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Quantitative Risk Assessment: Low Frequency Electromagnetic Fields As an Example

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Abstract. It is difficult to think of a worse example with which to illustrate the state of the art of quantitative risk assessment than the possible risks posed by power frequency electric and magnetic fields. Nothing seems to work. We don't know how to measure dose. We don't know whether "more is worse," let alone the shape of any effects functions. The limits that one can set with bounding analysis are too broad to be of much use. Yet despite all these problems, the science is far better than that available for such widely regulated risks as sulfur air pollution. This paper briefly reviews the subject and summarizes some of the problems and lessons.

Key words and phrases: 60 Hz fields, powerlines, risk assessment, policy analysis.

THE CONVENTIONAL RISK ANALYSIS PARADIGM

In doing risk analysis of some known or suspected hazard such as an environmental pollutant or a toxic chemical there are now a fairly well established set of tasks that must be performed (Morgan, 1981). First one builds models that will provide an estimate of the concentrations of the pollutant to which people or other animate or inanimate objects in the human or natural environment are exposed. Then one builds models that provide an estimate of the health and other effects which will result from this exposure. In building such models there is often uncertainty about both the functional form of the models and the value of specific coefficients within those models. Practitioners have devised a variety of techniques for dealing with both these situations. Uncertainty about model form is often treated by solving the problem parametrically in model form (Morris, Fischer, Moskowitz, Rybicha and Thode; 1984; Morgan, Nair, Florig and Hester, 1984) in order to determine the extent to which alternative models affect the conclusions which are reached. Uncertainty in the value of coefficients is often handled by asking experts to provide subjective judgments of parameter values in the form of probability density functions (Boyd and Regulinksi, 1979; Stael von Holstein and Matheson, 1979; Morgan, Morris, Henrion and Amaral, 1984; Morgan, 1981; Mullin, 1986).

Although one may not know the functional form of the effects function or its associated coefficients with precision, one thing that can almost always be safely assumed is that if exposure to the substance in question is bad at concentration C, then exposure to a concentration of 2C is as bad or worse . . . that is one can assume that "more is worse." Similarly, one can fairly safely assume that any measure that is proportional to the concentration of material to which people and objects are exposed will be at least a crude approximation of dose and will be directly related to effect because "more is worse."

The simplifying utility of the "more is worse" assumption is not apparent until one tries to perform risk analysis in a situation in which more may not be worse. For the past several years my colleagues Indira Nair, Keith Florig and I have been working on such a problem that has involved assessment of the possible risks of human exposure to power frequency electric and magnetic fields. As I will show, this is a problem in which the simple "more is worse" assumption is not justified and in which the science remains quite incomplete. The challenge to risk assessment and policy analysis is to try to say something useful about this problem while we wait for good scientific understanding.

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POWER FREQUENCY ELECTRIC AND MAGNETIC FIELDS

A Case When More May Not Be Worse

Contemporary interest in the possible biologic effects of exposure to low frequency electromagnetic fields has grown out of several strands of activity. First there are the long standing research activities of a group of neurophysiologists interested in the electrochemical processes of the nervous system. Second, interest in the specific issue of power frequency fields was stimulated by a series of reports from the Soviet Union in the 1960s of nonspecific complaints by workers in new 400–500 kV switchyards. Finally, environmentalists' concerns about proposals by the United States Navy to install a large low frequency underground antenna in the midwest to transmit messages to strategic submarines at sea stimulated a series of health and environmental studies.

By the early 1970s concern about possible adverse health effects from transmission line fields had grown to the point that it was impossible to site a new transmission facility in the United States without a protracted debate about possible field effects. Programs of research specifically on power frequency fields were mounted by both the Electric Power Research Institute and by the United States Department of Energy. Smaller programs have been supported by others including the State of New York and several utilities including Southern California Edison and Bonneville Power.

By its nature, experimental research on this topic requires a mixture of biology, physics and electrical engineering. Given the difficulties inherent in interdisciplinary work, it is not surprising that many early papers suffer from problems of quality control. However, since the late 1970s the volume of high quality research has grown rapidly. Today there is a large, and very solid experimental literature.

