METHODS OF REDUCING THE POSSIBLE HEALTH HAZARDS OF 60-Hz MAGNETIC FIeldS

A Thesis Presented to
The Faculty of the College of Engineering and Technology
Ohio University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

by

Hisnham Alnajjar
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I would like to express my deep gratitude to my advisor Dr. Herman W. Hill, for his guidance and encouragement. I would also like to thank him for offering invaluable suggestions throughout this study.

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CHAPTER 1

INTRODUCTION

Electric power is central to the energy systems of the United States and of other developed and developing countries. During the past decay, the electrical power needs of this nation have been increasing at a rate of from four to ten percent annually [7].

In order to meet such an increasing demand for power economically and efficiently, electrical utilities have increased their operating voltages and increased the size of their generating units. Also since transportation of bulk power becomes an important part of the overall efficiency of the system, the number of overhead transmission lines increased dramatically.

Today, the maximum transmission voltages in the United States are 765 kV ac and ± 400 kV dc. Research is being conducted for installation of transmission lines with 1000 kV or more. In the United States alone, there are 600,000 miles of overhead transmission lines in place and thousands more under construction or being planned [13].

Due to this high growth and progress in the use of high voltage and high current ac overhead transmission and distribution lines, there has been increasing concern among the public. Even though there is no real evidence of health effects, the construction of transmission lines have been delayed
due to public concern. While people hundreds of miles away from generation centers get the benefit of using electricity, persons living along transmission lines bear the risk.

Our environment is polluted by electromagnetic radiation with high magnitudes and various frequencies. New technologies created by man have probably changed the electromagnetic nature of the earth more than any other physical or biological nature on the earth.

In recent times, many medical researchers have conducted a lot of research about a possible link between some form of cancer and the extremely low frequency (ELF) fields emitted by electrical power lines. Some of these studies [4] suggest "an association between living or working near power lines and a higher incidence of cancer especially leukemia", while another [8] suggests "that electromagnetic fields may promote brain tumor development".

Recently, headlines are appearing in national newspapers cautioning the public about the environmental impact of power lines such as, "Electric Power Line Linked with Cancer" [9], "Power Lines and Cancer" [7], and "Health Questions are Raised by New York State Power Line Studies" [1]. Furthermore there have been instances of court cases concerning this issue. According to the Oct. 1987 issue of Technology Review, in 1985 Houston
Lighting and Power company was fined $25 million by the court for building a transmission line through a public school property. The evidence presented was that "the extremely low frequency (ELF) fields generated by power lines can modify cell's biochemistry".

This study reviews the recently aroused interest in the possibility of environmental pollution by power transmission lines, and other electromagnetic field sources, and examines possible biological and psychological effects. Recent electrical, medical, and psychological research papers were reviewed and the results were analyzed. In order to understand the physical and biological properties of a cell and its behavior under applied electromagnetic field, a brief look over the natural and artificial magnetic fields and their properties, in addition to the properties of a cell, were conducted focusing on how the magnetic field modifies the behavior of a cell. Then, in order to understand the distribution or the existence of the magnetic field around us, the maximum and the normal values of the magnetic fields were measured around many magnetic field sources. Based on these data, we found that it is logical and important to reduce the magnetic field intensity of power lines to the lowest possible value, and to protect those workers, who spend hours every day near the magnetic field sources, from possible risk. This has been done by shielding
a hard hat to protect those workers from 'brain tumor' development. The study explains the theoretical and practical aspects of the shielding factor and shielding effectiveness as a possible way to minimize the possible health hazards of power lines.

Finally, the study presents many different ways to minimize the effects of the magnetic field for the present time, and for the future.
CHAPTER 2

Review of Recent Electrical, Medical, and Psychological Papers

"Power Line and Cancer: The Evidence Grows" [7], is one of the latest headlines of Technology Review. It reflects the public concern and fear of power lines, and it shows how the decision makers are influenced by the potential threat. Then, it presents some of the recent research that were conducted by well known researchers in the health field, like Tom Tenforde (Lawrence Berkerly Lab.) who has said "something is going on and there is real need for further studies", Dr. Lennart Tomenius (Swedish researcher) who has confirmed that "the distribution of childhood cancer in Stockholm is linked to power line magnetic fields" [7], and Richard Phillips (one of the leading EMF researchers) who has said that "he would not buy a house along a power line right-of-way not even with a $25,000 discount to mitigate any perceived risks" [7]. Finally, the article focuses on what Dr. W. Ross Adey and Suzanne Bawin from the Veteran Hospital in Loma Linda, Calif., have discovered: "16 Hz fields, as well as microwave radiation modulated at 16 Hz could alter the behavior of calcium ions in brain tissue", and another study by Carl Blackman who found that "fields of 50 Hz and 60 Hz can activate the movement of calcium within cells and can alter the surface of cell membranes".
Another article in the *Science News Journal* [8] under "Brain tumor linked to EM radiation", claims that researchers in the Maryland Department of Health, "have found an apparent doubling of the usual risk of developing deadly brain tumors among men who are exposed to electric and magnetic fields".

Even the *Wall Street Journal* under "New study strengthens suspected links between Electromagnetic field and Cancer" [4], quotes Dr. Carpenter that: "The findings are sufficiently worrisome that we should begin to change the way we wire our homes". While looking for a link in his 3-year study, he has found "as much as a threefold higher incidence of child cancer in houses with the highest electromagnetic fields", and has said: "there is a strong justification for concern, but we clearly can't document the hazard like you can for asbestos or cigarette smoking". Finally, the article states what the researcher has said to explain this process: "the speculation is that an enzyme may be changing the activity of key cellular oncogenes genes involved in regulating cell growth and associated with cancer".

One of the most important studies done by the University of Texas Health Science Center [6], finds that: "exposure to electromagnetic fields from high voltage transmission lines causes certain human cancer cells to grow at a greatly accelerated rate, the results are the first step in
identifying a chain reaction of events which ultimately may effect cellular growth and functions in both humans and animals". The results of this study suggest that "sensitivities to electric field strengths, magnetic field strengths and combined electric and magnetic field strengths do occur in dog immune response cells after exposure to these fields". The important variables seem to be the "intensity of the field" and "the relationship between field intensity to duration of exposure", where weeks after an initial exposure of 12 to 24 hours, the cancer cells have shown a marked acceleration of growth. "Some types of existing cancer cells have grown at a rate 6.87 times faster than their normal growth rate after being exposed to magnetic field, after exposure to combined electric and magnetic fields, the cells have grown 6.8 times faster, and after exposure to pure electric fields they grew 2.15 times faster". The study adds: "the results strongly suggest that electromagnetic exposures can cause permanent changes in the ability of human tumor cells to grow". One of the most interesting findings of the study is "that exposure to alternating current, pure magnetic fields alone, can cause growth acceleration in human cancer cells".

Another important study done by the epidemiologist David Savits [5] of the University of North Carolina along with Frank Barnes and Howard Wachtel of the University of Colorado, finds a "fivefold increase in
childhood cancer particularly leukemia in those homes near the highest level of ELF fields. These results support a study done earlier by Nancy Wertheimer [5] of the University of Colorado Medical center. Wertheimer reported that "users of electrically heated beds—which give off ELF fields—are more likely to have miscarriages and longer gestation periods during seasons when heated waterbeds or electric blankets are used. Among users the median gestation period for winter conceptions was about one week longer than that for conceptions during July and August". For electric blanket users, "75% of the miscarriages occurred in September through January"; for waterbed users, "61%; and nonusers, 44%". No such seasonal variations were seen among those who did not use heated waterbeds or electric blankets. Figures 1 & 2 from [5] explain these results graphically. Wertheimer believes that: "for the individual, exposure to ELF fields does not pose a very big risk, but that from a public health viewpoint there may be need to worry."
Fig. 1 Abortion month from [5]

Fig. 2 Month of conception from [5]
CHAPTER 3

The Natural & Artificial Magnetic Fields

Life on earth is composed of quantities such as pressure, oxygen, temperature, water vapor, and light. These quantities are kept in their normal condition by the atmosphere, and any action that changes these conditions causes physiological effects.

As we know, there are other factors, dominant in our environment, which we can only sense with special instruments, such as the electromagnetic field.

For years the relationship between life and electromagnetism has been a source of argument. Today most of the facts about the biological tissue of the body are well defined, and the evidence suggests that "far from being unimportant byproducts of biochemical activity as previously believed, they play a vital role in diverse physiological processes" [18].

