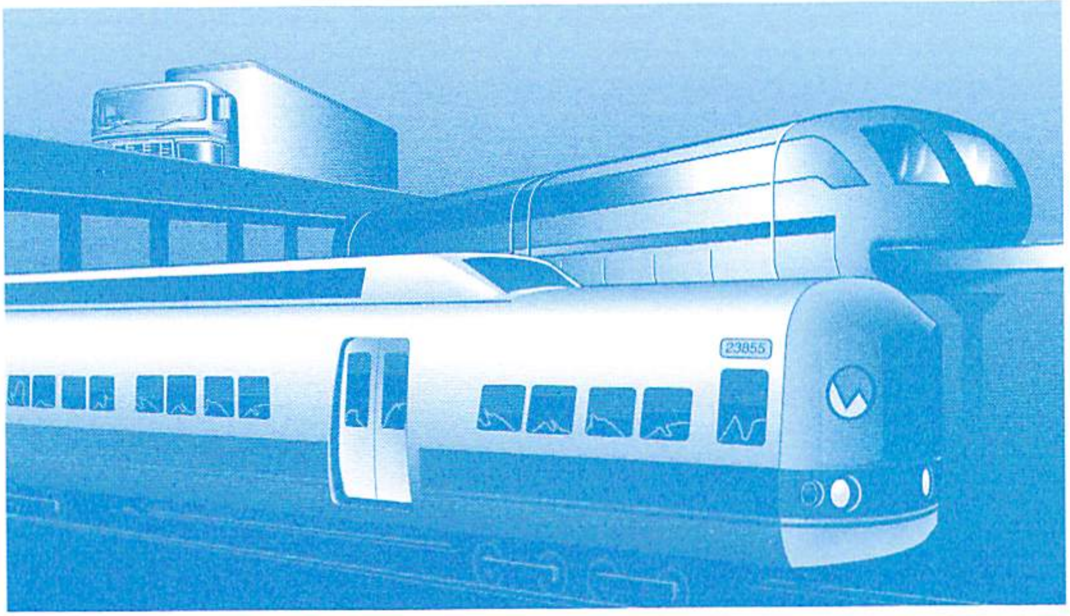
U. S. Department of Transportation
Federal Railroad Administration

Safety of High Speed Guided Ground Transportation Systems

Office of Research and Development
Washington, D.C. 20590

EMF Exposure Environments Summary Report



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August 1993

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13. ABSTRACT (Maximum 200 words)

This paper presents an overview of American exposure assessments for electric and magnetic fields (EMF) in the frequency range from 0 to 3 kHz. The exposure information available is very limited for all but a few occupations and sources of EMF. Much of the exposure assessment done to date has been conducted in conjunction with epidemiological studies. Beyond the shortcomings of using some of the published epidemiology studies, there are some serious obstacles to conducting definitive extreme low frequency (ELF)-EMF exposure assessments. The lack of a clear definition of what constitutes effective dose hampers the measurement of exposure considerably. Generally, the average power frequency magnetic flux density has been assumed to be the exposure measure of significance, however other parameters of the magnetic field are likely to be relevant as well.

The exposure assessments presented utilize different measurement approaches, protocols and equipment. A commentary has been provided discussing equipment and methods and they are briefly described for each study reviewed. The studies reviewed have been grouped into three categories: residential, occupational, and transportation. Currently, there is very little research available on transportation exposure environments. From the available data it appears that magnetically levitated (maglev) technology, as evidenced in the German TR-07 system, although a unique exposure environment, does not present any unusual ELF-EMF exposures to passengers of crew.

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PREFACE

This document was prepared for the U.S. Environmental Protection Agency (EPA), Office of Radiation and Indoor Air (ORIA), Radiation Studies Division (RSD), under an interagency agreement with the Department of Transportation (DOT) Research and Special Programs Administration (RSPA), John A. Volpe National Transportation Systems Center (Volpe Center), on behalf of the Federal Railroad Administration (FRA).

The purpose of this document is to identify, summarize, evaluate, and present results of exposure assessment studies of Americans exposed to electric and magnetic fields (EMFs) in the extremeley low frequency (ELF) range, from 0 to 3 kHz. The goals are to determine the extent to which the typical American exposure environment has been characterized, and to present the existing characterizations.

An understanding of typical American EMF exposure environments would provide a context for evaluating the exposures associated with new technologies such as magnetically levitated vehicles (maglev).

As a whole, the literature concerning interactions of extremely low frequency (ELF) EMF with biological systems has grown tremendously during the last several years. Concern regarding possible harmful health effects of human exposure to ELF-EMF has driven this growth. Epidemiologic studies and basic research on mechanisms of interaction have been particularly active research areas. The research community acknowledges, however, that exposure assessment requires further development.

In conducting the literature search and subsequent study reviews, emphasis has been placed on developing a broad picture of the assessment field, rather than extensively analyzing all literature in certain well-developed areas, such as magnetic fields associated with high-voltage transmission lines.

The primary literature sources are peer-reviewed journals. An increasing number of studies are not published in such a manner and are instead presented only at conferences or submitted as contractor's reports. Such studies have been included as available.

With a few notable exceptions, most of the exposure assessments reviewed have used instruments designed to measure power frequency (50-60 Hz) magnetic fields. Consequently, fields with frequencies outside of this range may not have been correctly characterized.

The technical monitor for this report was Dr. Aviva Brecher of the Volpe Center who manages the FRA's Research Program. Guidance and program support was provided by Robert Dorer, the High Speed Guided Ground Transportation Safety Program Manager at the Volpe Center. At the FRA, Arne Bang served as sponsor and is manager of Special Programs.

SYSTÈME INTERNATIONAL (SI) UNIT DEFINITIONS AND CONVERSIONS USED IN THIS REPORT

DISTANCE (ENGLISH-TO-SI CONVERSION):

1 inch (in)	= 2.54 centimeters (cm)	= 0.025 meters (m)
1 foot (ft)	= 30.5 centimeters (cm)	= 0.305 meters (m)
1 yard (yd)	= 91.4 centimeters (cm)	= 0.914 meters (m)
1 mile (mi)	= 1.61 kilometers (km)	= 1,610 meters (m)

ELECTRICAL QUANTITIES:

Electric Fields

1 volt/meter (V/m)	= 0.01 volts/centimeter (V/cm)
1 kilovolt/meter (kV/m)	= 1000 volts/meter (V/m)
1 kilovolt/meter (kV/m)	= 10 volts/centimeter (V/cm)

Magnetic Flux Densities (English-to-SI Conversion)

10,000 gauss (G)	= 1 tesla (T)
10 milligauss (mG)	= 1 microtesla (μT)
1 milligauss (mG)	= .1 microtesla (μT)
0.01 milligauss (mG)	= 1 nanotesla (nT)

Electromagnetic Frequency Bands

1 cycle per second	= 1 hertz (Hz)
1,000 cycles per second	= 1 kilohertz (kHz)

Ultra Low Frequency (ULF) Band	= 0 Hz to 3 Hz
Extreme Low Frequency (ELF) Band	= 3 Hz to 3 kHz
Very Low Frequency (VLF) Band	= 3 kHz to 30 kHz
Low Frequency (LF) Band	= 30 kHz to 300 kHz

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EXECUTIVE SUMMARY

This paper presents an overview of American exposure assessments for EMF in the frequency range from 0 to 3 kHz. Interest in human exposures to ELF and EMF is relatively recent and is motivated by a few epidemiology studies that suggest a link between ELF-EMF exposure and certain adverse health effects.

Currently, only very small portions of the American population have been studied for ELF-EMF exposure. Exposure assessments have been conducted for occupations with expected high exposures and as part of small case-control epidemiology studies of residential exposures. The usefulness of these exposure assessments vary considerably. A number of the epidemiology studies use only exposure surrogates such as job titles or wiring codes based on nearby outdoor power lines. Furthermore, epidemiology studies that make actual field measurements may only publish summary exposure statistics chosen for their utility to the epidemiology study.

Beyond the shortcomings of using some of the published epidemiology studies, there are some serious obstacles to conducting definitive ELF-EMF exposure assessments. The primary hindrance is the fact that there is no proven measure of dose when examining potentially adverse health effects of ELF-EMF. The lack of a clear definition of what constitutes effective dose hampers the measurement of exposure considerably. Attention has been directed towards magnetic fields and away from electric fields by laboratory and epidemiology studies. Generally, the average power frequency magnetic flux density has been assumed to be the exposure measure of significance, however, this is only an assumption and other parameters of the magnetic field may be relevant also. Other possible exposure metrics have been proposed and are discussed under ongoing research.

The exposure assessments presented utilize different measurement approaches, protocols and equipment. A commentary has been provided discussing equipment and methods and they are briefly described for each study reviewed. The studies reviewed have been grouped into three categories: residential, occupational, and transportation. Currently, there is very little research available on transportation exposure environments. From the available data it appears that maglev technology, as evidenced in the German TR-07 system, although a unique exposure environment, does not present any unusual ELF-EMF exposures to passengers or crew.

1. TECHNICAL BACKGROUND: FIELDS AND MEASUREMENTS

1.1 CHAPTER OVERVIEW

This chapter provides technical background for the understanding of the exposure information presented in chapters two through four and the commentary found in chapters five and six. This chapter is intended for an audience with a technical background. Section 1.2, "Definitions and Units," discusses basic concepts relating to electricity and magnetism, as well as units and terminology used in the paper. Section 1.3, "Characteristics of ELF-EMF," describes the ELF and EMF examined in this paper. Section 1.4, "EMF Measurements," provides a discussion on devices, measurement strategies and exposure metrics relevant to the exposure studies surveyed. Section 1.5, "The Natural ELF-EMF Environment," describes naturally occurring ELF fields and their relevance to the exposure studies surveyed. Section 1.6, "Data Quality," discusses the evaluation scale applied to the exposure assessments surveyed.

1.2 DEFINITIONS AND UNITS

Classical electrodynamics has been fairly well understood for over a century. While there is no dispute concerning the basic laws, different systems of measurement have produced different definitions of basic quantities, different units, and equations with additional or missing constants. This section presents the terminology and units used in this paper and provides a table of conversions. A glossary has been included for the convenience of the reader.

The electric field is characterized by the electric field strength, **E**. Electric field strength is a vector quantity (denoted by boldface) composed of three orthogonal vector components, $\mathbf{E}_x$, $\mathbf{E}_y$, and $\mathbf{E}_z$. Generally, only the magnitude or scalar value of **E**, (denoted as E) is of interest in this paper:

$$E = |\boldsymbol{E}| = \sqrt{E_x^2+E_y^2+E_z^2}$$

The unit used to measure E in this paper is the volt per meter (V/m) a unit in the MKS system (a system of units that uses the meter, kilogram, and second as basic quantities).

The analogous measure of the magnetic field is the magnetic field strength, **H**. The quantity used to characterize the magnetic field in this paper, however, is the magnetic flux density, **B**. The relation between the two magnetic quantities is:

$$\boldsymbol{B} = \mu \boldsymbol{H}$$

where μ is known as the magnetic permeability. Magnetic permeability is a characteristic of a particular medium. Air and most other nonmagnetic media have about the same permeability as a vacuum, symbolized as μ_o. The MKS unit for B is the Tesla, however, the cgs (a system of units based on the centimeter, gram, and second) unit of Gauss is used in this paper (1 Tesla = 10,000 Gauss). Typical values of B will be in the milligauss range (1 mG = 0.1 μT).

Table 1-1 presents selected quantities and units in the SI system (an internationally accepted variation of the MKS system) and shows the corresponding cgs unit and equivalent value.

The choice of quantities and units in this paper corresponds with common usage in this country. The terms "field" and "field strength" will be used to refer to both B and E.

TABLE 1-1. SELECTED ELECTRIC AND MAGNETIC QUANTITIES AND UNITS

Entity	Symbol	SI Unit	Equivalent cgs Unit
Frequency	f,ν	1 hertz (Hz)	1 cycle/sec
Electric field strength	E	1 volt/meter (V/m)	1/3 x 10^{-4} statvolt/cm
Electric flux density	D	1 coulomb/m^2 (C/m^2)	12π x 10^5 statcoulomb/cm^2
Capacitance	C	1 farad (F)	$1/(4\pi\epsilon_o) \approx 9 \times 10^{11}$ cm
Current	I	1 ampere (A)	3 x 10^9 statampere
Current density	J	1 ampere/m^2 (A/m^2)	3 x 10^5 statampere/cm^2
Electric charge	q	1 coulomb (C)	3 x 10^9 statcoulomb (esu)
Impedance	Z	1 ohm (Ω)	$4\pi\epsilon_o \approx 1/9 \times 10^{-11}$ s/cm
Magnetic field strength	H	1 amp per meter (A/m)	4π x 10^{-3} oersted
Magnetic flux density	B	1 tesla (T)	10^4 gauss (1 mG = 0.1 μT)
Permittivity	ϵ	1 farad/m (F/m)	
Permeability	μ	1 henry/m (H/m)	
Permittivity of vacuum	ϵ_o	$\epsilon_o = 8.854 \times 10^{-12}$ F/m	36π x 10^9
Permeability of vacuum	μ_o	$\mu_o = 12.57 \times 10^{-7}$ H/m	$1/4\pi$ x 10^7

1.3 CHARACTERISTICS OF ELF-EMF

This paper examines EMFs in the frequency range from 0 to 3,000 Hz (3 kHz). While there is not universal agreement on the exact frequency range denoted by the term ELF, in this paper it will refer to the entire frequency range from 0 to 3 kHz. The wavelengths in this frequency range vary from infinite in the case of a static (0 Hz) field to about 100 km for a 3 kHz field. Consequently, almost all exposures will occur in what is termed the near zone. The far zone exists at distances from a source much greater than the wavelength. In these far field conditions E and B exhibit a fixed amplitude relationship. In the near zone that exists between a source and its far zone, E and B do not have a fixed amplitude relationship. There is a trend to recognize this decoupling and speak of "electric and magnetic" rather than "electromagnetic" fields when discussing extremely low frequencies.

The area within about one half wavelength from the field source is termed the reactive near field. In this region, energy is pulsed back and forth between the source and the field, instead of being radiated away. Field strengths diminish quickly with distance in the reactive near zone compared to the far zone.

The primary frequency of the anthropogenic EM environment is the power frequency of 60 Hz used for electricity in this country. This sinusoidally alternating current (AC) is used to allow better transmission over long distances. Since EMF produced by an AC also alternate at that frequency, most ELF fields encountered are 60 Hz. Although current is supplied as a sinusoidal 60 Hz signal, certain devices may distort the signal and create local fields with distorted waveforms. These distortions can be put back onto local distribution lines.

Certain loads, such as the electric motor with commutators found in many home appliances, introduce harmonic distortion. Harmonic distortion adds frequency components to the signal other than the original (fundamental) frequency. Harmonics are integral multiples of the fundamental frequency, with the odd harmonics predominating. The third harmonic (180 Hz) is the primary harmonic found in 60 Hz power environments.

Another form of distortion is the transient. A transient occurs when a system suddenly switches from one state to another, such as when a device is turned on or off. Transients are short lived (in the msec to μsec range), high frequency (from 10 kHz to several MHz) signals. Any device switching on or off can produce a transient. Devices such as dimmer switches, motor speed controllers, and switching regulators in appliances produce significant transients.

When fields from multiple sources are superimposed, the resulting magnetic field is further complicated. Although each source may be linearly polarized, the resulting field generally will not be. The implications of nonlinear polarization are discussed under Measurement Devices.

In addition to the complexities mentioned above, EMF generally vary greatly over time and space. This being the case, it is virtually impossible to completely characterize the ELF-EMF environment over any sizable volume or length of time.

This paper will discuss the different methods and parameters used to characterize ambient levels of ELF-EMF. The equipment and methodologies used will be summarized and the data obtained will be presented.

1.4 EMF MEASUREMENTS

1.4.1 Measurement Devices

Device operation

Most devices used to measure ELF magnetic fields are based on the Faraday effect meter. Such a device measures the voltage produced on a coil by a changing flux density. The voltage induced in the coil (V) is given by:

$$V = n\ A\ \cos\theta\ \frac{dB}{dt}$$

where:

n is the number of turns in the coil

A is the area of the sensor coil

θ is the angle between the magnetic flux density vector and the normal axis of the coil

B is the average magnetic flux density vector over the area of the coil

It can be seen that the voltage is proportional to the time rate of change of the component of the average magnetic flux density perpendicular to the coil area. It is also proportional to the area and number of turns in the coil. The important differences between such measurement devices arise from: 1) the number of coils, 2) the way the voltage signal is processed, and 3) the way in which data is displayed or stored. The parameters that characterize device performance are: bandwidth; frequency response; accuracy; range; and data capacity.

Number of Coils

Sophisticated data-logging equipment generally uses three coils to make simultaneous measurements of the three orthogonal components of the vector quantity **B**, from which the magnitude of the field is calculated. Some devices, however, utilize a single pick-up coil. The usual procedure for making a measurement with a single coil is to rotate the coil in each of three orthogonal planes and record the maximum value. For the case of a linearly polarized field this procedure will yield the correct magnitude of B. However, to the extent that the field is not linearly polarized, the use of a single coil will introduce an error into the measurement. The worst case scenario occurs when the field is circularly polarized. In this situation, reliance on the maximum value recorded will underestimate the actual field by 29%. A measure of the response of a single coil device is given by the maximum component ratio, m_r:

$$m_r = \frac{B_{max}}{B_{60Hz}}$$

where B_{max} is the maximum B that would be measured with a single coil and B_{60Hz} is the true magnitude of the 60 Hz field. Possible values of m_r range from a worst case of 0.707 for a circularly polarized field to 1 for a linearly polarized field. Table 1-2 presents the distribution of m_r (in percent) over a database of residential measurements. For example, the first percentile value of m_r is 77.6 percent, meaning that for one percent of the measurements only 77.6 percent or less of the true 60 Hz field would have been detected by a single coil meter.

TABLE 1-2. DISTRIBUTION OF MAGNETIC FIELD PARAMETERS IN 18 RESIDENCES[a]

Quantity	Unit	Min	Percentile of measurements less than quantity							Max	Mean
			0.1	1	10	50	90	99	99.9		
m_r	%	70.9	73.2	77.6	88.2	98.0	99.9	100	100	100	97.0
f_r	%	13.6	46.7	70.0	92.5	99.0	99.8	100	100	100	98.0

[a] F.M Dietrich, W.E. Feero, D.C. Robertson and, R.M. Sicree, "Measurement of Power System Magnetic Fields by Waveform Capture," EPRI Final Report TR-100061 (1992).

Bandwidth

The bandwidth is the range of frequencies over which the device responds. Some devices have a narrow bandwidth centered on the power frequencies of 50 or 60 Hz. Other devices respond to a much broader range of frequencies, for example from 10 to 1,000 Hz. Some devices can be operated in either narrowband or broadband mode.

A measure that describes the response of a narrowband device to a field with harmonics is the fundamental ratio, f_r:

$$f_r = \frac{B_{60Hz}}{B_{rms}}$$

where B_{60Hz} is the 60 Hz fundamental component of the B-field that would be measured with a narrowband device and B_{rms} is the rms value of the total field including harmonics. Preliminary measurements made in 18 homes indicate that narrowband devices closely approximate the true rms total value most of the time. The distribution of f_r (in percent) for this data set is shown in Table 1-2. While the data set includes almost 300,000 samples, it can not be taken to be representative of all residences.

Signal Processing

The voltage output from a Faraday coil passes through two stages of processing. In the first processing stage, the voltage passes through either an integrator or a scaler. An integrator produces an output proportional to the actual B-field. A scaler uses a divider circuit to produce an output that is still proportional to the time derivative of B but is in the units of B. An integrator gives a flat frequency response and a scaler gives a linear response. The final stage is the voltage detector. There are three detector types: true rms, average rms, and corrected peak. Average rms and corrected peak detectors are scaled to read in rms units at 60 Hz, however they will introduce an error in the presence of harmonics.

