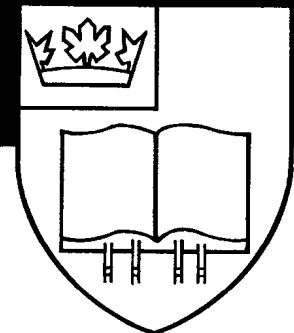


Report of the Panel Monitoring Ontario Hydro's Electromagnetic Field Risk Assessment Program

A Panel Report
prepared at the request of
The Royal Society of Canada
for
Ontario Hydro



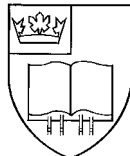
"studiis eodem diversis nitimur"
"different paths, one vision"

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Summary

The studies undertaken by Ontario Hydro to assess any possible risk of cancer from electromagnetic fields have added to the knowledge of the generation of 60 Hz electromagnetic fields in the human environment, and to their effects on cells, on small animals in the laboratory, on populations of workers in electrical industries, and on children. In general the results of these investigations support the comments and conclusions of the Working Group that was commissioned by the National Institute of Environmental Health Sciences in the U.S.(1998) to review this field. That is, they add to the plausibility and support the conclusion that electromagnetic fields are possibly carcinogenic to humans, although any risk is small. In addition, the research provides some rationale for the exposure guidelines such as those adopted by the International Committee for Non-Ionizing Radiation Protection. The Royal Society Panel monitoring the Electromagnetic Fields Risk Assessment Program of Ontario Hydro supports the conclusions of the NIEHS and suggests that it would be prudent to avoid long exposure to high fields as defined in the exposure guidelines of the International Committee for Non Ionizing Radiation Protection.

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1. Introduction

1.1 The use of electric power in the last half century has increased 20-fold in our houses and industries. Electric and magnetic fields always accompany the generation, distribution and use of electric power. We all live and work in this environment. The benefits of electric power to our well being have long been obvious and adverse effects have not been evident or of concern. Indeed as Fig.1 shows, there have not been any large effects in the particular case of cancer deaths in the United States [1].

1.2 Thus in 1979, when a report appeared linking childhood cancer with proximity of electric power lines, there was widespread concern and research was initiated to verify and understand this effect. In common with other utilities, Ontario Hydro started an extensive program, Electromagnetic Field Risk Assessment Program (EMFRAP), by contracting out many research projects and by performing some within its own organization. (We have retained the usage "Ontario Hydro" rather than name the most recently reorganized corporation because almost all of the work has been conducted under the Ontario Hydro label.) As the Program started, the Royal Society was asked to provide a Panel of scientists to monitor the research and to comment on the significance of the results. In 1988, the President of the Royal Society appointed W. Robert Bruce Chm., Carol Buck, F. Kenneth Hare, Harry S. Shannon, and Alec T. Stewart to the Panel. Appendices to the Report list the Meetings of the Panel, give brief backgrounds of the Members and record the contract - labeled "purchase order" - for the work of the Panel.

1.3 Twenty years and much research after the first report suggesting a relationship between health and electromagnetic fields, there is still considerable debate about the health effects of these fields and even the existence of health effects. One conclusion is clear: any effects that may exist are difficult to measure, probably because they are small - how small to be discussed later. This conclusion was reflected in a recent review by a Working Group of the National Institute of Environmental Health Sciences of the National Institutes of Health in the United States that has provided the most complete review of the subject [2]. They were unable to reach a conclusion that could be

agreed to by all scientists of the Working Group, but decided by a 19/29 majority that power line frequency Electromagnetic Fields *are possibly carcinogenic to humans* [2]. The other members of the Working Group (10/29) had reservations about this conclusion, many feeling that the evidence was insufficient.*

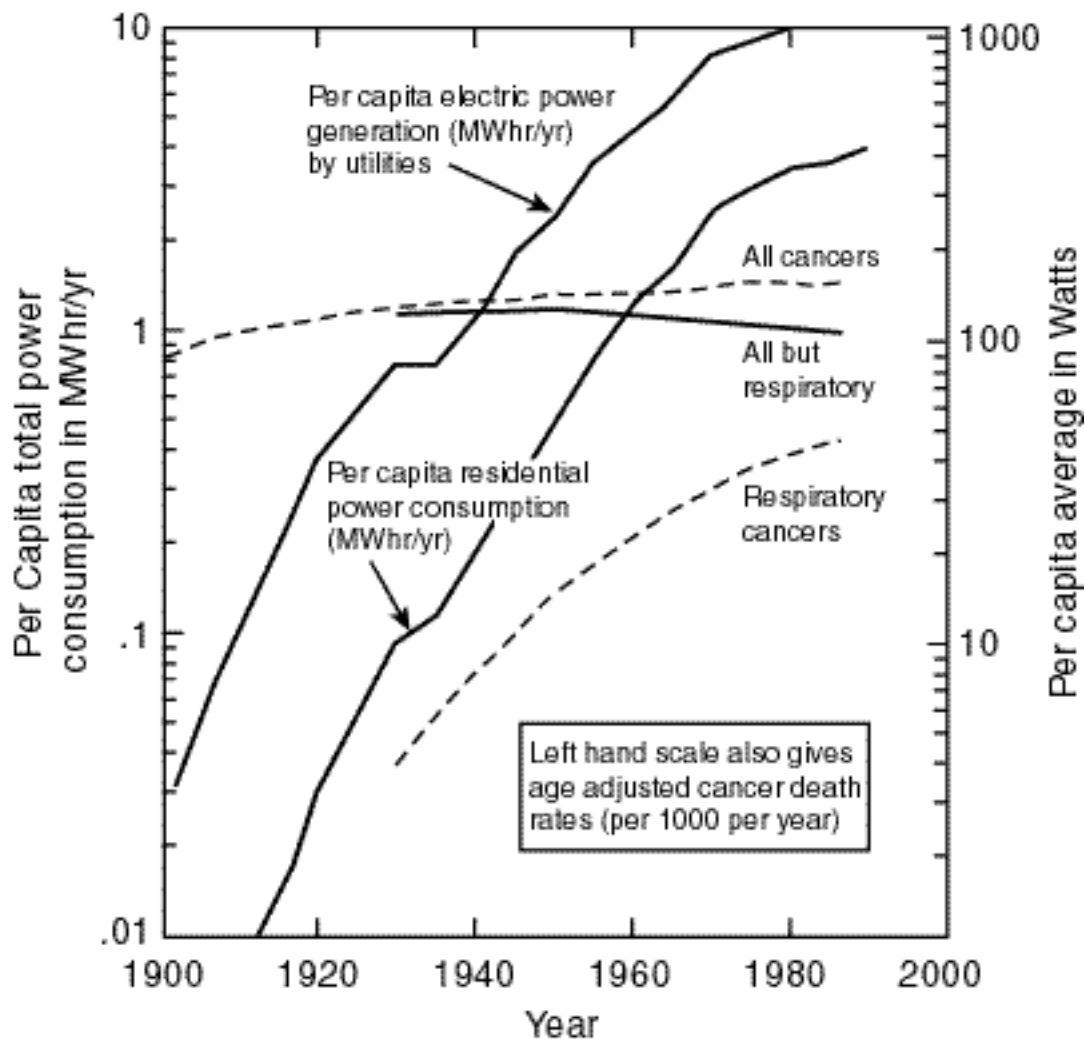


Figure 1

Figure 1: The variation in time of electrical power use and deaths from cancer [1].

* In this Report direct quotations are in italics and indented if longer than one line.

1.4 This Royal Society Report will outline the research sponsored by Ontario Hydro and place it in context with similar research done around the world. The next five Sections of the Report give an account of the results of each of the five projects contracted by Ontario Hydro and a short discussion placing these in the context of other similar research projects elsewhere and of more recently published results. These projects are:

---FIRST---Discussed in **Section 2**, Examination of the origin of electric and magnetic fields in our environment, the current guidelines for maximum electric and magnetic field exposure, and possibilities of mitigation of these fields if necessary. Studies in this field supported by Ontario Hydro are cited in references [4,5,7,8,9,15,16,17]. The Panel was not involved in the design or interpretation of these experiments and the resultant publications, but reviews them here because they add substantially to understanding this aspect of EM fields.

---SECOND---Discussed in **Section 3**. Experiments with cells exposed to fields in vitro for morphologic, genetic or molecular biologic changes. The study supported by Ontario Hydro is cited in reference [18]. The Panel reviewed and made comments on the design of this experiment.

---THIRD---Discussed in **Section 4**. Study of small animals exposed to magnetic fields for evidence of increased cancer. The studies supported by Ontario Hydro are cited in references [24,25,26]. The Panel reviewed the design and assessed the conduct of work reported in [26].

---FOURTH---Discussed in **Section 5**. Analytic epidemiological studies of the health of workers in electric utilities. The studies supported by Ontario Hydro are cited in references [30,31,34,38,39,40]. The Panel reviewed and made numerous comments on the design and reporting of these studies.

---FIFTH---Discussed in **Section 6**. Analytic epidemiological study of pediatric leukemia and other outcomes for children exposed to household fields. The studies supported by Ontario Hydro are cited in references [41,42]. The Panel reviewed and made numerous comments on the design and reporting of these studies.

. Although most research has been concerned with cancer, a few other effects of fields are also mentioned in **Appendix 1**. **Section 7** discusses some of the difficulties and uncertainties of the subject, mostly due to lack of knowledge of any interaction mechanism between these fields and biological systems, but makes no formal approach to risk assessment. **Sections 8** of the Report concludes with the comments of the Panel on the present state of understanding and notes the contribution to this understanding made by Ontario Hydro. **Section 9** outlines a recommendation. **Appendix 2** places the conclusions in the context of present Regulations, and **Appendix 3** contains brief biographies of the members of the Panel.

Note: Dr. Carol Buck and Dr. F. Kenneth Hare participated fully in the study but due to unfortunate circumstances were unable to read the final report.

2. Fields and Measurements

2.1 Electromagnetic Fields (EMF): The generation, distribution and use of electric power is always accompanied by electric and magnetic fields that are invisible and usually undetectable to humans. If an electric field is strong enough it may stand our hair on end or cause lightning strikes. The attraction of hand tools to an electric motor is an indication of magnetic fields. The fields that are produced by various common sources are illustrated in Fig.2. and the diminution of those fields with distance in Fig.3. [3] For comparison, these Figures show the electric field needed to make a spark in air and also the electric fields on the surface of the earth in normal conditions and in thunderstorms. Magnetic fields are less familiar but again, for comparison, the steady magnetic field of the earth is shown.

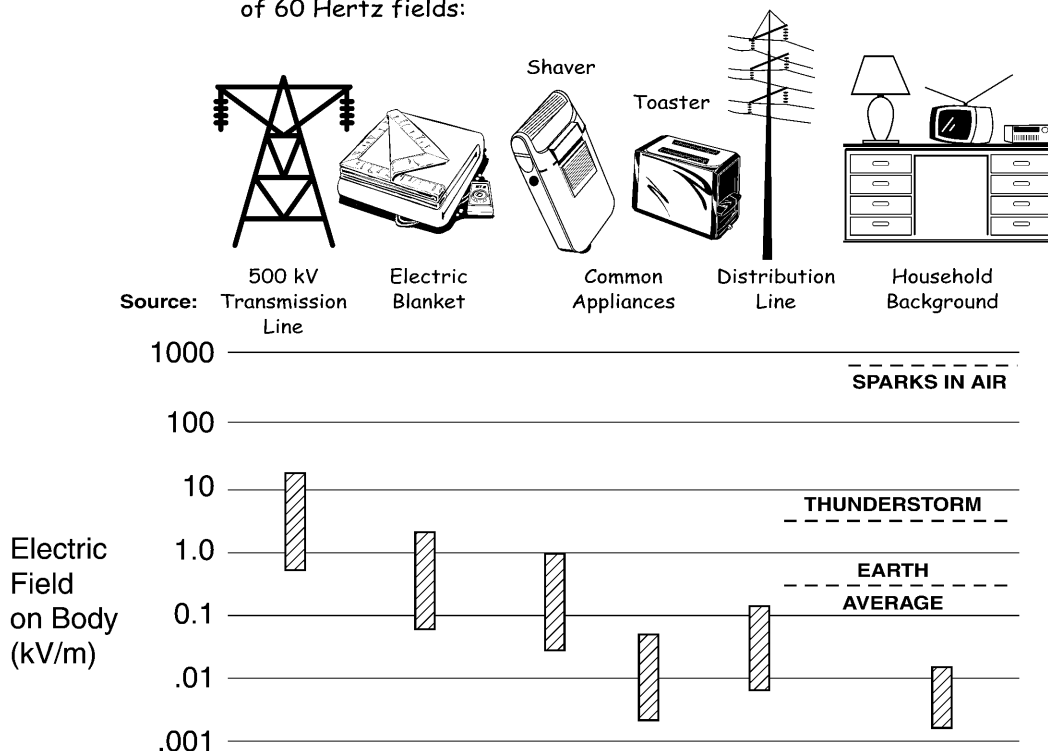
Most power lines in the world use alternating current; that is, the voltage and current reverse direction many times a second. In North America the complete cycle is repeated 60 times a second, written 60 Hertz (Hz), while in Europe the frequency is usually 50 Hz.