"From an evolutionary standpoint, nature would favor those organisms that developed a capacity to accept information about the earth, atmosphere, and the cosmic in the form of electromagnetic signals and to adjust their internal processes and behavior accordingly. Thus it follows from the initial hypothesis that natural environmental electromagnetic energy could convey information to an organism about its surroundings,
thereby facilitating behavioral changes" [18].

At this point it is perhaps logical to suggest that the electrical properties usually exhibited by a tissue are of interest. Because knowledge of them might give us an idea about how the body regulates its processes, and can explain the effects of applying electromagnetic field.

Does a tissue behave in the same manner as the other materials do under an applied electromagnetic field? To answer this question let us have a brief look at the conductivity and the behavior of materials in general.

The atoms, the molecules, and their positions are the main factors that can determine the conductivity of a material. By the use of a solid-state model, conductivity can be defined by the relation of an electronic process to valence and conduction bands. The valence band contains electrons with relatively low energy, the conduction band contains electrons with higher energy than those of the valence band, and they can move in response to any applied electromagnetic field.

The degree of conductivity is determined by the number and the mobility of conduction electrons. Now according to the gap between the valence and conduction bands, we can classify a material. If the gap is small, a material is a semiconductor, because at normal temperatures electrons can move from the valence to the conduction band and populate it.
If the gap is wide, the material is an insulator. A semiconductor's characteristics fall between that of a conductor and an insulator. It is an insulator at a specific temperature and a conductor at a higher one. However, since semiconductors contain impurity atoms, these impurities affect the conductivity of a material. The existence of the energy bands play an important role, they "permit electronic processes in one region of a material to affect not only the immediate area, but also the entire structure" [21].

Over the previous few years, the scientific knowledge of the body has been increased, and all the evidence indicates that "the perineural cells of the Central Nervous System (CNS) have been shown to have some properties analogous to semiconductivity and have been identified as responsible for the production and transmission of steady or slowly varying electrical currents within that tissue" [20]. An important attention should be given to these implication, because it could provide a linkage mechanism between life and electromagnetism.

So the evidence now suggests that "tissue exhibits essentially all the solid-state properties of ordinary materials"[18], in addition to its unique properties. However, the tissue behavior, and the knowledge of its properties are not sufficient to predict the biological effects of exposure to
the magnetic field. Thus, to learn what would happen when an organism is exposed to a given EMF under specific conditions, it is necessary to do the experiment for sufficient time (long time) and analyze the results.

In the U.S. the electromagnetic field is due to many sources with different characteristics. Some are operating at high frequencies: radio and television stations broadcast between 530 KHz and 860 MHz, microwave ovens operate at 2.45 GHz, satellite communications and telephone links operate at very high frequencies in the GHz band. Radar and electronic warfare systems use different types of radiation in the MHz and GHz bands. Others are operating at low frequencies such as the electrical power system (60 Hz U.S. and 50 Hz Europe) which is the primary magnetic field from low frequency. These fields are everywhere and "It is difficult to find places where the electric and magnetic fields are less than 0.1 V/m and 100 µ Gauss" [17].

So far we understand that the extremely low frequency (ELF) fields generated from power lines and some other sources can or may modify cells biochemistry, but the question is, how ELF fields affect the body?. It seems that the process is complicated and not easy to explain according to [7], the magnetic field hits the surface of a cell and a chemical change takes place on the surface. Then, it penetrates through the surface and
changes the process of the chemical reaction inside the cell. This results in the abnormal growth of the cell.
CHAPTER 4

GATHERED DATA

In order to have a complete idea about the existence of the magnetic field and to help us understand its distribution in the surrounding area, experimental data was gathered. Finding the maximum and the normal values of the magnetic field was our objective around the magnetic field sources. A field meter was used to measure these values. The AC magnetic field (B field) at the power line frequency can be measured with a shielded coil probe, as shown in Fig. (3).

Fig. 3 A field meter to measure AC magnetic field (B field) at 50-60 Hz.
In order to measure the horizontal, the vertical, or the maximum magnetic field, the shielded coil probe must be oriented in alternate directions. Since the adapter box is made from nonmagnetic material, the presence of the meter and the box will not affect the magnetic field. In order to have a reliable measurements, the meter should be calibrated. This can be done by placing the probe in a magnetic field whose magnitude and direction are known. This magnetic field can be generated by a coil with dimensions $X$ and $Y$ and with $N$ turns as shown in Fig. (4).

![Fig. 4 A square loop for magnetic field calibration](image)

In this case the current was obtained from a 110 Volt receptacle and was limited by a potentiometer. The magnetic flux density $B$ is calculated by Ampere's law from [17]:

$$B = \mu_0 H = \mu_0 \int dH = \mu_0 \frac{1}{4 \pi r^2} \int X \cdot dl$$

(1)
where $\mu = 4\pi \times 10^{-7}$ H/m is the permeability of air

$r$ is the distance from the element, $dl$, of the coil to the point of measurement,

$I$ is the current in the coil.

The SI unit of measurement of the magnetic flux density $B$ is the Tesla (T) or (Wb/m$^2$). The commonly used CGS unit is the Gauss (G).

The lateral profile of the magnetic field of a transmission line should be measured at 1 m. above the ground, as is the electric field profile. The probe should be oriented for a maximum reading, "The magnetic field is generally not perpendicular to the ground, and the vertical component of the field is generally not coincident with the maximum field" [14].

In addition to the well known magnetic field source the transmission lines, the measurements were oriented toward the magnetic field sources which we deal with in our daily life; at home in the kitchen, in the living room, etc., and at work in the office, in the work place, etc., because we discovered that too much attention has been given to the magnetic field from power lines even though it has little magnetic field, and much less attention has been given to these sources even though they have high magnetic fields. As an example many household items emit magnetic fields, such as television, mixer, and electric blanket.
The magnetic field depends on the line current, and since line currents are always changing with load, the resulting magnetic field fluctuations are difficult to correlate with time. Examples of maximum and normal magnetic field are listed in table (1), Where:

M: the frame of the household appliance is made from a magnetic material.