Frequency Response

The response of an electronic device is a relation between the input and output. The frequency response curve is a plot that shows the relative performance of the instrument across a wide frequency range, often scaled to the response at 60 Hz for ELF measurement devices. There are two common types of frequency-response curves: flat and linear. A flat curve weights all frequencies equally so that the device gives a true reading for any frequency within the operative bandwidth. A linear frequency response curve weights response linearly with frequency, so that there is a greater response for fields of higher frequency. Table 1-3 presents the measured response of six common gaussmeters at 60 Hz and the third, fifth and ninth harmonics.

TABLE 1-3. MEASURED FREQUENCY RESPONSE FOR SELECTED GAUSSMETERS[a]

Meter (Manufacturer/model/response type)	Response Per Unit (at 10 mG)			
	@ 60 Hz	@ 180 Hz	@ 300 Hz	@540 Hz
EFM/ 116+[b]/linear	0.945	1.775	1.985	2.084
Holaday/ HI-3600-02/flat	0.982	0.853	0.652	0.372
Monitor/ 42B-1/ flat mode	1.030	0.988	0.975	0.955
Monitor/ 42B-1/ linear mode	0.994	2.747	4.591	8.105
Integrity/ IER-109/ narrow band	0.981	0.088	0.060	0.025
EFM/ EMDEX-C/ flat	0.928	0.761	0.507	0.265

[a] adapted from "An Evaluation of Instrumentation Used to Measure AC Power System Magnetic Fields," presented by the IEEE Magnetic Fields Task Force at the IEEE/PES 1990 Summer Meeting, Minneapolis, MN, July 15-19, 1990.
[b] used with a Fluke 27 multimeter.

In situations where significant higher frequency harmonics are present, a linear response meter will tend to overstate the actual flux density and a narrowband meter will understate the flux density. In residences studied, it has been shown that the 60 Hz frequency component dominates the total flux density and other frequencies are not important contributors, particularly at high flux densities.[1]

Any device other than a three axis, integrating, broadband, true rms meter will not measure the total B-field when the field is not linearly polarized and has frequency components in addition to 60 Hz. The degree to which an error is introduced is dependent on the characteristics of the field being measured and the device used. A study was performed that modelled device responses over a database of residential waveform measurements.[2] Data from this study of 18 residences indicated that devices that use divider circuits to scale voltages recorded values that average 22 to 135 percent higher than the actual total flux density. Devices of this type that use corrected peak voltage detectors have the highest variations.

Hall Effect Devices

Some magnetic flux density measurement devices utilize a completely different principle: the Hall effect. The Hall effect arises from Lorentzian forces acting on charge carriers. The effect causes a voltage to be produced when a current-carrying conductor is subjected to a magnetic field, due to the drift of charge carriers in a direction perpendicular to both the B field and the current. The voltage produced is directly proportional to both the magnetic flux density and the current density. Since the Hall voltage is proportional to the B field itself, such devices can measure static as well as alternating fields. The devices made by F.W. Bell listed in table 1-4 are all Hall effect devices.

Magnetometer Overview

Table 1-4 lists product specifications for a number of gaussmeters and personal exposure meters currently available or in use. The table is not exhaustive, however it does give an overview of current instrumentation.

Waveform Capture Systems

Waveform capture systems are broadband recording devices with very fast sampling times that allow characterization of a wave amplitude during a single period. Such devices are capable of examining field amplitudes over both time and frequency, and can generally sample from a number of locations simultaneously. One particular system, developed by the Electric Power Research Institute (EPRI) for monitoring power system fields and related environmental variables, is the *Multiwave*™ Monitoring System. Several studies reviewed in this paper use this particular system. The *Multiwave*™ system consists of a central microcomputer-based control unit and a number of signal generating peripheral devices. The probes are placed in the locations for measurements and cabled to the control unit through multiplexors. The control unit sends dc power and control commands to the probes and multiplexors. Analog signals from multiple probes are buffered by the multiplexors and sent to the central control unit where the signals are digitized and analyzed. Up to eight probes can be connected to each multiplexor and up to five multiplexors can be connected to the control unit. Probes may be as far as 500 ft from the control unit. The different types of probes are identical in the way they interface with the control unit and are interchangeable. Probe types include AC magnetic field, DC magnetic field, AC current, AC voltage and primary voltage current.

Multiwave™ System Specifications (adapted from ref. 1)

Channel Capacity: 120 channels accommodate 40 probes.

Sampling Rate: Waveform digitization for standard operation is 3,840 samples per second per channel (64 samples per 60 Hz cycle). It can accommodate up to 5,000 samples per second for all channels or up to 75,000 samples per second for a single channel.

AC Magnetic Probe: Three air core coils. Range: 0.01 mG to 1000 mG. Bandwidth: 12 Hz to 2 kHZ (±5%). Magnitude accuracy: ±2% typical, ±4% worst case. Phase accuracy: ±5% for 60 to 780 Hz.

TABLE 1-4. GAUSSMETERS AND PERSONAL MONITORING DEVICES[a]

Company, Address	Meter Name	Bandwidth (other bands)	Min-Max	Size/Weight (inches/lbs)	Accuracy[b]	Other
F.W. Bell, Inc. 6120 Hanging Moss Road Orlando, FL 32807	Model 4048 Model 9200 Model 9500 Model 9903	0-12 kHz 10 Hz-10 kHz 20 Hz-10 kHz 20 Hz-50 kHz	0.1 G-20 kG 10 mG-20 kG 1 mG-300 kG 1 mG-3 MG	4x7x1.8/1 8.8x4.5x11/8 14x7.5x14/19 18x7.5x16/36	± 2.5% ± 2.5% ± 1% ± 1%	Hall effect Hall effect Hall effect Hall effect
Combinova AB c/o Ergonomics, Inc. PO Box 964 Southampton, PA 18966	MFM10	5 Hz-1 kHz	0.1 mG-10 G	15.2x4.6x10/6.6	< ± 2%	
Dexsil Corporation One Hamden Park Drive Hamden, CO 06517	Field Star 1000	55-65 Hz	.04 mG - 1 G	7.5x4x2.75/1.3	± 1%	three axis true rms
Electric Field Measurements (EFM) Box 326 W. Stockbridge, MA 01266	Model 116 Model 116+ EMDEX-C	60 Hz 60 Hz 40-400 Hz	0.1 mG-200 G 0.1 mG-200 G 0.1 mG-25 G	1.5x1.5x2/0.4 4.75x2.5x9/2 1.8x4.8x6.5/1.3	± 3% ± 3% ± 3%	 single axis three axis, avg rms
Electric Power Research Institute (EPRI) PO Box 10412 Palo Alto, CA 94303	3D-AMEX	40-800 Hz	0.35-150 mG	1x2x4/0.3	± 5%	three axis integrating dosimeter
Electro-Magnetics Design, Inc. 9100 W. Bloomington Freeway Bloomington, MN 55431	ACGM-1 ACGM-2	20-150 Hz 20-150 Hz	0.1 mG-9 G 0.1 μG-9 G	2x4x7/1 2x4x7/1	± 1% ± 1%	single axis single axis
Holaday Industries, Inc. 14825 Martin Drive Eden Prairie, MN 55344	HI-3600-02	50/60 Hz	0.1 mG-20 G	1.8x3.5x17/2.8 (with 8" diameter sensor)	± 5%	single axis true rms E field also
Integrity Electronics and Research, Inc. 558 Breckenridge Street Buffalo, NY 14222	IER-109	55-65 Hz	1 μG-2 G	3x4x7/0.9	± 2%	single axis

TABLE 1-4. GAUSSMETERS AND PERSONAL MONITORING DEVICES (continued)

Company, Address	Meter Name	Bandwidth (other bands)	Min-Max	Size/Weight (inches/lbs)	Accuracy[b]	Other
MacIntyre Electronics Design Associates, Inc. 11260 Roger Bacon Drive Reston, VA 22090	μMAG	0-100 Hz	10 μG-2 G	4x7.5x2/0.9	± 0.5%	
Monitor Industries 6112 Fourmile Canyon Boulder, CO 80302	Model 42B	40 Hz-1 kHz	0.01 mG-2.5 G	2.1x3.1x7.8/1.8	± 7-10%	single axis avg rms
Positron Industries, Inc. 5101 Buchan Street Montreal, Quebec H4P 2R9 Canada	"Dosimeter" 378101	60 Hz (5-20 MHz)	60 μG-4 G	6x3x1/0.5	± 5%	
Safe Computing Co. 368 Hillside Avenue Needham, MA 02194	Safe Meter Professional Meter	20 Hz-30 kHz (5-70 kHz) 5 Hz-1 kHz (1-40 kHz)	1 μG-230 mG 0.1-200 mG	6x3x4/0.7 5.5x3.3x1.5/0.8	± 5% ± 3%	
Schaefer Applied Technology 200 Milton Street, Unit 8R Dedham, MA 02026	Model EM1	10 Hz-1 kHz	0.45-10+ mG	5.5x3x1.5/0.8	± 5%	
Shoden Corp. 2-23 Ojima 1-chome, koto-kn Tokyo 136 Japan	MFM-12A	60 Hz (25 Hz-10 kHz)	0.1 mG-20 G	6x4x2/3	± 5%	
Sydkraft AB Carl Gustafs Väg 4 s-217 01 Malmö Sweden	MFDM 3D MFDM	50/60 Hz 50/60 Hz	10 μG-20 G 10 μG-2 G	16x12x5/2 24x17x8/24	± 5% ± 2%	
Walker Scientific, Inc. Rockdale Street Worcester, MA 01606	ELF-50 Field Monitor MF-5D Fluxmeter	50/60 Hz 0/100 kHz	1 mG-51.2 G 0.1 mG - 200 kG	6x3.3x1.5/0.5 2.8x8.5x9.3/5	± 1%	

[a] adapted from *Microwave News*, Jan/Feb, 1990 & manufacturer information.

[b] estimated accuracy.

DC Magnetic Probe: Three axis fluxgate magnetometer (measures static and slowly varying fields by varying the magnetic permeability of a special magnetic alloy core, which produces an electrical signal. The signal is processed into a proportional voltage output which is then input to a DC voltage probe). Range: 0.1 mG to 1000 mG. Bandwidth: 0 to 1 Hz. Accuracy: ± 3% typical, ± 5% worst case.

Personal Exposure Meters

A pair of personal exposure meters that merit individual discussion because of their prevalence of use in the literature reviewed are the EMDEX-C and the EMDEX II.

The EMDEX units (EMF Digital Exposure system) were developed for EPRI. The EMDEX-C is the commercially available version of the EMDEX and the EMDEX II is the latest version of the device.

The EMDEX units are both relatively compact and lightweight data recording units suitable for use in personal monitoring (see table 1-4). Both devices use three orthogonal coils to measure the **B** field and then calculate the resultant and record the information at specified sampling intervals. Both are broadband linear-response devices (40 to 400 Hz ± 3 db for the C and 40 to 800 Hz ± 2 db for the II) with the II having an additional harmonic bandwidth (100 to 800 Hz ± 2 db).[3,4] The EMDEX II incorporates signal rejection circuitry that gives a very sharp drop-off in response at lower frequencies. The devices are capable of accepting a current input from an attached electric field sensor. The devices record the values of all three B-field components and the signal from the probe input when triggered. The devices can be programmed to record data at regular time intervals or when triggered by a mapping wheel or set to simply display values on an LCD readout. Stored information can be downloaded to a microcomputer for analysis.

The AMEX-3D

The AMEX-3D (Average Magnetic Field Exposure) is a recently developed personal exposure meter designed to be small and lightweight (see table 1-4).[5] It warrants discussion because of its unique design and the fact that it represents that latest generation of personal monitoring devices. The AMEX-3D achieves such low mass, volume (and price) by recording only one parameter, the total cumulative exposure, X, received between time 0 and T:

$$X=\int_0^T B_{rms}\,dt$$

where B_{rms} is the root-mean-square flux density. Dividing the cumulative exposure, X, by the exposure period, T, yields the time-weighted average exposure. A special reader device is required to retrieve the data from the unit. The device uses three coils, has a broad bandwidth (25 - 1,200 Hz), a flat response and uses an average responding ac-to-dc converter. Batteries last two or three weeks, depending on the strength of the field. The device works by summing the output from the three coils with an applied offset and routing the current to an electrolytic cell (E-cell). A reversible chemical reaction in the E-cell is driven in one direction in proportion to the total current that passes through it. The reading device measures the amount of charge required to drive the cell back to its starting point. Due to the circuitry used, the actual quantity measured is:

$$X = \int_0^T (|B_x| + |B_y| + |B_z|)dt$$

Calibration factors have been chosen that lead to a claimed accuracy of ±20% from 0.2 to 150 mG.

1.4.2 Measurement Strategies

This section discusses the various approaches taken for making EMF exposure measurements.

Spot Measurements

A spot measurement evaluates the EM field at a particular point in space and time. The measurement requires only basic equipment. Because EMFs in most environments can show pronounced variation over time and space it has generally been thought that spot measurements would be inadequate for characterizing exposure in a particular environment. There are certain situations, however, where spot measurements may give a reasonable indication of exposure, namely when there is little spacial or temporal variation of field strengths throughout the environment of interest. Indeed, there is an emerging belief that residential spot measurements may be better for characterizing magnetic field exposure than was once believed.[6,7,8]

Source-Distance

Source-distance measurements characterize field strength as a function of distance from the field source. This measurement approach is often used to characterize exposures from home appliances and office equipment. It provides more information than a spot measurement, but if the field is not radially symmetric a simple source-distance measurement is not a complete characterization. A lateral profile is a particular source-distance study of an overhead power line, taken perpendicular to the line usually at a height of about 1 meter above the ground.

Personal Monitoring

Personal monitoring involves the wearing of a measurement device that either records field strengths at regular time intervals or accumulates a total exposure. These devices are commonly referred to a "dosimeters," however, they actually measure only exposure.

Area Mapping

A data-recording instrument is connected to a mapping wheel to produce an area mapping. The mapping wheel sends a signal to the device at regular intervals of distance. With operator input, the directions of all turns can be recorded to produce a true path plot. Depending on the path taken and the analysis software used, it may be possible to generate contour lines or a surface plot for the area mapped.

Stationary Monitoring

The use of a continuous monitor, such as normally used in personal monitoring or area mapping, in a fixed location for an extended time period is termed stationary monitoring.

1.4.3 ELF-EMF Exposure

Exposure is defined as the contact between a substance or physical agent and a potentially affected biological system that permits interaction. The physical agent in this instance is an EMF. Since exposure requires the presence of a person, much of the data in this paper reflects potential exposure or exposure environments. Attempts to quantify the extent of exposure are known as exposure assessment. Exposure assessment is part of a process of risk assessment, the purpose of which is to determine or estimate the risk an agent poses to an individual or population. A related component of risk assessment is dose-effect assessment which quantifies the relation between the amount of exposure and the amount or probability of harm.

In the case of human exposures to ELF-EMF, there is no identified dose-effect relationship. There is no generally accepted mechanism of interaction between humans and ELF-EMF that may lead to health effects. Epidemiologic studies have not produced a consistent, strong correlation between a particular measure of exposure and adverse health effects. Consequently, exposure assessment lacks a definitive measure of exposure.

In the absence of a clear empirical or theoretical basis for an exposure metric, researchers must rely on plausibility and, to a large extent, ease of measurement to guide the choice of exposure metric used. An exposure metric is composed of two parts: the quantity or quantities measured and the method used to aggregate the data.

For this paper, the quantities measured are E and B or dB/dt. Various methods or indices are used to aggregate multiple data points into a single measure of exposure. An interesting comparison of the results of the various indices when applied to the same data set has been performed by Armstrong, et. al.[9] A brief discussion of some common methods appears below.

Single (Spot) Measurement

A single measurement or an average of a small number of repeated measurements of the electric field strength, E, or magnetic flux density, B, is perhaps the most common exposure measure used.

Time-weighted Average (TWA)

The arithmetic mean (AM) of a series of E or B measurements taken at fixed time intervals is the most common exposure metric used with data- recording instrumentation. For n individual measurements, denoted as m_i, the arithmetic mean is given by:

$$AM = \frac{1}{n} \sum_{i=1}^{n} m_i$$

Known as a time-weighted average, this index has historically been used to measure exposure in industrial hygiene.

Geometric Mean (GM)

The geometric mean (GM) is sometimes used to aggregate multiple data points. The GM is the nth root of the product of n terms:

$$GM = \sqrt[n]{\prod_{i=1}^{n} m_i}$$

The main practical difference between the arithmetic and geometric means is that the geometric mean is less affected by the higher field strengths in the data range. The geometric mean may be a better way to summarize exposures from many people than the arithmetic mean, because a few high-exposure "outliers" will not have as much effect on a "typical" exposure expressed by the GM.

Median

The median, also known as the 50th percentile and L_{50}, is the value that splits the data set into two parts, with half of the points being greater than the median and the other half less than the median. The relation between the median and the means depends on the actual distribution of measurements, but the median will fall closer to the geometric mean than the arithmetic mean for a lognormal distribution.

Maximum or Peak

The maximum value of measured E or B fields, known as the peak field, is often included along with other indices. Some meters incorporate peak hold circuitry that displays the maximum value. In addition to the actual maximum value, another way of expressing the peak field is the 90th percentile of a series of measurements (also known as the L_{10} excedence level) defined as the value for which 90% of the data points are of lessor value.

Thresholds

Monitor data may be aggregated by means of a "bin sort," a procedure in which each measurement is assigned to a particular group or "bin." Each bin represents a range of E or B fields. A threshold index reports the proportion of measurements that were above a given threshold field value.

Windows

Window indices are another metric used with bin sorts (see Thresholds). A window index reports the proportion of measurements that fall within a particular range of field strengths.

Instantaneous Rate of Change (dB/dt): Transients

A sudden, brief change in a system is known as a transient. Transients can have very complicated spectral characteristics and require measurement devices with high frequency responses and short sampling times to accurately characterize them. Very few studies to date measure transients.

Low Time Resolution Rate of Change: Intermittency

Intermittency refers to changes in fields that appear on a time scale of seconds or minutes. Recent research indicates that field intermittency may be an important characteristic of exposure.[10] The rate of change metric expresses the intermittency of the B field as a single number. A recent study[11] of 220 pregnant women analyzed data from two 24-hour personal exposures to 60 Hz magnetic fields and compared the rate of change metric to the TWA, the TWA standard deviation (SD), the GM, and the GM standard deviation. The researchers found the rate of change metric to be correlated the most with the TWA SD and correlated the least with the GM over the data set studied.

Exposure Measures Not Considered

The following measures of exposure are *not* examined in this paper. They have not been included in the study summaries either because 1) they incorporate specific biological information and are more properly considered to be a dose, 2) they are only used for higher frequencies of electromagnetic radiation, or 3) they are surrogates for exposure, not actual measures of exposure.

Specific Absorption Rate (SAR)

The specific absorption rate is a measure of the rate of energy absorption of an object. It is used to measure the rate at which radiofrequency electromagnetic radiation is imparted to a mass element of a biological body. The ELF wavelengths are so much larger than the human scale, that quasistatic fields are the appropriate descriptor.

Body Current (Density), Surface Charge and Internal Fields

Currents can be induced within a biological body by an AC field. The electric component of the AC EMF induces both a surface charge and currents throughout the body. The magnetic field induces current loops known as eddy currents within the body. The magnitudes of these currents and charges can vary greatly throughout the body and depend on many factors. Another source of body currents is a contact current caused by touching an object carrying an induced charge.

Power Density

Power Density is a measure of the power per unit area normal to the direction of propagation of electromagnetic radiation. Power densities are not normally used in near field situations or below radio frequencies.

Exposure Surrogates: Wiring Codes and Load Histories

Epidemiologic studies have generally not measured exposure directly, but have instead relied on some exposure surrogate such as a wiring code. Wiring codes typically examine the geometry, voltage and power capacity of nearby electric power transmission and distribution lines. Recently, the load history of the lines has been included[12] for use in calculating the fields at specific distances from the lines. There is a fairly large body of literature that compares wiring codes with other measures, however, only actual field measurements are considered in this paper.