An electric field is the change in electric potential with distance and is measured in Volts per meter, written V/m. Small fields are written as milliVolts/meter (mV/m), ($1\text{mV}=10^{-3}\text{V/m}$), and large electric fields as kiloVolts/meter ($\text{kV/m} = 10^3\text{V/m}$). Similarly electric current is measured in Amperes, symbol A, and small currents in milliAmperes, symbol mA.

Magnetic fields have two units in use, Gauss and Tesla. For simplicity we have used only Tesla, throughout the Report and references to Gauss have been converted to Tesla, usually in units of a millionths of a Tesla, written, microT. The ratio is: 1 Tesla equals 10,000 Gauss. Hence $1\text{ T} = 10^4\text{ G}$. The static magnetic field of the earth is about 60 microT.

2.2 At these frequencies electric and magnetic fields may be considered independently and have quite different effects on living tissue. Electric fields cause a continuous current of electrical charges to flow in a conductor. In an insulator, where charges cannot flow, the electric field merely pulls positive and negative charges slightly

Approximate strength of the average electric field at the surface of the body produced by several common sources of 60 Hertz fields:



Approximate strength of the average magnetic field produced within the body by several common sources of 60 Hertz fields:

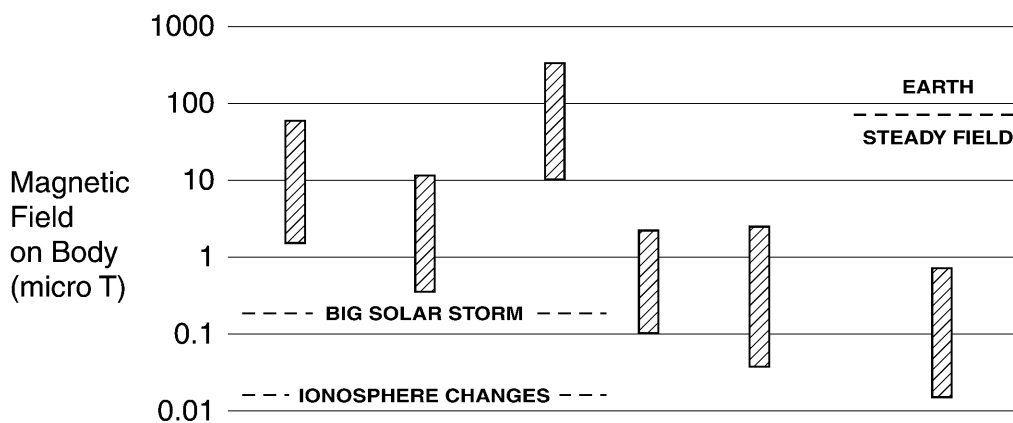


Figure 2: Strength of electric and magnetic fields produced by several common sources of 60 Hz fields [3].

The strength of the electric or magnetic field at different distances from power lines and appliances lies somewhere in these shaded regions

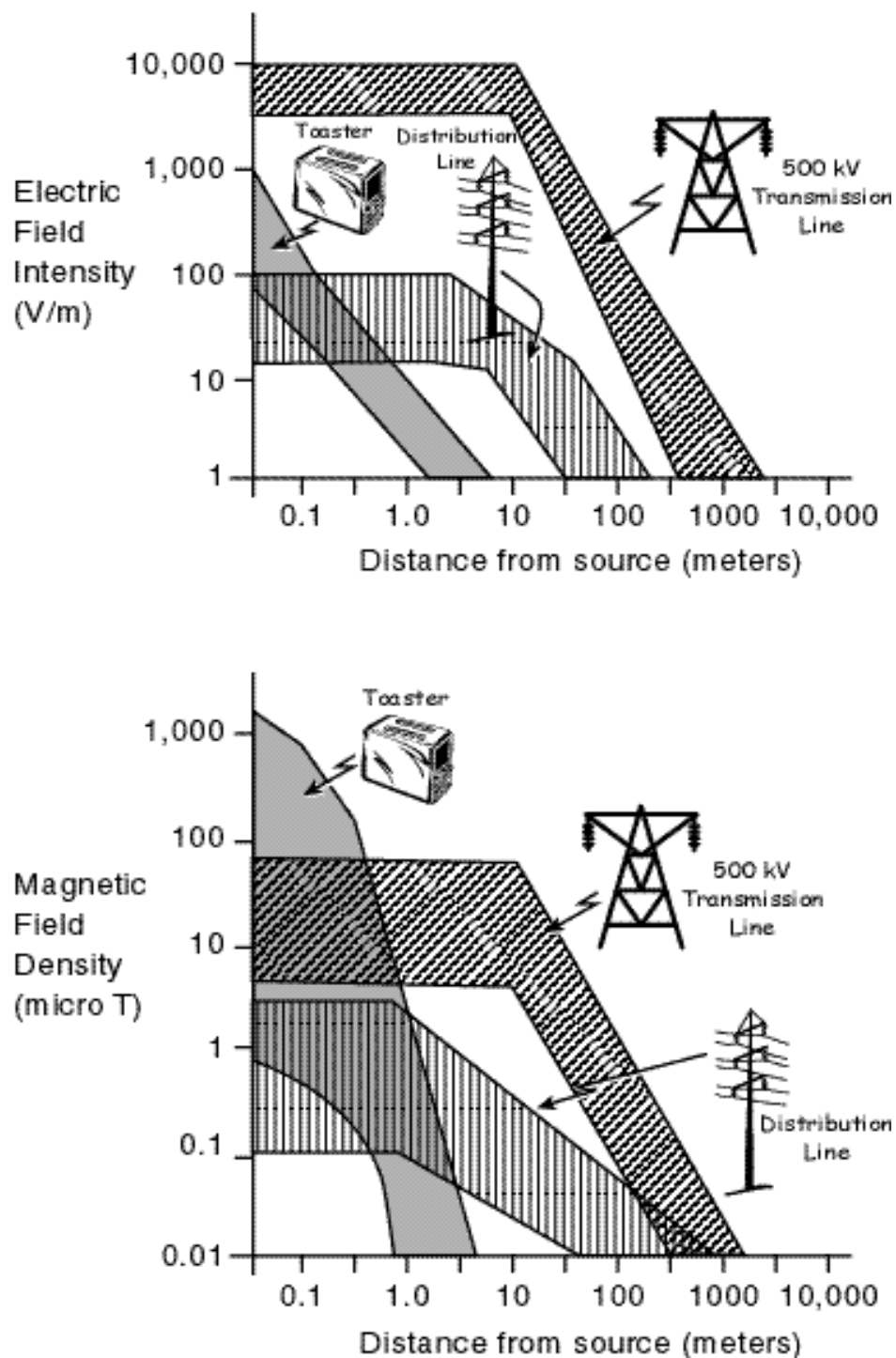


Figure 3: Strength of electric and magnetic fields at various distances [3].

apart, which "polarizes" the material to reduce the field, resulting in little penetration of the field. For example, while the fluids of the body can conduct electric current, the skin is a good insulator if unbroken and thus an external electric field is reduced inside the body by a large factor that may range from 10^5 to 10^7 [see for example references 4, 5 and 6]. An electric field of, say, 1000 V/m (larger than usually encountered, see Fig.2), would result in an internal electric field possibly ranging from 0.1 to 10 mV/m. The resistivity of tissue may be from 1 to 10 ohm m, and thus current density might be from 0.01 to 10 mA/ m².

Magnetic fields, in contrast to electric fields, penetrate the body completely if they are steady like the earth's field or alternating slowly with the frequency of power lines. While steady fields seem to have no detectable effects, alternating magnetic fields generate an electric field and current around any conducting loop. The total electric potential generated is proportional to the strength of the magnetic field times the area of the loop. (See Fig. 4) A conducting loop in the human body can easily have a radius of 10 cm. If the magnetic field were about 100 microT (larger than is commonly encountered, see Fig. 2), then the resulting electric potential around the loop would be 1.2 mV as shown in the Figure. The average electric field around the loop is about 1.9 mV/m, in the same general range as the electric field noted above and the current density could also be comparable. If the loop were made of a copper wire with a 1 mm gap between the ends,

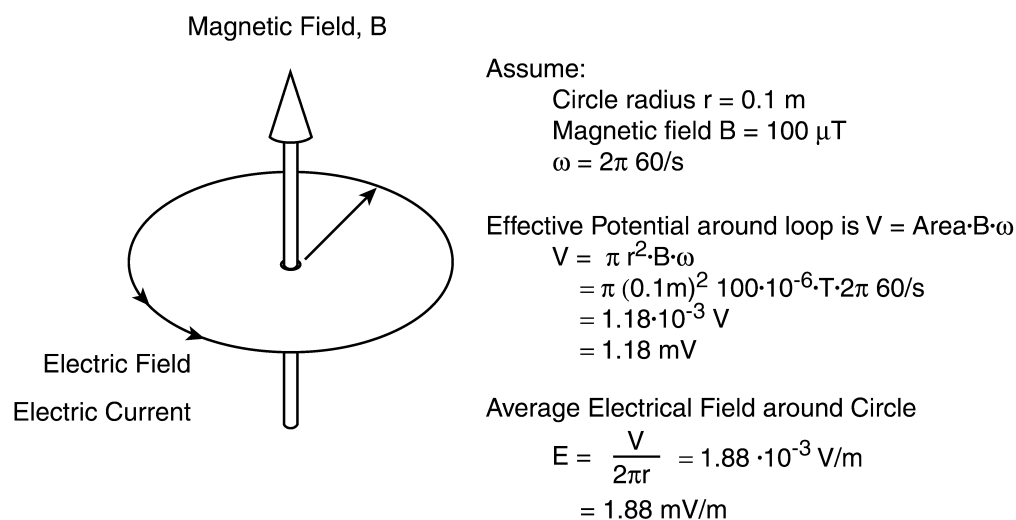


Figure 4: Illustrating the induced electric potential and average electric field generated by an alternating magnetic field.

there would be no electric field in the copper, the full electric potential would appear across the gap making an electric field of $1.2 \text{ mV} / 1 \text{ mm} = 1.2 \text{ V/m}$, nearly a thousand times the average electric field.

2.3 Many detailed and careful calculations of fields and currents in the human body have been made by Stuchly and colleagues [7,8,9], (and earlier by Kaune [10]). They have used realistic conductivities, different for different tissues and usually much lower than the 1 Siemens/m (resistivity greater than 1 ohm m) assumed above. They chose three different (orthogonal) orientations of the 60 Hz magnetic field and three different conditions of isolating or grounding the body in a vertical electric field. Their results show what parts of the body and which organs are most affected by external electric and magnetic fields. In the same magnetic field as above, 100 microT, their figures show that an average induced internal electric field generated is about 4 mV/m and average current density about 0.6 mA/m^2 . In an electric field of 1000 V/m, they calculate a range of internal fields and currents that include the values mentioned above for the magnetic field.