It is not feasible to summarize this literature here. Several very good reviews are available (Adey, 1981; Anderson and Phillips, 1982; Sheppard, 1983; Graves, Bracken, Griffin, de Lorge, Morgan and Tenforde, 1985; West Associates, 1986). Instead I will highlight a few of what I think are the most salient points:

1. Strong electric fields can produce effects through spark discharge, tactile stimulation and similar mechanisms. These mechanisms have been the focus of considerable study but in my opinion can be easily controlled and are of no great public health consequence.
2. Power frequency electric and magnetic fields that are too weak to produce effects of the sort discussed above, can interact directly with selected neural and other tissue to produce biologic effects. These interactions are subtle and are observed only under special experimental conditions in a few systems. They have been found only after careful looking, and after many null results.
3. There is a growing number of epidemiologic studies that purport to show an association between field exposure and cancer promotion. There are also studies that can be read as suggesting an association with developmental abnormalities. All of these studies suffer from serious difficulties. In my view there is not persuasive evidence that exposure to power frequency fields can result in serious public health consequences. At the same time I believe that current understanding precludes ones saying that there are not serious public health consequences arising from chronic exposure to power frequency fields.

The mechanisms by which power frequency fields interact with biologic systems are not yet clear but probably involve one or several kinds of nonlinear effects that occur at or near the cell membrane surface and may involve the complex structures that are associated with that surface. Because the details of these mechanisms are not understood, it is not apparent how to define "dose" in this context. The experimentally observed dependence of effects on parameters such as field strength, frequency and time of exposure to field varies markedly and includes experiments in which:

- The effect appears at some field strengths and frequencies but not at other higher and lower field strengths and frequencies. That is, the effects display reasonance or amplitude and frequency "windowing." In at least some cases, the location of these windows depends on the magnitude and orientation of the earth's natural d.c. magnetic field (Blackman, Benane, House and Jones, 1985).
- The effect appears only after exposure for an extended period of time, such as several weeks (Wilson, Anderson, Hilton and Phillips, 1981; Wilson, Anderson, Hilton and Phillips, 1983).
- The effect appears only for a short period, such as tens of minutes, after exposure begins. After this, the system apparently adapts in some way and the observed effect disappears (Byus, Lundak, Fletcher and Adey, 1984).
- The effect appears only when field strength exceeds some threshold value, and once this threshold has been exceeded the magnitude of the effect does not depend upon the field strength (Liboff, 1984).

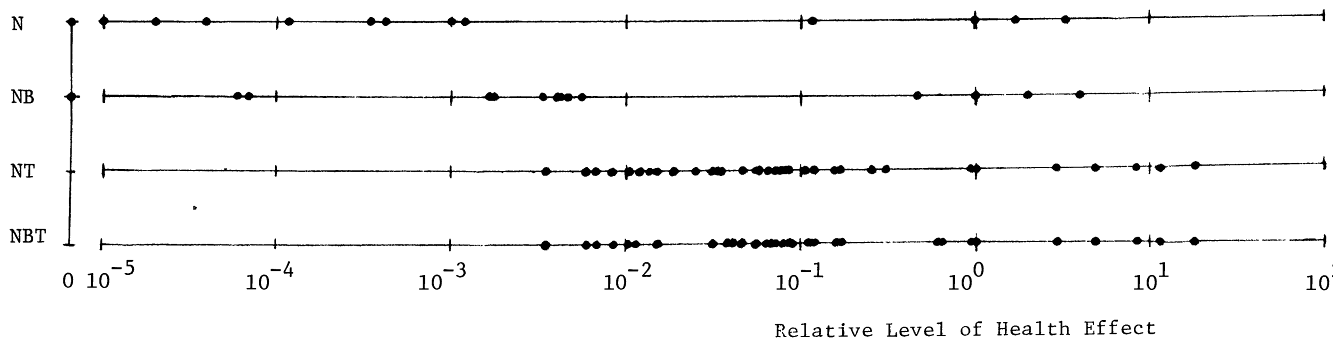

FIG. 1. *When a number of hypothetical exposure scenarios (labeled* N, NB, NT and NBT) *were modeled, and a dozen plausible (though arbitrary) alternative health effects function were applied, the resulting estimated range of health impacts spanned over seven orders of magnitude (from Morgan, Lincoln, Nair and Florig,* 1983). *The details are unimportant. The important insight is that parameterized approaches to risk assessment are unlikely to be useful until improved science understanding will allow a significant narrowing of the alternative possibilities.*

Although each of these results are for a different experimental setup and biologic system, together they suggest that an assumption that "more is worse" should not be made.