1.5 THE NATURAL ELF-EMF ENVIRONMENT

The ELF-EMF environment has changed drastically with the widespread use of electric power. At most frequencies, man-made fields are far stronger than natural fields. The exception is for static and slowly varying fields.

The static magnetic field varies from about 300 mG at the equator to over 600 mG at the poles. This static magnetic field includes pulsations up to 5 Hz lasting from minutes to hours. The geomagnetic field experiences spatial and temporal variations due to secular variations (e.g. polar drift), geomagentic field reversals, local magnetic aberrations and solar activity. There is a fair weather static electric field order 100 V/m, primarily in the vertical direction. Electric storm conditions could more than double this.

The presence of a strong static geomagnetic field has implications for power frequency magnetic field measurement. Since Faraday effect gaussmeters measure dB/dt, moving or rotating the coil in a direction that changes the average geomagnetic flux density across the coil generates a signal. Similarly, moving or riding, or flying across the geomagnetic field induces bioelectric currents. The frequency of the signal is a function of the speed and direction of rotation; however, it seldom exceeds a few Hertz. For broadband gaussmeters, it is important that frequency response to the low frequency end of the spectrum drops quickly. Many devices employ a bandwidth filter to attenuate these lower frequencies.

1.6 DATA QUALITY

Knowledge of the relative worth of the exposure values produced by the various studies would be useful. However, rating the quality of the exposure data is difficult for a number of reasons. First, there is no commonly accepted protocol for performing most of the exposure measurements discussed. Second, different methodologies simply produce different data sets. Fixed site measurements, personal monitoring and spot measurements produce different characterizations of the same environment, each with its own advantages and disadvantages. Lastly, our lack of knowledge concerning a definitive exposure measure precludes discounting the data produced by the use of a particular device that doesn't measure the "true field."

This being the case, the quality of the data can not be accurately assessed. Data reported is generally incomplete, either in the frequency domain information, or in inability to record transients, or spatial and directional variability. What is done is to report the procedures and devices used in each study. This information, along with the background provided in this chapter, should provide the reader with some understanding of the data presented.

For each category below, a study is given a capital letter for a positive rating and a lower case letter for a negative rating.

RATING	CRITERIA
A/a	Documents measurement devices used.
B/b	Documents specific measurement procedures used (protocols).
C/C	Reports proper calibration procedures.
D/d	Quality assurance program reported.
E/e	Overall appropriateness of devices and procedures.

2. RESIDENTIAL EXPOSURES TO ELF-EMF

2.1 CHAPTER OVERVIEW

Studies relevant to residential exposures have historically focused on one of three areas: 1) characterizing the ELF-EMF environment within residences; 2) characterizing the fields due to specific sources; and 3) collecting residential personal monitoring data. This chapter is organized accordingly. Section 2.2 provides a commentary on residential ELF-EMF exposure measurements. Section 2.3 covers source characterizations, and section 2.4 briefly describes personal monitoring. The summaries and results of the residential studies surveyed are contained in section 2.5.

2.2 RESIDENTIAL ELF-EMF MEASUREMENTS AND CHARACTERIZATIONS

Only very limited measurements of residential fields have been performed to date. Detailed knowledge of residential ELF fields, their associated parameters, and their distribution across the population of U.S. residences has yet to emerge. Early attempts at characterizing residential ELF fields were performed in the context of epidemiologic studies and used exposure surrogates.[1,2,3,4] These studies used wiring codes for their exposure assessments. A similar exposure surrogate which was used is the distance from transmission lines and calculated fields.[5] Later epidemiologic studies included spot measurements of flux density in addition to wiring codes.[6,7] More recent epidemiologic studies tended to collect spot and fixed site magnetic (B) field measurements in addition to recording information concerning electrical wiring characteristics.[8,9]

There are some problems with relying on epidemiology studies for exposure assessment information. Although such studies may use appropriate measurement protocols and equipment, the documentation contained in the published literature is sometimes lacking. In a similar fashion, an impressive database of exposure measurements may have been developed, however, the published study generally only provides limited descriptive statistics. The primary goal of these studies is to investigate the connection between exposure and adverse health effects, and the collection and distribution of detailed information about residential ELF fields is only ancillary to the study purpose.

2.3 SOURCE CHARACTERIZATION

The identified sources of residential ELF-EMFs are:

- Electrical appliances
- Grounding system of the residence
- Overhead power distribution lines
- Underground power distribution lines
- Overhead power transmission lines
- Ground connections at electrical subpanels

- Electrical wires used for ceiling or floor "radiant" heating
- Electrical wiring associated with some multiple-way switches
- Knob and tube wiring (an outdated home wiring technique)

The sources can be assigned to four groups: high voltage transmission lines, distribution lines, building wiring and home appliances. High voltage transmission lines are discussed separately in section three. Exposures to transmission lines is primarily an occupational issue due to the fact that electrical workers are much closer to the lines and the proportion of homes sited very near to transmission lines is rather small (see section 3.1 and 3.2).

2.3.1 Appliances

Initially, home appliances were not considered to be significant sources of residential ELF exposure because: 1) their fields tend to diminish quickly with distance; 2) fields are present only when an appliance is on; and 3) people need to be in proximity to an appliance for exposure to occur. Even though many appliances produce flux densities much higher than the ambient flux density in homes, the time-weighted average exposure from appliances were thought to be minimal. There are certain appliances, however, that may be in close proximity for prolonged periods, such as bed heating devices (e.g. electric blankets, waterbed heaters). In addition to these situations where appliances may have a significant effect on a person's Time Weighted Average (TWA) exposure to power frequency magnetic fields, the recognition of other exposure metrics requires a re-evaluation of the relative importance of appliances as a source of residential exposure. The use of a TWA metric for appliance exposure has typically involved measuring the magnetic B-field of an appliance while on and then weighting the value by the amount of time the appliance is on. The duty factor, F_d, is a measure of the fraction of time a device is on over an average 24-hour period. Table 2-1 shows the calculation of F_d for a group of appliances from a survey of monthly power consumption.

As mentioned above, appliance B-fields tend to diminish rapidly with distance from the source. Measuring flux densities at a few fixed distances is the approach that has generally been taken[10,11] to describe appliance exposure environments. Another method is to average the field over some volume. A recent paper combines volume-averaging with duty factors to provide an exposure assessment approach[12] that claims to measure appliance contribution to the total residential field. The authors model the appliance as a dipole source and average the spatial field over a volume contained between two concentric spheres defined by the appliance dimensions and the position of a subject during appliance use. This implies that the exposure metric of interest is only the field intensity, and not its direction or variability. Table 2-2 presents the results of this approach when averaging from 30 to 305 cm from the center of the appliance. The volume-averaged flux density is denoted as $<B>$ and the corresponding time-weighted average obtained by multiplying this quantity by the duty factor is denoted as B_{ave}. Table 2-3 presents the results of averaging over a smaller volume contained between 3 and 30 cm from the appliance surface for a number of handheld devices.

TABLE 2-1. TYPICAL APPLIANCE USAGE PATTERNS, AND ASSOCIATED DUTY CYCLE*

Appliance	Wattage	kW-hrs/mo	Hrs/day	F_d
Range	12,500	100	0.263	0.0109
Oven	12,500	100	0.263	0.0109
Dishwasher	1,300	18	0.455	0.0190
Refrigerator	300	100	10.965	0.4569
Clothes washer	500	8	0.526	0.0219
Clothes dryer	4,800	80	0.548	0.0228
Microwave	1,450	22	0.499	0.0208
Disposal	450	2	0.146	0.0061
Television	200	30	4.934	0.2056
Vacuum cleaner	800	4	0.164	0.0069
Coffee maker	900	6	0.219	0.0091
Toaster	1,150	4	0.114	0.0048
Crockpot	----	---	0.083	0.0035
Portable heater	1,000	30	0.987	0.0411
Portable fan	115	4	1.144	0.0477
Fluorescent fixture	100	12	3.947	0.1645
Fluorescent desk lamp	50	6	3.947	0.1645
Hair dryer	1,000	4	0.132	0.0055
Shaver	----	---	0.083	0.0035
Iron	1,000	12	0.395	0.0164
Can opener	175	1	0.188	0.0078
Mixer	125	1	0.263	0.0110
Blender	390	1	0.084	0.0035
Saw	275	1	0.120	0.0035
Drill	300	1	0.110	0.0046

* D.L. Mader, "Residential Exposure to 60-Hz Magnetic Fields From Appliances," Bioelectromagnetics 13, p. 291 (1992).

TABLE 2-2. WHOLE-BODY EXPOSURES (AVERAGED FROM 30 TO 305 cm FROM SURFACE OF APPLIANCE)[a]

Appliance	<B> (mG)	B_{ave} (mG)
Range	0.08742	0.00095
Oven	0.05512	0.00060
Dishwasher	0.29878	0.00566
Refrigerator	0.06789	0.03102
Clothes washer	0.13103	0.00287
Clothes dryer	0.06668	0.00152
Microwave	0.71030	0.01477
Disposal	0.07900	0.00048
Television	0.17793	0.03658
Vacuum cleaner	0.59604	0.00408
Coffee maker	0.01885	0.00017
Toaster	0.02754	0.00013
Crockpot	0.01060	0.00003
Portable heater	0.19873	0.00817
Portable fan	0.13830	0.00659
Fluorescent fixture	0.11349	0.01866
Fluorescent desk lamp	0.12692	0.02087
Hair dryer	0.15306	0.00083
Shaver	0.20788	0.00072
Iron	0.01421	0.00023
Can opener	0.79767	0.00624
Mixer	0.21541	0.00236
Blender	0.09207	0.00032
Saw	0.44956	0.00156
Drill	0.16181	0.00074

[a] D.L. Mader, "Residential Exposure to 60-Hz Magnetic Fields From Appliances," Bioelectromagnetics 13, p. 298 (1992).

TABLE 2-3. EXTREMITY EXPOSURES FROM CLOSE-RANGE APPLIANCES (AVERAGED FROM 3 TO 30 cm FROM SURFACE OF APPLIANCE)[a]

Appliance	<B> (mG)	B_{ave} (mG)
Hair dryer	120.2996	0.65953
Shaver	169.3913	0.58816
Iron	6.7153	0.11045
Can opener	605.5654	4.74281
Mixer	162.1525	1.77798
Blender	55.5468	0.19521
Saw	324.6812	1.12736
Drill	127.1828	0.58106

[a] D.L. Mader, "Residential Exposure to 60-Hz Magnetic Fields From Appliances," Bioelectromagnetics 13, p. 298 (1992).

The question of what distance(s) from the source should be used for exposure assessment serves to illustrate the problems created by the lack of a definitive exposure measure. Handheld devices typically produce much stronger flux densities at the proximal extremity than in distal body regions. Table 2-4 shows the very large flux densities that may be experienced in the areas of the head and the hand during the use of some electric razors. Whole body averages of these fields however would be rather small. A comparison of the whole-body exposures in table 2-2 with the extremity exposures displayed in table 2-3 for handheld appliances shows the effect of different averaging volumes.

Probably the best information concerning the 60-Hz magnetic fields near home appliances comes from the ongoing EPRI survey of residential magnetic field sources, discussed in the study summaries. Data from an interim report is displayed table 2-5, providing the distribution of measured field strengths at various distances for appliances in 707 homes nationwide.

TABLE 2-4. APPROXIMATE ELECTRIC SHAVER MAGNETIC FLUX DENSITIES (mG)[a]

Shaver	3 cm	10 cm	15 cm	30 cm	60 cm
Model B	15,000	2,000	450	80	10
Model C	5,000	200	100	17	2.5
Model E	150	20	4.5	0.8	-

[a] J.R. Gauger, "Household Appliance Magnetic Field Survey," prepared by the Illinois Institute of Technology Research Institute for the U.S. Naval Electronics Systems Command as Technical Report E06549-3 under Contract No. N00039-84-C-0070, p. 27 (1984).

TABLE 2-5. 60 Hz FIELD AT VARIOUS DISTANCES FROM ELECTRICAL APPLIANCES[a]

Appliance	Field at 27 cm (mG)	Field at 56 cm (mG)	Field at 117 cm (mG)
Refrigerator - 367 cases			
Maximum measured	15.65	11.40	10.42
Exceeded in 5% of cases	5.27	2.62	1.62
Exceeded in 10% of cases	4.19	2.04	1.13
Exceeded in 50% of cases	2.50	1.10	0.42
Exceeded in 90% of cases	1.48	0.67	0.21
Exceeded in 95% of cases	1.18	0.56	0.15
Minimum Measured	0.10	0.07	0.10
Electric Range - 272 cases			
Maximum measured	28.64	9.45	6.15
Exceeded in 5% of cases	18.91	3.47	1.40
Exceeded in 10% of cases	16.82	2.95	1.14
Exceeded in 50% of cases	8.49	1.67	0.38
Exceeded in 90% of cases	2.70	0.60	0.04
Exceeded in 95% of cases	1.86	0.45	0.01
Minimum Measured	0.56	0.24	0.00
Color Television - 397 cases			
Maximum measured	20.28	8.23	3.69
Exceeded in 5% of cases	12.04	3.29	1.12
Exceeded in 10% of cases	11.27	2.77	0.73
Exceeded in 50% of cases	6.61	1.76	0.41
Exceeded in 90% of cases	3.96	1.06	0.21
Exceeded in 95% of cases	3.13	0.82	0.17
Minimum Measured	0.40	0.10	0.04
Black & White Television - 60 cases			
Maximum measured	12.14	2.05	1.28
Exceeded in 5% of cases	8.79	1.81	1.16
Exceeded in 10% of cases	6.23	1.56	0.91
Exceeded in 50% of cases	2.90	0.65	0.25
Exceeded in 90% of cases	1.57	----	----
Exceeded in 95% of cases	1.29	----	----
Minimum Measured	0.98	0.00	----
Air Conditioner (window unit) - 63 cases			
Maximum measured	18.41	5.85	3.78
Exceeded in 5% of cases	8.66	3.33	2.92
Exceeded in 10% of cases	7.30	2.32	1.42
Exceeded in 50% of cases	3.38	1.23	0.28
Exceeded in 90% of cases	0.81	0.39	0.04
Exceeded in 95% of cases	0.46	0.21	0.02
Minimum Measured	0.11	0.11	0.00

TABLE 2-5. 60 Hz FIELD AT VARIOUS DISTANCES FROM ELECTRICAL APPLIANCES[a] (continued)

Appliance	Field at 27 cm (mG)	Field at 56 cm (mG)	Field at 117 cm (mG)
Microwave Oven - 371 cases			
Maximum measured	164.87	27.95	17.20
Exceeded in 5% of cases	69.12	17.04	6.62
Exceeded in 10% of cases	58.41	15344	4.47
Exceeded in 50% of cases	36.95	9.92	2.10
Exceeded in 90% of cases	19.99	5.96	1.30
Exceeded in 95% of cases	16.99	4.85	1.01
Minimum Measured	0.88	1.12	0.19
Clock / Clock Radio (digital) - 166 cases			
Maximum measured	8.46	2.48	1.43
Exceeded in 5% of cases	3.59	1.71	0.74
Exceeded in 10% of cases	2.77	0.66	0.55
Exceeded in 50% of cases	1.13	0.28	0.08
Exceeded in 90% of cases	0.61	0.10	0.00
Exceeded in 95% of cases	0.47	0.09	0.00
Minimum Measured	0.05	0.05	0.00
Clock / Clock Radio (analog) - 97 cases			
Maximum measured	30.07	5.15	3.20
Exceeded in 5% of cases	24.73	3.88	2.48
Exceeded in 10% of cases	22.19	3.35	0.77
Exceeded in 50% of cases	14.33	1.88	0.29
Exceeded in 90% of cases	3.62	0.63	0.07
Exceeded in 95% of cases	2.38	0.38	0.05
Minimum Measured	1.13	0.12	0.00
Ceiling Fan - 117 cases			
Maximum measured	49.41	6.02	1.48
Exceeded in 5% of cases	16.05	2.81	0.68
Exceeded in 10% of cases	13.53	2.32	0.59
Exceeded in 50% of cases	3.14	0.75	0.24
Exceeded in 90% of cases	0.40	0.17	0.00
Exceeded in 95% of cases	0.31	0.03	0.00
Minimum Measured	0.15	0.01	0.00
Fluorescent Light - 274 cases			
Maximum measured	31.98	7.70	3.51
Exceeded in 5% of cases	20.01	4.49	1.16
Exceeded in 10% of cases	16.61	3.84	1.00
Exceeded in 50% of cases	5.93	1.61	0.42
Exceeded in 90% of cases	2.01	0.55	0.14
Exceeded in 95% of cases	1.21	0.44	0.11
Minimum Measured	0.52	0.11	0.07

[a] High Voltage Transmission Research Center, "Survey of Residential Magnetic Field Sources--Interim Report," prepared for Electric Power Research Institute under Research Project 2942-06, pp.9-5, 9-6 (1992).

Some suggested exposure metrics increase the relative importance of fields from appliances. Measures of intermittency will boost the significance of appliances relative to the more stable fields from distribution lines and ground currents. This is due not only to the fact that some appliances may repeatedly switch on and off when people are nearby, but also because people move through appliance fields with some regularity.

If transients are found to be important, then the relative importance of appliance exposures will be increased. Transients in transmission and major distribution lines are usually small compared to the normal magnitudes of the magnetic fields. In homes, the transients caused by switching loads on or off can be equal to or greater than the magnitude of the normal magnetic field. Strong, high frequency transients are produced by certain types of small appliances, such as those that use motorspeed controllers or solid state switching.

2.3.2 Distribution Lines and Building Wiring

The ambient magnetic fields found in residences away from appliances are due to power distribution lines and building wiring. The term "building wiring" in this instance is being used to include the particular grounding system utilized in a residence. Measurement protocols that specify that spot or fixed-location measurements be made away from local sources measure the fields from the grounding system and distribution line. It should be noted that there is an outdated form of interior wiring, known as knob and tube, that can also contribute to ambient magnetic fields. Section 2.5.2 presents the values obtained for spot and fixed location measurements of ambient residential magnetic fields.

2.4 PERSONAL MONITORING

Several of the studies summarized in this paper involved the wearing of personal exposure monitors. When used in conjunction with a log that records the various environments inhabited during different time periods, true residential exposures can be calculated from personal monitoring data. Results of these studies appear in section 2.5.2. Additional residential personal monitoring data can be found in the non-work portions of data from the EMDEX project (section 3.1).

2.5 STUDY SUMMARIES AND RESULTS

Published studies of residential exposure to ELF/EMF are summarized in section 2.5.1. Section 2.5.2 presents some of the exposure data contained in the studies. The data quality rating used is shown on the following page (see Section 1.5).

For each category below, a study is given a capital letter for a positive rating and a lower case letter for a negative rating.

Rating	Criteria
A/a	Documents measurement devices used.
B/b	Documents specific measurement procedures used (protocols).
C/c	Reports proper calibration procedures.
D/d	Quality assurance program reported.
E/e	Overall appropriateness of devices and procedures.

2.5.1 Study Summaries

STUDY: "Ambient 60-Hz Magnetic Flux Density in an Urban Neighborhood," (Dlugosz, 1989)[13]

Summary: A residential neighborhood in Buffalo, N.Y. was surveyed. Measurements were made at 33 street corners, at junctures of sidewalk and curb (height of 1.3m), on seven non-consecutive evenings (6 to 9 pm) in July 1987. Information on overhead and underground wiring configurations was collected for each site. An additional 50 dwellings were chosen at random and measurements were made during three evenings in March at the residence side of front sidewalks and at the doorsteps of 45 residences where occupants permitted such measurements. The repeatability of sidewalk measurements and correlations with wiring configurations were calculated.

Measurement Device(s): EFM Model 113 Power Frequency Field Meter.