These numbers unfortunately cannot determine what 60 Hz electric fields exist across individual cells in different tissues. For instance, some cells of the nervous system are very long, perhaps a meter in length. When they are exposed to parallel external electric fields, the potential across their end membranes will be much higher than the potential across the membranes of much smaller more spherical cells. In the same way, cells that are electrically connected together by gap junctions or cells that populate long conducting channels such as blood vessels or lymph ducts could also experience different membrane potentials than individual cells in a homogeneous medium. The same principle applies to cells in a conducting loop in a magnetic field.

2.4 Since the area of a conducting loop in a human body may be 100 or 1000 times that in a mouse, the electric field generated by alternating magnetic fields in the mouse will be correspondingly lower. If electric fields so generated are thought to have physiological effects, and if these physiological effects are thought to be similar in small animals in the laboratory, the small animals will have to be exposed to fields perhaps 100

to 1000 times stronger to simulate the human response. In addition, of course, effects in experimental animals can be assessed for only a short time, compared with much longer possible exposures for humans.

2.5 While it is possible to estimate the electric fields and currents that flow in the body when exposed to 60 Hz magnetic fields, it is not at all easy to determine what fields and currents are probably not harmful. Later in this report data will be presented that suggest a connection between these fields, cellular effects and incidence of leukemias and cancers. These suggestions have led to an understandable desire to find exposure levels that might be judged "safe" from such deleterious effects. There is no simple answer to this question. In their search for reasonable guidelines regulators have decided that exposure should be limited. [11, see also 12,13]

In the frequency range from a few Hz to 1 kHz, for levels of induced current density above 100 mA/m², the thresholds for acute changes in central nervous system excitability and other acute effects such as reversal of the visually evoked potential are exceeded. In view of the safety considerations above, it was decided that, for frequencies in the range 4 Hz to 1 kHz, occupational exposure should be limited to fields that induce current densities less than 10 mA/m², i.e., to use a safety factor of 10. For the general public an additional safety factor of 5 is applied, giving a basic exposure restriction of 2 mA/m².

2.6 To determine the possible health risk that these ubiquitous fields may present, it is clearly necessary to measure them and the exposure of individual people to them. Many measurements and calculations of the fields in houses, in schools and in work places have been made by officers of Ontario Hydro. Mader reported [14,15,16] for the group doing source characterization:

They have calculated fields in about two dozen homes from the wiring configuration and have compared these calculations with direct measurements of fields in the same houses. The correlation is good as expected.

Some other features in their data are also interesting. Their measurements show in a spectacular way that a few Amperes current in a single water pipe entering the house can completely dominate the magnetic field in the house.

At a later meeting of the Panel, Harvey discussed [Meeting of 31-3-93 in Reference 14] *the magnetic field from transmission and distribution lines, pointing out that the field caused by a three phase wiring configuration transmission line diminished as $1/(\text{distance})^2$ when distance was large compared with wire separation.*

He outlined the status of source characterization by showing fields near overhead distribution lines, transformer stations, school wiring, domestic wiring and grounding, and fields near appliances. In transformer stations the highest field observed was about 0.8 G (80 microT), but inside the fence fell to about 1-10 microT while outside was generally less than 1 microT. Distribution transformers generally show less than residential background - if more than 2 m distant - and so have no significance in residences. Data have been collected for 11 schools which show much variability with fields generally higher near service panels. Appliances expose the hands using them to fields of about 1 microT on average while the whole body exposure is much smaller - of order 0.02 microT. It should be noted that some electrical tools when in use, drills and transformer soldering irons for example, can have fields of several hundred microT closer to their cases but much less even at the normal handle. In measurements made in 4000 houses the mean field was 0.3 microT with a very few having fields of 2-3 microT.

Higher fields are possible, up to even 100 microT very close to some machines and certain appliances.

2.7 For many epidemiological studies, when no other knowledge of fields was available, the arrangement and position of the wires delivering power to the house was codified as probably implying high or low fields within the house. These "wire codes"

have often been used by epidemiologists as a substitute for measurement and when both wire codes and direct measurements are available they have usually been shown to be well correlated [17, and page 77 in Reference 2].

2.8 The measurement process itself is not simple. The past two decades have seen the commercial development of small portable meters to measure magnetic fields. The meters available now are both personal monitoring and survey type. They are usually sensitive to a frequency range from 40 - 400 Hz in order to include the first few harmonics of the 60 Hz power frequency. The readings of these instruments are usually a direct measure of the instantaneous r.m.s. field strength. On more expensive meters, a record keeping system is used that samples the fields every few seconds and stores the result to be read out later. The cost of the least expensive meters is not much above \$100. Some can be made sturdy enough to be worn by children in a special pouch.

Similar portable meters have also been developed to measure electric fields. They can be used reliably to measure an incident electric field by suspending the meter with a nonconductor. However their use for personal monitoring poses a problem. The person carrying the monitor acts as a conductor and changes the incident field near his body. The change depends on the size of the individual, the orientation of his body, his clothing and the distance of the meter from the wearer and from the source of the electric field.

2.9 Ontario Hydro scientists and engineers have developed methods, and have made many field measurements for epidemiological studies of exposure of employees of the utility to electric and magnetic fields and for epidemiological studies of pediatric leukemia in Toronto. The results of these studies will be discussed in Sections 5 and 6.

2.10 Possible mitigation of these fields has been well assessed but not much implemented, in part because it has not been clear that they are a risk to health and in part because weak fields are so pervasive that mitigation would be very difficult. In the absence of knowledge of risk, some have adopted a policy of "prudent avoidance", meaning avoid large fields if it is easy to do so. In view of the fields shown in the Figures above, this is certainly easy. It should also be noted that some appliance manufacturers

have taken steps to reduce the fields that their appliances produce. For example, electric blankets are now usually wired in such a way that most of the fields from current in the wires cancel themselves.

3. Biological Cells in Fields

3.1 There has been an extensive search attempting to identify a mechanism that could allow low frequency, low intensity magnetic fields to interact with cellular processes. To this end, experiments to observe the effect of fields on cells have been many and varied. Ontario Hydro supported one such study at the British Columbia Cancer Research Center in Vancouver, to determine whether magnetic fields affected the morphology of mammalian cells in vitro. A published paper [18], describes their experiment and the results. In summary:

Automated image cytometry techniques were used to measure motility and morphology in 3T3 fibroblasts exposed to extremely-low-frequency (ELF) magnetic fields. Cell motility and morphology were measured as a function of time before, during, and after 3-4 hour exposures to vertically oriented, (i.e. perpendicular to the tissue culture dish) 100 microT RMS sinusoidal magnetic fields at various frequencies in the 10-63 Hz range. Sham exposures were also carried out Each experiment involved the tracking of 100 cells that were subjected to one of the test frequencies Changes were measured However because such results were seen for both the sham-exposed and the ELF-exposed cells, and because the range of values that was obtained for the sham exposure was the same as that obtained for the ELF exposures, we concluded that there was no evidence to show that any of the measured changes were attributable to the applied ELF magnetic field.

Many other studies of the effect of magnetic fields on mammalian cells in vitro have been reported. In magnetic fields below 100 microT almost all results are like the experiment quoted above, that is, any effects observed are not different from phenomena that seem to occur at random in living cells and show little or no reproducibility or replication in other laboratories.

3.2 Stronger magnetic fields can have more recognizable effects on cells. In this section we will describe some of them and their probable significance.

In experiments of similar design to that above, exposure of ciliated protozoa to fields of 126,000 microT (parallel to the tissue dish) was found to disorganize movement pattern. Of perhaps more interest are results of recent experiments with genetic end points.

Miyakoshi and his collaborators in Kyoto [19,20] exposed mammalian cells in vitro to magnetic fields of 50 Hz and 400,000 microT perpendicular to petri dishes that were 15 cm in diameter. They measured the frequency of mutations in a particular gene (HPRT) in these cells after they had been irradiated with gamma rays and in the absence of radiation. The radiation increased the rate of mutation in this gene. The high magnetic fields also increased the number of mutants. The presence of the magnetic field after irradiation increased the mutation rate significantly above that observed with radiation alone. This and other studies led to the suggestion that these very high magnetic fields were somehow interfering with the repair of errors in genetic replication that normally accompanies all DNA duplication. Miyakoshi's study also showed that the rate of mutation increased with radius within the petri dish, as does the induced electric field (see Fig.4). This evidence implies that the effect is due to induced electric field around the perimeter, up to 4-5 V/m.

Hahn and his colleagues [21] studied the effect on similar mammalian cells in vitro of 60 Hz magnetic fields of strength 200 - 400 microT. Their strategy focused on very rigorous control of possible vibration, heating and subjective effects. They observed a significant increase in mutations in irradiated cells that was clearly above background, again suggesting a deleterious effect of the magnetic field on repair mechanisms. These results were observed at fields that the authors state induced electric fields of 0.3 mV/m in their exposed dishes.

Stronger magnetic fields also affect cell signaling pathways and differentiation of mammalian cells. An example of the former is the recent demonstration of the induction of stress proteins by electromagnetic fields at 1000 microT but not at 100 microT. [22] An example of the latter is the effect of magnetic fields on the differentiation of osteoblastic cells in 30 Hz [23a,b]. This study with a 1,800 microT field, showed an increase in effect with increase in radius corresponding to electric fields ranging from 0.1 to 6 mV/m.

3.3 In summary; experiments with cells in vitro are now starting to show consistency and reproducibility in human cell lines, provided the magnetic field strength is greater than about 100 to 1000 microT . Below this field many experimental results seem unreliable and inconsistent. However in spite of this beginning success, studies are still being reported without defining the geometry of exposure that is needed to calculate induced electric fields. And of course, there is still no agreement about the mechanism of the relevant biological processes. As the Working Group of NIEHS points out:

There is no controversy about the theoretical basis and experimental evidence for biological effects at magnetic flux densities greater than 0.1 mT (100 microT) or internal electric field strengths greater than approximately 1 mV/m. Similarly there is general agreement about the lack of theoretical models and experimental evidence for effects at magnetic flux densities less than 0.1 microT, and theoretical models for effects at densities of less than 0.1 mT (100 microT), and particularly less than 5 microT, are controversial. It is important to note that most of the theoretical results reported to date are based on single-cell models. Realistic modeling of temporal and spatial averaging across functional groups of cells (e.g. synchronized neurons) is a newly developing area of research, which may serve to expand the range of physical mechanisms of interaction. Existing models and theoretical thresholds are only as good as the biological data used to construct them; advances in biology and biochemistry can therefore be expected to serve as a basis for advances in our understanding of the mechanisms of interaction with EMF. [Page 354 in Reference 2].

3.4 Finally the Working Group notes that at the low fields usually associated with residential exposure, (<0.2 microT), the small increased risks that are suggested by many epidemiological studies could not be observed in laboratory experiments. [Page 357 in Reference 2] However, in view of the lack of understanding of any interaction mechanism, and in view of the comments in Section 2.2 and 2.3, about unknown scaling

factors between experiments with cells, with small animals, and with humans, it is probably unwise to draw direct conclusions about risk to humans from these experiments with cells.

4. Small Animals in Magnetic Fields

4.1 There have been many studies of exposure of laboratory animals in controlled conditions to magnetic fields and some to electric fields. Ontario Hydro has been a participant in several. An early endeavor at the University of Toronto [24] investigated the possible effect of fields associated with video display terminals and found no teratogenic effects on mice. To quote:

Mated CD-1 mice were exposed to 20 kHz sawtooth magnetic fields similar to those associated with video display terminals (VDT). Four groups of animals were continuously exposed from day 1 to day 18 of pregnancy to field strengths of 0, 3.6, 17, or 200 microT. There were no less than 185 mated dams in each exposure group. On day 18 the dams were sacrificed and assessed for weight gain and pregnancy. The litters were evaluated for numbers of implantations, fetal deaths, and resorptions, gross external, visceral and skeletal malformations, and fetal weights. There were no less than 140 pregnant females in each group, and there were no significant differences between any of the exposure groups and the sham group (0 microT) for any of the end points. The results of this study do not support the hypothesis that the 20 kHz VLF magnetic fields associated with video display terminals are teratogenic in mammals.