NM: the frame of the household appliance is made from a nonmagnetic material.
<table>
<thead>
<tr>
<th>Appliance Name</th>
<th>The Maximum Magnetic Flux Density (Gauss)</th>
<th>The Normal Magnetic Flux Density (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU</td>
<td>$B = 0.02$</td>
<td>$B = 0.003$</td>
</tr>
<tr>
<td>Line printer</td>
<td>$B = 0.02$</td>
<td>$B = 0.004$</td>
</tr>
<tr>
<td>Toaster oven</td>
<td>$B = 0.5$</td>
<td>$B = 0.02$</td>
</tr>
<tr>
<td>Coffee maker</td>
<td>$B = 0.02$</td>
<td>$B = 0.01$</td>
</tr>
<tr>
<td>Dish washer</td>
<td>$B = 0.07$</td>
<td>$B = 0.02$</td>
</tr>
<tr>
<td>The appliance name</td>
<td>The normal magnetic flux density Gauss</td>
<td>The maximum magnetic flux density Gauss</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Dryer / Typical models/</td>
<td>B = 0.01</td>
<td>B = 0.01</td>
</tr>
<tr>
<td>Cloth washer / Typical models/</td>
<td>B = 0.4</td>
<td>B = 0.4</td>
</tr>
<tr>
<td>Blender / Oster Corporation / 120V, 370W, 25-60 Hz</td>
<td>B = 0.45</td>
<td>B = 1.5</td>
</tr>
<tr>
<td>Mixer / Suvill/ 120V, 90W 50-60Hz</td>
<td>B = 1.8</td>
<td>B = 0.02</td>
</tr>
<tr>
<td>The appliance name</td>
<td>The maximum magnetic flux density Gauss</td>
<td>The normal magnetic flux density Gauss</td>
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<tr>
<td>--------------------</td>
<td>----------------------------------------</td>
<td>----------------------------------------</td>
</tr>
<tr>
<td>Electric Oven</td>
<td>B = 0.32</td>
<td>B = 0.05</td>
</tr>
<tr>
<td></td>
<td>![Electric Oven Diagram]</td>
<td>![Electric Oven Diagram]</td>
</tr>
<tr>
<td></td>
<td>All elements were on</td>
<td></td>
</tr>
<tr>
<td>Microwave Oven</td>
<td>B = 1.0</td>
<td>B = 0.15</td>
</tr>
<tr>
<td></td>
<td>![Microwave Oven Diagram]</td>
<td>![Microwave Oven Diagram]</td>
</tr>
<tr>
<td></td>
<td>/Kenmore/</td>
<td>/Kenmore/</td>
</tr>
<tr>
<td>Microwave Oven</td>
<td>B = 1.3</td>
<td>B = 0.2</td>
</tr>
<tr>
<td></td>
<td>![Microwave Oven Diagram]</td>
<td>![Microwave Oven Diagram]</td>
</tr>
<tr>
<td></td>
<td>/Amana/</td>
<td>/Amana/</td>
</tr>
<tr>
<td>Food processor</td>
<td>B = 1.2</td>
<td>B = 0.03</td>
</tr>
<tr>
<td></td>
<td>![Food Processor Diagram]</td>
<td>![Food Processor Diagram]</td>
</tr>
<tr>
<td></td>
<td>/Farberware/</td>
<td>/Farberware/</td>
</tr>
<tr>
<td>The appliance name</td>
<td>The maximum magnetic flux density Gauss</td>
<td>The normal magnetic flux density Gauss</td>
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<tr>
<td>-------------------------</td>
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</tr>
<tr>
<td>Electric Drill</td>
<td>$B_1 = 8$ at high speed $B_2 = 4$ at low speed</td>
<td>$B_1 = 0.8$ at high speed $B_2 = 0.5$ at low speed</td>
</tr>
<tr>
<td>/Craftsman/</td>
<td></td>
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<tr>
<td>120Volt, 3 Amp.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refrigerator</td>
<td></td>
<td>$B = 0.02$</td>
</tr>
<tr>
<td>/Typical models/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Convection Oven</td>
<td>$B = 0.5$</td>
<td>$B = 0.04$</td>
</tr>
<tr>
<td>/Farberware/</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Macintosh computer lab.</td>
<td>$B = 0.14$</td>
<td>$B = 0.004$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>The appliance name</td>
<td>The maximum magnetic flux density in Gauss</td>
<td>The normal magnetic flux density in Gauss</td>
</tr>
<tr>
<td>--------------------</td>
<td>------------------------------------------</td>
<td>------------------------------------------</td>
</tr>
<tr>
<td>Electric Drill</td>
<td>$B = 2.5$</td>
<td>$B = 0.45$</td>
</tr>
<tr>
<td>/ Thor / one speed</td>
<td></td>
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<tr>
<td>115Volt, 3.1Amp.</td>
<td></td>
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<tr>
<td>Freezer</td>
<td>$B = 0.05$</td>
<td>$B = 0.002$</td>
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<tr>
<td>/ Typical models /</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Counter top range</td>
<td>$B = 0.07$</td>
<td></td>
</tr>
<tr>
<td>for handicapped</td>
<td></td>
<td></td>
</tr>
<tr>
<td>persons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformer</td>
<td>$B = 0.003$</td>
<td></td>
</tr>
<tr>
<td>13.6KV/220V 3Ø</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fig. (5) The magnetic field under a power line.
here are some other data that have been taken by:

* Jim Andrick, a Senior student.

** West Penn Power Company.

* Electric blankets:

  Single -control twin size: .060 G maximum located near the center.

  Double -control full size:

    left side: 0.053 Gauss max. located 2 ft. from side.

    right side: 0.061 Gauss max. located 2 ft. from side.

    middle: 0.081 Gauss max. near the center.

* Transmission line 345 KV (lines around 10m above surface)

<table>
<thead>
<tr>
<th>P(MW)</th>
<th>Q(MVAR)</th>
<th>I(A)</th>
<th>E(KV/M)</th>
<th>B(GAUSS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>390</td>
<td>15</td>
<td>650 lead</td>
<td>.6</td>
<td>.010</td>
</tr>
<tr>
<td>400</td>
<td>10</td>
<td>650 lag</td>
<td>.9</td>
<td>.005</td>
</tr>
<tr>
<td>723</td>
<td>125</td>
<td>1180 lag</td>
<td>.55</td>
<td>.020</td>
</tr>
<tr>
<td>740</td>
<td>40</td>
<td>1210 lag</td>
<td>.7</td>
<td>.022</td>
</tr>
</tbody>
</table>

* Transformer/18-345 kV/, Oil bath

  17.85 kV, 27 A, Pf .85 0.008 Gauss.

  344 kV, 1.2 kA, Pf .85 0.12 Gauss.

* Substation(18 kV/345 kV) 3Ø as it is indicated in Fig (6)

  at the surface P(2.21, 5.12, 0.0) 0.08 Gauss
at \( P(2.21, 5.12, 2.63) \) 1.8 Gauss

**Fig. 6** The magnetic field at a point \( P \) in a substation.

**Transmission line 500 kV**

<table>
<thead>
<tr>
<th>Distance (ft.)</th>
<th>0</th>
<th>20</th>
<th>50</th>
<th>80</th>
<th>100</th>
<th>150</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauss</td>
<td>0.05</td>
<td>0.048</td>
<td>0.036</td>
<td>0.029</td>
<td>0.023</td>
<td>0.01</td>
</tr>
</tbody>
</table>

[Fig. 7] gives us a better understanding of the data above.

- 325 Watt Soldering Gun: 10 - 25 Gauss
- Hair Dryer: 10 - 25 Gauss
- Can Opener: 5 - 10 Gauss
- Fluorescent Desk Lamp: 5 - 10 Gauss
Kitchen Range 5 - 10 Gauss
Electric Shaver 5 - 10 Gauss
Bench Grinder 1 - 5 Gauss
Food Mixer 1 - 5 Gauss
Color Television Set 1 - 5 Gauss
Electric Drill 1 - 5 Gauss
Conveyor belt (near the bottom) 0.025 Gauss
Fig. 7 The magnetic field of a 500kV, 2000A power line.
A very important aspect shown on figure (7) is the rapid reduction of the field magnitude with the increased distance from the transmission line. This fact illustrates the area of concern may be directly in the vicinity of the line and assuredly there can be no general overall detrimental effect from EHV transmission lines.

By reviewing these data carefully, it is clear that the maximum magnetic field is located almost on the body or the frame of many household appliances, and that is the area which is in contact with our body. We cannot ignore these high magnetic field values even though it is a short term exposure to the magnetic field. As a matter of fact, many people are dealing with these household items hours daily. One can mention workers in a restaurant spending the whole day in the kitchen, workers in a steel plant where the magnetic field is very high, or those who work for a telephone company, where a magnetic field exists. Many studies [2, 3, 6] suggest a link between these magnetic field sources and some kind of cancer.

For transmission lines, even though the values seem little compared to those of household appliances, but the long term exposure to the magnetic field day and night, makes it nevertheless a serious problem. In fact the studies we mentioned in the previous chapters suggest a possible link between cancer and magnetic fields from power lines. Also, it is important
to mention here that some studies suggest that magnetic field may promote brain tumor development [8], and that is the case mostly for those workers in high industrial environments like steel plants, accelerators, and conveyor welding belt, etc., in addition to those who work in electric companies where they are required to spend hours inside or around substations.

Finally, it is important to mention that although some of these fields are relatively small compared to the earth's magnetic field, the field around the earth is steady, while these small fields vary with time.
CHAPTER 5

The Magnetic Field of a Power Line

5.1- Calculating the Magnetic Field:

The magnetic fields from transmission lines are directly proportional to the current magnitude, and inversely proportional to the distance from the source d. Thus, the magnetic field is easy to calculate after taking into account the following factors:

1- A permeability constant is used everywhere, \( \mu = 4\pi 10^{-7} \, \text{H/m} \).

2- The line currents are known.

3- The unit vectors follow the right hand rule.

4- The magnetic flux density \( B = \mu H \).

5- The image depth is 800 m. Assuming that the earth is a real earth, the effect of the image conductors on the magnetic field at the ground level can be ignored because the image depth (800 m.) is a large distance compared to the height of the real conductors. The distance between the conductors and the earth is normally about 10 to 15 meters.

While the above definition states simply how the magnetic field is determined, the actual calculations are complex. The magnitudes are affected by: line geometry, number of circuits, height, size and separation of conductors, and position of the shield wires.
A single phase alternating current magnetic field at a point in space is a "vector that alternates its direction" [19]. A three phase alternating current magnetic field at a point in space is a "rotating vector varying in amplitude whose locus is an ellipse"[19]. The following graph shows the magnetic and the electric field surrounding a conductor.