Data Quality: Calibration and intercomparison performed regularly. Measurement procedures presented. A/B/C/d/e.

Comments: The use of a single coil meter to make a large number of repeated spot measurements can be tedious, as is noted in the paper. A three coil meter or a different spot measurement procedure may have been advised. It was noted that measurements were made during a period of unusually high electric power demand, due to a heat wave.

STUDY: "Survey of Residential Magnetic Field Sources--Interim Report," (EPRI, 1992)[14]

Summary: This interim report presents data from 707 randomly selected residences surveyed in 25 utility service areas. The goals of the nationwide residential survey are to:

- Identify all significant sources of 60 Hz magnetic fields in residences;
- Estimate the distribution of the statistical parameters of the 60 Hz magnetic fields in the living space of residences for each significant source;
- Determine the relation between field and source parameters; and

- Characterize the magnetic fields produced by each type of source in terms of magnitude of 60 Hz component, the harmonic content, and the spatial and temporal variation of the 60 Hz component.

The first phase of the project used a waveform capture system to make extensive measurements in employee homes in order to test and refine the protocol. This interim report presents some of the data obtained so far, but only in a limited form. The final report will contain analyses of the full database collected that will greatly aid in characterizing residential EMF exposure environments.

Measurement Device(s): The appliance measurements shown previously in table 2-5 were made with STAR magnetic field recorders.

Data Quality: While the interim report describes measurement procedures and contains the protocol, a full evaluation of the study based only on interim information is not provided.

Comments: This study promises to add appreciably to our knowledge of residential magnetic fields because of its scope and content. The goal of examining 1,000 homes in 25 different utility service areas makes this the broadest residential EMF study to date. The extensive array of data collected at each residence should allow development of an immense database that will allow numerous analyses relevant to residential magnetic fields. Data being collected at each site include:

- Documentation of residence and power line geometry, house wiring characteristics and other information including drawings and photographs;
- 24-hour fixed site magnetic field measurements at four locations;
- Lateral profile measurements of neighboring transmission and distribution lines;
- Measurements of fields around periphery of residence; and
- Appliance field measurements at different distances from selected appliances.

STUDY: Assessment of Children's Long-Term Exposure to Magnetic Fields (The Geomet Study), (Geomet, 1992)[15]

Summary: This pilot study investigated the exposure to magnetic fields of 28 children in Frederick, Maryland. Four areas of Frederick were chosen, each corresponding to one of the Wertheimer-Leeper wiring codes. Within each area, seven children were monitored; two during the winter only, two during the spring only, and three during both winter and spring. The study used personal monitoring, stationary monitoring, and spot measurements.

Children wore personal monitors for a 48-hour period for a total of 40 monitoring episodes. During the time of personal monitoring, "parallel" stationary monitoring was conducted in the children's bedrooms and at another residential location frequented by the children (for 23 of the 28 subjects). Spot measurements were taken at two different times at both indoor and outdoor locations for all subjects. Outdoors, measurements were taken around the perimeter of the home, at the front door, at the service drop, and over the water service line. Indoors, measurements were taken at the center of the child's bed, the center of a play area, at the child's mealtime location, and at one other frequented location. Additionally, 19 of the 28 subjects received long-term (96 hour) stationary monitoring for three separate episodes between February and June. The long-term stationary monitoring was conducted in the subjects' bedrooms and was intended to indicate the long-term stability of the magnetic field levels.

Measurement Device(s): Older children (ages 8 to 11) wore an EMDEX in a belt pouch and used the event marker and a log to record their movements. Younger children (below age 4) wore an AMEX 1-D around their waist and had an EMDEX kept near them by an adult. Spot measurements were taken with an EMDEX. Parallel stationary monitoring was conducted with "small computer-based recording magnetic field meters designed and built by ERM." Long-term stationary monitoring used either the ERM monitor or an EMDEX, with a subset of locations receiving an additional AMEX for comparison.

Data Quality: The report presents a reasonable description of the procedures followed in making each type of measurement. The description of the computer-based ERM devices used for some of the stationary measurements failed to provide any specific performance parameters and the specifications for the 1-D AMEX were not available for review. A calibration exercise was carried out shortly before the study. There was no discussion of a quality assurance program. a/B/C/d/E.

Comments: The magnetic exposure experienced by the older children during school was not measured. This was due to an unwillingness on the part of the local school board to allow monitoring to occur in the schools. Children removed their monitors before leaving for school and marked the event recorder. A technician measured the exposure experienced by driving to school via the child's normal route and made an estimate based on that measurement. Conclusions from the study include:

- The use of AMEX 1-D monitors for young children posed certain problems. The integrating AMEX device does not provide peak field information and had potential for tampering. The EMDEX monitors kept in the vicinity of the children could not be counted on to be a true measure of personal exposure;
- On average, exposure in the residence accounted for three-fourths of the time-integrated exposure for younger children and two-thirds of the time-integrated exposure for older children;
- Substantial seasonal variability was found for some of the field measurements taken; and
- Short-term variations in magnetic fields were substantial, nearly the same magnitudes as fields themselves.

STUDY: "Residential Magnetic and Electric Fields,"(Kaune, 1987)[16]

Summary: The study examined 43 homes in the King, Pierce, and Snohomish counties of Washington state. A specially built data acquisition system was used to make 24-hour magnetic flux density measurements and electric-field measurements. Additionally, power consumption during the 24-hour period was measured, scaled wiring maps of overhead transmission and distribution lines were made, and the wiring coding was determined. A subsequent interview was accompanied by spot measurements. The fixed-site 24-hour measurements were made simultaneously in three locations within the residence. Two of the measurements were made on opposite ends of the family room, where one probe was placed near possible local field sources and another was placed away from such possible sources. A third probe was placed in the bedroom near the head of the bed.

Measurement Device(s): Spot measurements were made with a pair of EFM Model 111 meters. The continuous monitor system consisted of three-axis magnetic flux density probes and a one-axis E-field probe. The data acquisition module could operate in both integrating flat response mode and as a voltage amplifier for a linear response. Recording both allowed computation of the harmonic distortion. A true rms ac-to-dc converter was incorporated. The frequency response in flat mode was 12 Hz to 2.0 kHz (± 3 db) for the magnetic flux density and 13 Hz to 1.9 kHz (± 3 db) for the E-field. The device sampled the fields every two minutes.

Data Quality: The study documents the procedures and instrumentation used. Instrument calibration is detailed in a referenced paper that has not been reviewed in this report. Estimated system accuracy is stated to be ±10%. There is no mention of a quality assurance plan. A/B/c/d/E.

Comments: The authors report that the study is part of an epidemiological study of possible associations between acute adult nonlymphocytic leukemia and residential exposure to residential EMFs. Although they reference the study,[17] the paper does not discuss the sample population presented in this study in terms of cases and controls.

Conclusions from the study include:

- The linear-regression correlation coefficient between the two 24-hour MFD measurements made in the family rooms was 0.34;
- The linear-regression correlation coefficient between the MFD measurements made in the family room and the bedroom was 0.65;
- The harmonic distortion of the B and E fields had upper bounds of 24% and 7% respectively;
- Residential B-fields showed a distinct diurnal rhythm. No such rhythm was observed for the E-field; and
- Spot B-field measurements were correlated with the 24-hour measurements (c = 0.5).

STUDY: "Magnetic Field Exposure Assessment for Adult Residents of Maine Who Live Near and Far Away From Overhead Transmission Lines," (Kavet, 1992).[18]

Summary: 60 Hz magnetic field exposures were measured for 45 adult residents of Maine. Thirty of the subjects resided near rights of way of 345-kV and/or 115-kV transmission lines. Fifteen resided far from transmission lines. Subjects wore personal exposure monitors on belts and used an event recorder button and a pocket diary to log away-from-home and at-home exposure times. 24-hour fixed location measurements were made in subjects' bedrooms. Additional spot measurements were made in other areas inside and outside of the house. Correlations between various measurements were calculated and comparisons made between exposure groups.

Measurement Device(s): Both the personal exposure measurements and the 24-hour fixed site measurements were made with the EMDEX meter. Spot measurements and lateral profiles of transmission lines were made with the EFM Model 113 Magnetic Field Meter and the Monitor Industries Model 42A milligaussmeter.

Data Quality: Measurement procedures for EMDEX are presented. No mention is made of calibration, intercomparison, or quality assurance. A/B/c/d/E.

Comments: The belt-worn EMDEX was left at the foot of the bed at night, unless that location was affected by local magnetic field. The fixed bedroom measurement was made in a location determined to be unaffected by appliances or other in-house sources.

STUDY: "Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia," (London, 1991).[19]

Summary: This case-control epidemiologic study examined residential EMFs for a group of children up to age 10 residing in Los Angeles County, California. A total of 164 cases and 144 controls participated in the study. The measurements made included spot E- and B-fields and 24-hour stationary measurements of the B-field. The 24-hour measurement was made in the location of the child's bed during the etiologic period under investigation. Spot measurements were made in three outdoor locations and three to four indoor locations. Indoor measurements were made in the main living area, parents' bedroom, child's sleeping area, and the living area closest to the electrical distribution wiring. Outdoor measurements were made in the front and backyard areas used by the child and over the water pipe. Spot measurements were made in both flat and linear response modes and with appliances on (normal power) and off (low power). Measurements were taken in three orthogonal directions and a resultant calculated. In the case of the water pipe measurement, only the horizontal component was used.

Measurement Devices: Power frequency E and B spot measurements were made with an Electric Field Measurements model 113 "Denometer." Static B-fields were measured with a flux-gate magnetometer (model MAG-01, Bartington Instruments, Ltd., Oxford, United Kingdom). 24-hour fixed site magnetic measurements were made using either an EMDEX recording every 10 seconds or the IREQ instrument (Institut de Recherche d'Hydro Quebec, Varennes, Quebec, Canada) recording every 50 seconds.

Data Quality: The devices and protocols used were both reasonably well documented and appropriate. The study reports calibration procedures for the magnetic field instruments (calibrated to a 60 Hz field). A mean bias of 5.3 percent or less was found for the magnetic field instrumentation. Factory calibration was used for electric field measurement instrumentation. Although no formal quality assurance (QA) program is reported, many components of such a program are mentioned, including: collocated or replicate measurements; repeated calibration; postmeasurement checks of data integrity; and regular reliability checks. The IREQ devices were abandoned in favor of the EMDEX units during the survey due to reliability problems. A/B/C/d/E.

Comments: Table 2-6 presents the results of the exposure component of the study.

2.5.2 Residential Study Results

Selected results from the studies summarized in section 2.5.1 are presented in table 2-7.

TABLE 2-6. RESULTS OF MEASUREMENTS BY CASE-CONTROL STATUS, LOS ANGELES COUNTY, CALIFORNIA[a]

Exposure Variable	Cases		Controls	
	No.	Mean ± SD[b]	No.	Mean ± SD[b]
24-hour magnetic field measurements (mG)	162[c]		143[c]	
Arithmetic mean		1.14 ± 1.34		1.15 ± 1.57
Median		1.02 ± 1.15		1.02 ± 1.42
Geometric mean		0.99 ± 1.11		1.01 ± 1.41
90th percentile		1.79 ± 2.69		1.86 ± 3.04
% time over 2.5 mG		10.15 ± 24.16		7.73 ± 21.71
Spot measurements: indoor magnetic field (mG)	140		109	
Child's bedroom normal power		1.11 ± 2.80		0.60 ± 0.79
Child's bedroom low power		0.60 ± 0.79		0.55 ± 0.76
Child's bedroom linear mode		0.76 ± 1.13		0.61 ± 0.77
Child's bedroom static field		443.72 ± 31.78		447.80 ± 48.14
Mean indoor (excluding bedrooms) normal power		0.69 ± 0.97		0.66 ± 0.92
Mean indoor Low power		0.63 ± 1.30		0.60 ± 0.88
Spot measurements: outdoor magnetic field (mG)				
Mean outdoor (excluding water pipe)	144	0.57 ± 0.64	116	0.68 ± 1.01
Over water pipe	168	0.62 ± 1.21	153	0.64 ± 1.47
Spot measurements: electric field (V/m)				
Child's bedroom normal power	136	7.48 ± 9.84	108	7.98 ± 12.27
Mean outdoor	144	1.87 ± 2.33	116	2.63 ± 4.21

[a] Stephanie J. London, Duncan C. Thomas, Joseph D. Brown, Eugene Sobel, Tsen-Chung Cheng, and John M. Peters, "Exposure to Residential Electric and Magnetic Fields and Risk of Childhood Leukemia," American Journal of Epidemiology 134, p. 930 (1991).

[b] SD, standard deviation.

[c] Two cases and one control with "outlier" values were excluded from the table.

TABLE 2-7. RESIDENTIAL STUDY RESULTS

Author/ Date	Measurement Approach	Comments/Location	Device	Quantity	Results (mG) Range	Mean	Other Results
Dlugosz 1989	Spot Measurement Repeated Three Days	n = 45 sidewalks leading to residences Buffalo	EFM Model 113	B 60 Hz Spot	0.1 13.1	2.2	
Dlugosz 1989	Spot Measurement Repeated Three Days	n = 45 doorsteps of residences Buffalo	EFM Model 113	B 60 Hz spot	0.1 4.7	1.0	
Dlugosz 1989	Spot Measurement Repeated Seven Days	n = 33 street corners all corners, Buffalo	EFM Model 113	B 60 Hz Spot	0.9 13.4	5.3	SD = 3.6 (mG)
Geomet 1992	Personal Monitoring 48 hour	n = 40 episodes 28 children Frederick, MD	EMDEX AMEX	B 40 - 400 Hz TWA	0.4 5.5	2.0	SD = 1.4 (mG) L_{75} = 0.8 (mG) L_{50} = 1.8 (mG) L_{25} = 2.8 (mG)
Geomet 1992	Personal Monitoring 48 hour	n = 40 episodes 28 children Frederick, MD	EMDEX	Peak B 40 - 400 Hz L_{10}, 1 min intervals	NA 12.3	3.9	SD = 3.2 (mG) L_{75} = 1.3 (mG) L_{50} = 3.1 (mG) L_{25} = 5.1 (mG)
Kaune 1987	Fixed Site 24 hour family room	n = 43 residences Western Washington	custom system	B TWA 12 Hz-2.0 kHz	~0.0 ~4.4	1.0	SD = 1.2 (mG) L_{50} = 0.6 (mG)
Kaune 1987	Fixed Site 24 hour family room	n = 43 residences Western Washington	custom system	E, Vertical TWA 13 Hz-1.9 kHz	NA NA	33 V/m	SD = 32 V/m L_{50} = 24 V/m
Kaune 1987	Fixed Site 24 hour bedroom	n = 43 residences Western Washington	custom system	B TWA 12 Hz-2.0 kHz	~0.0 ~3.6	1.0	SD = 1.4 (mG) L_{50} = 0.5 (mG)
Kavet 1992	Personal Monitoring At Home Only 24 hour	n = 15 people far away from power lines, Maine	EMDEX	B 40 - 400 Hz TWA	0.66 3.66	1.59	

TABLE 2-7. RESIDENTIAL STUDY RESULTS (continued)

Author/ Date	Measurement Approach	Comments/Location	Device	Quantity	Results (mG) Range	Results (mG) Mean	Other Results
Kavet 1992	Personal Monitoring At Home Only 24 hour	n = 45 people near & far from power lines, Maine	EMDEX	B 40 - 400 Hz TWA	0.66 5.78	1.82	
Kavet 1992	Fixed Site 24 hour Bedroom	n = 45 people near & far from power lines, Maine	EMDEX	B 40 - 400 Hz TWA	0.09 4.53	1.31	SD = 1.00 (mG)
Kavet 1992	Fixed Site 24 hour Bedroom	n = 15 people far away from power lines, Maine	EMDEX	B 40 - 400 Hz TWA	0.09 2.77	0.91	SD = 0.81 (mG)
London 1991	Fixed Site 24 hour Bedroom	n = 143 children controls Los Angeles, California	EMDEX/ IREQ	B 40-400 Hz TWA	NA NA	1.15	SD = 1.57 (mG) L_{50} = 1.02 (mG) L_{10} = 1.86 (mG) GM = 1.01 (mG) See text

3. OCCUPATIONAL EXPOSURES

Some of the most extensive EMF exposure assessments have been conducted for occupational exposures. Specifically, electrical workers and electrical transmission environments have both been subjects of numerous studies and research. Unfortunately, there has been virtually no systematic effort to characterize other work environments and occupations for ELF-EMF exposure.

Several epidemiologic studies of ELF exposure and electrical workers have been undertaken. The problems concerning exposure assessments performed in conjunction with epidemiology studies mentioned in the discussion of residential exposures also apply to occupational studies. Some studies use surrogates, such as job titles, instead of actual fields and time exposure measurements. Studies that collect actual exposure data often do not publish the complete data or detailed measurement protocols and device specifications. The purpose of the studies is to examine the relationships between occupational EMF exposures and specific health effects. The results of the exposure assessment portion are usually presented only as the descriptive statistics needed for this task. Finally, the study approach is generally not designed to collect the information that would be desired from the perspective of a pure exposure assessment. However, one major study of electrical worker exposure was designed solely for this purpose.[1] Section 3.1 discusses this study. Section 3.2 presents other studies of electrical workers and related work environments that include some of the relevant exposure information.

Finally, there are some work environments for which more limited information on EMF is available. These work environments have usually been investigated because of potential for high ELF fields. Section 3.3 reviews some of these studies.

3.1 THE EMDEX PROJECT[1]

Summary: The EMDEX project recorded personal exposure monitoring data from 1,991 utility volunteers at 59 sites over a total of 4,411 workdays and 1,512 non-work days. The goals of this project were (in order of priority) to: "1) transfer EMDEX (personal ELF EMF measuring device) technology to utilities; 2) develop measurement protocols and data management capabilities for large exposure data sets; and 3) collect, analyze, and document 60-Hz EMF exposures for a diverse population."

Each of the volunteers wore an EMDEX instrument in a belt pouch for one to 21 days. A small logbook was carried by each volunteer. Each time a new environment was entered the participant tripped the event recorder on the EMDEX and recorded the environment and time in the logbook. The defined environments appear in the left-hand column of tables 3-1 through 3-4. The unbroken time spent in a particular environment is termed a "partition."

Although a geographically diverse population was studied, the 55 American utilities and 4 foreign utilities participating were self-selected volunteers. Similarly, the individual participants were not randomly selected.

Device(s): The EMDEX device (developed for EPRI by Enertech) was used for all measurements, set to record field levels every 10 seconds. For measurement of electric fields the EMDEX was fitted with an "E-sock," a cloth cover for the EMDEX that contains two sections of conducting cloth.

Data Quality: The EMDEX project is one of the few studies reviewed that contain elements of a quality assurance plan. Currently, volume three with detailed project information is out of print. QA components mentioned in volume two include: daily checks for EMDEX functioning; field accuracy checks; calibration before, during, and after data collection; and a system of calibration and problem reporting. Detailed protocols are contained in the out of print volume three. A/B/C/D/E.

Results: Tables 3-1 and 3-2 present magnetic field distributions and tables 3-3 and 3-4 present electric field distributions. The partition means displayed in tables 3-3 and 3-5 are the time-weighted average exposures.

