STUDY OF OCCUPATIONAL MAGNETIC-FIELD PERSONAL EXPOSURES ASSOCIATED WITH SEATTLE METRO TRANSIT'S ELECTRIC TROLLEY SYSTEM

Prepared for:

National Institute of Occupational Safety and Health

Prepared by:

EM Factors
Richland, Washington

August 19, 1999

NOTICE

This report was prepared by EM Factors, Richland, Washington as an account of work sponsored by the National Institute of Occupational Safety and Health (NIOSH). Neither NIOSH, EM Factors, nor any person acting on behalf of either of them: (a) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report or that such use may not infringe upon privately owned rights; or (b) assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method or process disclosed in this report.

EXECUTIVE SUMMARY

This study characterized the occupational exposures to magnetic fields of workers employed in the electric trolley operations of Metro Transit, the agency that operates the public transportation system in and around the City of Seattle. From the approximately 700 individuals employed in this division of Metro Transit, 104 holding 18 different job title were selected for sampling. Volunteer workers were asked to wear Emdex II or Emdex Lite magnetic-field meters at a waist location for one work shift. Emdex II meters were set to record the broadband (40–800 Hz) and harmonic (100–800 Hz) magnetic fields sampled every 3 s. Emdex Lite meters were programmed to record the broadband (40–1000 Hz) magnetic field every 4 s. Using the resulting data the following nine exposure metrics were calculated:

- Time-weighted-average broadband personal magnetic-field exposure
- Time-weighted-average harmonic personal magnetic-field exposure
- 90th percentile broadband personal magnetic-field exposure
- 95th percentile broadband personal magnetic-field exposure
- Fraction of broadband measurements > 2 mG
- Fraction of broadband measurements > 5 mG
- Fraction of broadband measurements > 10 mG
- Temporal broadband magnetic-field variability using the *RCM* metric
- Temporal broadband magnetic-field variability using the RCM^* metric

The geometric means of the time-weighted-average (TWA) broadband magnetic-field exposures varied from a low of 0.59 mG for Dispatchers to a high of 6.0 mG for Electricians. Other job titles with TWA broadband exposures above 2 mG were Equipment Service Workers, Police who worked in the central business district, and Electricians. Both of the jobs that involve work in the central business district of Seattle (Supervisors and Police) had relatively large TWA broadband exposures. It seems likely that this exposure was not due to magnetic-field sources specifically associated with Metro Transit's electric trolley system but , instead, represented the cumulative effect of the myriad sources found in typical downtown areas.

The geometric mean of the TWA harmonic magnetic-field exposure varied from 0.2 mG for Dispatchers to 1.5 mG for Electricians. When compared against the corresponding broadband exposures, harmonic levels were elevated for those workers whose jobs involve close proximity to the power electronics and traction motors located in the rears or middles of trolleys. Such jobs include Utility Service Workers (who clean trolleys), Electronics Technicians, Supervisors who work in the transit tunnel under downtown Seattle, and Mechanics.

Five different metrics were used to capture peak magnetic-field exposure. The geometric means of the 90th percentile exposure ranged from 1.1 mG for Dispatchers to 13.4 mG for Electricians. Corresponding statistics for the 95th percentile exposure were 1.2 mG to 26 mG, respectively. Peak exposure was also assessed using three threshold measures. The fraction of measurements > 2 mG varied from 0.01 for Dispatchers to 0.44 for Police who worked the central business district. The pattern of exposure was rather different when the fraction of measurements > 10 mG was used as a metric. All job titles were less than 0.03 except for Electricians who were at 0.11.

Temporal variability of the broadband exposure magnetic field was assessed using two metrics, the so-called RCM and RCM^* metrics. The first is sensitive to both the temporal structure of the field, expressed as a percentage of the average field strength, and the size of the field. On the other hand, the second metric (RCM^*) depends only on the temporal structure of the magnetic field under study. The RCM metric varied from 0.33 mG for Dispatchers to 6.2 mG for Electricians. Interestingly, the RCM^* metric showed an almost inverse relation with job titles: Dispatchers had the largest exposures (0.79) while Electricians were near the bottom (0.36).

The correlations between the nine measures of exposure employed in this study were investigated. Most were fairly closely related. A minimal list of reasonably independent metrics could consist of TWA broadband personal exposure, the fraction of personal exposure measurements > 10 mG, and the second rate-of-change metric, RCM^*.

The magnetic fields in selected work areas were sampled with a Multiwave II Waveform Capture system to obtain information on frequency content. The predominant frequencies present in most areas were 60 Hz and the first few odd harmonics of 60 Hz (i.e., 180 Hz, 300 Hz). However, magnetic fields near the power control electronics in trolleys can have more complex frequency structures, including components near 360 and 720 Hz.

Because the meters used for the personal exposure measurements taken in this study had bandwidths that may have been too narrow to include all the frequency components produced by the power electronics used in trolleys, the data presented in this report may have understated true broadband magnetic-field exposure for some job titles. We estimate that this error was not more than 10% for jobs involving significant amounts of work near the power electronics in trolley, and was considerably less for other jobs. The jobs we expect would be most affected are Utility

Service Workers, Electronics Technicians, Supervisors who worked in the tunnel under the downtown area of Seattle, and Mechanics

The average TWA broadband personal exposure to magnetic fields for *all* workers employed in the electric trolley operations of Seattle was estimated to be about 1.5 mG, a value that is only modestly elevated relative to typical exposure levels in U.S. residence (Zaffanella, 1993). Based on our measurements, the predicted numbers of employees with TWA broadband personal exposures > 2 mG and > 3 mG were about 208 and 19, respectively. These numbers do not seem sufficient to support an epidemiological study with the goal of detecting associations between TWA broadband exposure and human disease.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

This report presents the results of a project conducted to characterize occupational magnetic-field exposures associated with the electric trolley system operated by the City of Seattle's Metro Transit Division. A previous study (Kaune et al., 1994) characterized magnetic fields found in occupational environments of Metro Transit's electric trolley operations. The main results of this study were ranges of magnetic fields that various types of workers could be exposed to during their jobs. There was, however, no attempt to perform any type of time-location-activity characterization of jobs, so no estimates of actual cumulative magnetic-field exposures received by workers could be made. The purpose of the study presented here is to extend the previous work to include personal measurements of occupational magnetic-field exposures of workers employed in Metro Transit's electric trolley operations.

II. BACKGROUND

II.1. Electric and Magnetic Fields

Scientists have identified four fundamental forces in nature: the force of gravity, the electromagnetic force, the weak nuclear force, and the strong nuclear force. The two that we most often experience in our everyday lives are the forces of gravity and electromagnetism. This report is concerned with the latter force—electromagnetism.

A fundamental characteristic of the fundamental particles that make up matter is their electric charge. Electromagnetic forces act between electrically charged particles and, among other things, bind together the constituents of atoms and molecules (i.e., protons, neutrons, and electrons). The electromagnetic forces between particles are "carried" by two types of fields, the electric field and the magnetic field. Electric fields are always produced by electric charge, but magnetic fields are produced *only* by electric charges in *motion.* An electrically charged particle placed in electric and magnetic fields will experience an electric force and, *if* it is moving, a magnetic force.

The basic element of an electric power system, such as the one that powers our homes, work places and, indeed, virtually all parts of our society, is the controlled application of electric and magnetic fields to electric currents. Since an electric current is the *movement* of electric charge, usually in a wire or other electrical conductor, the use of electric power inevitably involves the generation of electric and magnetic fields.

The electric field produced by an electric power system is directly related to the system voltage, which is measured in volts (abbreviated V). Electric fields have the units of volts per meter, or V/m. The magnitude of a current in a wire is defined to be the amount of electric charge that passes through it in one second. The unit of current is the ampere (abbreviated A).

A force has two characteristics: its strength and the direction in which it is acting. For example, the strength of the force of gravity depends on the mass of an object and its direction is always downwards. Since electric and magnetic fields are related to forces, it is not surprising that they also are each characterized by both a strength and direction. Measurement of three quantities, the x, y, and z components, is required to completely characterize a vector at any instant of time.