Fig. 8 The magnetic and the electric fields surrounding a conductor.

Using the coordinate system described in Fig.(9) the magnetic field strength, \( H_{ij} \) at a distance, \( r_{ij} \), from a conductor with a current, \( I_i \), has an amplitude given by [17] as:

\[
\hat{H} = \frac{I_i}{2\pi r_{ij}} \left( -\frac{y_i - y_j}{r_{ij}} \hat{u}_x + \frac{x_i - x_j}{r_{ij}} \hat{u}_y \right)
\]

where \( \hat{u}_x \) & \( \hat{u}_y \) are the unit vectors in the direction of the horizontal and the
vertical axes respectively.

\[ \vec{r}_{i,j} \]

\( i \) is the current point.
\( j \) is the observation point.

Fig. 9 Coordinate system for magnetic field calculations.

The total magnetic field for a \( 3\theta \) transmission line is the sum of all the contributions from line currents. The magnetic flux density is:

\[ \vec{B} = \mu \vec{H} \]  \hspace{1cm} (3)

where:

\[ \mu = 4 \pi 10^{-7} \text{H/m} \]

Suppose we have a single circuit power line, like the one which is presented in [17], with line configuration presented in fig ( 10 ).
* Voltage = 800 KV  
* Flat configuration  
* Phase spacing 14 m.  
* Conductor height 18.5 m.  
* Overhead ground wires  
  - Height 30.7 m.  
  - Separation 22.1 m.

\[ I_A = -1000 - j 1732 \text{ Amp.} \]
\[ I_B = 2000 \text{ Amp.} \]
\[ I_C = -1000 + j 1732 \text{ Amp.} \]

Fig. 10 A single circuit power line.
To calculate the magnetic field intensity at the center O, it is important to notice that the magnetic field here is a vector and it has two components: X component and Y component.

In this case it can be seen from Fig. (11.a) that the magnetic field intensity from conductor A is represented roughly by $|OA_1|$, from conductor B by $|OB_1|$, and from conductor c by $|OC_1|$. Also it is important to add to this magnetic field intensity the magnetic field which is omitted from overhead ground wires as it is indicated in Fig. (11.a) where $|Og_1|$ and $|Og_2|$ represent these values.
Fig. 11.a The magnetic field due to each conductor of a power line.

(18.5 m. height, 14 m. separation)
Using equation (2) the magnetic field strength for conductor A from fig. (11.a) is:

\[ \vec{H}_{OA1} = 5.46 \vec{U}_x + j 7.17 \vec{U}_y \]

for conductor B from fig. (11.a):

\[ \vec{H}_{OB1} = -17.20 \vec{U}_x \]

for conductor C from fig. (11.a):

\[ \vec{H}_{OC1} = 5.46 \vec{U}_x + j 7.17 \vec{U}_y \]

the total magnetic field intensity is:

\[ \vec{H}_0 = (\vec{H}_{OA1x} + \vec{H}_{OB1x} + \vec{H}_{OC1x}) + j(\vec{H}_{OA1y} + \vec{H}_{OB1y} + \vec{H}_{OC1y}) \]

\[ = 15.65 \angle 113.65^\circ \]

That is the magnetic field intensity from the conductors A, B, C. It is important to find the magnetic field intensity, which emitted from the overhead ground wires at this point O, and add its values to the previous values.

The magnetic flux density is:

\[ B = \mu H = 15.65 \times 4 \pi \times 10^{-7} \times 10^4 = 0.1967 \text{ Gauss.} \]

5.2- **Possible Ways to Reduce The Magnetic Field Intensity** :

As a solution to reduce the amount of the magnetic fields emitted from power lines, it is possible to build a higher tower 1 m. or 2 m. higher,
the limitation for this is the economical factor. Also as a solution we can put the conductors as close as possible to each other, as long as the space between the conductors does not cross the distance which is allowed by the voltage. To see the effects, a 1 m. higher tower than the previous one was used and the magnetic field under it was found, and here are the results:

for conductor A from fig.(11.b):

\[ \vec{H}_{OA1} = 5.23 \, \vec{u}_x + j \, 6.66 \, \vec{u}_y \]

for conductor B from fig.(11.b):

\[ \vec{H}_{OB1} = -16.32 \, \vec{u}_x \]

for conductor C from fig.(11.b):

\[ \vec{H}_{OC1} = 5.23 \, \vec{u}_x + j \, 6.66 \, \vec{u}_y \]

The total magnetic field intensity is:

\[ \vec{H}_0 = ( -5.86 ) + j ( 13.32 ) \]

\[ = 14.55 \, \text{Gauss} \]

\[ B = \mu H = 0.1828 \, \text{Gauss} \]

as it is indicated in fig.(12).

In another try, the original tower was used but with a space between the conductors 1 m. less: (Height 18.5 m., Phase spacing 13 m.) and the results
are:

\[
\begin{align*}
\vec{H}_{OA1} &= 5.70 \hat{u}_x + 6.94 \hat{u}_y \\
\vec{H}_{OB1} &= -17.20 \hat{u}_x \\
\vec{H}_{OC1} &= 5.70 \hat{u}_x + 6.94 \hat{u}_y
\end{align*}
\]

\[
\begin{align*}
\vec{H}_0 &= 15.05 \hat{u}_x + 112.66 \hat{u}_y \\
B &= \mu H = 0.1891 \text{ Gauss}
\end{align*}
\]

As a combination of both higher tower and closer conductors: (1 m. higher tower, 1 m. closer conductors) as in figure (11.d), the results are:

\[
\begin{align*}
\vec{H}_{OA1} &= 5.65 \hat{u}_x + 6.52 \hat{u}_y \\
\vec{H}_{OB1} &= -13.58 \hat{u}_x \\
\vec{H}_{OC1} &= 5.65 \hat{u}_x + 6.52 \hat{u}_y
\end{align*}
\]

\[
\begin{align*}
\vec{H}_0 &= 13.23 \hat{u}_x + 99.91 \hat{u}_y \\
B &= \mu H = 0.1663 \text{ Gauss}
\end{align*}
\]

So by a combination of higher tower and closer conductors, we have reduced the magnetic field from a value of 0.1967 Gauss, to a value of 0.1663 Gauss.
Fig. 11.b The magnetic field due to each conductor of a power line.

(19.5 m. height, 14 m. separation)
Fig. 11.c The magnetic field due to each conductor of a power line.

(18.5 m. height, 13 m. separation)
Fig. 11.d The magnetic field due to each conductor of a power line.

(19.5 m. height, 13 m. separation)
Fig. 12 The magnetic field due to conductor currents of a 800kV, 2000A power line.
Fig. 13 Magnetic field due to earth currents of a 800kV, 2000 A power line from [17].
Fig. 14 The total magnetic field of a 800kV, 2000 A power line.
6.1- **Introduction**: Shielding is the only practical method of reducing or eliminating the magnetic field which is radiated from a source. A perfect shield will not allow the passage of either electrostatic or electromagnetic energy. Shielding action can be considered either from "the viewpoint of field theory, or circuit theory" [15]. From the viewpoint of field theory, by shielding the area of interest the shield reflects part and absorbs part of the magnetic wave, and the absorbed part attenuates as it passes through the shield. From the viewpoint of circuit theory, the magnetic field induces currents in the shield, these currents develop or produce a magnetic field, resulting in two fields which are out of phase and cancel each other.

It is usually advisable to shield the source, however, in practice sometimes this may not be possible and the desired equipment or object may have to be shielded.

Shielding materials of high conductivity, such as copper, aluminum, silver, etc., usually offer good shielding efficiency toward electric field. However, this does not apply toward magnetic field, because in some cases "with certain materials and at certain frequencies, the magnetic fields are practically not reflected at all" [17].
There are some general shielding requirements and design criteria should be established in order to get satisfactory shielding efficiency against magnetic fields, for example:

1- All sources of magnetic field should be included.

2- The best materials for shielding against the magnetic field are those with high permeability.

3- Good electrical continuity must be maintained throughout the shield.

6.2- **Shielding effectiveness**: When a shield is placed between a source and an object, the magnetic waves traveling toward the object suffer a loss in power or magnitude. "The loss in power is the shielding effectiveness of a shield" [14].