4.2 Closer to the defined concerns of the Panel, were laboratory studies of rats exposed to 60 Hz magnetic fields. These studies, at the Armand-Frappier Institute in Montreal, were sponsored and funded in part by Ontario Hydro. The extensive facilities for these studies were designed by engineers and scientists of Ontario Hydro and built under contract with them.

The exposure system itself consisted of 20 identical exposure modules arranged in five rows of four modules each. Each row of modules produced a different exposure field with rectangular magnetic solenoidal coils. The field levels used were 2, 20, 200, and 2000 microT. Each module contained eight cages (two rats per cage) The entire system was

operated under the control of a computer software and turned itself on and off according to a daily program. The duty cycle was 20 h on (from 1.00 pm to 9.00 am) and 4 h off (from 9.00 am to 1.00 pm) . . . [There was continuous control and monitoring of] environmental parameters including: temperature, humidity, air flow, room lights, and room access. [25]

Each exposure group was 50 female F344/N rats. The first study suggested an effect to the immune system. Its authors suggest [26] that an exposure of rats for six weeks with 60 Hz magnetic fields induces significant immunology perturbation. However, most of the significant differences observed between exposed and non-exposed animals were with the control animals kept in a neighboring room and not with the appropriate sham exposed animals. Never the less this possible effect of magnetic fields continues to be investigated [27].

4.3 The major study supported by Ontario Hydro, also at the Armand-Frappier Institute, was the search for carcinogenic effects of magnetic fields [25]. This undertaking was one of the best controlled studies involving hundreds of rats in various magnetic fields. The researchers found no carcinogenic effects. They write:

. . . . The objective of the present study was to determine whether chronic exposure to 60 Hz linear (single axis) sinusoidal, continuous-wave magnetic fields might increase the risk of leukemia and solid tumor development in rodents born and raised under these fields. Five groups of 50 female F344 rats were exposed for 20 h/day to 60 Hz magnetic fields at intensities of 0.02 (sham controls), 2, 20, 200, 2000 microT. Full body exposure to the different fields was administrated for 104 wk starting from the prenatal period (2 days before birth) and continuing through lactation and weaning until late adult life. Body weight, survival, and clinical observations were evaluated for all groups of animals during in-life exposure. Necropsy was performed on all exposed and control animals that died, were found moribund, or were killed at termination of the study. To preserve and demonstrate the absence of any experimental bias, all

clinical observations and pathological evaluations were conducted under "blinded" conditions. Fifty organs and tissues were evaluated in each animal, with special attention to the incidence of mononuclear cell leukemia, brain tumors and mammary tumors. The findings from this chronic carcinogenicity study demonstrate that, under our experimental conditions, exposure to 60 Hz linear (single axis) sinusoidal, continuous wave MFs, did not affect animal survival, solid tumor, or mononuclear cell leukemia development in female F344 rats. No statistically significant, consistent, positive dose-related trends with the number of tumor bearing animals per study group could be attributed to MF exposure.

4.4 There are more than a dozen other small animal studies of the possibility of EMFs being initiators or promoters of cancers, especially mammary cancers, skin cancers, liver cancer and lymphoma/leukemia. These studies show no clear effects. The NIEHS Working Group concluded [Page 102 in Reference 2]

that most of the studies suggest a lack of carcinogenicity, and the few with borderline positive results are inadequate to conclude that exposure to magnetic fields at the magnitude and field configuration at which they were investigated increases the incidence of cancer in rodents.

There is inadequate evidence in experimental animals for carcinogenicity from exposure to extremely low electromagnetic fields.

Again the Committee could not form a consensus and the conclusion was supported by 19 of the 29 members. Most of the others found no evidence of carcinogenicity and preferred the terminology "lack of evidence" rather than the weaker "inadequate evidence".

4.5 Two recent reviews of studies up to 1999 consider that the combined bioassays are nearly uniformly negative for magnetic field exposure [28, 29]

4.6 The largest magnetic field in these animal experiments was 2000 microT . If the scaling between humans and small animals is, as suggested in Section 2.3 above,

100 to 1000, then the equivalent exposure for humans would be 2 to 20 microT, well above the usual ambient fields of 0.02 to 0.2 microT.

5. Employees of the Electrical Utilities

5.1 In the search for possible correlations between exposure to 60 Hz magnetic fields and human cancers, the employees of the electrical utility industries have often been selected for study. It is thought that they are probably exposed to higher fields for longer periods in their work place than other groups would be. Thus there have been many epidemiological studies of the health of workers in the electrical industry. Ontario Hydro has participated fully in these studies and was a collaborator in one of the largest of them, a joint study of workers in Ontario Hydro, in Hydro Quebec, and in Electricite de France. [30,31]. This study, with others, is discussed in more detail below.

5.2 To discuss EMFs and cancer we first note the probability of Canadians developing cancer and of dying from it as shown in the Table for 1998 [32].

Table 1: Lifetime probability of developing and of dying from cancer.

Male:	Developing	Dying	Female:	Developing	Dying
All Cancers	40.9	26.9	All Cancers	35.0	22.4
Prostate	12.3	3.8	Breast	10.8	4.0
Lung	9.1	8.2	Colorectal	5.6	2.7
Colorectal	6.3	2.9	Lung	4.7	4.2
Bladder	2.7	0.9	Lymphoma	2.2	1.3
Lymphoma	2.5	1.5	Body of Uterus	2.2	0.6
Oral	1.6	0.6	Ovary	1.5	1.1
Stomach	1.5	1.1	Pancreas	1.2	1.1
Kidney	1.5	0.6	Leukemia	1.0	0.7
Leukemia	1.3	0.9	Kidney	0.9	0.4
Pancreas	1.2	1.1	Stomach	0.9	0.7
Melanoma	0.9	0.3	Bladder	0.9	0.4
Brain	0.7	0.6	Cervix	0.8	0.3
			Melanoma	0.8	0.2

5.3 In the many epidemiological studies that have been made, there appears to be little risk from EMFs when all types of cancer are considered together. When the

various cancers are considered separately, increased risk has usually been observed with leukemia and brain tumors. The Table above shows that leukemias and brain tumors account for only a few percent of the malignancies observed in Canada. Because they are so rare, only large increases in relative risk will be easy to observe. Measurement of small increases of relative risk of these rare diseases requires large, well designed and carefully executed studies. Among the best attempts are the epidemiological studies by Theriault et al, [30] sponsored by Ontario Hydro. Their work is characterized by careful dosimetry: many workers wore a meter at their waist (but not hands or arms). Some results, taken from their data, can be seen in Fig 5. The Theriault study found that workers who had more than the median cumulative magnetic field exposure, which was 3.1 microT-years, had an increased risk of certain cancers compared with workers with less than the median exposure. Their results show [Table 3 in Reference 30]:

brain tumors	malignant brain cancer	OR = 1.5 (95% CI, 0.85-2.8)
	benign brain cancer	OR = 2.3 (0.8-6.7)
leukemia	acute myeloid leukemia AML	OR = 3.2 (1.2-8.3)
	chronic lymphoid leukemia CLL	OR= 1.5 (0.5-4.4)

Note: OR (odds ratio) is a measure of the relative risk of a particular cancer for high compared with low exposure, showing increased risk if greater than 1.0 (i.e. OR = 2.0 means twice the risk), and 95% CI (confidence interval) means 95% of the time the true value falls within this interval. It is sometimes referred to as a margin of error 19 times out of 20. This interval is sometimes written without the label "95% CI" as for example, OR = ---- (----,----).

However, as they point out,

there were no clear dose-response trends with increasing exposure [to magnetic fields] and no consistency among the three utilities.

These results and others are displayed in Figure 5.

5.4 An attempt to combine many such studies to extract the best estimate of risk has been reported by Kheifets et al, [33] in a recent meta-analysis of 38 studies. Their analysis yielded values for the relative risk for AML as an odds ratio OR=1.4 (with 95% CI (1.2-1.7)) and for CLL, 1.6, (1.1-2.2). Kheifets excluded studies that did not give data

for different kinds of leukemia separately, but finally presented data for all leukemias pooled together, obtaining OR = 1.18 (1.12-1.24). The point estimates and small

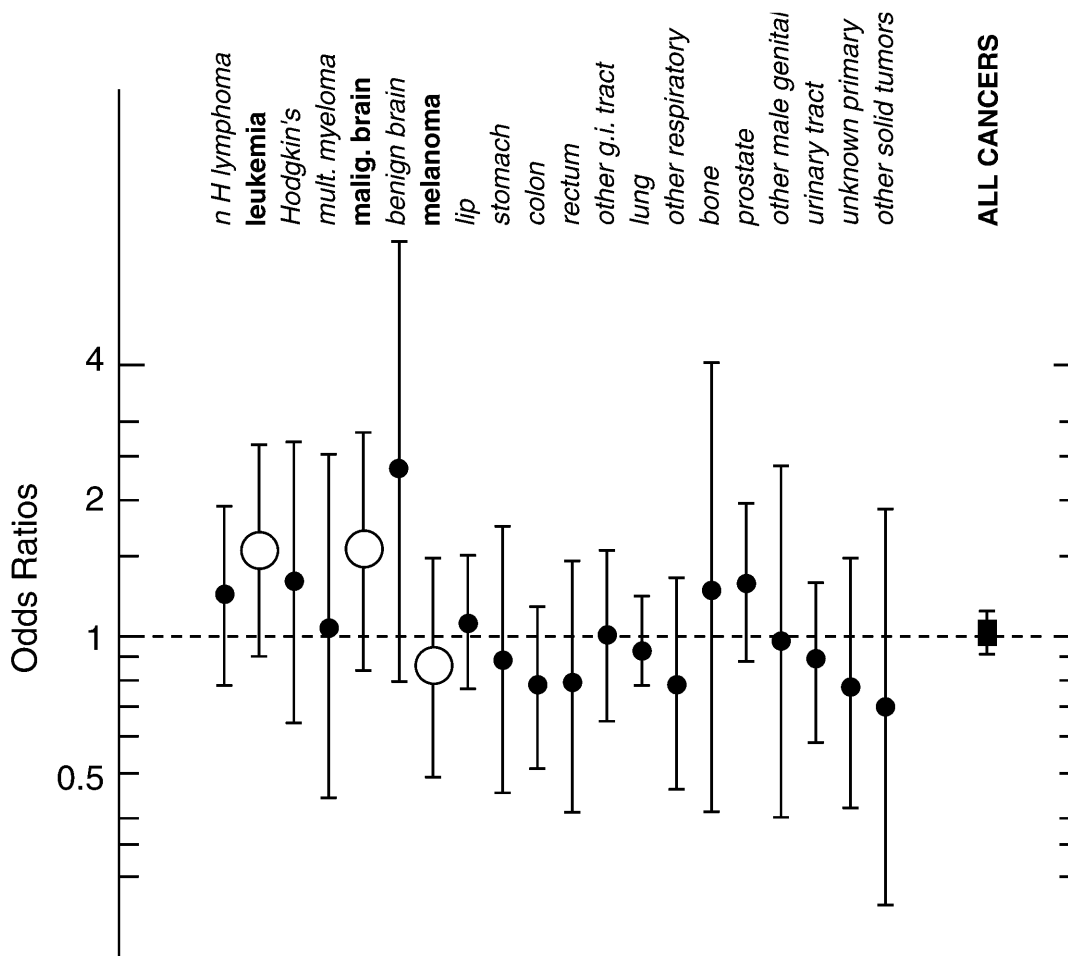


Figure 5: Odds ratios for cancer among electric utility workers in Ontario, Quebec, and France, by cumulative exposure to magnetic fields. Open circles denote the cancers identified by the a priori hypotheses. Vertical bars show the extent of the confidence interval [30].

confidence intervals probably do not represent the uncertainty in knowledge resulting from differences among the studies in the level of exposure and exposure criteria, length of employment, and extent and duration of follow-up after leaving employment in the industry, etc. The results of the many studies that were summarized are shown in Figure 6. It is interesting to note that the highest and lowest point estimates in this Figure come

from the data of Theriault et al and show risk factors for one group (Ontario) of about 3, while for the adjacent group (Quebec) it is about 0.3, implying a protective effect.