There are several other ways in which 50–60-Hz fields are different from other more familiar environmental agents. Unlike ionizing radiation such as x-rays or the radiations associated with the atom or the nucleus, power frequency fields do not carry enough energy to initiate biologic effects by breaking up atomic or molecular bonds. Also, unlike effects from very intense microwaves, power frequency fields do not produce effects by heating body tissue. Finally, unlike chemical agents, power frequency fields do not introduce substances from outside the body, although they may affect rates of action and metabolism of various biochemicals in the body. These facts mean that one must be very careful not to extrapolate "insights" gained in doing risk analysis and risk management on these other kinds of agents such as ionizing radiation to the area of power frequency fields.

Attempting to Do Risk Analysis on Power Frequency Fields

Although my colleagues and I have made serious efforts, we have been largely unsuccessful in our attempts to perform a conventional risk assessment of the possible health risks presented by human exposure to power frequency electric and magnetic fields. One of the first things we did when we began to work on this problem was to perform a thought experiment in which we took several simple hypothetical exposure situations and several measures of dose and effects functions which we believed were at least consistent with the evidence available in the literature. As Figure 1 indicates, the results ranged over more than 6 orders of magnitude.

For several specific health end points we attempted to build families of alternative models (Morgan,

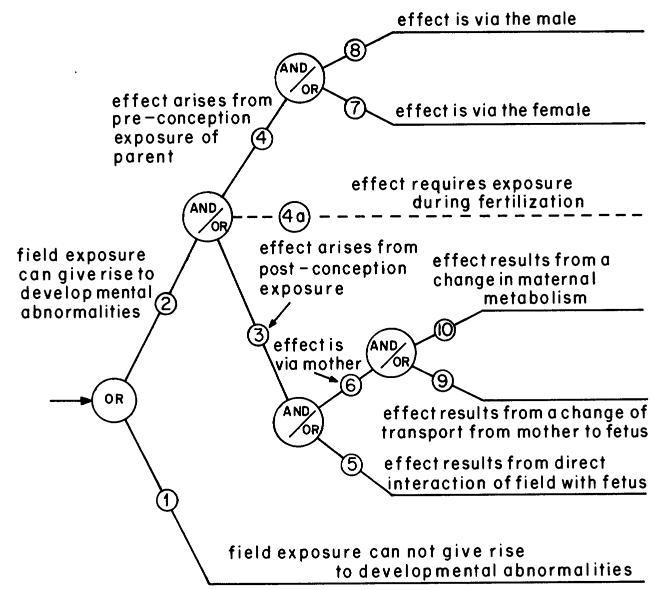

FIG. 2. *Alternative pathways by which exposure to* 50–60-*Hz electric and magnetic fields might lead to developmental abnormalities (from Morgan, Florig, Nair and Lincoln,* 1987).

Florig, Nair and Lincoln, 1987). For example, Figure 2 indicates a number of the alternative mechanisms which could give rise to the end point of developmental abnormalities. Figure 3 summarizes what we believed (as of 1984) the literature had to say about the likelihood that each of these mechanisms might actually be operating. Figure 4 provides a highly simplified outline of some of the functional forms that a health effects function for this end point might assume. If we are prepared to make a number of fairly heroic assumptions, then for each path through the tree in Figure 4 we could parameterize the variables involved and attempt to perform an assessment. We did this for a few simple cases (Morgan, Florig, Nair and Lincoln, 1987). The problem is that we rapidly suffer an increase in the number of parameters needed. Thus, while we can