Shielding effectiveness, SE, could be expressed in dB by the following equation from [16] as:

\[
SE_{dB} = R_{dB} + A_{dB} + RR_{dB}
\]  

(4)

where \( R \) is the reflection loss in dB

\( A \) is the absorption loss in dB

\( RR \) is the re-reflection loss in dB

This shielding effectiveness, the sum of the three factors (R, A, RR) represents the total loss. The factor R represents the reflection of some of the electromagnetic energy which hits the shield, the factor A represents
the absorption (penetration) of the remaining energy, while the factor RR represents the re-reflection of some of the remaining energy inside the shield.

"Magnetic fields, are generally difficult to shield, particularly at low frequencies. So sometimes inserting a shield would not offer an effective shielding, but by a combination of methods, shielding can be accomplished. Materials that are excellent against high-impedance (Electric) fields offer very little shielding to low-impedance (Magnetic) fields at low frequencies because of their conductivity" [15]. The magnetic field induces eddy currents in the shield. These eddy currents, produce or develop a magnetic field of opposite polarity to the magnetic component of the source, canceling it out.

After the magnetic field enters a shield; it is the absorption loss through this shield that reduces the magnitude of the field. So in the design or in the process of choosing a shield, there are some steps should be followed:

1. The degree of required attenuation, this is probably the key, since the amount of attenuation is a function of the material and its thickness.
2. After specifying a particular material, the required thickness of the material must be considered so the desired attenuation can be achieved.
Figure (15) represents an electromagnetic wave propagating toward a shield surface. From a shielding point of view, the normal component and the parallel component of the propagating wave, are of our interest.

Fig. 15 Electromagnetic wave propagating toward a barrier surface.

The electromagnetic wave impedance is a function of:

- the impedance of the source, which generates the wave,
- the distance \( r \), from the source to the metal barrier measuring point,
- the frequency.

so the wave impedance \( Z_W \) is defined by [15]:

\[
Z_W = k Z_0
\]

where: \( Z_0 = \text{free space impedance} = \sqrt{\mu_0/\varepsilon_0} = 376.99 \ \Omega \)
\[ \mu_0 = \text{permeability of free space} \left( 4 \pi \times 10^{-7} \text{ H/m} \right) \]

\[ \varepsilon_0 = \text{permittivity of free space} \left( \frac{1}{36\pi} \right) \times 10^{-9} \text{ F/m} \]

\( k \): a factor depends on whether we are dealing with an electric field or a magnetic field, and whether it is a far or near field.

**Metal Impedance:**

Homogeneous materials are characterized by a quantity which known as the intrinsic impedance of the material \( Z_m \) depends upon both the permeability and the conductivity of the metal, and defined by [15] as:

\[ Z_m = \sqrt{\frac{j \omega \mu}{\sigma + j \omega \varepsilon}} \quad (6) \]

Metals are defined as conductive materials when conductivity is high relative or compared to air, such that \( \sigma \gg \omega \varepsilon \). Thus the intrinsic impedance of a metal (a shield) can be written as:

\[ Z_m = \sqrt{\frac{j \omega \mu}{\sigma}} = \sqrt{\frac{j 2\pi f \mu}{\sigma}} \]

\[ = (1 + j) \sqrt{\frac{\pi f \mu}{\sigma}} \quad \text{for} \ \sigma \gg \omega \varepsilon \quad (7) \]

where: \( \mu = \text{permeability of the material} \)

\[ \omega = 2 \pi f \ \text{radians/sec} \]
\[ \sigma = \text{conductivity in Siemens/meter} = \sigma_c \sigma_r \]

\[ \sigma_c = \text{conductivity of copper} = 5.8 \times 10^{-7} \Omega/m \]

\[ \sigma_r = \text{the relative conductivity of metal referred to Copper} \]

\[ \mu_r = \text{permeability of material relative to free space} \]

Here we have two different impedances, the wave impedance and the shield impedance, the mismatch between these two impedances or the change in the impedance which the wave will face as it travels will reflect part of the wave and will absorb the other part. The following presentation explain the details.

It is possible to write the shielding effectiveness (SE) by [15]:

\[
SE_{\text{dB}} = 20 \log_{10} \left( \frac{\text{Incident power density}}{\text{Transmitted power density}} \right)
\]

(6)

Where:

- Incident power density = power density at a measuring point before a shield is inserted.

- Transmitted power density = power density at the same measuring point after a shield is inserted.

The amount of attenuation or reduction of the magnetic field offered

\[
\]
by a shield depends upon three mechanisms as indicated. The first is a reflection of the wave by the shield. The second is an absorption of the wave by the shield as the wave passes through the shield. The third is a re-reflection that takes place as the wave hits the other side of the shield after passing through the metal, this normally happens an infinite number of times inside the metal.

Eq. (8) may be defined as:

$$SE_{dB} = 20 \log_{10} \left( \frac{H_b}{H_a} \right)$$  \hspace{1cm} (9)

Or it could be defined as:

$$SE_{dB} = 20 \log_{10} \left( \frac{B_b}{B_a} \right)$$  \hspace{1cm} (10)

where:

$B_b$: the magnetic flux density before a shield is inserted.

$B_a$: the magnetic flux density after a shield is inserted.

Fig. (16) shows a representation of shielding phenomena for a plane wave by [16] with some modification. It is detailed in fig. (17) and may be explained as follows:

First let us consider the incident field to be normalized. The first mechanism of shielding effectiveness, as we mentioned, is due to the reflection that occurs because of the impedance mismatch at the "air-metal
interface" [16].

Fig. 16 Representation of shielding phenomena for plane waves.

Fig. 17 Geometry of metal barrier used in explaining shielding effectiveness.
The normalized reflected field is defined by [16] as:

\[ \rho = \frac{1 - k}{1 + k} = -1 \text{ for } k \gg 1 \]

\[ = 0 \text{ for } k = 0 \]

\[ = +1 \text{ for } 0 \ll k < 1 \]  \hspace{1cm} (11)

where:

\[ k = \frac{Z_w}{Z_m} \]

(12)

\( Z_w = \) wave impedance as defined in eq.(5)

\( Z_m = \) Metal impedance as defined in eq.(7)

so the reflection coefficients are defined by [16] as:

\[ \rho_{am} = \frac{1 - K_{am}}{1 + K_{am}} \]  \hspace{1cm} (13)

\( \rho_{am} = \) Reflection coefficient at the air-to-metal interface.

\[ \rho_{ma} = \frac{K_{ma} - 1}{K_{ma} + 1} \]  \hspace{1cm} (14)

\( \rho_{ma} = \) Reflection coefficient at the metal-to-air interface.

The transmitted field, \( \Gamma_{am} \), just inside the left edge of the shield "air-to-metal interface" [16] is:

\[ \Gamma_{am} = 1 - \rho_{am} \]  \hspace{1cm} (15)

The field here undergoes an attenuation as it passes through the thickness
of the shield, which is the second mechanism of shielding effectiveness. The arriving field at the other side of the shield results in a lower field, and is described by [16]:

\[
\Gamma_{AR} = \Gamma_{am} e^{-\gamma t} = e^{-(\alpha + j\beta)t} \Gamma_{am}
\]

\[= e^{-(\alpha + j\beta)t} (1 - \rho_{am})\]  

(16)

where:

\[\gamma = \text{propagation constant} = \alpha + j\beta\]

\[\alpha = \text{attenuation constant}\]

\[\beta = \text{phase constant} = 2\pi/\lambda\]

\[t = \text{metal thickness}\].