Many electric currents flow in only one direction (e.g., the currents that flow from an automobile battery to a load such as the car's driving lights). Such currents are called direct currents (abbreviated dc). The direction of a magnetic field produced by a direct current will remain constant as time passes. If the magnitude of a direct current is also constant, the strength and direction of the resulting magnetic field will be constant. Such a field is often called a static field. One common example of this is the earth's magnetic field. However, nothing is constant forever, so the use of the term static is somewhat relative and really means essentially constant during the course of an experiment. In this report, the term static will be used to mean a field whose strength and direction were constant during the duration of an individual measurement, which typically required about 1/3 of a second to complete.

In many other situations, including most involving our electric power system, the flow of electric current in a wire periodically and regularly shifts from one direction to the opposite and back. Currents with this character are called alternating currents (abbreviated ac). Magnetic fields produced by such currents have continually varying magnitudes and directions. The number of times in one second that a current or field goes through one complete cycle, that is from one direction to the other and back, is called the quantity's frequency and is expressed using the unit hertz, abbreviated Hz.

Typical electric-field strengths measured in residences are in the range 0.1 - 10 V/m (Caola et al., 1983; Barnes et al., 1989). Electric fields at ground level directly under the conductors of a very high voltage transmission line (e.g., 500,000 volt transmission line) range from about 3,000 through 10,000 V/m. In the United States, magnetic fields with frequencies ranging from static through a few thousand hertz are generally specified in units of milligauss, abbreviated mG. The earth's static magnetic field is about 500 mG, although this value is easily altered by structures that utilize iron, steel, or other ferromagnetic materials. Typical magnetic fields in residences measured at one point in time in the centers of rooms (hence, not near home appliances) range from about 0.1 through 10 mG (Zaffanella, 1993). Under heavily-loaded transmission lines (i.e., transmission lines carrying large amounts of electric power and, thus, large currents), magnetic fields typically range from about 10 to 100 mG; in a few situations, even larger ground-level magnetic fields can be measured near power lines.

II.2. Physical Interaction of Electric and Magnetic Fields With Living Tissues

Electric and magnetic fields are produced by charged particles (particles in motion for magnetic fields) and exert forces on other charged particles (again, charged particles in motion for magnetic fields). The human body is made up of a vast number of charged particles. All of these particles will experience electric and magnetic (if they are moving) forces when placed in electric and magnetic fields. It is at least conceivable that these forces could have some effect on the functioning of living tissues.

The character of the interaction of living tissues with electric and magnetic fields depends strongly on frequency. For example, the frequency used in a microwave oven has been selected so that electric and magnetic fields produced in the unit can rapidly raise the temperature of foods by 100°F or more. The situation at 60 Hz is very different. At this low frequency, only extremely small amounts of energy can be delivered to living tissues by alternating electric and magnetic fields of even the very highest strengths that can be produced in air. Indeed, the amount of energy that can be delivered by these fields is normally much less than the amounts of energy involved with the normal thermal and physiological processes that occur naturally in all living tissues.

At 60-Hz, electric fields applied to the body through air are almost completely shielded by the surface of the body. In most parts of the body, the electric field induced inside by an externally applied electric field is reduced by at least a factor of one million. (That is, the electric field inside the body is at least one million times smaller than the field outside it.) Similar, although not nearly as strong, shielding is produced by the exterior walls of a home or commercial building (Caola et al., 1984). Sixty-hertz magnetic fields, on the other hand, are able to penetrate living tissues (and the walls of most buildings) virtually without attenuation. Magnetic fields can induce current flow inside a living body. The sizes of these currents appear to be generally small compared to the natural currents that occur in tissues (Weaver and Astumian, 1990).

The situation is quite different if some part of the body comes into direct physical contact with an energized conductor (i.e., a conductor with a voltage applied to it). In this case, there is no need to couple electric fields into the body through an intervening length of air. Rather, the fields can be coupled directly into the body through conductive contact. As is certainly well known to the reader, this coupling can be very dangerous, especially if the voltage is much above 100 V. It takes a only a very small current (a small fraction of 1 ampere) passing in the neighborhood of the heart to interfere with its operation. If this interference is sufficiently strong, death will result.

II.3. Concern About Health Effects Resulting From Magnetic-Field Exposure

To date, studies of magnetic fields and adverse human health effects have tended to concentrate on linking elevated exposure with cancer, most frequently, brain cancer, various types of leukemia, and male and female breast cancer (A comprehensive recent review of magnetic-field health effects research is given in NIEHS, 1988). Other diseases have been studied, with less intensity, and there are published reports that, for example, link magnetic-field exposure with amyotrophic lateral sclerosis (Davanipour and Sobel, 1997) and Alzheimer's disease (Sobel et al., 1995; Sobel et al., 1996).

The first suggestion that magnetic-field exposure might be a risk factor for human disease was made by Wertheimer and Leeper (1979) who found that children who lived in homes near certain types of configurations of external electric wiring were at a higher risk of developing leukemia. Similar finding were subsequently obtained by Savitz et al. (1988) and London et al. (1991). However, a recent study (Linet et al., 1997) failed to find any link between wiring configuration and childhood leukemia, in contrast to the three previously mentioned studies. Linet et al. (1997) did find, on the other hand, some evidence of an association between measured magnetic fields and disease. Similar associations with measured or calculated magnetic fields have been reported in other studies (e.g., Feychting and Ahlbom, 1993; Olsen et al., 1993; Verkasalo et al. 1993).

The strength of the average magnetic field in U.S. residences is about 1 mG (Zaffanella, 1993). Since some occupations involve work near equipment that use or convey large amounts of electric power, it may be that workers in these occupations are exposed to magnetic fields considerably larger than those found in residences. Thus, studies in occupational environments might be a more fruitful area to examine for possible human health effects of magnetic field exposure. And, indeed, a number of occupational studies have been performed (a review of occupational studies is given in NIEHS, 1998), many of which have reported increased health risks in occupations what were thought to involved larger exposures to magnetic fields.

The majority of the occupational studies conducted to date have focused on job titles loosely classed as "electrical workers." A 1982 report published by Dr. Samuel Milham on mortality rates in Washington State was the first to suggest that electrical workers have a higher risk of leukemia compared to workers in other occupations. Since this report, scientists have used occupational classifications as a surrogate for exposure assessment in many epidemiological studies. Recent studies have incorporated actual magnetic-field measurements as part of their exposure assessment protocol. Of these latter studies, several have shown associations between occupational exposure measurements and increased risk for certain cancers (Savitz and Loomis, 1995; Theriault et al., 1994; Floderus et al., 1993, London, 1994) and at least one has found no association between exposure and cancer (Sahl et al., 1993).

Finally, attention has been given to the possible association between male breast cancer and magnetic field exposure. This interest was initially stimulated by the discovery by Stevens (1987) of a possible mechanism linking this exposure to breast cancer. And, there are some occupational epidemiological data (see NIEHS, 1998 for a summary) that suggest a possible link between male and female breast cancer and magnetic-field exposure.

One lesson that has been learned from occupational studies of magnetic-field exposures is that exposure estimates based on area field measurements tend to overstate the true exposure of interest (Kromhout et al., 1995). Based on area measurements made in various facilities associated with a city electric trolley system (Kaune, 1994), one might reasonably conclude that occupational exposures to magnetic fields will be elevated, especially for jobs that involve the maintenance of the trolley electronic power systems. However, more careful measurements that account for time-location-activity behavior of workers are required before any firm conclusions can be reached regarding actual occupational magnetic-field exposures in this industry. The purpose of the research presented in this report was to perform these measurements.