STUDY	PATH												
	1	2	4	7	8	2	3	6	9	10	2	3	5
Direct Animal Studies with Electric Fields:													
Chickens													
Graves et al. (1983) [24]	Ī	Ī	N	N	N	Ī	Ī	N	N	N	Ī	Ī	**-**
Rodents													
Sikov et al. (1979, 1984) [52, 54]	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Smith et al. (1981)	**+**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
Fam (1980) [20]	+	-	-	-	-	-	-	-	-	-	-	-	-
Cerretelli (1979) [8]	Ī	Ī	Ī	-	N	Ī	N	N	N	N	Ī	N	N
Marino (1976, 1980) [69, 34]	-	+	C	C	C	+	C	C	C	C	+	C	C
Pigs													
Battelle Pig Studies [45]	**-**	**+**	C	C	N	**+**	C	C	C	C	**+**	C	C
Mahmoud & Zimmerman (1984) [68]	+	-	-	-	N	-	-	-	-	-	-	-	-
Cows													
Hennichs (1982) [26]	Ī	Ī	-	N	-	Ī	-	-	-	-	Ī	-	-
Direct Animal Studies with Magnetic Fields:													
Drosophila													
Ramirez et al. (1983) [46]	-	+	C	C	C	+	C	N	N	N	+	C	C
Chickens													
*Delgado et al. (1982) Ubeda et al. (1983) [10]	**-**	**+**	N	N	N	**+**	**+**	N	N	N	**+**	**+**	**+**
*Maffeo et al. (1984) [32]	Ī	Ī	N	N	N	Ī	Ī	N	N	N	Ī	Ī	-
*Tell et al. (1984) [70]	Ī	Ī	N	N	N	Ī	Ī	N	N	N	Ī	Ī	-
*Mild et al. (1984) [36]	-	+	N	N	N	+	+	N	N	N	+	+	+
Direct Animal Studies with Electric & Magnetic Fields:													
Durfee et al. (1976) [16]	Ī	Ī	N	N	N	Ī	N	N	N	N	Ī	-	-
Krueger et al. (1975) [71]	Ī	Ī	-	-	-	Ī	N	N	N	N	Ī	N	N
Direct Human Studies with Electric & Magnetic Fields:													
Kouwenhoven et al. (1973) [31]	Ī	Ī	Ī	N	Ī	Ī	N	N	N	N	Ī	N	N
Knave et al. (1979) [30]	C	Ī	Ī	N	-	Ī	N	N	N	N	Ī	N	N
Nordstrom et al. (1983) [43]	-	+	+	N	+	+	N	N	N	N	+	N	N
Wertheimer et al. (1984) [63]	-	+	C	C	C	+	C	C	C	C	+	C	C

*Note: These studies involve pulsed magnetic fields (~30 μsec rise time) and do not see an effect for 60Hz sinusoidal fields. They are thus not relevant to exposure from transmission and distribution line fields but may be relevant to occupational and residential exposures.

FIG. 3. *Subjective evaluation performed by the author and his colleagues in* 1984 *of the evidence available to support or argue against the existence of the various links in the diagram in Figure* 2. *The kinds of evidence are classified into the following simple categories*: N = *no information relevant to the branch in question*; C = *evidence is consistent with the existence of the branch*; Ī = *evidence is not inconsistent with the branch*; + = *evidence argues for the existence of the branch*; − = *evidence argues against the existence of the branch. We use a very bold* + *and* − *to indicate definitive evidence (in our view at the moment there is none), a bold* + *or* − *for evidence which argues for or against the existence of a branch and a weak* + *or* − *for evidence which argues for or against the existence of a branch but which in our view is at best marginally persuasive because of problems in experimental power, design and/or execution* (*from Morgan, Florig, Nair and Lincoln*, 1987).

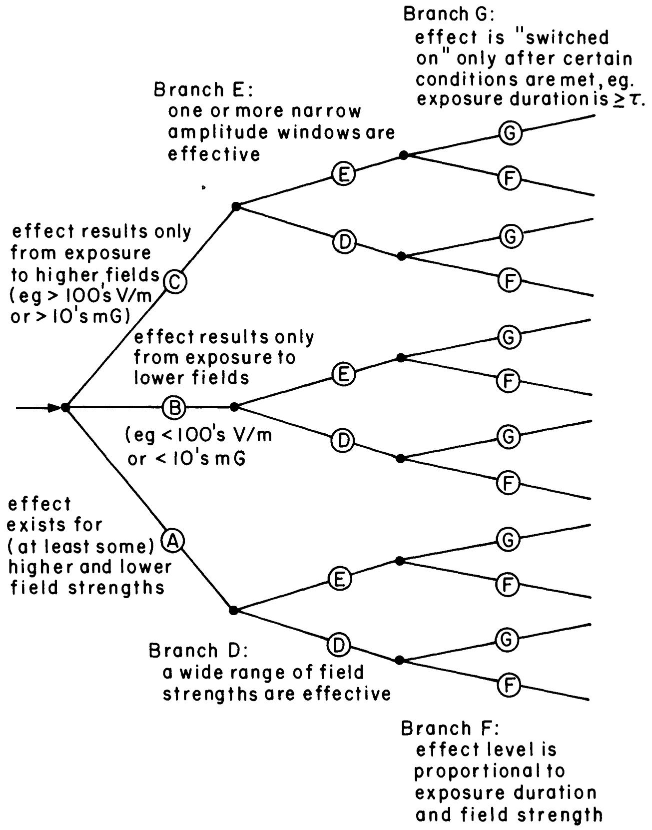

FIG. 4. *Simplified diagram of factors that could be important in selecting an appropriate exposure metric or determining the form of the effects function (from Morgan, Florig, Nair and Lincoln,* 1987).

perform the analysis, we would end up producing an enormous number of parameterized plots for all of the possible functional forms which might obtain. We concluded that such results would be of no use to anyone.