The third mechanism of shielding effectiveness is due to re-reflection. The re-reflection, \(\Gamma_{RR}\), at the inside right edge of the (metal-to-air) interface of the shield of Fig. (17) from [16] is:

\[
\Gamma_{RR} = \rho_{ma} \Gamma_{AR}
\]

\[= e^{-\gamma t} \rho_{ma} (1 - \rho_{ma})\]  

(17)

Now the transmitted field, \(\Gamma_{RT}\), to the right just outside the shield is:
When all fields are combined, the relation may be expressed as [16]:

\[
\Gamma_{RT} = 1 - \rho_{ma} \Gamma_{AR}
\]

\[
= e^{-\gamma t} (1 - \rho_{am}) (1 - \rho_{ma})
\]  

(18)

Expressing the shielding effectiveness as a loss rather than a gain, and converting it to decibels the result could be expressed as [16]:

\[
SE_{dB} = 20 \log_{10} \left( \frac{1}{\Gamma_T} \right)
\]

\[
= 20 \log_{10} \left\{ e^{a t} \left[ \frac{(1+k)^2}{4k} \left(1 - \frac{(k-1)^2}{(k+1)^2} e^{-2\gamma t} \right) \right] \right\}
\]

\[
= A_{dB} + R_{dB} + RR_{dB}
\]  

(20)

where: Absorption loss  \( A_{dB} = 20 \log_{10} e^{at} = 8.686 \alpha t \)  

(21)
Reflection loss $R_{dB} = 20 \log_{10}(1 + k)^2/4k$ \hspace{1cm} (22)

Re-Reflection loss $RR_{dB} = 20 \log_{10}(1 - [(k-1)^2/(k+1)^2]e^{-2\gamma t})$ \hspace{1cm} (23)

let us now examine in further detail the three loss components:

Absorption loss:
It is possible to write equation (21) as:

$$A_{dB} = 8.686 \alpha t$$
$$= 8.686 t \sqrt{\pi \mu \sigma}$$

where: $\gamma = \alpha + j \beta$

$$= \sqrt{j \omega \mu (\sigma + j \omega \epsilon)}$$
$$= \sqrt{j \omega \mu \sigma} \quad \sigma \gg \omega \epsilon$$
$$= (1+j) \sqrt{\pi \mu \sigma}$$
$$\alpha = \beta = \sqrt{\pi \mu \sigma} \quad \text{for metals}$$
$$= 1.3143 \cdot t \cdot c \cdot \sqrt{\frac{\mu_r \sigma_r}{\mu \sigma}} \quad \text{dB} \quad (24)$$

where $\mu_r$ and $\sigma_r$, are the permeability and conductivity relative to copper.

Reflection loss:
Due to the impedance mismatch at the metal surface, we have the reflection loss which is the main contribution of the overall shielding effectiveness.

Thus, it is useful to substitute the impedances of $Z_w$ and $Z_m$ by their values from equations (5) and (7) in to equation (22), the result is:
where: $k = 2\pi r/\lambda = 2\pi f \sqrt{\mu_0 \varepsilon_0}$ for $H$ fields.

$$K = r \sqrt{2\pi f \sigma \mu_0 / \mu_r}$$

so the earlier reflection loss term in eq.(22) may be expanded in terms of the wave and metal impedance as [16]:

$$R_{dB} = 74.6 - 10 \log_{10}(\mu_r/f \sigma_r r^2) \text{ dB}$$

Re-reflection loss:

Equation (23) may be expressed in terms of wave and metal impedance as:

$$RR_{dB} = 20 \log_{10}\left(1 - \left[\frac{(K-1)^2}{(K+1)^2}\right] e^{-2\gamma t}\right)$$

$$= 20 \log_{10}\left[1 - e^{2(\alpha + j\beta)t}\right]$$

(27)

6.3-Shielding materials:

The general characteristics of shielding materials are to be homogeneous, independent of frequency, and linear. Many of the metals that the designer might expect are listed with their relative permeability and conductivity in table (2). "Nonmagnetic materials provide relatively poor absorption loss, all magnetic materials, on the other hand, have relative absorption loss values exceeding 2 and are relatively good absorbers of energy at low frequencies, compared to nonmagnetic materials" [16].
The proper value of $\mu_r$ for a magnetic shielding material is not a fixed number. Its value usually varies with the frequency. Mischoosing the proper value of $\mu_r$, can lead sometimes to an optimistic prediction of shielding effectiveness.

"The situation experienced by a shield material in real life is, of course even more complex. Shields are only used in the presence of alternating fields. So in the more general situation, several effects take place, including eddy current losses which are a function of (1)- magnetic field strength, (2)- frequency, (3)- distance to the metal barrier, (4)- metal thickness, and (5) metal permeability and resistivity" [15]. Thus it is concluded that unless all conditions are known, it is impossible to define an equivalent $\mu_r$ and to use directly the $\mu_r$ values in table (2).

6.4- Availability and application of Shielding Materials:

Several of the metals in table (2) are available off the shelf in sheet stock form from thickness of about "1/64th inch (0.4 mm) or less to about 1/8 inch (3.2mm) or more" [15]. Metals having thicknesses less than 1/64th inch are some times classified as foils. "Many of the high permeability metals come in foil thicknesses ranging from about 1 mil (25.4µm) to 10 mils (254µm). They are usually available in both sheet and tape form. The
foil stock is also available in the form of adhesive-backed foil and in rolls" [15].
<table>
<thead>
<tr>
<th>Metal</th>
<th>(2) Relative Conductivity $\sigma_T$</th>
<th>(3) Relative Permeability $\mu_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>1.064</td>
<td>1</td>
</tr>
<tr>
<td>Copper (solid)</td>
<td>1.00</td>
<td>1</td>
</tr>
<tr>
<td>Gold</td>
<td>.70</td>
<td>1</td>
</tr>
<tr>
<td>Aluminum (soft)</td>
<td>.63</td>
<td>1</td>
</tr>
<tr>
<td>Platinum</td>
<td>.17</td>
<td>1</td>
</tr>
<tr>
<td>Manganese</td>
<td>.039</td>
<td>1</td>
</tr>
<tr>
<td>Supermalloy</td>
<td>.023</td>
<td>100,000</td>
</tr>
<tr>
<td>Mumetal</td>
<td>.0289</td>
<td>20,000</td>
</tr>
<tr>
<td>Commercial Iron</td>
<td>.17</td>
<td>200</td>
</tr>
<tr>
<td>Nickel</td>
<td>.23</td>
<td>100</td>
</tr>
<tr>
<td>Silicon Iron</td>
<td>.037</td>
<td>1,500</td>
</tr>
<tr>
<td>50% Nickel Iron</td>
<td>.0384</td>
<td>1,000</td>
</tr>
<tr>
<td>Stainless Steel</td>
<td>.02</td>
<td>200</td>
</tr>
<tr>
<td>Hot-rolled silicon steel</td>
<td>.0384</td>
<td>1,500</td>
</tr>
</tbody>
</table>

Table (2) Relative conductivity and permeability of metals.
CHAPTER 7

SHIELDING METHODS

7.1- Shielding Factor and Shielding Effectiveness:

One method to minimize the effects of the magnetic field is to shield the area of interest from the magnetic field as we mentioned. Shielding reduces the magnetic field and consequently its effects. Because most field effects occur close to ground level and are a function of the magnitude of the unperturbed magnetic field at one meter above the ground, the reduction of this field is the primary objective of the shielding methods discussed in this section.

Different shielding methods represent alternative means of reaching specific objectives. However, neither cost evaluation nor complete analyses of advantages and disadvantages of the methods have been made in detail, because any choice depends on subjective considerations that are often a function of local conditions.

The magnetic field values which will be indicated during the discussion of this section are based on several measurements taken from areas and places around power lines and substations, where permanent magnetic field exists. Each shielding method changes the value of the magnetic field intensity from a value without the shield to a value with the
shield. A useful parameter to categorize the degree of shielding is the Shielding Factor (SF) defined as:

\[ B_i = B_e \times SF \]  \hspace{1cm} (28)

where: \( B_i \) : is the magnetic field at specific level with the shield present (Internal field).

\( B_e \) : is the unperturbed magnetic field with the shield (External field).

Also the Shielding effectiveness factor (\( SE_{dB} \)), as described in the previous chapter can be used as well. The concept of shielding factor and shielding effectiveness may be applied to objects in uniform or nonuniform field or to objects distance from ground, as in our case.

Assume that a magnetic field is induced by high-current conductor far from an object and the ground. A perfect shielding method would be a plane at the desired level. This would be impractical and hard to realize. A more practical and convenient method would be to shield the area or the object of interest.

After reviewing the properties of metals used for shielding, it is found that the most convenient magnetic shielding material is (MUmetal) which is a metal alloy that helps protect equipment from magnetic field interference.
The metal is available in flexible foil and in flat sheet stock. The foil is easily cut and shaped with scissors to fit the desired area. This metal also is available with different thicknesses ranging from 0.002 to 0.030 in. and with high or low permeability. In this study 2 pieces of an Mumetal of thickness 0.010 in. and 0.002 in. each were used. The relative permeability and the relative conductivity of the Mumetal are \( \mu_r = 20000, \sigma_r = 0.0289 \).