II.4. Metro's Electric Trolley System

The City of Seattle, WA operates an electrically powered transit system that includes three different types of trolleys. Direct-current (dc) electric power is supplied to these trolleys via overhead wires maintained at a fairly constant voltage of 700 volts (V) by nearby substations (i.e., facilities that convert alternating current electric power from Seattle City Light into dc electric power). The resulting electric current in these wires, and in the trolleys drawing power from them, always moves in one direction, from the positive to negative wire. In a trolley system, the current only flows when a trolley is in operation, and its magnitude rapidly and continually varies as the vehicle accelerates, coasts, goes up or down hills, and decelerates. Thus, the current drawn by a trolley contains not only dc but also time-varying components.

The actual current supplied to the *electric motor* in a trolley is even more complicated because Metro's trolleys use electronic "chopping" systems to control power flow. These systems chop the incoming current and deliver it to the motor in pulses rather than continuously. By adjusting the width and number of pulses per second, the trolley driver controls how much power is actually delivered to the motor and, hence, the bus's acceleration and speed. Consequently, the shape of the alternating component of the current drawn by a trolley, and the magnetic field produced by this current, is more complicated than the simple and repetitive sinusoidal current utilized by most systems powered by 60-Hz electricity.

Metro has constructed a number of small substations to supply the dc voltage used to energize their trolley system. These substations draw alternating-current power from Seattle City Light's 26,000 volt (26-kV) distribution system, transform it to the voltage levels required for the trolley system, and convert it to direct current.

The complete characterization of the complex magnetic fields produced as a result of the conversion of 60-Hz ac power into the dc power supplied to Metro Transit trolleys, and the electronic conditioning of the power that takes place in the trolleys themselves, requires that both the magnitude and frequency structure of the fields under study be measured. The resulting data are most effectively presented as frequency spectra, essentially graphs of magnetic-field strength as a function of frequency. Figure 1 shows five such spectra, measured near one of the substations Metro Transit uses to power their trolley routes (Kaune, 1994). The first spectra was taken near that part of the substation where 60-Hz electric power from the city of Seattle enters. Note the vertical line at a frequency of 60 Hz. This represents the rms magnitude of the 60-Hz frequency component, which was about 21 milligauss (mG). The next observable peak occurs at 180 Hz, and is the third harmonic of 60 Hz. Peaks at 300 Hz and 360 Hz are also present in this figure. Except for the 360-Hz component, the frequency spectra exhibited in this graph is commonly observed near systems powered by 60-Hz power. Look now at the left-most spectrum in the lower row of Figure 1. This spectrum was measured near the dc cables that carry power from the substation. Note here the prominent 360-Hz peak. It turns out that this frequency is expected to be the dominant because it is produced by the conversion process (rectification) of three-phase ac power into dc.

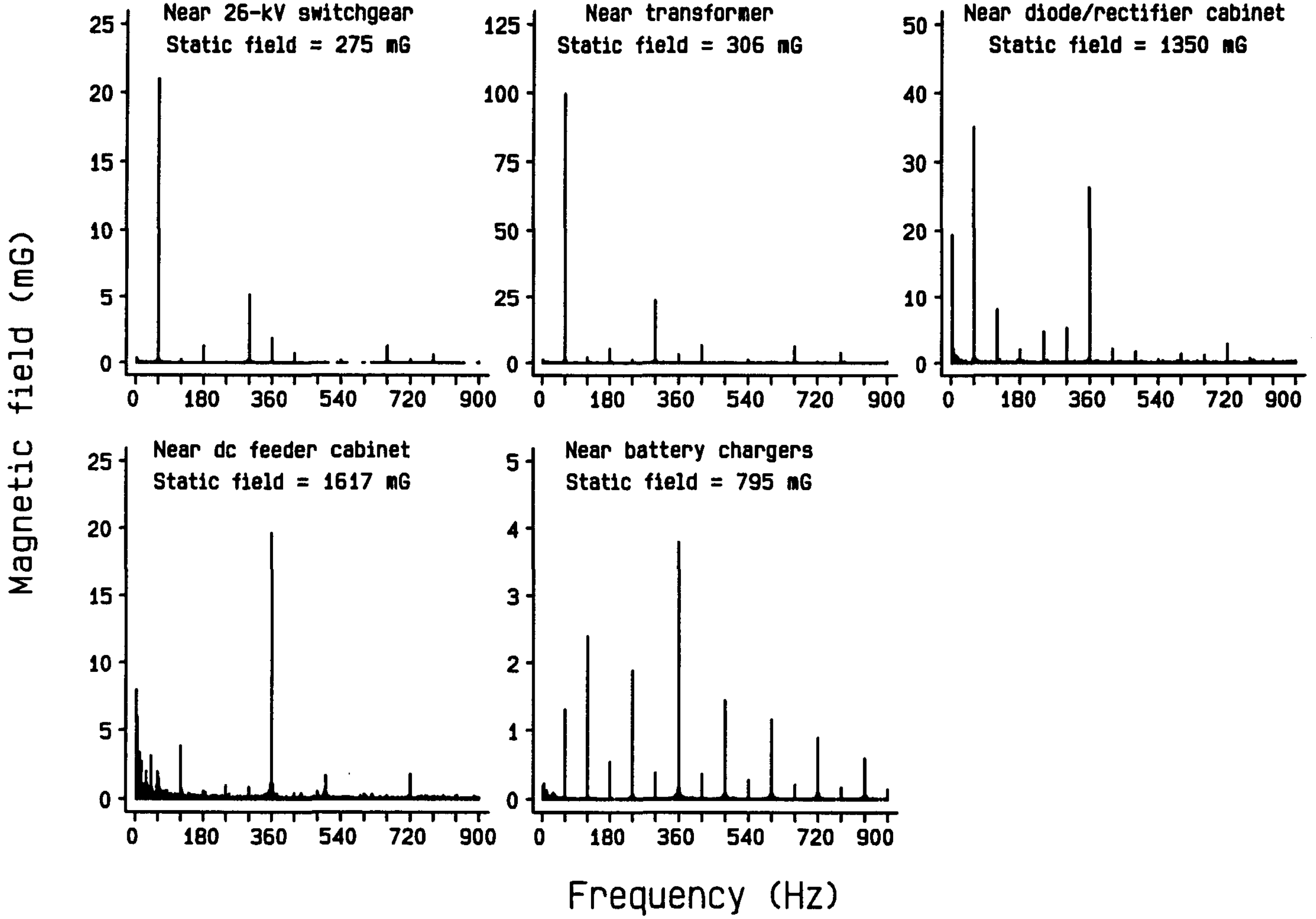

Figure 1. Frequency spectra measured at five locations near equipment in a Seattle Metro Transit Substation. The static components are suppressed in these figures but are given in the title of each spectrum.

Figure 2 shows a second set of frequency spectra, this time taken on and near a AMG 400 Series Trolley, one of the three types of trolleys used by Metro Transit. The middle spectrum in the bottom row was taken outside the trolley and shows strong field components at 60 Hz and the harmonic frequencies, 180 Hz, 300 Hz, 540 Hz, and 720 Hz. The other spectra show more complexity. For example, the first spectrum was taken at the rear of an accelerating trolley, near the power conditioning electronics. Note the peaks in magnetic-field strength at about 200 Hz, 400 Hz, and 600 Hz. These frequencies are not harmonics of 60 Hz and, in fact, have nothing to do with the power frequency. They represent the operating (chopping) frequency of the power electronics and are established by the operating mode of the trolley.

Metro Transit's system contains a number of routes which are served by electrically powered trolleys. In addition, about 10 years ago a transit tunnel was built under the downtown area of Seattle to reduce city street traffic. To utilize this tunnel, a large number of busses were purchased that incorporate both electric- and diesel-powered propulsion units. Normally, busses use their electrical capacity while passing through the tunnel and switch to diesel power when outside it.

In general, both electric and magnetic fields will be produced by various systems associated with Metro Transit's electric trolley system. The Metro Transit system does not use really high voltages, so it can reasonably be predicted that the electric fields it produces will, in general, not be much larger than normal ambient levels (0.1–10 V/m). Electric fields are easily shielded by nearly any conducting surface or body. Hence electric fields inside Metro trolleys will be small because of the shielding afforded by the metal surfaces of the vehicle. This statement also applied to Metro substations, where all electrically energized equipment are placed inside metal cabinets. These conclusions are supported by other work on similar electrified transportation systems, where no elevated electric fields greater than 10 V/m were measured (Dietrich et al., 1993a, 1993b).