Next we tried to perform a bounding analysis . . . to answer, for the case of cancer and developmental abnormalities, the question "if exposure to power frequency fields can give rise to such-and-such, what is the upper bound on how large the effect could be?" Again the results turn out not to be very useful. The precision with which we can presently attribute the sources of cancer and developmental abnormalities is such that, especially in the case of the latter, the bounds that one can set are too large to be of much practical use in risk management decision making.

Should Risk Analysts Perform Every Calculation They Know How to Do?

There is one calculation which we know how to do but have not performed. If we take the increases in cancer incidence rates reported in the various epidemiologic and occupational proportional mortality cancer studies; if we assume that any effect observed results only from magnetic field exposure, and if we make a set of crude estimates of the average magnetic field strengths which correspond to each study, then we can produce a swarm of points in an effect level versus fields strength space to which we could fit some individual or family of effects functions. These in turn could be used along with total population estimates of exposure to power frequency magnetic fields to produce an overall estimate of cancer incidence.

We have not performed such an analysis, even in the privacy of our own office. To do so would require a "more is worse" assumption which we do not believe can be justified. It is not clear to us that the effect estimate number that would be obtained from such a calculation would have any meaning or be of any use. At the same time, our intuition and our knowledge of the problem suggest to us that such a calculation would yield a large number . . . a number which despite all caveats would almost surely take on a life of its own in the subsequent policy debate. Given the observation of Kahneman and Tversky (1973) that "people respond differently when given no specific evidence and when given worthless evidence," we've resisted performing this calculation.

Providing Policy Guidance When the Science Is Unable to Support a Policy Choice

While we have been unable to perform an effective risk analysis of the possible risks posed by human exposure to power frequency electric and magnetic fields, our work has not left us completely without useful things to say to regulators and other decision makers faced with growing public pressures to take action in this area. Specifically we have:

- Argued, that at least given present knowledge, this potential problem should be framed and thought about broadly as a problem of exposure to all sources of power frequency fields in the human environment (appliance, wiring, distribution line, transmission lines, etc.) and not just as a problem of extra high voltage transmission lines and cautioned vigorously against extrapolating "more is worse" based ideas from other areas of risk management to this field too rapidly (Graves, Bracken, Griffin, deLorge, Morgan and Tenforde, 1985; Morgan, Lincoln, Nair and Florig, 1983).
- Provided decision makers with a careful structuring of the problem so that they can develop a better understanding of what the science can and cannot tell them, what judgments they must make and what the implications of some of those judgments are (Morgan, Nair, Florig and Hester, 1987).
- Argued that much of the public concern about exposure from transmission lines may arise

from equity considerations, that is from an argument that says "sure we're all exposed to fields and we don't know whether exposure to fields possesses any dangers . . . but by siting a transmission line near me you're asking me to undergo an exposure that's quite different from that which the rest of the population receives." This has led us to investigate the feasibility of a "similarity" based approach to field control which would at least address the equity issue, although in the absence of better scientific understanding, it would do nothing to address the issue of actual risk (Florig, 1986).

- Developed a siting fee-based approach to transmission line regulation which should allow one to "exercise prudence" without making unjustifiably large investments in "exposure control" which may subsequently be found not to have made things better (Morgan, Florig, Nair and Hester, 1988).

Thus, while limits in our knowledge have thus far precluded a successful risk analysis of this problem, they have not prevented the development of a variety of policy insights and guidance.

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REFERENCES

ADEY, W. R. (1981). Tissue interactions with nonionizing electromagnetic fields. *Physiol. Rev.* **61** 435–514.

ANDERSON, L. E. and PHILLIPS, R. D. (1982). *Biological Effects and Dosimetry of Nonionizing Radiation: Static and ELF Electromagnetic Fields.* Plenum, New York.

BLACKMAN, C. F., BENANE, S. G., HOUSE, D. E. and JONES, W. T. (1985). Effects of ELF (1–120 Hz) and modulated (50 Hz) RF fields on the efflux of calcium ions from brain tissue in vitro. *Bioelectromagnetics* **6** 1–11.