Now let us apply the theoretical study from the previous chapter to shield an object with Mumetal.

from equation (5):

\[
Z_w = k Z_0 = 39788.73 \ \Omega
\]

and from equation (7):

\[
Z_m = (1 + j) \sqrt{\frac{\pi \times 60 \times 20000 \times 4 \pi \times 10^{-7}}{5.8 \times 10^{-7} \times 0.0289}} = 168115.4 \ \Omega
\]

\[
K = \frac{Z_w}{Z_m} = 0.2367
\]

from equation (13):

\[
\rho_{em} = \frac{1 - 0.2367}{1 + 0.2367} = 0.617
\]

and from equation (14):
\[ r_{am} = \frac{0.2367 - 1}{0.2367 + 1} = -0.617 \]

The relative transmitted field of the air to metal barrier is from equation (15):

\[ \Gamma_{am} = 1 - r_{am} \]

\[ = 1 - 0.617 = 0.382 \]

The arriving field from equation (16):

\[ \Gamma_{AR} = \Gamma_{am} e^{-\gamma t} \]

\[ = 0.382 e^{-\sqrt{\frac{\pi f \mu \sigma}{t}}} \]

\[ = 0.382 e^{-\sqrt{\frac{\pi \times 60 \times 20000 \times 4 \pi \times 10^{-7} \times 0.0289 \times 10^{-7} \times 0.10}} \]

\[ = 0.382 \times 0.97 \]

\[ = 0.371 \]

The relative re-reflected field from equation (17):

\[ \Gamma_{RR} = r_{am} \Gamma_{AR} \]

\[ = 0.371 \times 0.617 \]

\[ = 0.228 \]

And the relative transmitted field from equation (18) is:
\[ \tau_{RT} = 1 - \tau_{RR} \]
\[ = e^{-\gamma t} (1 - \rho_{am})(1 - \rho_{ma}) \]
\[ = 0.97 (1 - 0.617)(1 - 0.617) \]
\[ = 0.141 \]

and in further details the loss components from eq. (24, 26, 27) are:

\[ A_{dB} = 1.3143 \times t_{cm} \sqrt{f \mu_{c} \sigma_{r}} \]
\[ = 1.3143 \times 0.025 \sqrt{60 \times 20000 \times 0.289} \]
\[ = 6.11 \text{ dB} \]

\[ R_{dB} = 74.6 - 10 \log_{10}(\mu_{r}/(60 \times 0.289 \times 10^2)) \]
\[ = 74.6 - 65.40 \]
\[ = 9.19 \text{ dB} \]

\[ RR_{dB} = 20 \log_{10}[1 - e^{-2 \times 0.00028 \times 0.025}] \]
\[ = 0.43 \text{ dB} \]

the total is \[ SE_{dB} = 6.11 + 9.19 + 0.43 \]
\[ = 15.73 \text{ dB} \]

7.2- **Shielding a hard hat with Mumetal**:  

The health hazard threat from power lines due to the magnetic field right now may be far from proven. However, the significant growing concern
among workers who spend hours every day near the presence of magnetic
fields, and due to some studies [8] suggesting a high risk of developing
cancer and brain tumor among workers in electric utilities, we decided it is
important to find a solution to the the problem. This could be done in many
different ways and for many different applications. We chose to do so by
shielding a hard hat from the magnetic field which the workers in
substations and steel plants are subject to. On the average the total
magnetic field in a substation is around 1.5 - 1.8 Gauss.

There are several different ways to shield a hat. They involve using
different procedures to form the shield and place it inside the hat. During
this process the objective was to find the most economical, and most
practical procedure.

The hat was placed ( without the shield ) in an area where a magnetic
field existed, here it is a magnetic field originated from a simulated power
line. Then the magnetic fields outside and inside the hat were measured
using the field-meter, let's call them External field and Internal field
respectively. It was noticed that the magnetic field was not attenuated,
since the hat made from plastic, it did not shield the magnetic field. The
shield was then placed inside the hat as shown by the graphs of figure ( 18,
20, 22 ) consequently. The Internal magnetic field was measured for
The following data and graphs show the External and the Internal magnetic field for different shielding methods (involving different thicknesses of the MUmetal as well).

The results are tabulated in table (3), as one can see different shielding methods indicate different SF and SE:

<table>
<thead>
<tr>
<th>External field (Gauss)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>.001</td>
<td>.00035</td>
<td>.00030</td>
<td>.0048</td>
<td>.00032</td>
<td>.0007</td>
<td>.00066</td>
<td></td>
</tr>
<tr>
<td>.007</td>
<td>.0022</td>
<td>.0016</td>
<td>.0045</td>
<td>.003</td>
<td>.0045</td>
<td>.0042</td>
<td></td>
</tr>
<tr>
<td>.015</td>
<td>.0052</td>
<td>.0046</td>
<td>.010</td>
<td>.007</td>
<td>.013</td>
<td>.010</td>
<td></td>
</tr>
<tr>
<td>.036</td>
<td>.0144</td>
<td>.0129</td>
<td>.026</td>
<td>.016</td>
<td>.026</td>
<td>.025</td>
<td></td>
</tr>
<tr>
<td>.10</td>
<td>.053</td>
<td>.030</td>
<td>.038</td>
<td>.030</td>
<td>.069</td>
<td>.065</td>
<td></td>
</tr>
<tr>
<td>.17</td>
<td>.057</td>
<td>.050</td>
<td>.072</td>
<td>.061</td>
<td>.12</td>
<td>.069</td>
<td></td>
</tr>
<tr>
<td>.30</td>
<td>.099</td>
<td>.090</td>
<td>.16</td>
<td>.12</td>
<td>.21</td>
<td>.19</td>
<td></td>
</tr>
<tr>
<td>.60</td>
<td>.175</td>
<td>.160</td>
<td>.26</td>
<td>.23</td>
<td>.45</td>
<td>.40</td>
<td></td>
</tr>
<tr>
<td>.70</td>
<td>.23</td>
<td>.20</td>
<td>.35</td>
<td>.29</td>
<td>.50</td>
<td>.45</td>
<td></td>
</tr>
<tr>
<td>1.0</td>
<td>.35</td>
<td>.30</td>
<td>.50</td>
<td>.45</td>
<td>.72</td>
<td>.62</td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>.53</td>
<td>.49</td>
<td>.71</td>
<td>.69</td>
<td>1.09</td>
<td>1.005</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: the External and the Internal magnetic fields for different shielding methods and different thicknesses.

The data in column 2 represent the Internal field for the shielding method illustrated in figure (18). The thickness in this method is 0.010 In. and the metal covers the whole hat from inside. As we know, there is a
little space between the hat outer shell and the head. The internal field was measured at the different points shown in figure (18) below.

\[ B_e = 0.7 \text{ Gauss} \]

Fig. 18 Illustration of a shielding method

(Full cover, 0.010 in.)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>chin strap</th>
<th>SF</th>
<th>SE_{dB}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010 in.</td>
<td>Full cover</td>
<td>No</td>
<td>0.32</td>
<td>9.66</td>
</tr>
</tbody>
</table>

Figure (19) shows the relation between \( B_e \) and \( B_i \) for this design.
Fig. 19 The relation between $B_e$ and $B_i$ for the shielding method of Fig. 18.
Then a chin strap was added to the hat as illustrated in figure (20), in order to cancel out the effect of the induced current created by the magnetic field around the edge of the shield.

The results are shown in column 3 of the table (3).

\[ B_e = 0.7 \text{ Gauss} \]

Fig. 20 Illustration of a shielding method

(Full cover, .010 in., chin strap).

<table>
<thead>
<tr>
<th>Thickness</th>
<th>Shield type</th>
<th>Chin strap</th>
<th>SF</th>
<th>( SE_{dB} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010 in.</td>
<td>Full cover</td>
<td>Yes</td>
<td>0.28</td>
<td>10.88</td>
</tr>
</tbody>
</table>

Figure (21) shows the relation between \( B_e \) and \( B_1 \) for this design.
Fig. 21 The relation between $B_6$ and $B_1$ for the shielding method of Fig. 20.
Taking in account the economical factor, the same previous procedure was repeated using the same shielding material but with a thickness of 0.002 In. Column 4 of table (3) tabulates the results.

\[ B_e = 0.7 \text{ Gauss} \]

Fig. 22 Illustration of a shielding method

( Full cover, 0.002 In.).

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>chin strap</th>
<th>SF</th>
<th>SE(_{dB})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>Full cover</td>
<td>No</td>
<td>0.37</td>
<td>8.60</td>
</tr>
</tbody>
</table>

Figure (23) shows the relation between \( B_e \) and \( B_i \) for this design.
Fig. 23 The relation between $B_e$ and $B_1$ for the shielding method of Fig. 22.
Also with the same thickness a chin was added to see the effects. Column 5 of table (3) tabulates the internal magnetic field for this case.

\[
B_e = 0.7 \text{ Gauss}
\]

Fig. 24 Illustration of a shielding method (Full cover, 0.002 in., chin strap).