TABLE 3-1. MAGNETIC FIELD DISTRIBUTIONS (IN MILLIGAUSS) FOR ENVIRONMENTS BY PARTITION MEANS[a]

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	stdev	gmean
Generation	1814	0.09	0.51	1.28	2.63	7.04	37.34	1973.99	13.17	75.51	3.25
Transmission	712	0.15	0.35	1.87	5.98	15.42	61.62	630.56	18.22	0.82	5.44
Distribution	1771	0.09	0.26	0.66	1.58	6.11	63.68	14385.52	24.56	350.49	2.31
Substation	2360	0.09	1.09	4.57	10.56	22.06	63.11	26582.43	54.80	886.70	9.87
Office	3860	0.09	0.30	0.59	0.98	1.76	5.05	274.79	1.81	6.26	1.07
Shop	2243	0.10	0.30	0.67	1.15	2.16	5.68	244.93	2.45	9.81	1.23
Travel	7618	0.09	0.46	0.83	1.32	2.16	6.02	21474.04	5.46	247.08	1.44
Other	2328	0.09	0.25	0.59	1.11	2.43	10.97	1944.48	4.25	43.09	1.26
Home	3307	0.09	0.21	0.44	0.73	1.33	4.01	489.72	1.63	10.03	0.81
Travel (non-work)	4790	0.13	0.45	0.85	1.18	1.67	3.43	388.00	1.61	5.96	1.21
Other (non-work)	1497	1.09	0.23	0.53	0.88	1.62	5.03	43.57	1.56	2.55	0.96

[a] T. Dan Bracken, Inc., "The EMDEX Project: Technology Transfer and Occupational Measurements, Volume 2: Project Description and Results," prepared for Electric Power Research Institute under Research Project 2966-1, EPRI EN-7048, p. 9-19 (1990).

TABLE 3-2. MAGNETIC FIELD DISTRIBUTIONS (IN MILLIGAUSS) FOR ENVIRONMENTS BY ALL MEASUREMENTS[a]

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	stdev	gmean
Generation	2365435	0.09	0.22	0.57	1.24	3.51	26.61	42169.65	8.35	117.04	1.55
Transmission	524275	0.09	0.17	0.60	2.79	11.09	51.88	3672.82	15.70	59.49	2.73
Distribution	1238612	0.09	0.17	0.38	0.97	3.59	63.83	43151.91	47.38	841.56	1.41
Substation	1753215	0.09	0.45	2.37	7.00	17.58	59.57	42169.65	34.43	629.49	6.17
Office	2690501	0.09	0.17	0.43	0.75	1.46	5.96	25409.73	2.07	83.61	0.82
Shop	1367358	0.09	0.17	0.45	0.88	2.02	6.84	34276.78	2.87	55.67	0.98
Travel	2056525	0.09	0.17	0.41	0.79	1.76	7.16	36728.23	3.09	139.02	0.88
Other	879383	0.09	0.17	0.38	0.79	1.97	9.44	25409.73	3.46	91.06	0.93
Home	3320924	0.09	0.17	0.33	0.61	1.22	4.32	3427.68	1.47	8.73	0.65
Travel (non-work)	1165844	0.09	0.17	0.38	0.73	1.46	4.73	3845392	1.56	11.67	0.77
Other (non-work)	701983	0.09	0.17	0.36	0.61	1.27	5.19	1011.58	1.36	3.24	0.68

[a] T. Dan Bracken, Inc., "The EMDEX Project: Technology Transfer and Occupational Measurements Volume 2: Project Description and Results," prepared for the Electric Power Research Institute under Research Project 2966-1, EPRI EN-7048, p. 9-19 (1990).

TABLE 3-3. ELECTRIC FIELD DISTRIBUTIONS (IN kV/m) FOR ENVIRONMENTS BY PARTITION MEANS[a]

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	gmean
Generation	729	0.001	0.002	0.003	0.005	0.008	0.021	0.0595	0.009	0.006
Transmission	364	0.001	0.003	0.006	0.026	0.173	1.897	11.534	0.410	0.035
Distribution	736	0.001	0.002	0.001	0.008	0.032	0.437	2.761	0.076	0.014
Substation	1325	0.001	0.002	0.007	0.020	0.066	0.351	10.261	0.098	0.023
Office	1571	0.001	0.002	0.003	0.004	0.007	0.015	0.064	0.006	0.005
Shop	1052	0.001	0.001	0.003	0.004	0.007	0.015	0.146	0.006	0.005
Travel	3687	0.001	0.001	0.003	0.004	0.007	0.018	0.473	0.007	0.005
Other	1057	0.001	0.001	0.003	0.005	0.008	0.024	0.791	0.010	0.005
Home	1395	0.001	0.002	0.004	0.007	0.011	0.022	0.183	0.009	0.007
Travel (non-work)	2067	0.001	0.001	0.003	0.004	0.006	0.013	0.319	0.005	0.004
Other (non-work)	653	0.001	0.001	0.003	0.004	0.008	0.022	1.872	0.015	0.005

[a] T. Dan Bracken, Inc., "The EMDEX Project: Technology Transfer and Occupational Measurements Volume 2: Project Description and Results," prepared for the Electric Power Research Institute under Research Project 2966-1,EPRI EN-7048, p. 10-17 (1990).

TABLE 3-4. ELECTRIC FIELD DISTRIBUTIONS (IN kV/m) FOR ENVIRONMENTS FOR ALL MEASUREMENTS[a]

Occupied Environment	n	min	5%	25%	50%	75%	95%	max	mean	gmean
Generation	998092	0.001	0.001	0.001	0.003	0.005	0.018	29.174	0.008	0.004
Transmission	296892	0.001	0.001	0.003	0.005	0.029	1.718	78.524	0.444	0.011
Distribution	552040	0.001	0.001	0.003	0.003	0.012	0.272	29.854	0.071	0.006
Substation	1069854	0.001	0.001	0.003	0.005	0.016	0.335	45.186	0.115	0.007
Office	1091882	0.001	0.001	0.003	0.003	0.005	0.016	3.350	0.006	0.003
Shop	629312	0.001	0.001	0.001	0.003	0.005	0.018	2.723	0.006	0.004
Travel	1056530	0.001	0.001	0.001	0.003	0.005	0.018	7.674	0.007	0.003
Other	418614	0.001	0.001	0.003	0.003	0.008	0.025	10.351	0.012	0.004
Home	1371725	0.001	0.001	0.003	0.005	0.010	0.027	3.199	0.006	0.005
Travel (non-work)	523377	0.001	0.001	0.001	0.003	0.005	0.014	3.428	0.006	0.003
Other (non-work	333143	0.001	0.001	0.001	0.003	0.008	0.018	4.842	0.007	0.004

[a] T. Dan Bracken, Inc., "The EMDEX Project: Technology Transfer and Occupational Measurements, Volume 2: Project Description and Results," prepared for the Electric Power Research Institute under Research Project 2966-1, EPRI EN-7048, p. 10-17 (1990).

3.2 ELECTRICAL WORKERS

STUDY: "Exposures to Extremely Low Frequency (ELF) Electromagnetic Fields in Occupations with Elevated Leukemia Rates"[2]

Summary: Spot measurements of ELF-EMF were made at the work sites of 105 "electrical" workers and nine non-electrical workers in the Los Angeles area. Additional measurements were made at the residences of 18 University of Southern California personnel for comparison. The results of these residential measurements are not reported in detail.

Measurements were made close to the workers and in the direction of likely field sources. Sometimes two electric field measurements were made and averaged. The measurements were made "under a wide variety of circumstances" and not in accordance to particular measurement plan.

Device(s): All measurements were made with an Electric Field Measurement Company model 113 power frequency field meter operated in "integrator" mode.

Data Quality: The study neither reports, nor apparently used, strict protocols for making and documenting occupational measurements. Likewise, there is no report of either calibration procedures or a quality assurance program. A/b/c/d/e.

Results: EMF measurements are presented in table 3-5.

TABLE 3-5. OCCUPATIONAL EXPOSURES TO ELF EMF BY JOB CLASS[a]

Job Class	Environments	Magnetic Field			Electric Field		
		N	Geo. Mean (mG)	Range (mG)	N	Geo. Mean (V/m)	Range (V/m)
Electricians	Industrial power supply	1	103.1	---	1	4.2	---
Power line workers	Underground Lines Overhead Lines Home hook-ups	3 2 14	57.4 42.5 1.1	38-91 32-57 0.04-12	2 2 13	0.8 157.6 3.8	0.5-1.2 120-206 0-71
Welders and flame cutters	TIG*/AC* TIG/DC*	4 4	41.3 6.5	24-90 4-16	1	2.0	---
Power station operators	Transmission station Distribution substation Generating station Control rooms	3 3 12 8	38.6 28.6 6.0 2.1	16-72 7-54 0.1-118 1-4	3 3 7 4	290 71.5 0.4 1.0	165-621 22-222 0-4 0.3-24
Electronics assemblers	Sputtering Soldering Microelectronics	2 2 3	24.3 1.3 0.03	14-43 1.3-1.6 0.01-0.06	1 2 2	5.5 8.4 1.6	--- 8.2-8.7 0.8-3
Projectionists	Xenon arc	7	14.4	1-45	4	0.6	0-2
Fork-lift operators	Battery powered	9	11.7	0.9-1250[b]	1	0.2	---
Electronics engineers and technicians	Laser lab Calibration lab Office	9 4 1	10.6 0.6 0.2	2-202 0.5-0.7 ---	4 4 1	1.9 1.9 1.0	0.6-8 0.5-4 ---
Radio and TV repairers	Repair shops	11	6.3	1-26	11	45.2	4-110
Radio operators	Dispatchers	3	0.3	0.2-0.4	1	0.8	---
Secretaries	VDT* Other	6 3	3.1 1.1	0.8-29 0.2-4	1 3	3.1 4.1	--- 2-5
"Electrical workers"	combined	105	5.0	0.01-1250	67	4.64	0-621
All occupations	combined	114	4.7	0.01-1250	71	4.58	0-621

[a] J.D. Bowman, D.H. Garabrant, E. Sobel, and J.M. Peters, "Exposures to Extremely Low Frequency (ELF) Electromagnetic Fields in Occupations with Elevated Leukemia Rates," Applied Industrial Hygiene 3, p. 191 (1988).
[b] Peak measured during acceleration
* TIG - Tungsten Inert Gas
* VDT - Video Display Terminal
* AC - Alternating Current
* DC - Direct Current

STUDY: "Leukemia in Telephone Linemen"[3]

Summary: This study is a case-control investigation of leukemia among white male telephone industry workers. One component of the study involved measuring magnetic exposure by job category. Personal exposure monitors were worn around the waist for the duration of a shift for a total of 204 shifts. Measurements were conducted at six geographically diverse locations (MD, CO, UT, AZ, MS, OR). Control measurements were obtained from 34 episodes of non-work monitoring to establish a background for comparison with occupational exposures. To some extent, worker environments during monitoring were recorded by an observer on a survey log and noted with the EMDEX-C event marker.

Device(s): Measurements of sources were made with a Monitor Industries 42B-1 Milligaussmeter operated in flat mode. Personal exposure monitoring was conducted with Electric Field Measurements EMDEX-C devices sampling at 10 second intervals. A limited number of additional measurements were made with wrist-worn AMEX (1-D) monitors, however, the results of these measurements were not reported.

Data Quality: It was mentioned that Enertech Consultants calibrated and maintained the measurement equipment, however the actual calibration procedures and measurement protocols are not documented in the published report. There is no mention of a quality assurance program. A/b/c/d/e.

Results: Table 3-6 presents the results of the EMDEX-C monitoring by job category. It should be noted that the average absolute sequential difference (ASDD) is a measure of intermittency calculated from 10 second interval measurements.

STUDY: "Occupational and Residential 60-Hz Electromagnetic Fields and High-Frequency Transients: Exposure Assessment Using a New Dosimeter"[4]

Summary: This exposure assessment study examined a group of twenty workers occupationally exposed to potentially high ELF-EMF and a comparison group of 16 office workers. Participants wore a personal exposure monitor for a period of one week. The monitors recorded power frequency EMF as well as high frequency electric transients. Daily log sheets were maintained by the participants describing the exposure sites, potential exposure sources, and the exact position of the personal exposure monitor. This study is one of only a few to collect information on transient events.

Device(s): Although unnamed in the paper, the monitors used have come to be known as the IREQ (Institut De Rechérche D'Hydro-Quebec) device. The three orthogonal components of power frequency magnetic flux density are measured and stored. Fields can be sampled and recorded at a rate of up to once a second. Sample time was one minute for this survey. The power frequency electric field perpendicular to the body surface was measured as were electric transients. For high frequency electric transients, the device measured the proportion of time during the sampling period that electric fields in the 5 to 20 MHz range exceed a threshold of approximately 200 V/m.

TABLE 3-6. SUMMARY OF AVERAGE MAGNETIC EXPOSURE FOR TELEPHONE COMPANY JOB CATEGORIES[a]

	Job Category					
Exposure Index	N = 33 COT[*]	N = 61 CST[*]	N = 15 IMR[*]	N = 40 OPT[*]	N = 55 NLW[*]	N = 34 Controls
Central Tendency						
1. Average Mean, mG	2.5 (0.3)	4.3 (0.5)	1.7 (0.2)	1.6 (0.1)	1.5 (0.1)	1.6 (0.3)
2. Average Median, mG	2.2 (0.4)	3.2 (0.5)	0.9 (0.1)	0.9 (0.1)	1.2 (0.1)	1.3 (0.3)
Maximum Levels						
1. Average Peak, mG	21.0 (2.8)	99.2 (40.1)	31.0 (5.2)	26.9 (5.0)	29.1 (4.6)	26.3 (4.6)
2. Average 95th Percentile, mG	5.1 (0.5)	11.1 (1.7)	6.0 (0.8)	4.6 (0.6)	3.1 (0.3)	3.2 (0.4)
3. Average Time Above Bkg., Min.	92.9 (21.3)	156.0 (16.5)	68.4 (9.8)	48.5 (7.0)	48.0 (11.3)	-- --
Variability Measures						
1. Average Standard Deviation, mG	1.6 (0.2)	6.7 (2.0)	2.4 (0.3)	1.9 (0.2)	1.5 (0.2)	1.3 (0.1)
2. Average Absolute Sequential Difference[b], mG	0.31 (0.04)	0.64 (0.12)	0.31 (0.28)	0.37 (0.02)	0.25 (0.02)	0.14 (0.01)

(standard error)

[*] COT - Central Office Technician
CST - Cable Splicing Technician
IMR - Installation Maintenance Repair

[*] OPT - Outside Plant Technician
NLW - Non-Lineworker

[a] Johns Hopkins University School of Hygiene and Public Health, "Leukemia in Telephone Linemen," prepared for the Electric Power Research Institute under Research Project 2964-04, p. 3-6 (1992).

[b] The average absolute sequential difference (AASD) for a total of N measurements, M_i, is given by $|\Sigma(M_i - M_{i+1})|/N$

Data Quality: The paper briefly reports the measurement protocols used. No mention is made, however, of calibration or quality assurance. There is a note of some problems with the first batch of prototype detectors. A/B/c/d/e.

Results: Table 3-7 presents mean weekly exposures by occupation and table 3-8 presents exposures by activity and exposure group.

TABLE 3-7. MEAN WEEKLY 60-Hz ELECTRIC, MAGNETIC AND HIGH-FREQUENCY TRANSIENT EXPOSURES DURING WORK FOR EXPOSED AND BACKGROUND GROUPS[a]

Occupation	Number Sampled	E Geometric Mean (V/m)	B Geometric Mean (mG)	Transients 5-20 MHz Geometric mean ppm[b]
Lineman (distribution)	10	62.5	14.5	0.286
Apparatus electrician (transmission)	3	181.7	34.4	0.862
Lineman (distribution)	2	418.9	13.1	3.051
Splicer (distribution)	2	6.7	20.8	0.039
Apparatus Mechanics	2	4.7	11.8	0.044
Generating Station assistant operator	1	5.0	11.4	7.965
All exposed occupations	20	48.3	16.6	0.331
Background group	16	4.9	1.6	0.002

[a] J.E. Deadman, M. Camus, B.G. Armstrong, P. Héroux, D. Cyr, M. Plante and G. Thériault, "Occupational and Residential 60-Hz Electromagnetic Fields and High-Frequency Transients: Exposure Assessment Using a New Dosimeter," American Industrial Hygiene Association Journal 49, p.414 (1988).
[b] ppm = parts per million per sample period.

TABLE 3-8. WEEKLY TWA EXPOSURES BY ACTIVITY AND EXPOSURE GROUP[a]

Quantity Group	Work Geom. Mean	Nonwork Geom. Mean	Sleep Geom. Mean	Weekly TWA Geom. Mean
60 Hz B field				
Exposed	16.6 mG	3.1 mG	1.6 mG	6.0 mG
Background	1.6 mG	1.9 mG	1.4 mG	1.7 mG
60 Hz E field				
Exposed	48.3 V/m	10.8 V/m	10.6 V/m	22.6 V/m
Background	4.9 V/m	10.5 V/m	19.0 V/m	13.7 V/m
5-20 MHz E transients				
Exposed	0.331 ppm[b]	0.017 ppm	0.002 ppm	0.120 ppm
Background	0.002 ppm	0.002 ppm	0.001 ppm	0.002 ppm

[a] J.E. Deadman, M. Camus, B.G. Armstrong, P. Héroux, D. Cyr, M. Plante and G. Thériault, "Occupational and Residential 60-Hz Electromagnetic Fields and High-Frequency Transients: Exposure Assessment Using a New Dosimeter," American Industrial Hygiene Association Journal 49, p.415 (1988).
[b] ppm = parts per million per sample period.

3.3 OTHER OCCUPATIONAL EXPOSURE ENVIRONMENTS

Video Display Terminals (VDTs)

Video display terminals have become ubiquitous in most office environments. Magnetic fields from VDTs have components in both the ELF range and at much higher frequencies. Table 3-9 shows the ELF magnetic flux densities measured for seven different models of VDTs[5]. For each side of the monitor, the location of the maximum field at the surface was determined and measurements were made at distances of 10, 30, and 50 cm. Measurements made at operator's chair were made in the location where a fetus would be positioned were the operator a pregnant woman.

Nuclear Magnetic Resonance (NMR) Facilities

Nuclear magnetic resonance (NMR) is a research method used in chemistry, physics and medicine. A particular clinical application, magnetic resonance imaging (MRI), uses this noninvasive technique for diagnostic imaging of patients. The technique involves placing the patient or sample in an extremely strong static magnetic field and then irradiating with a varying radiofrequency (RF) signal. This section discusses NMR operator exposure to static magnetic fields only. Exposure to radiofrequency fields, or to EMF in the course of clinical diagnostics, is outside the scope of this report.

TABLE 3-9. MAGNETIC FLUX DENSITY (mG) AS A FUNCTION OF DISTANCE FROM VIDEO DISPLAY TERMINALS

[background (power off) measurements given in parentheses][a]

Location of Measurement	Distance 10 cm	30 cm	50 cm	At operator's Chair, 35 cm
Data General D 211				
Front	11	2.5	1.3 (1.0)	1.6 (0.5)
Right side	31	5.7	2.8 (0.6)	
Left side	29	6.0	1.9 (0.4)	
Back	23	1.1	0.6 (0.4)	
Hewlett-Packard 82913A				
Front	10	3.0	2.5 (2.0)	2.1 (1.9)
Right side	16	4.0	2.3 (1.9)	
Left side	21	4.6	2.4 (2.0)	
Kaypro 16/HD				
Front	15	4.4	1.4 (0.8)	2.5 (0.3)
Right side	19	2.6	2.3 (0.3)	
Left side	50	8.2	2.5 (0.1)	
LSI ADM 32				
Front	11	3.0	1.3 (0.4)	1.9 (0.4)
Right side	15	3.1	1.3 (0.4)	
Left side	28	5.0	2.1 (1.0)	
Back	19	3.1	1.3 (0.4)	
Nokia VDU 52				
Front	11	2.8	1.1 (0.3)	2.5 (0.1)
Right side	28	5.3	0.9 (0.1)	
Left side	29	5.0	1.9 (0.9)	
Back	29	3.4	0.9 (0.1)	
Nokia VDU 202				
Front	12	3.3	1.3 (0.4)	3.9 (0.9)
Right side	46	6.7	2.9 (0.4)	
Left side	25	5.3	2.4 (0.4)	
Back	41	5.4	1.9 (0.4)	
Wyse WY 85				
Front	11	3.9	0.9 (0.1)	2.1 (0.4)
Right side	34	5.5	2.0 (0.5)	
Left side	39	6.7	2.1 (0.4)	
Back	24	4.0	0.9 (0.4)	

[a] Jukka Juutilainen, "Measurements of Extremely Low-Frequency Magnetic Fields Around Video Display Terminals," Scandinavian Journal of Work, Environment and Health 12, p. 610 (1986).