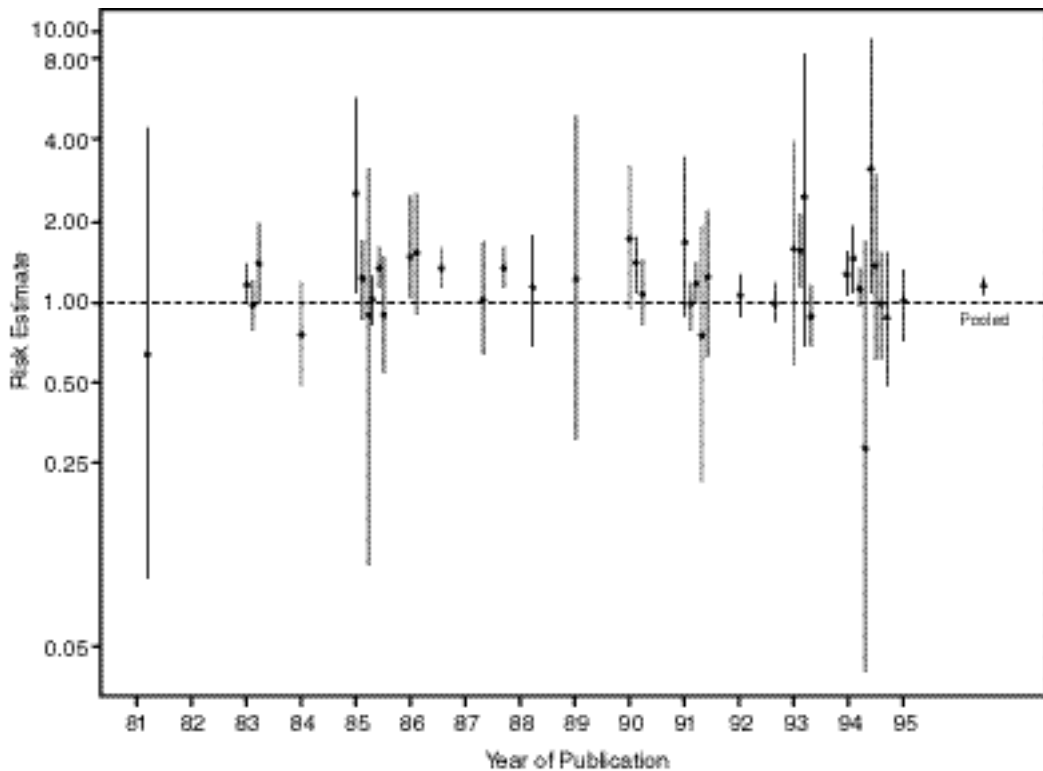


Figure 6: Pooled and individual risk estimates (and 95% CI) for 38 studies of leukemia in electrical workers [33].

This example illustrates the difficulty of measuring small effects in epidemiological studies in this area. Kheifets also did a meta-analysis of brain tumor data from 29 studies that yielded an odds ratio $OR = 1.2$ (1.1-1.3). The same limitations apply to this point estimate and confidence interval as were discussed for leukemia. The Working Group found

the studies suggest an association between exposure to magnetic fields and brain cancer, although the results are somewhat inconsistent [Page 131 in Reference 2].

5.5 The data for Ontario Hydro workers that were included in the three utilities study [30], augmented somewhat by more recent observations, were reanalyzed for magnetic and electric field effects by Miller et al [34]. This time the cohort of workers

was divided equally into three categories of cumulative exposure to both electric and magnetic fields. They noted that for leukemia

Odds ratios were elevated for hematopoietic malignancies with cumulative electric field exposure. After adjustment, the odds ratio for leukemia in the upper tertile [compared to the lowest tertile] was 4.45 (95% confidence interval (CI) (1.01 - 19.7).

While raised, the comparable odds ratio for magnetic fields was not statistically significant. Moreover the dose-response relationship for electric fields was more consistent than for magnetic fields. There was very little indication of increase in brain malignancy with increasing exposure to electric and magnetic fields.

The possible importance of electric fields has also been noted by Guenel et al [35] who reanalysed the French data and found the odds ratios for brain tumors were elevated with higher cumulative electric fields, though the ratios for leukemia were not.

5.6 Leukemia risk has been associated with transmission and distribution lines when the voltage is above 49 kV in a case control study [36] of residential exposure from Quebec. In a combined analysis of seven such studies [37] :

The combined analysis of the contributive studies indicated an estimate of risk (odds ratio (OR)) for exposure >[0.2 microT] of 1.3, 95% confidence interval (95%CI) 1.0 to 1.7. The ORs increased with exposures at [0.3, 0.4, and 1.0 microT]. The risks were also increased for [houses at] distances of 50 and 25 m from the lines.

5.7 The results with electric and magnetic fields raised the possibility that the data from these and other studies could be evaluated in a more complete way rather than referring to exposure as averages over time of either the electric or magnetic fields. A systematic review of several indices of electric and magnetic exposure was made using the Ontario utility workers data [38]. While recognizing that this procedure had serious limitations, the authors found that:

Our results suggest that the variability in exposure data can only be accounted for by using several exposure indices, and consequently, a

series of metrics should be used when exploring the risk of cancer owing to electric or magnetic field exposure . . .

This analysis provided, among other things, the arithmetic mean and field levels that include 95% of workers, for both electric and magnetic fields by occupational group. The average across all workers was 22 V/m and 0.56 microT, while 95% of workers were below 91 V/m and 1.75 microT. Using the analysis from Section 2, our calculations show that the average and 95% level electric fields would induce internal electric fields of about 0.1 mV/m and 0.5 mV/m while the corresponding magnetic fields would induce internal electric fields of 0.02 and 0.08 mV/m implying that the electric fields are much more important than magnetic fields in this population.

5.8 Villeneuve et al [39] have recently examined the correlation of additional measures of electric and magnetic field exposure and leukemia risk. They found that

The percentage of time spent above electric thresholds of 20 and 39 V/m was predictive of leukemia risk after adjusting for duration of employment . . . among employees who had worked at least 20 years, those in the highest tertile of percentage of time spent above 10 and 20 V/m . . . had odds ratios of 12.7 (95%CI 2.1-78) and 11.1 (95%CI 1.7-71) respectively, when compared to the lowest tertile.

They feel that this result supports

the hypothesis that electric fields act as promoting agents in the etiology of adult leukemia.

Because of multiple testing concerns they note the need for replication of any results.

In a further evaluation of alternative indices, this time with Non-Hodgkin's lymphoma (NHL), Villeneuve et al [40] found that their

data suggests that exposures above electric field threshold intensities of 10 and 40 V/m are important predictors of NHL.

5.9 It is difficult to draw a conclusion from the plethora of results each exhibiting a considerable range of risk. At the highest levels of exposure the Canadian study shows a relative risk as high as 4.5, but with small numbers there is great

uncertainty: 95% CI (1.0-20) [34], and the risk seems more related to electric than magnetic fields. In most studies the odds ratio for leukemia is between 1 and 2.

6. Leukemia in Children

6.1 The study of cancer in children is more difficult than studies with adults because children have many fewer cancers than adults. With children (age up to 14 years) the cancer incidence is about 16 per year per 100,000 population. With adults the incidence is much greater and very age dependent; from almost zero at age 20 up to about 1000 per 100,000 at age 65. It is not easy to perform a statistically significant study for any disease that is so rare. None the less there have been many studies of the possible effects of power lines and house wiring on the health of children; in particular, carcinogenicity. The measure of exposure has been variously wire codes, spot measurements, calculations of fields from nearby power lines, and 24 hour monitors of fields in the houses of the children. Although some studies found no increased risk of leukemia associated with the magnetic fields, more than half did find small but statistically significant increases in risk. This puzzling result seems to occur over a wide variety of study designs, several countries, and methods of measuring exposure. Most of the various results show a relative risk ranging from 1 to 2 .

6.2 One of the large studies, sponsored by Ontario Hydro, was of children in Ontario in the vicinity of Toronto. The authors have reported: [41]

A population-based case-control study was conducted in Ontario, Canada, to assess the relation between the risk of childhood leukemia and residential exposure to magnetic fields. . . . For children younger than 6 years at diagnosis, outside perimeter measurements of the residence, >0.15 microT, were associated with increased leukemia risk, [However] Our findings did not support an association between leukemia and proximity to power lines with high current configurations. .

Data were also collected using personal magnetic field monitoring by children wearing a measuring instrument (beside the bed during sleep) for about two days. These results were published [42] and confirm the general trend shown in the above.

An association between magnetic field exposures as measured with the personal monitor and increased risk of leukemia was observed. The risk was more pronounced for those children diagnosed at less than six years of age and those with acute lymphoblastic leukemia.

Typical results from both these studies are shown in Fig 7.

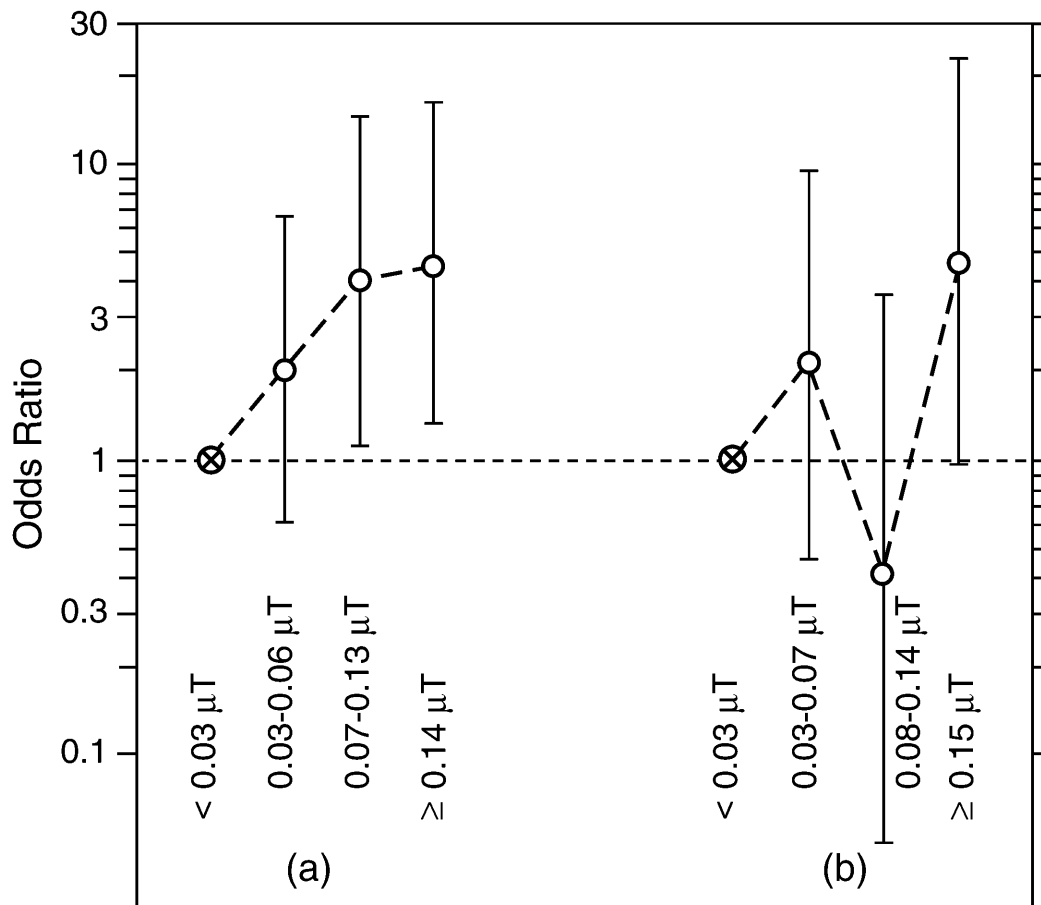


Figure 7: (a) Typical data showing odds ratios for leukemia in children age up to 14 years. The magnetic fields were measured by a monitor worn by the children. [From Table 4, reference 41]. (b) Typical data showing risk of leukemia for children less than 6 years old as a function of the magnetic field measured close to the outside of the house. [From Table VI, reference 42].