In fact, the only unshielded electric field source we have been able to identify that is associated with Metro Transit's electric trolley system is the overhead wires used to supply electric power to trolleys. Assuming these wires are long, straight, and isolated, the electric field produced by them can be approximately calculated. The voltages of the two wires are 700 V and 0 V, respectively, they are separated by 24 inches, and they are typically about 19 feet high. It is not difficult to show that the static electric field produced by these wires within 10 feet of the

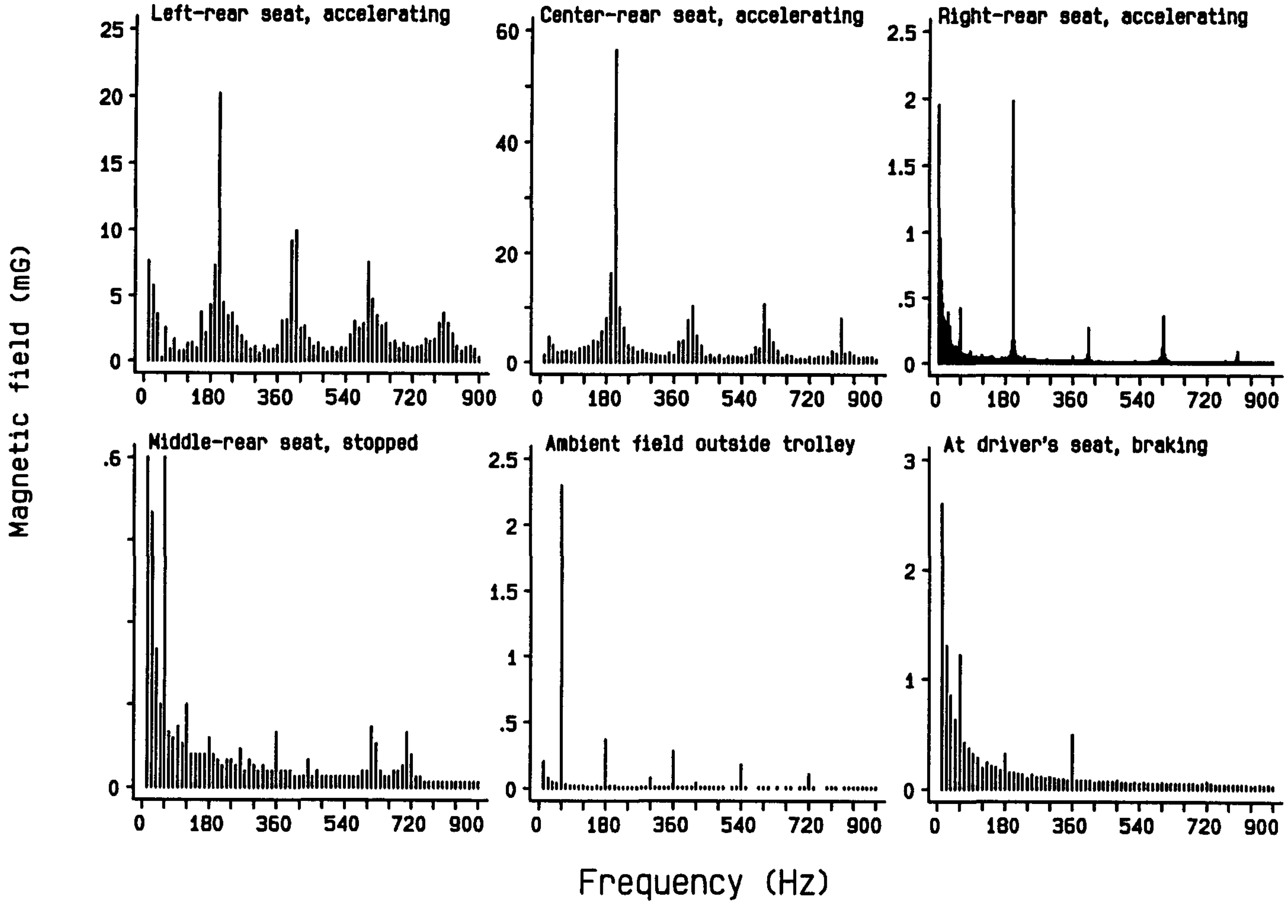

Figure 2. Frequency spectra measured at five locations inside, and one location outside, an AMG 400 Series Trolley. The static components are suppressed in these figures.

ground is less than about 20 V/m. The ac component of the field will be considerably less than the value, hence comparable to, or even smaller than, normal ambient levels.

The considerations put forth in these paragraphs led us to conclude that it would not be necessary to measure electric-field exposures produced by Metro Transit's electric trolley system.

II.5. Measurements in Other Electrically Powered Transportation Systems

The Federal Railway Administration (FRA) of the U.S. Department of Transportation has studied the electric and magnetic fields produced by several different types of conventional and advanced electrically powered ground transportation systems. The results of this study are presented in several reports and are summarized in a separate one (Dietrich et al., 1993c). Of the systems studied in this project, the two that are most similar to Metro's trolley system are the trolley system of the Massachusetts Bay Transportation Authority (MBTA) and the Washington DC Metropolitan Area Transit Authority Metrorail System (Dietrich et al., 1993a, 1993b).

The trolley system of the MBTA appears to be similar to Metro's system except for one potentially important difference: speed control on MBTA trolleys is achieved by the insertion or removal of resistors whereas speed control in Metro's system utilizes solid state switching. Because of this difference, it is likely that the magnetic fields associated with Metro's system will be more complex than those produced by MBTA trolleys. The second system studied by the FRA is the DC Metrorail system in Washington DC. This is a underground subway (railway) system. Trains normally consist of multiple cars, but each car is self powered. Speed control in this system is achieved using solid state switching. Thus, an individual car in the DC Metrorail system is analogous in some ways to a Metro trolley.

The measurements made in this study were of the area type and were acquired to define the ranges of magnetic fields to which individuals riding and working near electrically powered trains might be exposed. As in the earlier Seattle Metro Transit measurements, relatively strong magnetic fields were measured in some environments. However, these measurements are not very useful for determining actual occupational exposures because they did not take into account the behavior of workers.

III. MATERIALS AND METHODS

III.1. Sampling Plan

This study examined only those workers employed by Seattle Metro Transit who were directly involved with their electrified trolley system. This worker population consisted of about 700 workers holding 35 job titles. A list of the job titles and number of people employed in each of the categories are given in the first two columns of Table 1.

Resource and time constraints made it impossible to measure the exposure of every worker employed by Metro Transit. Instead, a sampling plan was developed in order to apportion the number of workers to be sampled among the total population. Suppose that we have J job titles under study, and let the total number of workers in the j^{th} job title be W_j. The total number of workers in all job titles is W, where $W = W_1 + W_2 + \ldots + W_J$. Suppose that we have the resources to make a total of S measurements and want to know how to distribute these measurements between the various job titles under study.

Suppose that S_j workers are sampled from job title j ($S_j \leq W_j$). Let the measured exposure for the k^{th} sampled worker in this job title be X_{jk}. Then, the best estimate, X_j, of true exposure of this job title is obtaining by averaging the results of the sample, that is,

$$X_j = \frac{1}{S_j}\sum_{k=1}^{S_j} X_{jk} . \tag{1}$$

The average exposure, X, for all workers can now be estimated using the formula

$$X = \frac{1}{W}\sum_{j=1}^{J} W_j X_j , \tag{2}$$

where W is the total number of workers.

The quantity X is an estimate of the true population exposure and is, therefore, subject to sampling error. Assuming no correlation between the sampling errors of different job titles, the standard

Table 1. Job titles of Metro Transit workers associated with their electric trolley operations, numbers of workers holding each, size of sample selected with probability proportional to size (PPS), and final sample size.