The sample to be studied in NMR is placed inside a solenoid magnet during imaging. Operator exposure is produced by the fringe fields surrounding the solenoid. The magnitude of the fringe fields depends on the flux density in the solenoid, the geometry of the solenoid and the distance from the solenoid. Flux densities of up to 140,000 G (14 Tesla) can be found in the solenoid center. The fringe fields diminish with the cube of the distance from the solenoid center. Table 3-10 presents data collected from seven different NMR magnets including those used for *in vitro* and *in vivo* research as well as clinical whole-body imaging.[6] The whole-body TWA exposure was an estimate based on observed and reported work practices. The authors included the location of the 600 G contour because it relates to certain applicable exposure guidelines.

Arc Welding

Arc welders typically use power frequency current to produce a plasma arc. High currents in proximity to the operator result in significant magnetic field exposures, usually at power frequencies. Table 3-11 presents operator exposures for an ensemble of arc welders.[7]

TABLE 3-10. NUCLEAR MAGNETIC RESONANCE FRINGE FIELD MEASUREMENTS AND ESTIMATED 8-HOUR TIME WEIGHTED AVERAGE EXPOSURE[a]

Magnet			Location[b] of 600 G Contour (m)	Estimated Whole-Body TWA (G)
Flux Density (X 10^3 G)	Bore Diameter (mm)	Orientation		
94	54	Vertical	0.41 (0.08)	15 - 40
70	89	Vertical	0.33 (0.03)	40 - 60
85	89	Vertical	0.56 (0.2)	30 - 150
18.9	300	Horizontal	0.84 (0.48)	20 - 120
47	400	Horizontal	1.7 (0.91)	140 - 640
15	500	Horizontal	2.62 (1.3)	90 - 170

[a] Margaret L. Philips, "Industrial Hygiene Investigation of Static Magnetic Fields in Nuclear Magnetic Resonance Facilities," Applied Occupational Environmental Hygiene 5, p.355 (1990).

[b] Maximum horizontal distance from magnet isocenter (distance in parenthesis is the distance from the magnet housing).

TABLE 3-11. ARC WELDER OPERATOR EXPOSURE TO MAGNETIC FIELDS (RMS VALUES AT THE FREQUENCY OF THE STRONGEST FIELD IN THE 5 Hz - 10 kHz RANGE)[a]

Model	Current (A)	Head (mG)	Chest (mG)	Waist (mG)	Gonads (mG)	Hand (mG)	Leg (mG)
Airco AC/DC Heliwelder	300	4	50	90	210	90	50
Canox AC Arc Welder	100	560	820	-	1510	630	1190
Canox AC Arc Welder	140	1190	2640	-	2890	1130	-
Canox Arc Welder	130	20	20	10	20	40	-
Canox Mig Welder	300	-	-	60	-	-	-
Canox Mig Welder	450	70	100	190	250	230	-
Canox Spot Welder Portable	36	750	1880	4400	6280	10050	2510
Canox Spot Welder	575	750	880	1880	1260	-	-
Canox Arc Welder	125	940	1130	4400	4400	3770	1880
Canox Arc Welder	90	250	880	1260	1260	1260	1130
Elektra-Beckum Mig Welder	20	60	70	70	70	90	-
Hobart H.F. Tig Welder	120	2010	2260	-	1380	1510	1380
Hobart H.G. Tig Welder	50	940	1380	-	1510	750	1260
Lincoln Tig Arc Welder AC	375	1000	1260	3140	3140	3140	3140
Lincoln Tig Arc Welder DC	-	750	150	380	750	1260	500
Linde Welder	240	750	820	1510	3640	-	3770
Linde Welder	185	500	1260	2510	1880	-	1260
Liquid Carbonic Stick Welder	180	500	1130	2510	2260	1510	-
Miller Bancroft Welder	500	2000	880	1260	1000	-	560
Miller Inert Tig AC/DC Gas	320	160	500	-	750	1260	-
Miller Portable Spot Welder	15	-	-	5	-	-	-
Thermal Dynamics Cutting System	400	40	40	60	80	80	100

[a] M.A. Stuchly and D.W. Lecuyer, "Exposure to Electromagnetic Fields in Arc Welding," Health Physics 56, p. 299 (1989).

4. TRANSPORTATION

Comprehensive assessments of the ELF-EMF exposure environments associated with transportation systems are virtually non-existent. The only relevant assessments identified are a series of field studies of electric rail transit and maglev systems commissioned by the DOT and only recently completed.[1-5]

Some limited information can be gleaned from personal monitoring studies that incorporate a log or other method of recording the environments where transportation exposures also occurred (see section 3.1). Otherwise, knowledge of transportation ELF-EMF exposures is largely anecdotal or tied to occupational epidemiological inferences (as in foregin studies of Italian, Swiss, British, Norwegian and Japanese rail workers). This chapter presents selected summary statistics from the field studies commissioned by the DOT and compares maglev exposures to other rail transport systems.

4.1 MAGLEV AND COMPARISONS

Review of the available information on magnetic fields associated with various kinds of electric rail transport technologies indicates that there are not likely to be any significant potential exposures uniquely associated with maglev operation. In terms of flux density, the maglev fields are certainly not higher, either on a peak field or average field basis, than those from the other rail technologies considered in this report. While there are no unique exposures in terms of flux density or frequency as determined by the ERM bandwidth designations, the combination of dc fields and the range of frequencies encountered in the TR-07 is clearly not matched in any of the rail transport technologies considered here.

Magnetic field flux densities measured in the TR-07 vehicle passenger area as a function of frequency are listed in table 4-1. Table 4-2 provides the same information for the Engineer area. Conclusions in this chapter regarding the lack of substantially unique magnetic fields associated with maglev operation are based largely on comparisons by frequency and flux density, between maglev and currently deployed electric rail and transit transport technologies, displayed in table 4-3. Tables 4-4 through 4-14 provide similar information for other systems for which data are available from measurements using the *Multiwave*™ system.

In terms of frequency components or spectral density characteristics, the maglev fields are more variable and cover a wider frequency range than do the single fundamental frequency (e.g., 60 Hz) surface rail systems such as Amtrak. maglev-generated fields exhibited high spectral power density in the 15 Hz range. This 15 Hz component is close to the 16.6 Hz fundamental used in Switzerland, for example, and according to the bandwidth designation scheme used by ERM, falls into the same band as the 25 Hz fundamental used by Amtrak on a portion of its electrified track on the North-East Corridor (NEC).

TABLE 4-1. SUMMARY OF TR-07 MAGNETIC FIELDS IN PASSENGER COMPARTMENT (TOTAL OF 95 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	12.7 111.76	166.81[b] 225.96[c]	1501.63[b] 1036.18[c]	834.42[b] 635.5[c]	304.13[b] 220.54[c]
5 - 45 Hz	12.7 111.76	31.37 7.44	235.53 76.76	89.77 26.06	39.83 11.33
50 - 60 Hz	12.7 111.76	3.76 1.22	42.60 27.17	14.80 5.18	8.36 3.30
65 - 300 Hz	12.7 111.76	10.65 3.11	88.22 29.55	32.48 13.72	17.11 6.01
305 - 2560 Hz	12.7 111.76	0.45 0.23	4.57 2.29	1.93 1.00	0.96 0.56
5 - 2560 Hz	12.7 111.76	34.84 9.92	253.50 76.92	98.37 30.55	40.06 11.69

[a] "Final Report on Magnetic Field Testing of TR07 Maglev Vehicle and System," Electric Research and Management, Inc., State College, PA, prepared for the Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-16 (1992).

[b] The fluxgate sensor was saturated on one axis for 20 of the 95 measurements.

[c] The fluxgate sensor was saturated on one axis for four of the 95 measurements.

TABLE 4-2. SUMMARY OF TR-07 MAGNETIC FIELDS IN REAR ENGINEER SECTION (TOTAL OF 20 SAMPLES)[a]

Frequency	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	12.7 111.76	792.03 655.67	1098.48[b] 954.96	986.02[b] 791.35	76.13[b] 94.75
5 - 45 Hz	12.7 111.76	31.11 16.83	180.31 80.83	75.53 37.29	37.69 13.69
50 - 60 Hz	12.7 111.76	3.08 2.17	29.41 24.65	16.28 11.53	6.88 7.09
65 - 300 Hz	12.7 111.76	24.60 28.58	85.48 61.99	55.28 45.21	15.96 7.95
305 - 2560 Hz	12.7 111.76	0.94 0.91	4.28 4.17	2.09 1.96	0.89 0.98
5 - 2560 Hz	12.7 111.76	39.80 37.13	190.89 98.37	96.59 60.47	37.55 14.59

[a] "Final Report on Magnetic Field Testing of TR07 Maglev Vehicle and System," Electric Research and Management, Inc., State College, PA, prepared for the Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-29 (1992).
[b] Fluxgate sensor was saturated on one axis for nine of the 20 measurements.

TABLE 4-3. COMPARISON OF MAGNETIC FIELDS MEASURED IN PASSENGER AREAS OF THE TR-07, MBTA, WMATA METRORAIL, TGV HIGH SPEED RAIL, AND AMTRAK SYSTEMS[a]

Frequency Range	Height Above Floor	TR-07	MBTA Subway	MBTA High Speed Trolley	MBTA Trolley Bus	WMATA Metro Rail	TGV High Speed Rail	Amtrak 25 Hz	Amtrak 60 Hz
	(cm)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)	AVG / SD (mG)
Static	10 110	834 / 304[b] 636 / 220[c]	766 / 321 430 / 217	1502 / 760 412 / 55.20	366 / 58.81 252 / 41.86	14285 / 27537 1008 / 1074	954 / 558 1145 / 492	568 / 463 539 / 135	758 / 109 552 / 162
5 - 45 Hz	10 110	89.77 / 39.83[b] 26.06 / 11.33[c]	10.79 / 13.03 3.12 / 2.64	9.67 / 7.34 2.13 / 1.71	3.54 / 2.89 0.77 / 0.82	562 / 532 33.88 / 24.93	29.64 / 20.85 16.47 / 10.87	126 / 100 113 / 101	2.16 / 1.49 0.92 / 0.74
50 - 60 Hz	10 110	14.80 / 8.36[b] 5.18 / 3.30[c]	2.10 / 2.21 0.64 / 0.34	1.29 / 1.17 0.62 / 1.03	1.40 / 0.68 1.52 / 0.74	70.29 / 56.62 4.37 / 2.93	14.31 / 13.60 22.17 / 21.92	10.42 / 9.12 2.97 / 2.23	43.57 / 41.91 45.40 / 52.16
65 - 300 Hz	10 110	32.48 / 17.11[b] 13.72 / 6.01[c]	2.95 / 2.81 0.82 / 0.57	1.63 / 1.02 0.39 / 0.26	1.64 / 1.12 0.56 / 0.16	738 / 456 44.17 / 26.89	2.68 / 1.91 2.01 / 1.04	16.08 / 11.43 12.22 / 10.07	3.69 / 3.76 5.01 / 4.43
305 - 2560 Hz	10 110	1.93 / 0.96[b] 1.00 / 0.56[c]	1.15 / 0.83 0.46 / 0.54	0.70 / 0.47 0.17 / 0.15	3.41 / 3.25 0.39 / 0.17	230 / 121 13.65 / 6.82	1.34 / 0.84 1.14 / 0.48	2.83 / 1.75 2.20 / 1.79	1.10 / 0.95 1.18 / 1.13
5 - 2560 Hz	10 110	98.37 / 40.06[b] 30.55 / 11.69[c]	11.67 / 13.34 3.43 / 2.64	10.09 / 7.25 2.48 / 1.72	5.88 / 3.83 1.97 / 0.88	997 / 657 60.23 / 32.66	35.04 / 22.10 30.22 / 21.32	129 / 99.53 114 / 102	43.88 / 42.02 45.76 / 52.31

[a] Data compiled from references 1-5.
[b] Measurements made at a height of 12.7 cm above floor.
[c] Measurements made at a height of 11.76 cm above floor.

4.2 MASSACHUSETTS BAY TRANSPORTATION AUTHORITY (MBTA) URBAN TRANSIT SYSTEM

TABLE 4-4. SUMMARY OF MBTA SUBWAY MAGNETIC FIELDS IN PASSENGER AREAS OF ORANGE, BLUE, RED, AND GREEN LINE CARS (TOTAL OF 144 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10	235.74	1981.24	765.75	321.35
	110	11.82	1360.97	429.79	217.19
5 - 45 Hz	10	0.31	66.00	10.79	13.03
	110	0.07	16.65	3.12	2.64
50 - 60 Hz	10	0.17	14.65	2.10	2.21
	110	0.18	2.18	0.64	0.34
65 - 300 Hz	10	0.07	18.34	2.95	2.81
	110	0.09	2.73	0.82	0.57
305 - 2560 Hz	10	0.08	4.70	1.15	0.83
	110	0.04	2.27	0.46	0.54
5 - 2560 Hz	10	0.44	68.36	11.67	13.34
	110	0.22	16.71	3.43	2.64

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S.Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-45 (1993).

TABLE 4-5. SUMMARY OF MBTA SUBWAY MAGNETIC FIELDS MEASURED IN OPERATOR'S AREA (TOTAL OF 185 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	161.18 133.10	3078.42 2066.26	840.72 697.33	431.10 334.35
5 - 45 Hz	10 110	0.24 0.12	45.38 21.07	7.52 2.85	7.28 3.02
50 - 60 Hz	10 110	0.22 0.19	9.50 3.07	1.70 0.78	1.51 0.53
65 - 300 Hz	10 110	0.11 0.09	25.18 7.92	2.22 0.82	2.81 0.80
305 - 2560 Hz	10 110	0.20 0.10	5.27 2.08	0.98 0.64	0.76 0.43
5 - 2560 Hz	10 110	0.44 0.37	52.86 21.11	8.26 3.29	7.80 3.04

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S.Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 4-10 (1993).

TABLE 4-6. SUMMARY OF MBTA MATTAPAN HIGH SPEED TROLLEY MAGNETIC FIELDS MEASURED IN PASSENGER AREAS (TOTAL OF 14 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	620.25 339.73	3074.28 555.80	1501.55 411.93	760.32 55.20
5 - 45 Hz	10 110	2.56 0.60	25.61 7.17	9.67 2.13	7.34 1.71
50 - 60 Hz	10 110	0.30 0.14	4.75 4.10	1.29 0.62	1.17 1.03
65 - 300 Hz	10 110	0.33 0.13	3.68 1.18	1.63 .39	1.02 0.26
305 - 2560 Hz	10 110	0.29 0.06	1.84 0.63	0.70 0.17	0.47 0.15
5 - 2560 Hz	10 110	3.32 1.00	26.03 7.33	10.09 2.48	7.25 1.72

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S.Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-46 (1993).

TABLE 4-7. SUMMARY OF MBTA MATTAPAN HIGH SPEED TROLLEY MAGNETIC FIELDS MEASURED IN OPERATOR'S RIGHT REAR SEAT CORNER AREA (TOTAL OF 12 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	542.67 70.08	737.57 385.45	631.44 147.19	54.68 90.10
5 - 45 Hz	10 110	0.31 0.16	11.29 2.66	4.96 1.58	3.05 0.78
50 - 60 Hz	10 110	0.22 0.27	1.06 0.51	0.55 0.40	0.23 0.07
65 - 300 Hz	10 110	0.04 0.35	1.77 0.67	0.78 0.48	0.44 0.09
305 - 2560 Hz	10 110	0.08 0.11	0.89 0.35	0.38 0.22	0.21 0.07
5 - 2560 Hz	10 110	0.39 0.48	11.52 2.77	5.08 1.74	3.07 0.72

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S. Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 4-11 (1993).

TABLE 4-8. SUMMARY OF MBTA TROLLEY BUS MAGNETIC FIELDS MEASURED IN PASSENGER AISLE BEHIND REAR AXLE (TOTAL OF 31 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	289.60 210.39	467.28 323.55	365.81 252.01	58.81 41.86
5 - 45 Hz	10 110	0.30 0.10	12.85 4.54	3.54 0.77	2.89 0.82
50 - 60 Hz	10 110	0.48 0.57	2.84 2.98	1.40 1.52	0.68 0.74
65 - 300 Hz	10 110	0.34 0.16	3.37 0.83	1.64 0.56	1.12 0.16
305 - 2560 Hz	10 110	0.44 0.19	9.25 0.73	3.41 0.39	3.25 0.17
5 - 2560 Hz	10 110	0.96 0.88	13.24 4.64	5.88 1.97	3.83 0.88

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S.Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-48 (1993).

TABLE 4-9. SUMMARY OF MBTA TROLLEY BUS MAGNETIC FIELDS MEASURED IN OPERATOR'S RIGHT REAR SEAT CORNER AREA (TOTAL OF 25 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10	293.83	407.60	384.36	22.54
	110	452.35	654.01	491.74	36.38
5 - 45 Hz	10	0.11	1.35	0.63	0.34
	110	0.10	1.22	0.45	0.27
50 - 60 Hz	10	0.46	2.33	1.12	0.49
	110	0.29	2.72	1.07	0.54
65 - 300 Hz	10	0.06	0.25	0.13	0.06
	110	0.10	0.35	0.26	0.07
305 - 2560 Hz	10	0.06	0.16	0.09	0.03
	110	0.06	0.20	0.09	0.04
5 - 2560 Hz	10	0.55	2.48	1.34	0.46
	110	0.60	2.74	1.24	0.50

[a] Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System," prepared for U.S. Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 4-13 (1993).

4.3 THE FRENCH TRAIN A GRANDE VITESSE (TGV) RAIL SYSTEM

TABLE 4-10. SUMMARY OF TGV HIGH SPEED RAIL MAGNETIC FIELDS MEASURED IN ALL TGV COACHES WHILE TRAVELING ALL SECTIONS OF THE LINE (TOTAL OF 322 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	281.64 74.73	5341.73 4545.70	953.97 1144.87	557.75 492.43
5 - 45 Hz	10 110	0.19 0.12	106.21 58.65	29.64 16.47	20.85 10.87
50 - 60 Hz	10 110	0.13 0.16	60.97 87.84	14.31 22.17	13.60 21.92
65 - 300 Hz	10 110	0.24 0.37	10.40 5.54	2.68 2.01	1.91 1.04
305 - 2560 Hz	10 110	0.18 0.18	4.92 2.68	1.34 1.14	0.84 0.48
5 - 2560 Hz	10 110	0.44 0.80	106.67 92.00	35.04 30.22	22.10 21.32

[a] Electrical Research and Management, Inc. "Final Report on Magnetic and Electric Field Testing of the French Train A Grande Vitesse (TGV) Rail Systems", prepared for U.S. Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-23 (1992).

TABLE 4-11. SUMMARY OF TGV HIGH SPEED RAIL MAGNETIC FIELDS MEASURED AT THE RIGHT REAR CORNER OF THE ENGINEER'S SEAT IN THE CAB ON NORMAL SCHEDULED SERVICE OPERATING ON A 25 kV CATENARY (TOTAL OF 95 SAMPLES)[a]

Frequency Range	Height above floor (cm)	Magnetic Flux Density (mG)			
		Minimum	Maximum	Average	Standard Deviation
Static	10 110	1324.59 657.25	1661.89 1052.70	1455.89 816.75	73.39 87.54
5 - 45 Hz	10 110	4.17 3.55	54.50 33.90	24.40 13.53	8.68 5.55
50 - 60 Hz	10 110	0.76 0.48	89.60 104.12	31.54 35.75	17.88 21.43
65 - 300 Hz	10 110	0.84 0.52	7.27 6.23	2.81 2.35	1.36 1.01
305 - 2560 Hz	10 110	0.73 0.59	3.74 3.48	1.82 1.81	0.58 0.52
5 - 2560 Hz	10 110	14.34 11.55	94.73 105.80	42.25 39.74	14.52 19.51

[a] Electrical Research and Management, Inc. "Final Report on Magnetic and Electric Field Testing of the French Train A Grande Vitesse (TGV) Rail Systems", prepared for U.S. Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 4-20 (1992).