6.3 In the same study, external electric fields were measured for a group of sibling pairs and for many of the cases (or siblings of deceased cases) and controls. They found that there was very little correlation between the electric field exposure of siblings, that most of the exposure occurred neither at home nor in school but presumably in travel; and as might be expected, there was no significant difference between electric field exposures of cases and controls.

6.4 Other recent studies yield a variety of results. One of the largest by Linet et al [43] that focused only on children with acute lymphoblastic leukemia (ALL) reported three times as many cases as the above study by Green et al. They found *little evidence that living in homes characterized by high measured time-weighted average magnetic field levels or by highest wire code category increases the risk of ALL (acute lymphoblastic leukemia) in children.*

Most of the available results of such studies have been combined by Wartenberg in a comprehensive meta-analysis [44] His study is best illustrated in Figure 8 that shows a

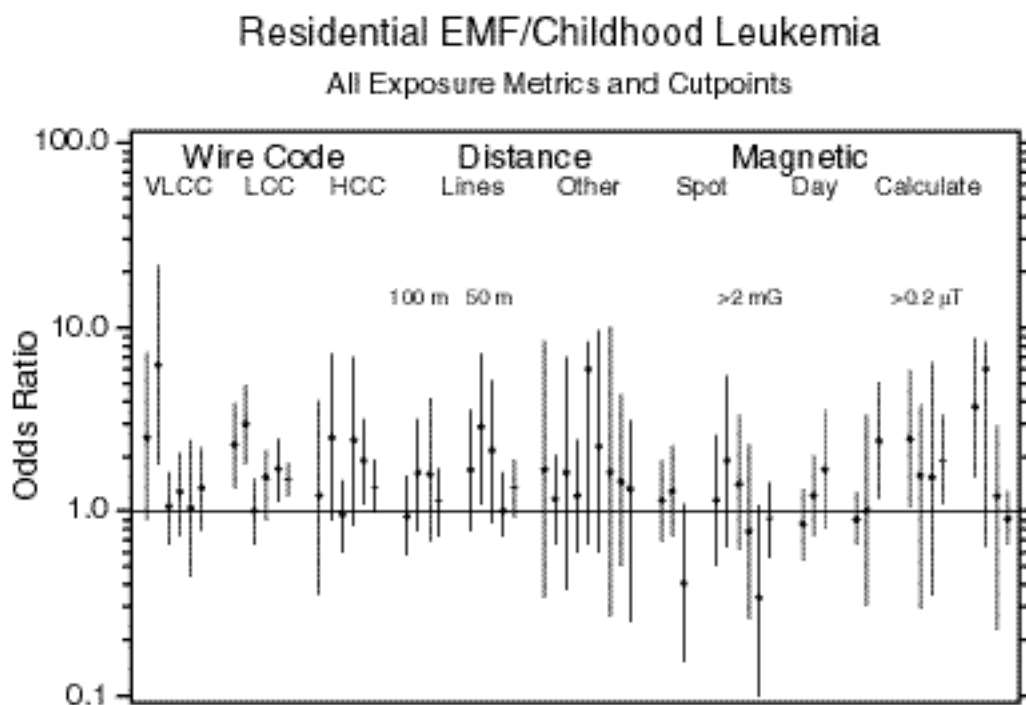


Figure 8: Showing odds ratios for the several studies relating risk of leukemia to magnetic fields, wire codes, and proximity to power lines [44].

range of odds ratios most of which lie between slightly less than 1.0 (i.e. protective) to about 2.0. Because of various inconsistencies he did not make a meta-analysis to obtain an overall estimate of the risk of EMF exposure. He concludes that,

overall, the data provide relatively strong and consistent support for a somewhat weak elevated risk of leukemia for children .

The attempt to find a dose-response relationship yielded nothing significant.

6.5 It should be added that a recent Canadian study by McBride et al [45] that was too recent to have been considered by the Working Group of NIEHS or by Wartenberg has found

little support for a relation between power frequency EMF exposure and risk of childhood leukemia.

This study with about twice the number of cases as Green's will lower somewhat the estimated risk that probably lies in the range of 1.0 to 1.5 found by Wartenberg, but will probably not change the overall conclusion of any meta-analysis.

6.6 The NIEHS Working Group reviewed about a dozen of these studies as satisfying their conditions of acceptability. These studies examine various possible correlations between exposure to EMFs and childhood cancer. Most types of cancer showed little correlation with fields but the data often suggested that leukemia and brain tumors might be affected by these fields. The Working Group comments [Page 188 in Reference 2]:

As research on EMF evolved, both exposure assessment and study designs have improved. The results of studies would then have been expected to become more consistent. In fact, this has not occurred, which raises questions about whether the 'improvements' in exposure assessment have more accurately captured the relevant EMF exposure.

In sum, although the exposure metrics used as surrogates for exposure to magnetic fields are of varying precision, it is difficult to find an explanation other than exposure to magnetic field for the consistency of the reported excess risks for childhood leukemia in studies conducted in

different countries under different conditions, with different study designs. . . . The Working Group considers, with some minor reservations, that the strength and consistency of these study results are suggestive in spite of their limitations.

And they conclude: [Page 189 in Reference 2]

There is limited evidence that residential exposure to ELF magnetic fields is carcinogenic to children

by a vote of 20/29 with many of the minority preferring the word "inadequate" to "limited". They also concluded that there was inadequate evidence for an association between EMFs and brain tumors and lymphoma in children.

6.7 It is noteworthy that the Working Group of NIEHS declines to quantify the risk of leukemia. They merely draw attention, in their own analysis, to the fact that the relative risk can be above 1.0 and is in most studies below 2.0. A recent meta-analysis [46] suggests a narrower confidence interval and estimates a relative risk of 1.6(1.3-2.1) for childhood leukemia. As noted earlier (5.4) these studies have some limitations.

7. Discussion

7.1 The task of making a good estimate of the risk to people of the environmentally all pervading electric and magnetic fields is difficult. The first and most serious problem is that, as mentioned earlier, any effects that exist are certainly small and therefore not easy to measure. Not only are any possible effects small but in addition, since there is no understanding of a biological mechanism, it is not known just what constitutes an exposure to EMFs. There have been suggestions that certain systems are sensitive to selective frequencies and possibly their harmonics. It may be that there is a threshold of field strength that has to be exceeded; or perhaps some combination of threshold and field strength. Some data suggest that electric and magnetic fields combined are more likely to produce an effect. None of these questions has been resolved in spite of serious attempts to do so.

7.2 EMF exposure of cells: There are fundamental problems in the study of cells in EM fields. Perhaps the most important is the choice of exposure fields and their intensities. Early studies were generally made at relatively low field strengths, approximating those in the human environment from 0.1 - 100 microT. In spite of improvements in methodology, including control of temperature, vibration, and the use of active sham control magnetic fields, improvement in quality of results from repeated studies has not been realized. No conclusively positive results in studies of cells in fields below about 100 microT have been observed. More recent cellular studies have used magnetic fields as high as 400,000 microT and genetically modified cells with increased susceptibility to genetic effects. A number of these have reported physiological and genetic effects in cells exposed to magnetic fields. None involved direct effects on the carcinogenesis process, but the effects observed might be expected to increase carcinogenesis.

Many of the results that have been reported require further detail and further replication. The studies of EMF exposures to date, with few exceptions, do not describe the geometry of the magnetic field with respect to the container of the exposed cells. This

makes it impossible to calculate the average induced electric fields. The results of studies with apparently similar exposure conditions often differ considerably. There has been no replication of the important study by the Kyoto group. This study showed that the frequency of increased mutations was dependent on the radius of the possible circular path in the petri dish, a result that indicated the importance of induced electric fields. There have been no molecular or genetic studies with appropriately delivered electric fields on cells in vitro, though studies of this sort might greatly facilitate understanding in this field.

7.3 Animal carcinogenesis studies: Animal carcinogenesis studies have not been carried out with high field strengths or with animals with increased potential for carcinogenesis. Fields above 2000 microT are certainly possible though careful attention would have to be given to temperature and vibration control. Genetically modified, transgenic and "knock-out" animals could be used in these studies. Given the effects on cells exposed in vitro, it might be expected that at high fields and with the appropriate strain of animals, it would be possible to show that electromagnetic fields could affect carcinogenesis. The difficulty with the results of such studies would be the problem of interpretation. If as suggested by the discussion in Section 2.4, the biologic effects of magnetic fields are caused by induced electric fields inside tissue, the exposure required for biological effects in small animals may be 100 to 1000 times the exposure for a similar effect in man.

Several of the results that have been reported require replication. A breast carcinogenesis experiment that demonstrated a promoting effect of magnetic fields has been replicated many times within a German group [47] but has failed to be replicated elsewhere. A skin carcinogenesis study [48] that demonstrated an apparent enhanced promoting effect of intermittent magnetic fields has been described but replication of the results has not been reported. Studies of small animals in electric fields up to 100,000 V/m have been reported [49], though most of these studies examined only growth rate and hematological and blood chemistry effects, not measures relating to carcinogenesis [50].

7.4 Employees of the Electrical Utilities: The epidemiological reports grapple with the usual problems of such studies, perhaps accentuated in this case by the comparatively small relative risks among rarer cancers. This necessitates the study of large populations, followed (historically) for a considerable time. Data are apparently available for only a limited number of workforces, and the employees of Ontario Hydro and Hydro Quebec may represent our only resource in this country. A second problem is the determination of exposure in populations of workers whose jobs and work practices have changed over the years. As well, in common with other epidemiological studies of EMF effects, it is not known what constitutes an "exposure". It is not evident whether peak, cumulative, average, or excursion above some threshold or other measure should be assessed. Distinction can also be made between electric and magnetic fields. These issues mean that inconsistencies in exposure-response relationships do not necessarily rule out a causal connection between EMFs and certain cancers. A third concern is the identification of and correction for confounders, factors associated with exposure and disease, which might account for or change any relationship found. Concerns about confounders are likely to be small within exposure sub-groups. As well analyses were conducted allowing for a variety of occupational confounders.

Overall then, despite the limitations, there appears to be some small increase in risk of leukemias and perhaps brain tumors associated with EMF exposure. We note that in a number of studies brain tumors and leukemias are each observed to be increased, providing replication not seen for other cancers. The pattern, while not entirely consistent, seems clear, although the increased risk is small.

In the Ontario Hydro workforce, the possible risk implied by these studies may be calculated. A nested case-control study by Miller et al [34] within the cohort of Ontario Hydro workers provides the data. The primary focus of this study was on leukemia but relevant data were also provided on brain tumors. The analysis divided the cumulative exposure (of both electric and magnetic fields) into three categories and used the lowest as the reference. From the number of cases (N) and the adjusted odds ratio for the exposed group (OR) in each of the other two categories, the cases attributable to exposure may be calculated as

$$\frac{N \times (OR - 1)}{OR}$$

For example, from Table 4 of the paper, the estimated adjusted OR for all leukemias in the highest exposure category (≥ 7.1 microT yrs) is 1.56 based on 24 cases. The number of cases attributable to the exposure is thus

$$\frac{24 \times (1.56 - 1)}{1.56}$$

which equals 8.6. Comparable calculations for the exposure group 3.2 - 7 microT yrs (for which the OR is 1.67, with 16 cases) gives an estimate of 6.4 cases attributable to magnetic fields. Summing the two gives a total of roughly 15 out of the 50 leukemias (there were 10 in the reference exposure category) attributable to this exposure. The procedure was repeated for malignant and benign brain tumors giving 13.8 cases attributable to magnetic field exposure. The total for brain tumors and leukemia is thus about 29 out of a total 85 cases of these diseases.