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>Chin strap</th>
<th>SF</th>
<th>(SE_{dB})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002</td>
<td>Full cover</td>
<td>Yes</td>
<td>0.32</td>
<td>9.66</td>
</tr>
</tbody>
</table>

Figure (25) shows the relation between \(B_e\) and \(B_l\) for the last design.
Fig. 25 The relation between $B_e$ and $B_I$ for the shielding method of Fig. 24.
Also because of the importance of the economic factor, many different ways were investigated to form the shield, the objective was to use the least possible amount of shielding material (Mumetal). This led me to form a mesh of Mumetal. The shielding design is shown in figure (26), and the results are shown in column 6 of table (3) for a thickness of 0.002 in.

$$B_e = 0.7 \text{ Gauss}$$

Fig. 26 Illustration a shielding method (mesh, 0.002 in.)

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>chin strap</th>
<th>SF</th>
<th>$SE_{dB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002 in.</td>
<td>Mesh</td>
<td>No</td>
<td>0.71</td>
<td>2.92</td>
</tr>
</tbody>
</table>

Figure (27) shows the relation between $B_e$ and $B_t$ for the previous design.
Fig. 27 The relation between $B_e$ and $B_1$ for the shielding method of Fig. 26.
For the same mesh a chin strap was placed also and column 7 of table (3) shows the internal field values.

Figure (28) illustrates a shielding method (mesh, 0.002 in., chin strap).

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>Chin strap</th>
<th>SF</th>
<th>$SE_{dB}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.002 in.</td>
<td>Mesh</td>
<td>Yes</td>
<td>.64</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Figure (29) shows the relation between $B_e$ and $B_i$ for the mesh method with a chin strap. Column 7 of table (3) shows the results.
Fig. 29 The relation between $B_e$ and $B_i$ for the shielding method of Fig. 28.
Fig. 30 Comparison between $B_e$ and $B_l$ for three shielding methods (Full cover, .010 in. - Full cover, .002 in. - Mesh, .002 in.).
Fig. 31 Comparison between $B_e$ and $B_i$ for three shielding methods (Full cover, .010 in. - Full cover, .002 in. - Mesh, .002 in.) with a chin strap.
Fig. 32 Comparison between $B_e$ and $B_1$ for the shielding methods with the least internal field of Fig. 29 & 30.
A summary of the results is shown here:

<table>
<thead>
<tr>
<th>Thickness</th>
<th>The shield type</th>
<th>chin strap</th>
<th>SF</th>
<th>SE_{dB}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.010 in.</td>
<td>Full cover</td>
<td>No</td>
<td>0.32</td>
<td>9.66</td>
</tr>
<tr>
<td>0.010 in.</td>
<td>Full cover</td>
<td>Yes</td>
<td>0.28</td>
<td>10.88</td>
</tr>
<tr>
<td>0.002 in.</td>
<td>Full cover</td>
<td>No</td>
<td>0.37</td>
<td>8.60</td>
</tr>
<tr>
<td>0.002</td>
<td>Full cover</td>
<td>Yes</td>
<td>0.32</td>
<td>9.66</td>
</tr>
<tr>
<td>0.002 in.</td>
<td>Mesh</td>
<td>No</td>
<td>0.71</td>
<td>2.92</td>
</tr>
<tr>
<td>0.002 in.</td>
<td>Mesh</td>
<td>Yes</td>
<td>0.64</td>
<td>3.82</td>
</tr>
</tbody>
</table>

Observing the results shown by the graphs, taking into account the different thicknesses used, the different forms of shielding applied, the shielding factors and the shielding effectiveness, and the effects of the chin strap on the whole internal field, it is clear that figure (20) gives us the best shielding method. It indicates full cover of the internal hat with Mumetal of thickness 0.010 in., with a chin strap added to it. This is where we obtained the lowest internal magnetic field compared with the other shielding methods. Economically, a thickness of 0.010 in. of the Mumetal is cheaper than that of thickness 0.002 in.

According to the theoretical results, the shielding effectiveness is 15.75 dB as compared to 10.88 dB obtained experimentally for the same
shielding material. The error lies in the experimental results due to the discontinuity in the shield. Actually we could have had better shielding effectiveness for the same shielding type if we could have obtained a better way of forming the shield. In the way the shields were formed here, there was not very good continuity between the metal since the shield was actually 3 pieces due to the fabrication. I believe that the external magnetic field could have been reduced more and we could have gotten almost perfect results experimentally.

The Mumetal at this thickness is very light compared to the weight of the hard hat. Actually the Mumetal weighs 2.50 Oz. and the hard hat weighs 12 Oz. The Mumetal weight constitutes 20% of the weight of the hard hat. Therefore, this wouldn't cause an additional burden on the workers who use the hat.
CHAPTER 8

Conclusions and Recommendations for The Future

Since the beginning of time, the magnetic field intensity has not been large enough to create a considerable problem. But since the fifties, man-made EMF was the dominant factor of the earth's electromagnetic environment. A scientific look at our environment suggests that man has created biological problems at the cost of solving other problems. We can see now that it is dangerous to make such an alteration in our environment without first studying its potential biological impact. But the fact is that the only immediate effects of electricity at that time were shock and fires.

Unlike nuclear and X-ray radiation, EMFs are not powerful enough to break chemical bonds. As a result, many researchers have suggested that as long as EMFs do not cause shock or heating of body tissue, there is nothing to worry about. However, over the years more and more studies have suggested that EMFs can produce non-thermal effects, and the pressure to admit the non-thermal EMF effects has come from those who spent years to prove that electromagnetic fields can cause biological hazards.

Based on the collected data, we can say that man-made EMFs are present in the environment at levels capable of affecting biological functions. It follows, therefore, that uncontrolled exposure to such EMFs is
a potential public health risk.

There is a great public concern toward the EMF problem. So far, the action taken by regulatory committees is very limited for two reasons. First: there is no definite evidence on health effects. Second: there is pressure by the utility companies to expand the electric system. They argue that expanding the transmission system is efficient and economical.

There are, of course, various ways to reduce exposure to ac power line fields. Public opponents of such lines frequently propose undergrounding which is the most expensive and technically uncertain solution of these control strategies. The cost of a such proposal in the current time is normally around 6–7 times the cost of the existing system. Besides, if we do so the cost of the electricity will go up in order to cover the initial cost, which is not an acceptable solution. So we need to look for other solutions, for the current time and for the future.

For the current time, under the existing transmission line systems, we have no choice since we can not do anything to reduce the magnitude or the intensity of the magnetic field, therefore, the potential risk is still there. The best thing one can do is to avoid living under or close to transmission lines which carry high currents as much as possible. In the technology field we should think about possible ways to reduce the amount
of the existing magnetic field from the sources or to protect the workers from these magnetic fields, like what we have done to protect the workers in substations or welding plants where a hard hat was shielded with Mumetal to reduce the existing magnetic field.

In the future, it is important to start planning right away to think about reducing and limiting the magnetic field from the power lines, as some states have done. Recently, some states began drawing up regulations to limit the amount of electromagnetism that new power lines may generate. Six states already limit the intensity of electrical fields around power lines, but Florida would be the first to restrict magnetic field strength around its new power lines. Florida has proposed a standard which limits the strength of electromagnetic fields at the edge of new power line right-of-way to be between 30 and 500 milligauss. This could be achieved by using higher towers and using the minimum distance between the conductors, in addition to limiting the maximum current which could be carried by the transmission lines. Also we need to do something about the household items which, as we found out, emit a considerable amount of magnetic field since people are in contact with these items for hours daily. It is possible and inexpensive to reduce the magnetic field from these items. A senior student [25] succeeded in reducing the magnetic field from
an electric blanket by a factor of 6 - 8 times just by rewiring the blanket. The industry should manufacture these items in such a way that the magnetic field emitted is as low as possible.

Finally, it is important to mention here that the first connection between smoking and lung cancer did come from just such research. As with the smoking case, a direct cause and effect relationship between magnetic fields and leukemia requires many further studies, including follow up studies of large numbers of people over an extended period of time.
LIST OF REFERENCES


27. 50 & 60 Hertz field meter manual, Electric Field Measurements Co., West Stockbridge, Mass., Nov. 1978.