4.4 AMTRAK AND METRO NORTH NORTHEAST CORRIDOR AND NEW JERSEY TRANSIT NORTH JERSEY COAST LINE RAIL SYSTEMS

TABLE 4-12. SUMMARY OF AMTRAK NORTH NORTHEAST CORRIDOR AND NORTH JERSEY COAST (LONG BRANCH) LINE MAGNETIC FIELDS IN COACHES BY SECTION[a]

Field Frequency Band	Section of Corridor	Minimum Magnetic Field (mG)	Maximum Magnetic Field (mG)	Average Magnetic Field (mG)
0 Hz	25 Hz	172.85	1207.70	606.17
	60 Hz	386.92	25.97	630.39
	Non-electric	407.69	699.62	531.39
	Long Branch	561.22	850.25	734.04
	Average	382.17	920.89	625.50
5 - 45 Hz	25 Hz	5.22	624.17	131.93
	60 Hz	0.17	8.99	1.35
	Non-electric	0.21	3.94	1.42
	Long Branch	0.21	7.47	1.57
	Average	1.45	161.15	34.07
50 - 60 Hz	25 Hz	1.39	26.91	5.89
	60 Hz	3.80	304.45	52.03
	Non-electric	0.71	12.52	6.04
	Long Branch	0.37	59.83	18.23
	Average	1.57	100.93	20.55
65 - 300 Hz	25 Hz	2.06	72.81	16.17
	60 Hz	0.85	27.32	5.66
	Non-electric	0.21	2.37	0.88
	Long Branch	0.41	9.40	2.47
	Average	0.88	27.97	6.29
305 - 2560 Hz	25 Hz	0.31	11.41	2.71
	60 Hz	0.24	7.47	1.37
	Non-electric	0.07	0 80	0.27
	Long Branch	0.18	1.91	0.66
	Average	0.20	5.40	1.25
5 - 2560 Hz	25 Hz	7.14	627.67	133.77
	60 Hz	4.20	305.23	52.46
	Non-electric	0.92	12.60	6.42
	Long Branch	2.85	60.68	18.61
	Average	3.78	251.54	52.81

[a]Electric Research and Management, Inc., "Final Report on Magnetic and Electric Field Testing of the Amtrak and Metro North Northeast Corridor and New Jersey Transit North Jersey Coast Line Rail Systems Volume 1 - Analysis," prepared for U.S. Department of Transportation Federal Railroad Administration under Contract No. DTFR53-91-C-00047, p. 3-60 (1993).

5. ONGOING RESEARCH

5.1 INTRODUCTION

EMF exposure assessment has progressed considerably since the initial report of an association between a magnetic field exposure surrogate and increased risk for leukemia in 1979.[1] In contrast to the use of a surrogate in the initial study, exposure assessment of magnetic fields can now be conducted using a variety of relatively sophisticated instruments and methods. This section will discuss the need for continued research in the area of exposure assessment.

For some cancers, including childhood leukemia, surrogate measures continue to show stronger associations with incidence in epidemiologic studies than do actual magnetic field flux density measurements. This represents a challenge for those working in exposure assessment. In the four principal residential studies to date[2-5] magnetic field flux density spot and 24-hour area measurements in the home did not correlate as well with disease outcome as did the surrogates (wiring code or proximity to high-current-carrying power lines external to the home). The failure of specific magnetic field flux density measurements to correlate better with increased risk than do general surrogates, such as wiring code or proximity, continues to be an issue of concern.

This situation suggests that attributes of the magnetic fields taken to represent dose may not accurately reflect a causal insult, particularly with regard to childhood leukemia. Some suggest it is reasonable to hypothesize that an as yet undiscovered factor associated with proximity to power lines is a causative agent in childhood leukemia.[6] In either case, the situation underscores the need for a better understandinging of bioeffect mechanisms for improved exposure assessment.

Most magnetic field exposure assessments reported to date were carried out under the assumption that the parameter being measured (TWA of the 60 Hz magnetic field flux density) has some association with effective dose as determined by biological effects or changes in health. However, it is by no means clear what attributes of the magnetic field, if any, may constitute dose nor whether threshold or linear dose-response concepts apply to EMF bioeffects. Because power lines produce mainly 60-Hz magnetic fields, the assumption has been that time-weighted average 60-Hz magnetic field flux density would be the exposure of interest. The validity of this assumption is a significant issue for ELF-EMF exposure assessment.

5.2 MECHANISMS AND METRICS

It appears likely that no single mechanism can account for the various biological effects that are now being reported with some consistency from laboratory studies. It should therefore be anticipated that no single aspect or parameter of EMF exposure will account for an observed increase in health risk linked with EMF exposure, should a causal relationship eventually be demonstrated between EMF exposure and increased risk.

Some progress has been made on narrowing the EMF parameters that could be associated with increased risk. For example, in recent years attention has been directed away from the electric field component and toward the magnetic field as the component of main interest in EMF studies. Magnetic field experiments in the laboratory have been fairly consistent in showing biological effects in certain areas (e.g., effects on pineal gland function) and not so consistent in others (e.g., gene transcription). It is the demonstration of these biological effects induced by magnetic fields, in concert with the epidemiologic study results indicating that the electric field is not associated with risk of disease, that has directed interest toward the magnetic field in EMF health effects research.

Characteristics of the field that are currently being determined in exposure assessment are limited. To some extent this is because of limitations in the available measurement technology and the lack of standardized measurement protocols. Eventually, however, the scope of these assessments may have to be broadened considerably to provide any reasonable correlation with adverse health outcome, and hence allow some estimate of possible risk.

The issue of dose is a central one. Some authors have suggested that the de facto measure of dose currently used, the time-weighted average or TWA, is inadequate. The time-weighted average exposure has proved quite useful in chemical toxicology and was adopted in the early studies of the possible link between EMF and cancer. However, laboratory data suggest that the TWA magnetic flux density may not be the main parameter of interest.

The same conclusion has been drawn by many reviewing the epidemiologic literature. In determining the time-weighted average for EMF exposure in epidemiologic studies, the most common measures have been surrogates for the magnetic field flux density. These have included job title,[7] proximity to high-current carrying power lines external to the home[8] and the Wertheimer/Leeper (W/L) wiring code.[9] When considered along with time on the job, or time in residence at a particular dwelling, the surrogates are generally thought to represent TWA. In the residential studies, however, the W/L wiring code and proximity measure surrogates have shown a better correlation with increased leukemia and brain cancer risk than have actual measurements of the magnetic field flux density.[10-12] The TWA exposure metric, based on the assumption that magnetic field flux density is the EMF parameter of interest, and determined from spot and 24-hour measurements, has not shown good correlation with increased disease risk.

Consistent with the view that the EMF interaction with organized biological tissue is multifactored and complex, new exposure metrics need to be developed that can better predict health outcome from available exposure assessment data. Chapter 1 discussed some of the magnetic field attributes and indices that have been proposed as possible measures of exposure. These measures and some additional ones are displayed in table 5-1 with examples from the literature that are consistent with the proposed metric or attribute. Clearly, this is not an exhaustive listing. Combinations of factors may also be important.

TABLE 5.1 EXAMPLES OF STUDIES CONSISTENT WITH PROPOSED DOSE METRICS

Dose Metric	Effect and study first author
Time weighted average magnetic field*	Childhood leukemia studies. (Savitz, et al., London, et al.) Skin tumor co-promotion (McLean et al., Beniashvili, et al.)
Intermittency/on-off nature of the field	Heart interbeat interval increase (Cook, et al.) Human mental task performance (Cook, et al.) Melatonin reduction in rats (Lerchl, et al.)
Frequency/frequency content/repetition rate	Bone growth stimulaton (Pilla et al.) Transcription effects (Goodman, et al.)
Clock time or circadian phase of exposure	Circadian activity thythms (Groh et al.) Baboon blood melatonin levels (Rogers et al.) Hamster melatonin phase shift (Yellon, et al.)
Resonance conditions (AC frequency and DC field flux density)	Radial maze performance (Lovely, et al.) Calcium efflux (Blackman, et al.) Re-evaluation of London, et al. data (Bowman, et al.)
Peak field exposure	Leukemia in electrical workers (Matanoski, et al.) Intensity dependent effects in co-promotion cancer studies (Beniashvili, et al.; McLean, et al.)

* for the epidemiologic studies; as estimated by proximity to power lines

5.3 PROPOSED ALTERNATIVE EXPOSURE METRICS

Alternative metrics have been proposed that can be determined from existing data sets such as those that are obtained with the EMDEX or other recording magnetic field meters as well as spectral data collected in broadband field exposure assessments. Examples are discussed here briefly.

Peak Field: The time spent in fields above a certain flux density threshold level has been proposed as a possible metric.[13] For example[14] Matanoski et al.(1991), showed that adult leukemia risk in workers was more strongly associated with peak magnetic fields than with TWA 60 Hz exposures measured in the same work environments.

Rate of Change: The proposed rate of change (ROC) metric can be defined generally as the square root of the sum of squares of the absolute differences for a time series of repetitive measures of magnetic field flux density. The metric provides an estimate of an average rate of change of the magnetic field (in G/sec) and is a measure of how often the magnetic field environment changes (on an approximate 10-second time scale) over a given period of time (e.g., per hour or per 24 hours), and the magnitude of that change. This metric has been tested as an alternative to the time-weighted average on an EMDEX data set and found to differentiate much more strongly between exposures from water bed heaters and exposure from electric blankets, for example, than does the TWA. When applied to night time personal dosimeter measurements in a recent epidemiologic study, the ROC metric showed an approximate 7- fold difference in exposure between water bed users and electric blanket users, whereas the TWA metric from the same data set showed only an approximate 2-fold difference in the exposure from the two devices.[15] The relatively stable load on transmission lines would be differentiated by a ROC metric from the variable load and EMF due to distribution lines and cycling home appliances.

Coherence: The coherence model of Litovitz[16] is in apparent contrast to the intermittency hypothesis addressed by the ROC metric. According to Litovitz, an important exposure metric of interest is the length of time that a biological system is exposed to a coherent signal (e.g., a nearly pure sinusoidal signal at 60 Hz). In the coherence model, tissue can respond to a weak electromagnetic signal if the signal is coherent in time and space and thus affects a number of cells at substantially the same time and in the same way. In evaluating data for consistency with this model, frequency data would be reviewed for the absence of electromagnetic noise and frequency components other than 60 Hz, for example.

Parametric Resonance: The parametric resonance model was considered by Bowman and colleagues[17] in their re-evaluation of exposure data from the London et al.[18] (1991) study. This model predicts that there should be greater biological effect from 60 Hz magnetic fields in areas where the static magnetic field was near either 380 or 506 mG. From static magnetic field measurements made at case and control homes in the London study, they selected homes that had static magnetic fields near these two flux densities and compared them to homes that had static flux densities in between these (i.e., not near) these two values. Although there were not many homes in the 380 or 506 mG categories, the homes in the 506 mG range were statistically significantly more likely to be a case home than a control home. The hypothesis will be tested in other studies. These results would suggest that information on static magnetic field levels is a potentially important component of a thorough exposure assessment in residential studies and in occupational studies wherever such data reflect exposure of populations or individuals of interest.

5.4 USE OF NEW EXPOSURE ASSESSMENT APPROACHES IN ONGOING STUDIES

In this section, several current exposure assessments being done in conjunction with epidemiologic studies are described as examples of how new technologies or protocols are being applied.

Rate of Change Metric and Clinical Evaluations: Two new assessment approaches, use of the ROC metric on EMDEX data and assay of hormonal status, will be used in a nested case-control study to determine possible association between miscarriage and EMF exposure. In this joint project, Kaiser Permanente and the California State Department of Health Services are studying the effects of a number of lifestyle variables and environmental exposures, including magnetic fields, on pregnancy outcome. Volunteers for this study were selected from participants in a larger study of pregnancy outcome in healthy women, in which more than 6000 females have participated.

In the EMF portion of this study, women who were pregnant, or attempting to become pregnant, wore an EMDEX personal magnetic field dosimeter for at least 24 hours. Matched control volunteers also used the dosimeters. EMF exposure information ascertained from this study was broken into three categories (work time, during sleep, and other) for analysis. Data recorded by the EMDEX dosimeters was analyzed to obtain the exposure according to the rate of change metric (described above), as well as the conventional time-weighted average exposure normally ascertained from EMDEX records. In addition, medical histories were available for each volunteer, all participants completed questionnaires providing details on electric appliance use. Exposure data obtained from the study will be analyzed to determine if, in this population, there was an association between either exposure metric and miscarriage. This exposure assessment is likely to be particularly valuable because the study was prospective; that is, exposure data were obtained during gestation, prior to outcome. Also, urine samples from the women in the study were analyzed for estradiol, progesterone, and luteinizing hormone fragments, as well as the urinary metabolite for melatonin, thus providing information on endocrine function which will also eventually be analyzed for association with EMF exposure data.

Ambient Light Levels in Conjunction with Personal Dosimetry: In the Fred Hutchinson Cancer Center/Battelle Study on EMF and Female Breast Cancer, some 800 female breast cancer cases will be ascertained immediately after diagnosis and prior to any treatment. The study was started in 1993 and is being conducted in Washington State in King and Pierce Counties. Volunteers in the study, both cases and controls, will wear EMDEX personal dosimeters to determine daily EMF exposure. In addition, residences of cases and matched controls will be wire coded, and spot magnetic field measurements will be taken in the home.

For this study, light meters were fabricated that use an available channel in the EMDEX to record light levels in the bedroom during the night. In addition, urine samples will be collected from cases and controls, and these samples will be analyzed for melatonin. The hypothesis that pineal function may be an etiologic factor in breast cancer was taken into account in the design of this study. In studies on laboratory animals, magnetic field exposure has reduced concentrations of melatonin in the pineal and the blood. Exposure of the eyes to light during the dark phase of the 24-hour cycle can reduce the night time increase in production of melatonin.

Concurrent ELF and VLF Magnetic Field Measurements: Battelle Pacific Northwest Laboratory has recently completed field work on an exposure assessment study comparing ELF and VLF magnetic field flux densities for several environments in and around a military communications facility in Hawaii. This study is of interest because it directly compares magnetic flux densities in the ELF and VLF ranges for a variety of environments. This exposure assessment was carried out in conjunction with a review of disease incidence from census tract data for tracts near the facility.

The report will compare ELF and VLF fields in open areas far away from buildings and power lines as well as in built-up residential areas and inside a medical clinic. The final report will be submitted to the U.S. Coast Guard for inclusion in an Environmental Impact Statement for a military housing project at Omega Station, Hawaii.

5.5 FUTURE DIRECTIONS

In this section, several areas of merging interest in exposure assessment are discussed.

Proximity to Power Lines: By far the largest residential exposure assessment effort reported to date (in terms of population studied) has been carried out in conjunction with the study of Feychting and Ahlbom, in Sweden. Assessments in this study consisted of determining the distance of residences from transmission and primary distribution lines, and of spot and 24-hour measurements in the home. This same approach of accurately determining proximity to high-current-carrying power lines is ideally suited for work in many European countries where national health systems can provide accurate health records and tumor data for nearly everyone in the country. The ability to obtain accurate health records from large populations in this way is important when relatively rare diseases such as childhood leukemia and male breast cancer are being studied. The proximity metric, such as the distance to line as used in the Swedish study, combined with historic load data, has been shown to be a better predictor of risk for childhood leukemia than actual flux density spot measurements.

Transients and High Frequency Fields: A recent workshop hosted by the Electric Power Research Institute focused on magnetic field transients and their importance in exposure assessment. The workshop dealt with the ways in which transients in general, and in particular power line transient phenomena, may be important in health exposure assessments related to epidemiologic studies and the EMF health effects issue in general. Issues raised during the workshop are important in advancing exposure assessment for magnetic fields that are generated at frequencies other than 60 Hz. Much of the following discussion of transients and high-frequency exposures is based on notes made available from that workshop. It was concluded from the discussions that although more information was needed, available data suggest that power transmission lines are not an important source of transients. The major source of transients on the power line circuits is capacitive switching for load factor correction. These are relatively infrequent, occurring no more than a few times a day, on average. Measurements of these transients showed that they had frequency components in the 10-20 kHz range. Transients could be common in certain work (e.g. transportation) environments and in the home (use of appliances).

Conceptual design for new equipment that would provide data on transient events was discussed. If transients or short-duration exposures to high-frequency exposures are important, then such equipment could be of use not only to the power industry but would be valuable to exposure assessment in general.

Short-Duration, High-Flux Density/High-Frequency Exposures: Lovely and Wilson have recently set forth the case for giving increased attention to short-term exposures from small electrical devices such as handheld appliances. Such exposures may be of short duration, but nonetheless they may be to high-flux density and or high-frequency magnetic fields. These authors point out that these exposures are largely elective and may occur in both the occupational and residential settings. Although often of short duration, the flux densities and frequencies sometimes associated with these exposures are such that the local electric fields induced are above those that are normally present in the body. As discussed in the conclusions chapter, this is not the case for 60-Hz magnetic fields at flux densities normally encountered in the environment. Lovely and Wilson maintain that the recently reported data on the magnetic fields generated by home appliances used close to the body, especially motor-driven personal appliances, should lead to a re-evaluation of the working assumptions regarding residential magnetic fields.

In summary, the major issue in exposure assessment as related to epidemiologic studies is to determine what attributes of the magnetic field, if any, constitutes dose. To address this issue, new approaches to exposure assessment are being taken in conjunction with epidemiologic studies. Many of these are designed to test specific hypotheses regarding both physiologic and biophysical mechanisms of action for the magnetic field. As the results from these exposure assessments and their associated epidemiologic studies become available, it will be possible to select likely candidates among the proposed mechanisms both for physiologic and biophysical mechanisms of effect.

6. CONCLUSIONS

- **Current understanding of typical American ELF-EMF exposure environments is incomplete.** It is not now possible to describe the relevant ELF-EMF exposure parameters and their distribution across the population.

- **There are important unresolved questions concerning the proper measure of exposure to ELF-EMF with regards to long-term adverse health effects.** Until the issue of appropriate exposure measure is resolved, it is difficult to consider any exposure environment well characterized.

- **The number of different types of occupational environments assessed for ELF-EMF exposure is very small compared to the population of all American occupations.** Most occupational exposure efforts have been directed at occupations with potentially high exposures or high rates of disease incidence.

- **Ongoing research in certain areas may extend current knowledge concerning ELF-EMF exposure assessment.** EPRI's ongoing development of a national database of residential magnetic field information will help characterize the distribution of a number of residential magnetic field parameters.

- **Maglev technology, as evidenced by the German TR-07 system, does not present substantially unique exposures to passengers or crew.** Comparisons made between Maglev and a number of other electric rail transport technologies suggest that Maglev fields do not differ significantly in terms of flux density or frequency content (see section 4.1 and the following figures).

- **Major research efforts are required to characterize typical EMF-ELF exposures.** A large scale, nationwide study that uses personal exposure monitoring in conjunction with activity logs is required to develop a typical exposure profile. Such a study must include a large number of individuals from a variety of occupations, geographic areas, and socio-economic groups.

Figures 6-1 through 6-3 provide a rough indication of the potential exposures associated with Maglev compared to home, occupational and other transportation environments. Due to the differences in instrumentation, measurement approach, protocols, and data reported, the comparsions made in the figures are not definitive.