Using the upper and lower 95% confidence limits of the adjusted odds ratios, a sense of the possible range of attributable cases may be obtained. (The term "range" is used because a formal confidence interval has not been calculated.) When the lower limit of a confidence interval is less than 1, the odds ratio then implies a preventive effect. Since we consider this unrealistic because standardized mortality ratios for electrical workers do not show protection, we have set the lower limit to be zero. The resulting number of attributable cases then ranges from 0 to about 55.

The same estimates may be made for electric fields (Table 3 in [34]) resulting in about 27 attributable cases, ranging from an assumed zero to about 50. The authors also showed the result of partitioning the leukemia cases into 9 categories, each of the 3 magnetic groups being subdivided into 3 electric groupings. Two statistical models were tested. The first assumed additive effects, but since the interaction between the two fields proved significant, the second model included interaction terms. For the first, the estimate of attributable cases was 24 (range 0-41) and for the second model it was 38 (range 7-45). Comparable data for brain tumors were not shown in the paper.

In conclusion, we note that these cases of leukemia and brain tumors occurred over the 19 years in the study so that the incidence rate is roughly 1-2 extra cases a year attributable to EMF exposure in this large cohort of workers, leavers and retirees. This

estimate may range from zero to about two and one half. Deaths from these cancers occur for about two-thirds of those developing the disease. By way of comparison, among an average (1970-1992) of more than 22,000 employees and retirees, deaths from leukemia and brain tumors together average about 4/yr, from colon cancer about 5/yr and from prostate cancer about 6/yr. Deaths caused by lung cancer average 15/yr and from accidents 14/yr [51].

7.5 Leukemia in children: The problems encountered in the pediatric study parallel those faced in the occupational studies in several ways. First, the study population again represents one of only a few available to study in this country. Given the limited number of cancers that have been associated with EMFs, study of pediatric leukemias in southern Ontario includes a large fraction of cases potentially associated with EMFs. Second, there is a significant difficulty in determining exposure of children who have moved from house to house. One study [42] suggests that other children may act as surrogates for assessing magnetic field dose but not for electric fields. Thus there seems no way to determine electric field exposure retrospectively. Third is the problem of correcting for confounders. Relatively little is known of the factors influencing the development of leukemias. As new factors are found that may be important, studies can be modified to correct for these factors, but this is not always possible after a study has been completed. For instance, birth weight and dietary factors thought to inhibit DNA topoisomerase II, may affect the risk of pediatric leukemia [52, 53]. However, dietary data are difficult to assess after the study has been completed. Socioeconomic level may affect both birth weight and diet, and may also affect the location of the home and hence exposure to EMFs.

It should be noted that a recent extensive study in the U.K. showed no correlation between pediatric leukemia and EMFs but noted that most (97%) of the children were exposed to fields less than 0.2 microT.

Finally, it appears again that, despite the limitations, there is some increase in pediatric leukemia associated with EMFs although the magnitude of the increase is still difficult to assess.

8. Conclusions

8.1 The studies undertaken by Ontario Hydro to assess any possible risk of cancer from electromagnetic fields has added to the knowledge of the generation of EM fields in the human environment, and to their effect on cells, on small animals in the laboratory, on populations of workers in electrical industries, and on children as has been described in Sections 2 to 6. In general these investigations are part of, and consistent with, the comments and conclusions of the Working Group of the National Institutes of Environmental Health Sciences [2]. That is, they support their conclusion that 60 Hz electromagnetic fields are *possibly carcinogenic* to humans. Some of the investigations also provide the basis for a more complete understanding of the effect of electromagnetic fields on the human body possibly through the induced internal electric field. In particular they provide the basis for increased understanding of possible links between these 60 Hz EM fields and the risk of cancers.

The classification of an agent as *possibly carcinogenic to humans* is based on the criteria used by the International Agency for Research on Cancer [54]. They have assigned 228 agents, groups of agents, mixtures and exposure circumstances to this category including: glass wool, lead and lead compounds, gasoline engine exhaust, and exposure circumstances in carpentry and joinery.

They assigned 59 to the category *probably carcinogenic to humans* including: formaldehyde, human papillomaviruses, creosotes, and the use of sun lamps and sun beds.

They assigned 77 to the category of *carcinogenic to humans* including; benzene, X-ray and gamma radiation, tobacco smoke, and exposure circumstances in iron and steel founding.

8.2 The evidence for a concern about possible cancer risk being associated with these fields comes from three Ontario Hydro sponsored studies.

First is the detailed investigation by Stuchly of the effect of 60 Hz electric and magnetic fields on the induced electric fields in the body (see Section 2.3). We have noted earlier that it seems likely that the biologically important factor is the internal

electric field. Reproducible biological effects can be seen with the average internal electric field as low as 1-3 mV/m. Quoting “average“ electric fields (and the resulting “average” current densities) is misleading. A uniform field of this size cannot perturb a cell. However living tissue is very heterogeneous, the highly conducting parts will have very low fields and poor conductivity material, e.g. cell membranes, can have an electric field many orders larger than the average. (recall the discussion in Section 2).

Earlier studies assumed that magnetic fields were more important than electric fields because they were fully penetrating while electric fields were reduced by 10^5 to 10^7 in the body (See Section 2.2). However as Section 2.2 has shown, the electric fields inside the body resulting from magnetic and electric fields in the environment can be similar. At 60Hz, the external magnetic field needed to generate an internal electric potential of 1.2 mV, which leads to an “average” field of 2 mV/m, in a loop of 10 cm radius is about 100 microT. (see Fig.4) Smaller loops will require higher magnetic fields to induce an “average” field of 2 mV/m internally. The external electric field needed to generate an “average” field of 2 mV/m internally is in the range 200 to 20,000 V/m.

The more detailed calculations of Stuchly yield similar results. Her work shows that average internal currents of 2 mA/m^2 or average internal electric fields of 2 mV/m in bone marrow, where leukemia cells presumably originate, require external electric fields from 400 V/m to 10 kV/m, or magnetic fields from 120 to 600 microT. As is evident from Figs. 2 and 3, fields of these magnitudes can be found in our environment although exposure is infrequent. Even these fields are larger than those most often encountered in epidemiological studies.

Second are the studies of malignancies among employees of Ontario Hydro, examined alone and together with similar studies at Hydro Quebec and Electricite de France (see Section 5.3). These studies suggest, albeit with some inconsistencies, a relationship between magnetic and electric fields, and the risk of leukemia and possibly brain tumors. These results are consistent with the meta-analyses of other studies as reported by the Working Group.

Third is the study of pediatric leukemia in Ontario. This study used a wide range of methods of assessing exposure and the results suggest an increased risk associated with increased magnetic field exposure (see Section 6.2).

8.3 The magnitude of the electric and magnetic fields thought to be important from epidemiological studies needs to be discussed. The Ontario Hydro studies imply an increased risk of disease for average electric fields above 20 V/m and average magnetic fields above 0.2 microT. However, there are no direct data that show that continuous exposure to these low fields can cause any harmful health effects. In fact, as Figure 2 shows, the natural magnetic and electric fields of the earth, though steady, are much larger. It is likely that these low fields for Ontario Hydro workers are the result of relatively brief exposures to large electric and magnetic fields averaged with long periods spent in normal low background fields.

8.4 The exposure guidelines adopted by the International Committee for Non-Ionizing Radiation Protection (ICNIRP) correspond for the general public to a basic exposure restriction of 2 mA/m² (see Section 2.5) that they take to be created by 80 microT and 4 kV/m magnetic and electric fields. The recommended limit for workers in the electrical industries was chosen to be five times higher than these values. Given a tissue resistivity ranging from 1 to 10 ohm m, the current density above, 2 mA/m², would be achieved with an electric field of 2 to 20 mV/m. Using the factors 10⁵ to 10⁷ from Section 2.2, the external electric field needed ranges from 200 V/m to 200 kV/m. The equivalent magnetic field, estimated from Fig.4, is 100 to 1000 microT. This calculation uses the area of a 10 cm radius circle. Smaller loops than this will require larger fields.

The extensive calculations of Stuchly, cited above in 8.2, show that the external fields needed to induce internal currents of 2 mA/m² or average internal fields of 2 mV/m range from about 1 kV/m to 10 kV/m for electric fields, and for magnetic fields, from 120 to 600 microT in good agreement with the above.

Fig.2 shows that fields of this magnitude can be found in our environment but they are rare and ordinarily exposure to them is very brief. These exposure limits are a few orders of magnitude larger than the range covered in most epidemiological studies that were typically up to 0.15 microT and 20 V/m. These low fields are unlikely to pose

any significant risk. It seems possible that above the ICNIRP guidelines, there is some risk.

The NIEHS made its final report in June 1999 [55].

The NIEHS concludes that ELF-EMF exposure cannot be recognized as entirely safe because of weak scientific evidence that exposure may pose a leukemia hazard. In our opinion this finding is insufficient to warrant aggressive regulatory concern. However, because virtually everyone in the United States uses electricity and therefore is routinely exposed to ELF-EMF, passive regulatory action is warranted such as a continued emphasis on educating both the public and the regulated community on means aimed at reducing exposures.

The Panel of the Royal Society agrees with this proposal to reduce exposure. These studies and others suggest that *passive regulatory action*, or in the words of MG Morgan [3], "prudent avoidance", should be directed to reducing exposure to the higher fields identified by the ICNIRP guidelines.

9. Recommendation

9.1 Despite their limitations, epidemiological studies now appear to show a small increase in risk of leukemias and perhaps brain tumors associated with EMF exposure. Similarly, genetic studies, though at present not rigorously replicated, demonstrate that EMFs can have deleterious effects on mammalian cells, presumably through induced electric fields. Recent calculations of induced electric fields in the human body indicate that fields sufficient to effect genetic damage could occur, though rarely, in environments in which employees of Ontario Hydro and the public are exposed.

9.2 To reduce the possible risk from EMF effects it may be wise to limit the long term maximum exposure to high EMF fields by following the general guidelines of the International Committee on Non-Ionizing Radiation [11]. These are:

	For workers	For the public
Magnetic fields	400 microT	80 microT
Electric fields	8000 V/m	4000 V/m

9.3 In making this recommendation the Panel is aware that the risk from leukemia and cancer attributable to 60 Hz electromagnetic fields is likely small compared with other environmental and lifestyle factors including diet, exercise level and exposure to respiratory insults. From a public health point of view, we have not assessed whether the expenditure for mitigation to the levels suggested above (9.2) would yield a larger benefit with relation to cancer mortality outcome than expenditures directed toward these other risk factors.

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A1. Other Effects of EMFs

A1.1 In the many studies of animals other non-cancerous effects are thought to have been seen. However almost all of these effects have proven to be somewhat ephemeral and difficult to reproduce. The major review by the Working Group of NIEHS concluded [Pages 209-271 in Reference 2] that there was no evidence for effects in the immune system, for hematological effects, for effects on reproduction and development, or for effects on melatonin production in sheep and baboons. The same Group concluded that there was weak evidence for effects on melatonin production in rodents, and weak evidence for neurophysiological, neurochemical, and neurobehavioral effects in animals.

Pulsed electromagnetic fields have been used for many years for the treatment of fractures [A1.1]. Recent investigations are evaluating the use of these fields in the treatment of other musculoskeletal conditions including osteoarthritis and wound healing.

A1.2 Deleterious effects of 60 Hz EMF have been reported relating to depression [A1.2], cardiovascular disease [A1.3] and neurodegenerative disease [A1.4]. The Working Group wrote that

there is weak evidence that short term human exposure to ELF EMF causes changes in heart-rate variability, sleep disturbance, or suppression of melatonin, and also that there is no evidence that such exposure has other effects on the biological end-points studied in the laboratory [Page 316 in Reference 2].