BOYD, D. W. and REGULINSKI, S. G. (1979). Characterizing uncertainty in technology cost and performance. Decision Focus, Inc. Report III4. Los Altos, Calif.

BYUS, C. V., LUNDAK, R. L., FLETCHER, R. M. and ADEY, W. R. (1984). Alterations in protein kinase activity following exposure of cultured lymphocyte to modulated microwave fields. *Bioelectromagnetics* **5** 341–351.

FLORIG, H. K. (1986). Human exposure to power-frequency fields. Ph.D. thesis, Dept. Engineering and Public Policy, Carnegie Mellon Univ.

GRAVES, H. B., BRACKEN, T. D., GRIFFIN, J., DE LORGE, J., MORGAN, M. G. and TENFORDE, T. S. (1985). Biological effects of 60 Hz power transmission lines. Report of the Florida Electric and Magnetic Fields Science Advisory Commission, Florida Department of Environmental Regulation, Tallahassee, Fla.

KAHNEMAN, D. and TVERSKY, A. (1973). On the psychology of prediction. *Psychol. Rev.* **80** 237–251.

LIBOFF, A. (1984). Time-varying magnetic fields: Effect on DNA synthesis. *Science* **223** 818–820.

MORGAN, M. G. (1981). Probing the question of technologically induced risk. *IEEE Spectrum* **18** 58–64.

MORGAN, M. G., FLORIG, H. K., NAIR, I. and HESTER, G. L. (1988). Controlling exposure to transmission line electromagnetic fields: A regulatory approach that is compatible with the available science. *Public Utilities Fortnightly* **121** March 17, 49–58.

MORGAN, M. G., FLORIG, H. K., NAIR, I. and LINCOLN, D. R. (1987). Some first steps toward assessing possible health risks from exposure to 50/60 Hz electromagnetic fields. In *Interaction of Biological Systems with Static and ELF Electric and Magnetic Fields* (L. E. Anderson, B. J. Kelman and R. J. Weigel, eds.). Proc. of the 23rd Hanford Life Sciences Symposium, Battelle Pacific Northwest Laboratories, Richland, Wash., CONF-84.

MORGAN, M. G., LINCOLN, D. R., NAIR, I. and FLORIG, H. K. (1983). An exploration of risk assessment needs and opportunities for possible health consequences from 50/60 Hz electromagnetic fields. EPP/CMU working paper.

MORGAN, M. G., MORRIS, S. C., HENRION, M. and AMARAL, D. A. L. (1984). Technical uncertainty in quantitative policy analysis: A sulfur air pollution example. *Risk Anal.* **5** 195–208.

MORGAN, M. G., NAIR, I., FLORIG, H. K. and HESTER, G. (1987). Power-frequency electromagnetic fields: The regulatory dilemma. *Issues Sci. Tech.* Summer 81–91.

MORRIS, S. C., FISCHER, H., MOSKOWITZ, P. D., RYBICHA, K. and THODE, H. C., JR. (1984). Risk assessment: Cancer. *Mech. Eng.* **106** 40–45.

MULLIN, T. (1986). Understanding and supporting the process of probabilistic estimation. Ph.D. thesis, School Urban and Public Affairs, Carnegie Mellon Univ.

SHEPPARD, A. R. (1983). Biological effects of high voltage transmission lines, with reference to Report to Montana Department of Natural Resources and Conservation, Energy Division, Helena, Mont.

STAEL VON HOLSTEIN, C.-A. S. and MATHESON, J. E. (1979). *A Manual for Encoding Probability Distributions.* SRI International, Menlo Park, Calif.

WEST ASSOCIATES (1986). A critical review of the scientific literature on low frequency electric and magnetic fields: Assessment of possible effects on human health and recommendations for research. A report to Southern California Edison, Inc.

WILSON, B. W., ANDERSON, L. E., HILTON, D. I. and PHILLIPS, R. D. (1981). Chronic exposure to 60-Hz electric fields: Effects on pineal function in the rat. *Bioelectromagnetics* **2** 371–380.

WILSON, B. W., ANDERSON, L. E., HILTON, D. I. and PHILLIPS, R. D. (1983). Erratum: Chronic exposure to 60-Hz electric fields: Effects on the pineal function in the rat. *Bioelectromagnetics* **4** 293.