Job Title	Number of workers holding	PPS sample size	Number actually measured
Electronics Technicians/Leads	19	3	7
Mechanics/Leads	103	17	13
Equipment Service Workers/Leads	47	8	2
Utility Service Workers	12	2	5
Dispatchers	5	1	1
Chiefs, Supervisors	15	2	7
Clerks	6	1	0
Administrative Specialists	1	0	0
Parts Workers	14	2	0
Base Millwrights	3	0	0
Drivers assigned to electric trolleys	300	47	17
Electricians	17	3	6
Line Workers Utilities	13	2	6
Line Workers Materials	9	1	3
Line Worker Helpers	13	2	4
Cable Splicers	1	0	0
Crew Chiefs Line	3	0	0
Crew Chiefs Electricians	2	0	0
Chief of Power	3	0	0
Supervisor of Power	1	0	0
Administrative Specialists	1	0	0
Data Analysts (work order systems)	1	0	0
Engineers	5	1	0
Leads, Chiefs, Supervisors (trolley drivers)	5	1	0
Office Custodians (tunnels)	5	1	0
Shop Custodians	11	2	6
Service Supervisors (work in tunnels)	34	5	11
Revenue Processors	4	1	0
Metro Police (work in tunnels)	22	4	11
Grounds Specialists (work at substations)	2	0	0
Equipment Operators (sweepers)	2	0	0
Maintenance Workers (clean shelters)	10	2	2
Facilities Carpenters	2	0	0
Facilities Painters	2	0	0
Instructors	12	2	4
Total	705	110	104

deviation (i.e., error in the estimate), σ_X, of X is

$$\sigma_X^2 = \frac{1}{W^2}\sum_{j=1}^{J} W_j^2 \sigma_{X_j}^2 , \tag{3}$$

where σ_{X_j} is the error of the estimate of exposure in the j^{th} job title. The estimated exposure for the j^{th} job title is given by Eq. (1), so $\sigma_{X_j}^2 = \sigma_j^2 / S_j$, where σ_j is the standard deviation of the exposure distribution for this job title. Placing this in Eq. (3) yields the expression

$$\sigma_X^2 = \frac{1}{W^2}\sum_{j=1}^{J} W_j^2 \sigma_j^2 / S_j . \tag{4}$$

The question we now address is how to select the sample sizes, S_j, to provide the most accurate estimate of the population exposure, that is, what values of S_j minimize the error, σ_X, in our estimate of the population exposure subject to the constraint that the total sample size must be equal to S. Using the methods of the calculus, it is relatively easy to show that the optimum estimate of X is obtained when

$$S_j = S\frac{W_j \sigma_j}{W_1\sigma_1 + W_2\sigma_2 + \ldots + W_J\sigma_J} . \tag{5}$$

When the sample was drawn, we had no information about the values of σ_j. Consequently, for planning purposes, we assumed that $\sigma_1 \approx \sigma_2 \approx \ldots \approx \sigma_J$, in which case Eq. (5) becomes

$$S_j = \frac{W_j}{W} S . \tag{6}$$

Thus, the guideline we used for allocating our sample across job titles was that this allocation should be in proportion to the number of workers in each, that is a sampling probability proportional to size (PPS sample). The third column of Table 1 lists the numbers of workers we would have sampled if we had rigorously followed the prescription embodied in Eq. (6).

The last column in Table 1 defines the actual sample that was finally selected for the study. There are some differences between this and the PPS sample. First we felt that a sample size of 3 or fewer workers was simply too small to provide meaningful characteristic of any job title, and so we changed the sample size for these jobs to 0. Secondly, while the PPS sample called for 47 drivers to be sampled, we knew from earlier work (Kaune, 1994) that this was not a job that entailed high exposure, so we reduced substantially this sample to 17. We increased the numbers of electronic technicians from 3 to 7 because earlier measurements suggested this job might involve high exposures. The other differences between the PPS and actual samples reflect our estimates of the likelihood of exposures and certain practical considerations such as the ease of obtaining volunteers.

III.2. Magnetic-Field Measurements

Two types of meters were used to collect the personal-exposure data (i.e., data obtained from a meter worn by a subject during their work shift) for this study: Emdex II and Emdex Lite meters. The following two sections describe these meters.

III.2.1. Emdex II Meter

The Electric and Magnetic Field Digital Exposure (Emdex) II meter was developed by Enertech Consultants in Campbell, CA. These battery powered meters are quite small (16.8 × 6.6 × 3.9 cm^3) and lightweight (about 330 grams). They can be programmed to repetitively sample the magnetic-field at selected time intervals and retain the resulting data in memory until the end of a data run. These data can be transferred to a personal computer (PC) for archival storage and later analysis.

A Emdex II meter contains three small coils that sense the magnetic field along the x, y and z axes. Normally, these three field values are aggregated into a single summary values known as the resultant field strength, B, defined as follows:

$$B = \sqrt{B_x^2 + B_y^2 + B_z^2}\ , \qquad (7)$$

where B_x, B_y, and B_z are the measured x, y and z magnetic-field components.

Emdex II meters are designed to cover the power-frequency range. The manufacturer's specified frequency bandwidth in the "broadband" mode is 40 to 800 Hz with a range of 0.1 to 3,000 mG. These meters do record values for field components that fall outside of this frequency range, but with reduced sensitivity. For example, a 1 mG 1,000-Hz magnetic field will be measured as having a strength of about 0.6 mG.

Emdex II meters can also operate in a second mode, called the "harmonic" mode where the unit's bandwidth is reduced to include the range from 100 Hz through 800 Hz. For the personal exposure measurements conducted in this study, Emdex II meters were programmed to take samples every 3 seconds in both broadband and harmonic modes.

Prior to the start of the study, all Emdex II and Emdex Lite® meters were calibrated at a calibration facility located in Richland WA. This facility uses a Helmholtz coil to produce highly uniform magnetic fields that are known to an accuracy of better than ± 2%. All meters used in this study were found to be within ±5% of their nominal calibration at 60 Hz.

Extensive experience with this type of meter has shown that they are very reliable and stable. Nevertheless, to verify that they were operating properly, a secondary calibration was performed every other day throughout the study. Meters were placed in a field of known strength in three different orientations to test each of the three internal field sensors. Readings at each of these orientations were recorded for all meters in calibration logs.

III.2.2. Emdex Lite

This meter is similar in many ways to the Emdex II but is smaller ($11.9 \times 6.0 \times 2.5$ cm^3), lighter (160 g), and has only a broadband mode with a slightly broader bandwidth of 40–1000 Hz. The accuracy of an Emdex Lite meter is about ±8% at 60 Hz. These meters were calibrated in the same facility used for the Emdex II meter, and were checked throughout the study in a manner similar to the Emdex II as described above.

For the measurements presented in this report, Emdex Lite meters were programmed to acquire and hold a sample every 4 s.

III.2.3. Multiwave II Waveform Capture System

Emdex meters measure rms magnetic-field strengths and, thus, provide only limited information about the spectrum of frequencies actually present in any given magnetic field. This is usually not much of a problem near most electrically powered systems because the only frequencies that are present are 60 Hz and the first few odd-integer multiples of 60 Hz. However, as discussed in Section II.4, previous measurements (Kaune, 1994) have shown that frequency spectra of the magnetic fields produced by electrically powered transportation systems are more complex. Thus, to provide information beyond that which could be obtained using Emdex meters, we made use of a NIOSH-owned Multiwave II Waveform Capture System (ERM, 1993).

The Multiwave II Waveform Capture System is portable, battery-powered, and incorporates sensors for the three vector components of the static and alternating (through about 3800 Hz) magnetic field. The Multiwave II system repetitively samples the instantaneous x, y, and z magnetic fields and stores these data in its memory. The sampling protocol for the measurements presented in this report was: length of total sample = 0.067 seconds (4 60-Hz cycles), sampling rate = 7,680 samples/second, total number of samples/measurement = 512/measurement. The frequency resolution was ±7.5 Hz (i.e., the frequency of any component in the frequency of the magnetic field under study could be determined to a resolution of ±7.5 Hz.)

