiology 139, 550-572 (1994) and 140, 805-820 (1994). (A)

97. "Magnetic Field Exposure Among Utility Workers," T. D. Bracken, et al., Bioelectromagnetics 16, 216-226 (1995). (A)

98. "Utility Workers and EMF Health Risks," T. Moore, EPRI Journal 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.

99. "Containing the Costs of the EMF Problem," H.K. Florig, Science 257, 468-9, 488, 490, 492 (1992). Present costs of $1 billion/year. (E)

100. 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)

101. "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 Physics 58, 113-122 (1990). Approved in 1993. (E)

102. 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-Bl-E53, 1989). (I)

103. "60 Hz Electromagnetic Fields: Problems in Risk Assessment and Policy Response," G. Morgan, Phys. and Society 19, 10 (Oct. 1990), and "Prudent Avoidance," Public Utility Fortnightly, March 15, 1992. (E)

104. "The Imprudence of Prudent Avoidance," D. Hafemeister, Phys. and Society 24, No. 3, 9-11 (July 1995). (E)

105. "Electromagnetic Fields: Physics, Biology and Law," E. Gerjuoy, Jurimetrics 35, 55-75 (1994). (E)

106. "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 reduced health risks.

107. Of Acceptable Risk: Science and the Determination of Safety, W.W. Lowrance (Kaufmann, Kaufmann, CA, 1976). (E)

108. "Perception in Risk," P. Slovic, Science 236, 280-285 (1987). (I)

109. "Risk Analysis and Management," M.G. Morgan, Sci. Am. 269, 32-42 (July 1993). (E)

110. "Societal Risk versus Technological Risk," C. Starr, Science 165, 1232-1238 (1969). (E)

111. "Energy Hazards: What to Measure, What to Compare," J.P. Holdren, Tech. Rev. 85, 33-38, 74-75 (April 1982). (E)