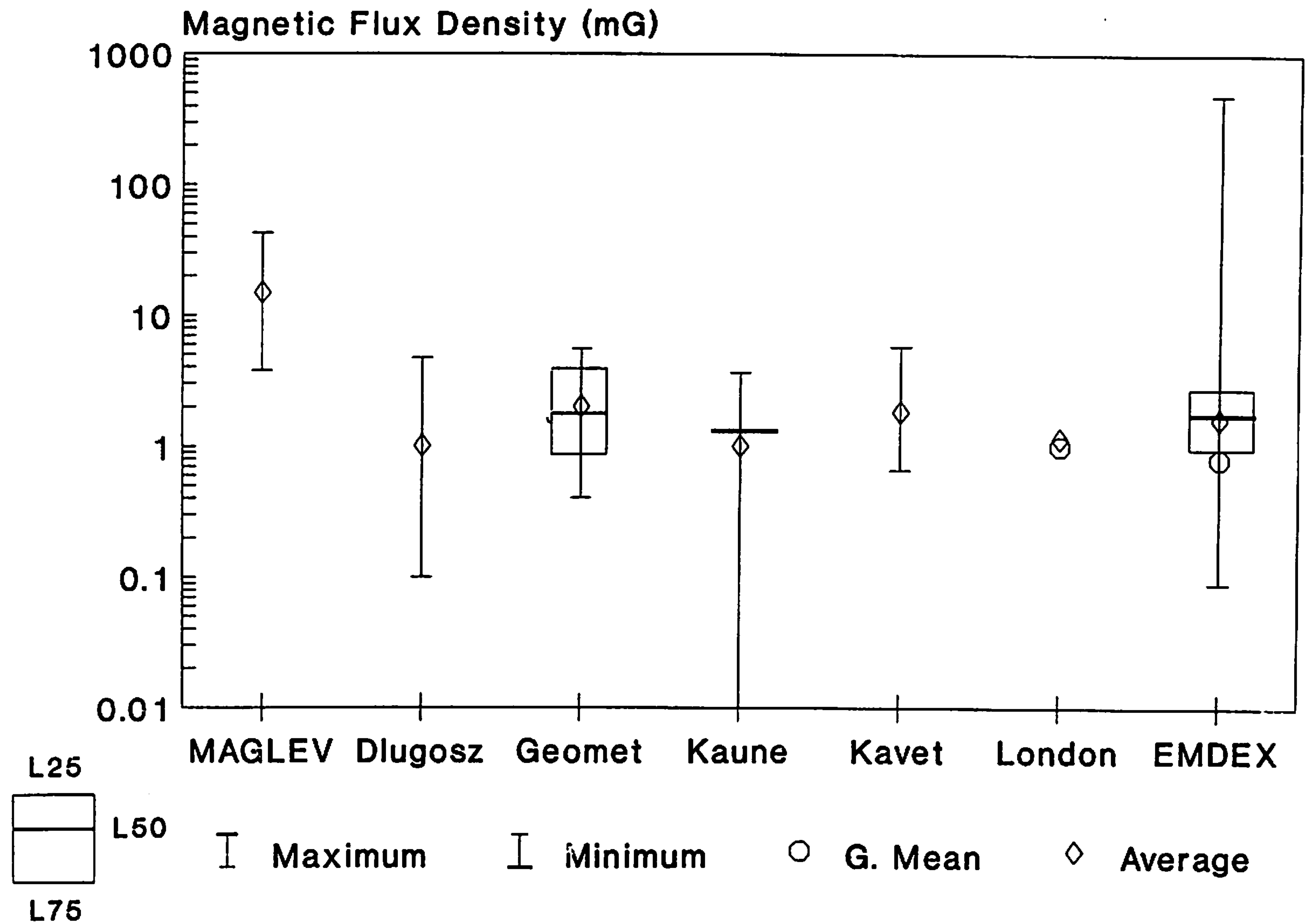

FIGURE 6-1. MAGNETIC FLUX DENSITIES ASSOCIATED WITH MAGLEV (TR-07, 50-60 Hz @ 12.7 cm) AND RESIDENTIAL EXPOSURES (see section 2.5 for study descriptions)

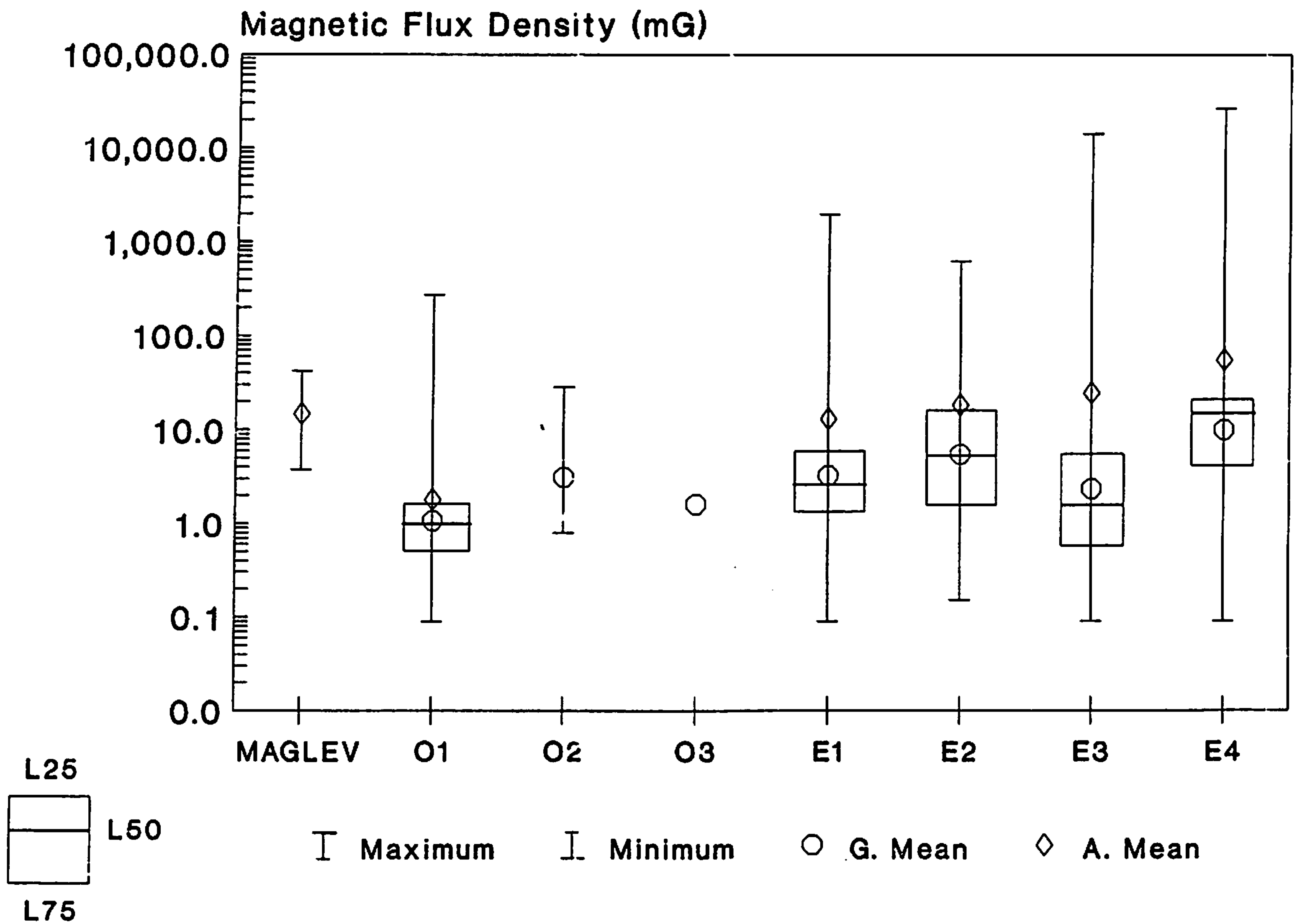

FIGURE 6-2. MAGNETIC FLUX DENSITIES ASSOCIATED WITH MAGLEV (TR-07, 50-60 Hz @ 12.7 cm), OFFICE ENVIRONMENTS, AND ELECTRICAL OCCUPATIONS (See text for full descriptions. O1 = Office: EMDEX Project, O2 = Office: Bowman, O3 = Office: Deadman, E1 = Electrical Generation: EMDEX Project, E2 = Electrical Transmission: EMDEX Project, E3 = Electrical Distribution: EMDEX Project, E4 = Electrical Substations: EMDEX Project)

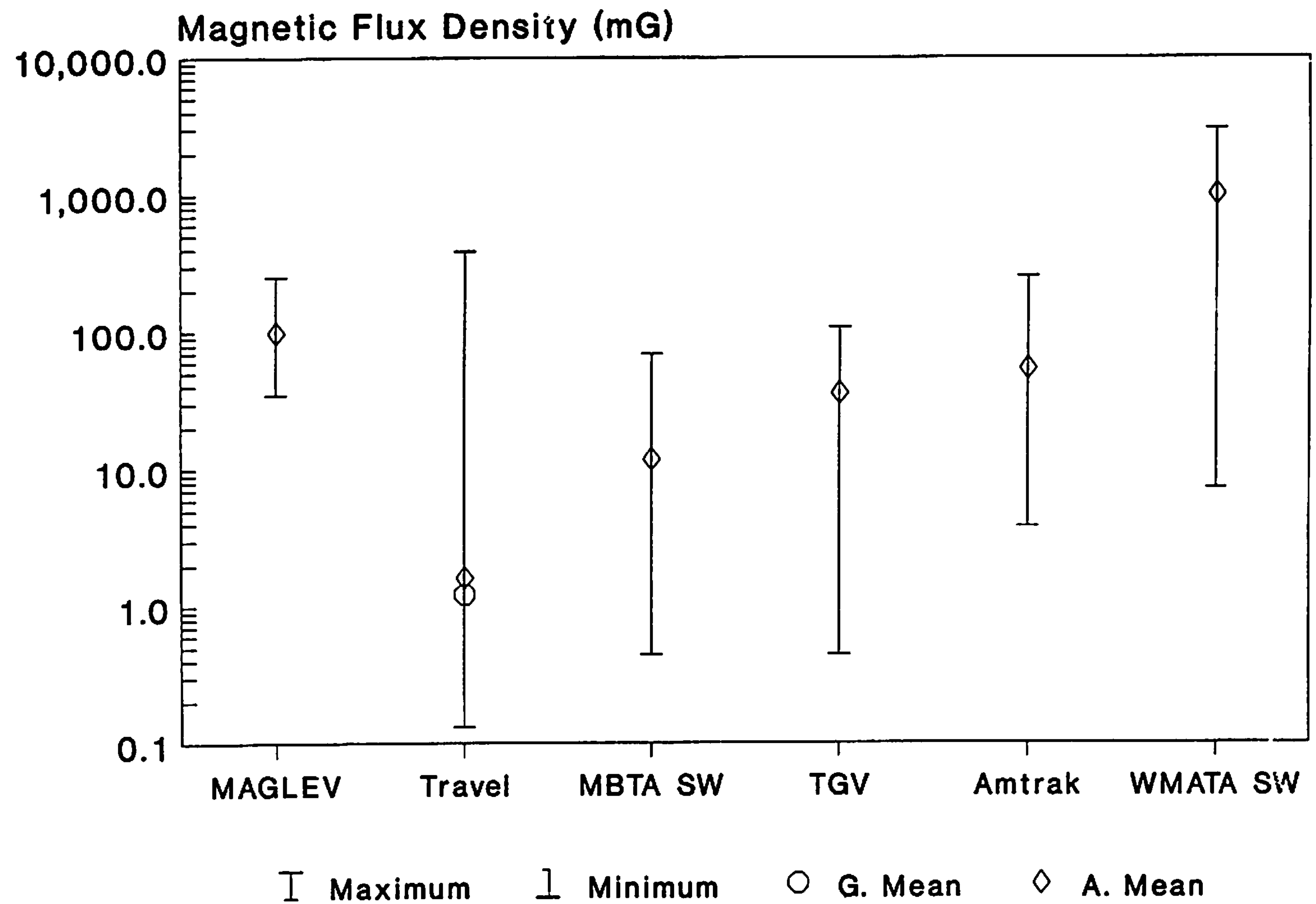

FIGURE 6-3. **MAGNETIC FLUX DENSITIES ASSOCIATED WITH MAGLEV (TR-07, 50-60 Hz @ 12.7 cm), OFFICE ENVIRONMENTS, AND ELECTRICAL OCCUPATIONS** (See text for full descriptions. O1 = Office: EMDEX Project, O2 = Office: Bowman, O3 = Office: Deadman, E1 = Electrical Generation: EMDEX Project, E2 = Electrical Transmission: EMDEX Project, E3 = Electrical Distribution: EMDEX Project, E4 = Electrical Substations: EMDEX Project)

6-4

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GLOSSARY[a]

attenuation rate: For magnetic fields, the rate at which a magnetic field magnitude decreases with distance from its source; also called fall-off rate.

axial ratio (a_r): The ratio of the semiminor (B_{min}) to the semimajor (B_{max}) axis of the polarization ellipse (i.e. the minimum to the maximum component) of the magnetic field at a particular frequency.

$$a_r = \frac{B_{min}}{B_{max}}$$

circular polarization: Type of polarization where the polarization ellipse expands to a circle and the minimum component of the magnetic field (B_{min}) equals the maximum component (B_{max}).

coefficient of linear correlation (c): Measure of the strength of the linear relationship between two variables. This is a scaleless measure that varies between -1 and 1.

control unit: A PC-compatible desktop or industrial-grade microcomputer containing data acquisition equipment that provides control signals, digitization, and signal processing for the MultiWave System.

cut-off frequency: A frequency at which the output of a circuit or circuit component decreases by 3 decibels.

ELF: Extremely low frequency, from 0 Hz to 3 kHz.

fluxgate sensor: A sensor that measures both dc and ac magnetic fields. The fluxgate sensor works by continuously varying the magnetic permeability of a special magnetic alloy core, which converts static or slowly varying magnetic flux into a measurable electrical signal. The sensor electronics process this signal to provide a proportional output voltage that is the input for the dc voltage probe.

fundamental frequency: In this report, 60 Hz.

fundamental ratio (f_r): For the MultiWave System, the ratio of the 60 Hz, or fundamental, rms scalar field (B_{60Hz}) to the total rms magnetic field (B_{rms}), including both the 60 Hz field and the harmonic field (B_{har}). This ratio shows what fraction of the total rms magnetic field would be measured by a narrowband, three coil measuring system. In equation form:

$$f_r = \frac{B_{60Hz}}{B_{rms}} = \frac{B_{60Hz}}{\sqrt{B_{60Hz}^2 + B_{har}^2}}$$

fundamental scalar field: The rms scalar field, taken over three axes, of the 60 Hz component.

ground current: Current flowing in the earth or in a grounding connection.

harmonic: Frequency that is an integral multiple of the fundamental frequency of a periodic system.

harmonic component: Magnitude and phase of that portion of a signal at a harmonic frequency.

harmonic field (B_{har}): An rms scalar field equal to the root-sum-square, or geometric sum, of the rms scalar fields of all measured harmonic frequencies excluding the fundamental (here harmonics 2 through 13). In equation form:

$$B_{har} = \sqrt{B_2^2 + B_3^2 + \ldots B_{13}^2}$$

harmonic number: Integer equal to the harmonic frequency divided by the fundamental frequency.

linear polarization: Type of polarization where the polarization ellipse collapses to a line segment and the minimum component of the magnetic field (B_{min}) at that frequency is zero.

magnetic field: Technically, a vector field describing the force experienced by magnetic objects or moving electrical charges in space. The unit is the ampere per meter (A/m). In this report, magnetic field is used as a general term for magnetic flux density.

magnetic field vector: The rotating vector describing the magnitude and direction of the magnetic field in three dimensions at a given point in time.

magnetic flux density: A vector field that is related to the magnetic field by the magnetic permeability of the medium. The SI unit is the tesla (T). The unit used in this paper is the milligauss (10 mG = 1 microtesla).

maximum component of the magnetic field (B_{max}): The rms magnitude of the semimajor axis of the polarization ellipse at a given frequency. This is the field measured by narrowband, single coil meters after they are rotated in space to find the largest magnetic field reading.

maximum component ratio (m_r): For this report, the ratio of the rms maximum component

(B_{max}) to the rms scalar field (B_{60Hz}) at the fundamental frequency. This ratio shows what fraction of the 60 Hz scalar magnetic field would be measured by a single coil measuring system. In equation form:

$$m_r = \frac{B_{max}}{B_{60Hz}} = \frac{B_{max}}{\sqrt{B_{max}^2 + B_{min}^2}}$$

milligauss: The historical unit for measuring magnetic flux density. One milligauss equals one thousandth of a gauss, the magnetic flux density unit in the centimeter-gram-second system of metric units. One gauss equals one ten-thousandth of a tesla, the magnetic flux density unit in the meter-kilogram-second system of units. Ten milligauss equal one microtelsa.

minimum component of the magnetic field (B_{min}): The rms magnitude of the semiminor axis of the polarization ellipse at a given frequency. This field lies normal to the maximum component, or semimajor axis, in the plane of the polarization ellipse. (Because all magnetic fields normal to the plane of the polarization ellipse at this frequency will be zero, the minimum component is not the lowest field that can be found by rotating a narrowband, single coil meter in space. It is the lowest field however, that can be measured within the plane of polarization.)

multiplexer: For the MultiWave System, a switching device that connects to the control unit on one side and to up to eight probes on the other through cables. The control unit uses the multiplexer to select the probe that is to receive control signals or send data signals.

narrowband measuring system: With magnetic field measuring systems for power frequency sources, one that responds only to 50 or 60 Hz fields and not their harmonics.

peak magnetic field: Maximum amplitude of the magnetic field waveform.

polarization: For a magnetic field vector at a fixed point in space, the polarization describes the locus of the endpoint of the magnetic field vector and the direction in which this locus is traversed. For a single-frequency magnetic field vector, the locus is an ellipse centered at the fixed point where the field is measured.

polarization ellipse: The ellipse traced by the endpoint of a single-frequency magnetic field vector as it rotates in space and time. If the ellipse expands to a circle, the field is circularly polarized. If the ellipse collapses to a line segment, the field is linearly polarized. No non-zero magnetic fields at the given frequency exist normal to the plane of the polarization ellipse.

power cycle: The duration of one 60 Hz waveform: 16.67 milliseconds.

power frequency: The 60 Hz frequency and its major harmonics.

rise time: The time required for a signal to increase from 10 to 90 percent of its value.

rms: Root-mean-square.

root-sum-square: The square root of the sum of the squares.

scalar rms magnetic field: The root-sum-square of the rms magnitudes of the magnetic field along three orthogonal axes. The scalar field can be calculated for a single frequency or a group of frequencies. The scalar field for the nth harmonic, B_n, is given by:

$$B_n = \sqrt{B_{x_n}^2 + B_{y_n}^2 + B_{z_n}^2}$$

single coil measuring system: With magnetic field meters, one that uses a single sense or pickup coil, oriented manually, to measure the maximum component of the magnetic field. Also called single axis measuring system.

spatial variations: Variations in the magnetic field at different locations during the same measurement period at the same site.

spot measurements: In this report, measurements extending for less than two hours at a limited number of locations at a site, such as those taken by visiting technicians with hand-held instruments.

switching events: Transients caused when a load turns on or off.

temporal variations: Variations in time.

total harmonic distortion (h_d): The ratio of the harmonic scalar field (B_{har}) to the scalar field of the fundamental frequency (B_{60Hz}). In equation form:

$$h_d = \frac{B_{har}}{B_{60Hz}}$$

total rms magnetic field (B_{rms}): The root-sum-square of the rms magnitudes of the magnetic field along three orthogonal axes over all frequencies. It is a special case of the scalar rms magnetic field that includes all harmonics. The total rms magnetic field is given by:

$$B_{rms} = \sqrt{B_1^2 + B_2^2 + \ldots B_n^2}$$

transient: A transition from one magnitude to another that contains an exponential rather than a sinusoidal response within one cycle.

waveform: A plot of amplitude versus time of a quantity over one power cycle.

* Selected glossary entries taken from F.M. Dietrich, W.E. Feero, D.C. Robertson, and R.M. Sicree, "Measurement of Power System Magnetic Fields by Waveform Capture," EPRI Final Report TR-100061 (1992).

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