Two Multiwave II operating modes were used during the Metro measurements. In the first, individual samples were taken at the instigation of the user. This mode was seldom used. In the second mode, the Multiwave II system was programmed to take 12 repetitive measurements at a programmed rate of one measurement every 5 s.

All waveform data acquired by the Multiwave II system were stored on 3.5-inch floppy diskettes. Subsequently, during the analysis phase, the data from each sample were retrieved and subjected to the Fast Fourier Transform (FFT) algorithm which calculated the frequency spectrum. Examples of these spectra have already been given in Figures 1 and 2.

III.3. Measurement Protocol

Meters were distributed at pre-shift meetings to personnel who volunteered to participate. Meters were turned on, set to collect data every three seconds (four seconds for the Emdex Lite), and were placed in padded cases by the research staff before being given to the worker. Study participants were instructed to wear the meters at waist level and were asked to avoid tampering in any way with them. At the meeting, each worker was given an information sheet (Appendix A) that provided a brief description of the study. Workers were instructed to perform their duties normally. Participants were also asked to record their activities in a diary that was provided prior to giving out the meters. They were asked to record events and significant blocks of time such as driving a trolley, eating lunch, working on overhead transmission lines. Diaries were kept in the event that a correlation between any unusual data readings and activities needed to be conducted. At the end of the work shift, meters and diaries were collected. Data collected from the meters was then downloaded to a PC. Workers were shown graphs of field strength by time. This was done to share the results with the volunteers, to identify any abnormal readings, and in some cases, to augment the diaries. Duplicate copies of all data files were made on 3.5 inch diskettes. Along with the original copy of each data file that was maintained on the hard drive of the PC used in the field, we thus produced a total of three copies of each data file.

Multiwave II measurements were taken by a field technician who followed workers while they performed their jobs and took samples at various locations.

III.4. Data Analysis

Data collected during the study were converted to ASCII format using the software provided with the Emdex meters, and were imported into a commercial statistics package (STATA, Stata Corporation, College Station, TX). STATA was used to calculate nine different statistics characterizing magnetic-field exposure. First, time-weighted-average (TWA) broadband and harmonic magnetic-field exposures were calculated by computing the average of all broadband and harmonic fields measured during each worker's work shift. The 90th and 95th percentile broadband exposures were determined by computing the 90th and 95th percentiles of the set of broadband measurements contained in each worker's exposure recording. The numbers of broadband measurements in each recording that exceeded 2 mG, 5 mG, and 10 mG were then computed and used to determine the fractions of total measurements that exceeded these thresholds.

Finally, two statistics that characterize temporal broadband magnetic-field variability were calculated. The first metric we used was originally introduced by Wilson et al. (1996) and has come to be called the "Rate-of-Change" metric, abbreviated *RCM*. It is defined for a temporal sequence of regularly sampled broadband magnetic fields, B_1, B_2, …, B_N, as follows:

$$RCM = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N-1}(B_{k+1} - B_k)^2} \ . \qquad (8)$$

Note that *RCM* has units of magnetic field strength (mG), which means that its magnitude depends not only on the temporal structure of the magnetic field but also on its magnitude.

A second metric, denoted RCM^*, has recently been introduced to provide a more specific measure of temporal variability. This metric is simply the RCM metric defined by Equation (8) divided by the standard deviation of the broadband magnetic-field data in the time series under investigation. That is,

$$RCM^* = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N-1}\left(B_{k+1} - B_k\right)^2} \Bigg/ \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}\left(B_k - \overline{B}\right)^2}\,, \tag{9}$$

where $\overline{B}$ is the mean of the sequence B_1, B_2, ..., B_N. The RCM^* metric is closely connected to the autocorrelation function for B. Indeed, when N is large, $RCM^* \approx \sqrt{2[1 - A(\tau)]}$, where $A(\tau)$ is the autocorrelation function for the time lag, τ, between two consecutive samples.

Calculation of RCM and RCM^* is complicated by the fact that two different sampling times were used for the data collected in this project. Seventy-eight (78) of the exposure records were collected using Emdex II meters with a sampling interval of 3 s, while 26 were collected with Emdex Lite meters programmed with a sampling interval of 4 s. The term $(B_{k+1} - B_k)$ that appears in the definition of both RCM and RCM^* will, in general, depend on the sampling time. Thus, a correction is needed to the RCM and RCM^* values calculated for the Emdex Lite data before they can be aggregated with the Emdex II data. We estimated these correction factors using two different models.

Denote by τ_{II} and τ_{L} the sampling times for the Emdex II and Emdex Lite meters, respectively, and let the RCM value calculated directly for Emdex Lite data be denoted RCM_{L}. We first assume the time development of the magnetic field can be approximated as a random walk process. For such a process, it is well known that the mean square change in the variable under study in a time period τ is directly proportional to τ (Chatfield, 1989). That is, $(B_{k+1} - B_k)^2 \propto \tau$. Using this in Equations (8) and (9), it can be seen that both RCM and RCM^* are proportional to τ. Consequently, to correct RCM_{L} to the sample time used for the Emdex II measurements, we need merely write

$$RCM_{\mathrm{II}} = \sqrt{\tau_{\mathrm{II}}/\tau_{\mathrm{L}}}\; RCM_{\mathrm{L}}\,. \tag{10}$$

Using the values for the two sampling times, we thus arrive at the correction $RCM_{\mathrm{II}} = 0.866 \times RCM_{\mathrm{L}}$.

The simple random walk model indicates that the mean square deviation from a starting value of a magnetic field will grow without bound as time elapses, which is a behavior not exhibited by environmental magnetic fields. Thus, over a long time, the random walk model cannot be correct, but over a short time interval, it may be a good approximation.

A second model, suggested to us by Professor Michael Yost, University of Washington, assumes that the autocorrelation function, $A(\tau)$, for a magnetic-field time series depends on τ as $e^{-\gamma\tau}$, where γ is a constant. Many actual time series exhibit this behavior (Chatfield, 1989). Consequently, $A(\tau_{\mathrm{II}}) = A(\tau_{\mathrm{L}})^{\tau_{\mathrm{II}}/\tau_{\mathrm{L}}}$. As noted above, $A(\tau)$ is related to RCM^* as follows: $RCM^* = \sqrt{2[1 - A(\tau)]}$. Therefore, the corrected value of RCM can be obtained from the uncorrected value using the formula:

$$RCM^*_{\mathrm{II}} = \sqrt{2\left\{1 - \left[1 - \left(RCM^*_{\mathrm{L}}\right)^2 / 2\right]^{\tau_{\mathrm{II}}/\tau_{\mathrm{L}}}\right\}}\,. \qquad (11)$$

The two correction methods given by Equations (10) and (11) yield nearly the same result. In the first method, the correction is a constant factor of 0.866 whereas in the second method the mean correction is 0.877 (S.D. = 0.013). We ultimately used Equation (11) to correct all *RCM* and *RCM** values calculated for Emdex Lite data.

All of the statistical results and graphs presented in this report were prepared using STATA. As will be shown, the distribution of the exposure data obtained in this study was much more nearly log normal than normal. However, there were departures even from log normality. Consequently, a non-parametric statistical test, namely the Kruskal-Wallis test (Sokal and Rohlf, 1995), was used to test for differences between groups of measured data. Trend testing was performed using a nonparametric test that is included with the STATA software.

IV. RESULTS

IV.1. Distribution of Personal Exposures

The distribution of magnetic-field exposure data is invariably skewed, with most measurements falling at lower levels and only a relative few appearing at larger values. This pattern is illustrated in the left histogram in Figure 3, which contains the TWA personal exposures for all 104 workers monitored in the study. Note that nearly all of the exposures fall below 2 mG, with a few at considerably larger levels.

The right-hand histogram in Figure 3 shows the same data but log transformed. The data are much more nearly normal in distribution, but are still slightly skewed. Because they are more nearly log normally than normally distributed, we shall summarize them using both arithmetic and geometric statistics, with more emphasis placed on the latter than the former.