Both of these conclusions had only about 50% support from the members of the Group.

A1.3 It is well known that alternating currents of sufficient magnitude can excite nerves in the brain and induce convulsions or seizures. The threshold current for this effect depends strongly on the duration of the stimulation, apparently as the product of current and time. Well defined seizures with excitations of about three seconds duration at 60 Hz have been used for over seventy years in the treatment of severe depression.

Transcranial magnetic stimulation with very low (lower than 60 Hz) frequency fields, introduced 15 years ago, is being clinically applied to the treatment of major depression [A1.5]. The study of such defined fields and fields at higher frequency on cognitive function is now a very active area of neurobiological research with about 200 publications in the first 6 months of 2000.

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A2. Regulations

The International Commission on Non-Ionizing Radiation Protection in cooperation with the World Health Organization has issued a set of guidelines for limiting exposure to electric, magnetic and electromagnetic fields over a wide range of frequencies. [A2.1] At power line frequencies, 50/60 Hz, they considered many studies including the list of topics considered in this Report. As none of these studies result in a sharply defined relationship between risk of (mostly) cancers and exposure to the electromagnetic fields, they have chosen to base their recommendations on the effect of electromagnetic fields on the central nervous system. It is known that an internal current density of 1 A/m^2 causes dangerous disturbances in rhythmic cardiac function, and that below 100 mA/m^2 many effects are inconclusive. Therefore they chose 10 mA/m^2 (two orders below known serious effects) as a recommended limit for workers exposure and for the general public, a factor of five less, i.e. 2 mA/m^2 . The Commission considered that an electric field limit of 8000 V/m for electrical industry workers was a conservative estimate of the field needed to produce this internal current density and thus suggested that public exposure should be limited to half this figure or 4000 V/m . For magnetic fields they suggested a limit of about 400 microT for workers and one-fifth of that, about 80 microT , for the public. These fields are calculated using their judgement of the wide ranges used by the many different jurisdictions quoted in their Report.

Some jurisdictions have suggested higher limits for shorter exposure times but the Commission (ICRIRP) did not make any explicit recommendation concerning higher fields for shorter times.

References

A2.1 Reference 11 in Report

A3. Members of the Panel

W. Robert Bruce

Dr. W. Robert Bruce was born in 1929 in Hamhung, Korea. He obtained his B.Sc. in Chemistry from the University of Alberta in 1950 and Ph.D. in Physics from the University of Saskatchewan in 1956. He then obtained an M.D. from the University of Chicago in 1958 and a year later obtained the L.M.C.C. He was elected Fellow of the Royal College of Physicians and Surgeons in 1978.

Dr. Bruce joined the Ontario Cancer Institute in 1959 and became a member of the senior scientific staff. He has been a Professor in the Department of Medical Biophysics of the University of Toronto since 1965, a Professor of Nutritional Sciences since 1985. He was the Director of the Toronto Branch of the Ludwig Institute for Cancer Research at the Ontario Cancer Institute from 1980 to 1988. Through this period he has coached dozens of students and post-doctoral Fellows and, together with them, has published research in nearly 200 scientific articles and books. He is currently Associate Editor of the journals, *Cancer Epidemiology, Biomarkers and Prevention* and *European Journal of Cancer Prevention*.

In 1980 Dr. Bruce was elected Fellow of the Royal Society of Canada. He has also been honored by medals and prizes from many research societies, from the Damashek Award of the American Society of Hematology in 1968 to the O. Harold Warwick Award of the National Cancer Institute of Canada in 1995.

Dr. Bruce's medical research interests began with his studies of cancer treatment, studies of radiation physics and radiation biology related to radiation therapy, and cell biology related to cancer chemotherapy. His interests then turned to environmental factors in the origin of cancer and to the possibilities of cancer prevention. He pioneered computer studies of patient records that led to the development of the Cancer Registry of Ontario, which is now being widely used in studies of work environment, life style and genetic factors on cancer development in the Province. Beginning in 1975 his studies have focused primarily on the origin of breast and colon cancer, especially on the effects of diet on the development of these diseases in animal studies and in clinical trials. These studies presently suggest that specific processes in the preparation of our food lead to the markedly elevated rates of these cancers in our population.

Robert Bruce and Margaret MacFarlane married in 1957; they have one daughter and two sons. His chief recreation is raising the family vegetables through the winter hydroponically and swimming.

Carol Buck

Dr. Carol Buck, a native of London, Ontario, received her education at the University of Western Ontario where she obtained her M.D. in 1947, her Ph.D. in 1950 followed by a D.P.H. from the London (England) School of Hygiene and Tropical Medicine in 1951 where she studied as a Rockefeller Fellow.

Joining the Faculty of Medicine in 1952 as an Assistant Professor in the Department of Psychiatry and Preventive Medicine, she became Professor and Chairman of the Department of Community Medicine, then Chairman of the Department of Epidemiology and Preventive Medicine. She is now Professor Emerita of Epidemiology and Biostatistics.

Dr. Buck has served the medical profession in many ways. She is a member of the Canadian Association of Teachers of Social and Preventive Medicine, Canadian Public Health Association, the Society for Epidemiologic Research and the International Epidemiological Association in which she served as President for three years. Her election to this Office took place at its IXth International Scientific Conference in Edinburgh in 1981, and she became the host for the Xth Conference in Vancouver in 1984. Dr. Buck has also served on Advisory Committees of the Pan American Health Organization, and the National Health and Research Council of Australia. Her work in Canada on many federal and provincial health care organizations is well known. She has served on the Editorial Boards of public health and epidemiological journals including The American Journal of Epidemiology.

Her own research work has resulted in about one hundred publications in professional journals and parts of books on topics ranging from schizophrenia, psychiatric epidemiology and preventive medicine to clinical epidemiology for developing countries. All of her work demonstrates a passionate commitment to advancing the health of people by identifying and correcting the causes and determinants of ill health, by using the rigorous methods of epidemiology.

Many honors have been awarded her including election to Fellowship in the Royal Society, an honorary degree from Dalhousie University, and the Defries Award, the highest honor of the Canadian Public Health Association.

F. Kenneth Hare

Dr. F. Kenneth Hare is University Professor Emeritus in Geography at the University of Toronto. From 1988 to 1995 he was Chancellor of Trent University. He recently served as Chairman of the Technical Advisory Panel on Nuclear Safety, Ontario Hydro, and as a member of the Research and Development Advisory Panel of AECL Research. In 1996 he Chaired the Expert Panel on Asbestos Risk of the Royal Society of Canada, and was Chairman of an Advisory Panel on Nuclear Waste Management, established by Ontario Hydro, until 1999. He is active as a consultant in energy and climate related matters.

He was educated at the University of London King's College and the Université de Montreal. His academic career included appointments as Dean of Arts and Science at McGill University, Master of Birkbeck, University of London, President of the University of British Columbia, Director of the Institute for Environmental Studies at the University of Toronto, and Provost of Trinity College of the University of Toronto. Dr. Hare has served with many official commissions and enquiries, notably as Chairman of the Royal Society Commission on Lead in the Environment, Chairman of the Royal Society study on the Nuclear Winter Phenomenon, Chairman of the peer review panel on documents related to the proposed Canada /United States Treaty on Transboundary Air Pollution, Chairman of the Federal Study Group on Nuclear Waste Management, and Commissioner of the Ontario Nuclear Safety Review. He acted as the first Chairman of the Special Advisory Committee on the Environment for the City of Toronto, and of the Global Change Board of the Royal Society. His fundamental interest, however, has always been the global climate and its stability.

He is a Companion of the Order of Canada, and in 1989 received the Order of Ontario. He is a Fellow of the Royal Society of Canada, has received eleven honorary degrees, and in 1989, in Geneva, received the International Meteorological Organization Prize from the World Meteorological Organization - the second Canadian to be so awarded in 34 years. Dr. Hare lives with his wife, Helen, in Oakville, Ontario.

Harry S. Shannon

Dr. Harry S. Shannon was born in Liverpool, England in 1949. He obtained his B.A. in Mathematics from Oxford University in 1970, an M.Sc. in Mathematical Statistics from Birmingham in 1971, and a Ph.D. in Applied Statistics from the University of London in 1978.

In 1972 he began work at the TUC Institute of Occupational Health, at the London School of Hygiene and Tropical Medicine. After working there for five years, he moved to Canada in 1977 to join the embryonic Occupational Health Program at McMaster University. He is currently a full Professor there in the Department of Clinical Epidemiology and Statistics. He was acting Chair of the Department for a year in 1997-8. In 1999 he was appointed Director of McMaster's Program in Occupational Health and Environmental Medicine.

Since 1991 Dr. Shannon has been seconded part time as Senior Scientist to the Institute for Work & Health in Toronto. For several years he was the Work Environment Research Coordinator.

Dr. Shannon's research interests have concentrated on work and health. His Ph.D. thesis examined occupational accidents at a large automobile plant. He then conducted a series of mortality and cancer morbidity studies on workers in nickel mining and processing, glass fiber production, lamp manufacturing, etc.. For the last decade he has returned to research on occupational injuries. Several major studies include: a case-control study of low back pain at a large General Motors complex; a study of upper extremity disorders at the Toronto Star; and examination of organizational factors in work place safety. The back pain study led to his being co-recipient of the Clinical Biomechanics Award of the International Biomechanics Society. His interest in organizational factors continues, as does his work in understanding how to create safer and healthier work places. He has published some 80 papers in peer reviewed journals as well as numerous other reports and book chapters.

Dr. Shannon is involved in the U.S. National Occupational Research Agenda process, as a member of the Committee on Social and Economic Consequences of Occupational Injuries and Illnesses.

In 1977, he married Eileen Tattersall - they have two sons. Harry is a keen soccer player, and derives most of his personal experience of injuries from this pursuit. He is also a soccer referee, but for this he receives only verbal assaults.

Alec T. Stewart

Dr. Alec T. Stewart was born on a farm in Saskatchewan in 1925. The family - parents and two small boys - moved to Nova Scotia in the depression where he attended public schools and Dalhousie University, earning a B.Sc. degree in 1946. At that time he was planning to study chemical engineering and entered the third year of that course in the University of Toronto. Changing to physics, he returned to Dalhousie for a M.Sc. in 1949. A scholarship took him to Cambridge where he studied nuclear physics and measured the slow neutron scattering and absorption of H₂ for a Ph.D.

In 1952 he left Cambridge for the Atomic Energy of Canada laboratories in Chalk River. There he enjoyed the opportunity of participating in the first experiments that measured the vibrating motion of atoms within crystals using the new technique of neutron scattering. (This field was developed by B.N.Brockhouse at Chalk River for which he was awarded the Nobel Prize in 1994) Leaving these laboratories after five years, he taught at Dalhousie University, at the University of North Carolina in Chapel Hill and at Queen's University. In most of his research he pioneered a new field, using the annihilation of positrons with electrons as a probe of the behavior of electrons in solids and liquids. Many students, post-doctoral Fellows, and visiting scientists have worked in this subject in his laboratory. With them, he has published more than a hundred scientific articles for the professional journals and books.

Dr. Stewart has been a visiting Professor and lecturer in many institutes and universities in India, China, Japan and Europe, as well as in the United States and Canada. Some honors include election to the Royal Society of Canada (1970), Canada 125 Medal, an Honorary degree LL.D. (Dal.) in 1986, and the Canadian Association of Physicists Medal for Achievement in Physics in 1992.

Dr. Stewart has held administrative positions at Queen's University - Department Head - and in professional societies. He has been President of the Canadian Association of Physicists, President of the Academy of Science of the Royal Society of Canada (3yrs), and first Chairman of the International Advisory Committee for Positron Annihilation Conferences for nearly two decades to 1997. He has served on review committees for several universities and also for some years as Chairman of adjudication committees for the research granting agencies of the National Research Council of Canada and for the Natural Sciences and Engineering Research Council of Canada.

Alec Stewart and Alta Kennedy married in 1960; they have three sons. His chief recreation is yacht cruising and racing.