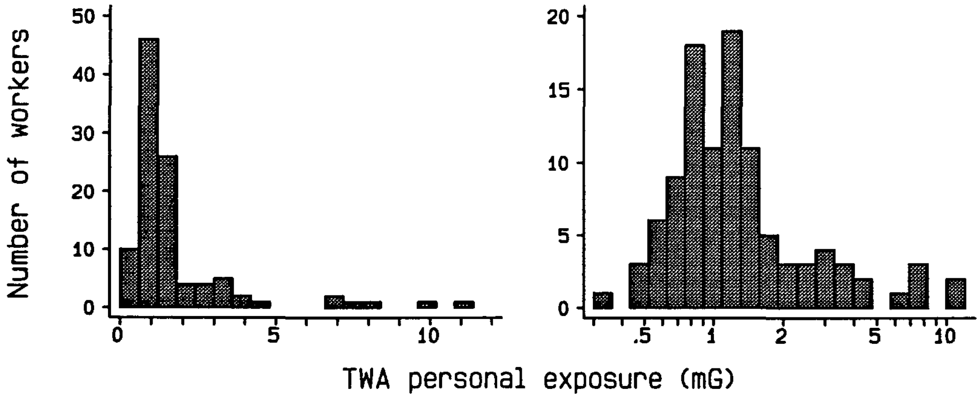

Figure 3. Histograms showing distributions of TWA magnetic-field exposures and log-transformed TWA exposures.

IV.2. TWA Broadband and Harmonic Exposures

Figure 4 is a modified box-and-whisker plot that summarizes the TWA broadband (40–800 Hz) personal exposures measured for each of the 18 job titles that were sampled in the study. The box for each job title extends vertically from the 25th percentile personal exposure to the 75th percentile personal exposure. The horizontal line through the box marks the 50th percentile (i.e., the median). The whiskers extend vertically from the box to the 5th percentile (lower whisker) and the 95th percentile personal exposure. (Since only one dispatcher was measured, all the percentiles are assigned the same value, so the box-and-whisker for this job collapses into a single horizontal line.)

Job titles are displayed from left to right in Figure 4 in the order of increasing geometric mean TWA broadband personal exposure. Summary statistics, including geometric means of the TWA broadband personal exposures measured for the workers sampled in each job title, are listed in Table 2. Because of the order in which job titles are arranged, Figure 4 exhibits an exposure gradient across job titles. Job title is a statistically significant grouping variable in these data ($p = 0.002$, Kruskal-Wallis test).

The pattern of exposure exhibited in Figure 4 and Table 2 is interesting, and not particularly what the authors expected on the basis of available previous field measurements (Kaune, 1994). Dispatchers had the lowest measured personal exposures (geometric mean = 0.59 mG), but with a sample of 1 this value is a poor estimator of the population mean. Shop Custodians and Utility Service Workers had the next lowest measured exposures. (Utility Service Workers clean trolleys and related facilities.) Instructors spend much of their time teaching individuals to drive trolleys. Thus, it is not surprising that their exposures are similar to those received by Drivers. Since both are relatively low, it is apparently the case that being on a trolley near the driver's position does not confer much exposure above normal ambient levels.

Previous measurements (Kaune, 1994) had shown that Electronics Technicians could be exposed to relatively large magnetic fields while testing certain high-power components used in trolleys. However, this potential was not realized in our sample: Geometric-mean TWA personal exposures for these individuals were only about 1.1 mG, hardly above average levels that would be produced in the typical U.S. residence (Zaffanella, 1993). Examining activity

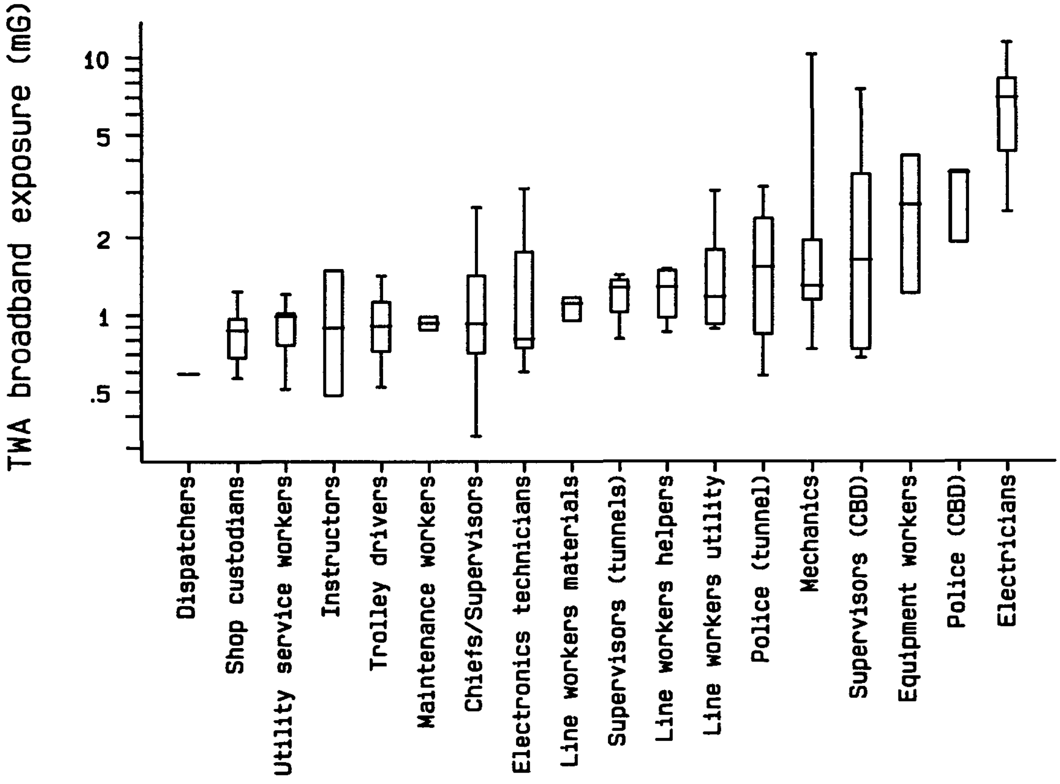

Figure 4. Modified box-and-whisker plot summarizing measured TWA broadband personal exposures measured for each of 18 job titles.

Table 2. Statistics summarizing TWA personal broadband (40–800 Hz) exposures to magnetic fields received during one shift by workers holding indicated job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D. (mG)
Dispatchers	1	0.59	–	0.59	–
Shop Custodians	6	0.87	0.23	0.84	1.32
Utility Service Workers	5	0.90	0.26	0.86	1.39
Instructors	3	0.96	0.51	0.86	1.76
Trolley Drivers	17	0.94	0.27	0.90	1.35
Maintenance Workers	2	0.93	0.08	0.93	1.09
Chiefs and Supervisors	7	1.15	0.74	0.97	1.90
Electronics Technicians/Leads	7	1.24	0.90	1.05	1.79
Line Workers Materials	3	1.07	0.11	1.07	1.11
Supervisors (Tunnels)	4	1.19	0.27	1.17	1.29
Line Workers Helpers	4	1.23	0.31	1.20	1.31
Line Workers Utilities	6	1.49	0.82	1.34	1.61
Police (Tunnels)	8	1.64	0.96	1.41	1.84
Mechanics/Leads	13	2.04	2.49	1.51	1.95
Supervisors (Central Business District)	7	2.53	2.40	1.80	2.40
Equipment Service Workers/Leads	2	2.67	2.06	2.24	2.38
Police (Central Business District)	3	3.01	0.97	2.89	1.44
Electricians	6	6.67	3.06	6.01	1.70

logs filled out be these personnel indicates that some component testing was performed, so it seems likely that the exposures we measured were representative.

Line Workers maintain the overhead wires that supply dc power to trolleys and help maintain the substations that transform ac power into dc power for trolley use. Helpers and Materials individuals work on the ground and drive the line trucks. Elevated work is performed by individuals with the Line Worker Utility job classification and involves, at times, close proximity to the overhead wires. Thus, it is not surprising that their magnetic-field exposures are larger than those received by ground-based line workers. However, the increase in exposure is slight and is far from being statistically significant. Apparently, overhead trolley wires are not a strong exposure source.

Police who work in the underground tunnel under the central business district and mechanics have slightly higher exposures, around 1.5 mG. (Mechanics perform general mechanical maintenance on trolley, primarily in the central shop but also on the road at times. They also test trolleys.) Both Supervisors and Police who work in the central business district have exposures around 2–3 mG. Judging from the activity logs filled out by these workers, much of their job involves patrolling the central business district, often on foot. Thus, their magnetic-field exposure seems to be associated more with the central business district than with the trolley system.

Equipment Service Workers also had more elevated exposures. (These individuals perform routine maintenance on trolleys and spend much of their time in the yards where trolleys stage at the beginning and end of work shifts. They also apparently work out of a small building next to the staging yard that, for an unknown reason, had quite large interior magnetic-field levels.) Electricians received the largest geometric-mean broadband personal exposure (6.0 mG) of any group that was studied. These individuals spent much of their time in the various substations that Metro Transit maintains.

One signature of magnetic-field exposure received from power lines and most 60-Hz sources is a dominant 60-Hz frequency component. The broadband (40–800 Hz) and harmonic (100–800 Hz) modes of the Emdex II meter were developed to help discriminate between sources that produce a dominant 60-Hz component and sources that produce strong fields at frequencies substantially larger than 60 Hz. Figure 5 is a modified box-and-whisker plot that summarizes the TWA harmonic personal exposures measured for the sampled Metro Transit electric trolley

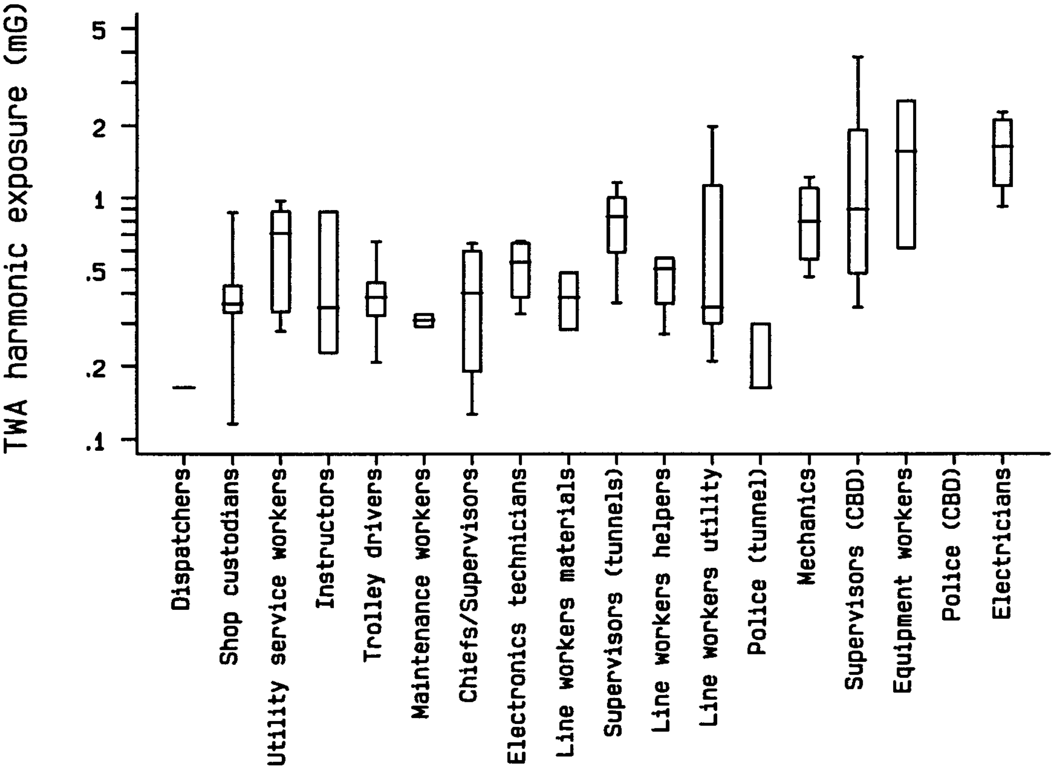

Figure 5. Modified box-and-whisker plot summarizing measured TWA harmonic personal exposures measured for each of 18 job titles.

workers. Table 3 presents arithmetic and geometric statistics for these exposures. Note that no harmonic data were obtained for one job title, Police who worked in the central business district, because all of these subjects wore Emdex Lite meters which were only able to measure the broadband component. Comparison of Figures 4 and 5 shows that the harmonic exposures are lower than the broadband, but it is difficult to make an accurate comparison from these figures alone. To help in this assessment, the ratio of the TWA harmonic and broadband exposures was calculated for each subject. Figure 6 is a modified box-and-whisker plot that summarizes these calculated ratios. Summary statistics are listed in Table 4.

The ratios of harmonic to broadband exposures for Electricians, the job title with the largest broadband exposures, are relatively small, in the range 0.2–0.4. This means that the dominant frequency component was between 40 and 100 Hz, almost certainly 60 Hz. Other job titles with relatively low harmonic-to-broadband ratios are Dispatchers, Maintenance Workers, Chiefs and Supervisors, Line Workers who stay on the ground, and Police who work in the tunnel. The jobs with the highest harmonic-to-broadband ratios were Utility Service Workers, Electronics Technicians, Supervisors who work in the tunnel, and Mechanics. All of these jobs, except Tunnel Supervisors, involve work in close proximity to various parts of trolleys. As noted earlier, the power electronics in trolleys produce magnetic fields with complex frequency spectra with components at frequencies well above 100 Hz (see Figure 2 for an example). Note that the harmonic to broadband ratio for Trolley Drivers is not large. Since these electronics are located at the rear of two of the types of trolleys that Metro Transit operates and in the middle in the other trolley type, drivers who sit at the front of the trolley are apparently not normally exposed to significant fields from these sources.

IV.3. Peak Personal Exposures

We next examined the exposure data to see which jobs were characterized by the largest peak exposures during work shift. Remember that the exposure record for each worker consisted of a sequence of magnetic-field samples, taken at periodic time intervals (every 3 s for Emdex II meters, 4 s for Emdex Lite meters) throughout work shifts. Starting from these data, we defined the following measures of peak exposure:

- 90th percentile broadband exposure
- 95th percentile broadband exposure
- fraction of broadband measurements > 2 mG
- fraction of broadband measurements > 5 mG

Table 3. Statistics summarizing TWA personal harmonic (100–800 Hz) exposures to magnetic fields received during one shift by workers holding indicated job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D. (mG)
Dispatchers	1	0.16	–	0.16	–
Shop Custodians	6	0.41	0.25	0.35	1.91
Utility Service Workers	5	0.63	0.31	0.56	1.77
Instructors	3	0.48	0.34	0.41	1.99
Trolley Drivers	13	0.40	0.12	0.38	1.35
Maintenance Workers	2	0.31	0.02	0.31	1.08
Chiefs and Supervisors	4	0.39	0.24	0.33	2.12
Electronics Technicians/Leads	4	0.51	0.16	0.50	1.39
Line Workers Materials	2	0.38	0.14	0.37	1.47
Supervisors (Tunnels)	4	0.79	0.33	0.73	1.64
Line Workers Helpers	4	0.46	0.13	0.44	1.40
Line Workers Utilities	5	0.79	0.76	0.55	2.60
Police (Tunnels)	3	0.21	0.08	0.20	1.42
Mechanics/Leads	8	0.82	0.30	0.77	1.46
Supervisors (Central Business District)	7	1.29	1.21	0.95	2.25
Equipment Service Workers/Leads	2	1.56	1.34	1.24	2.70
Police (Central Business District)	0	–	–	–	–
Electricians	4	1.61	0.60	1.51	1.50

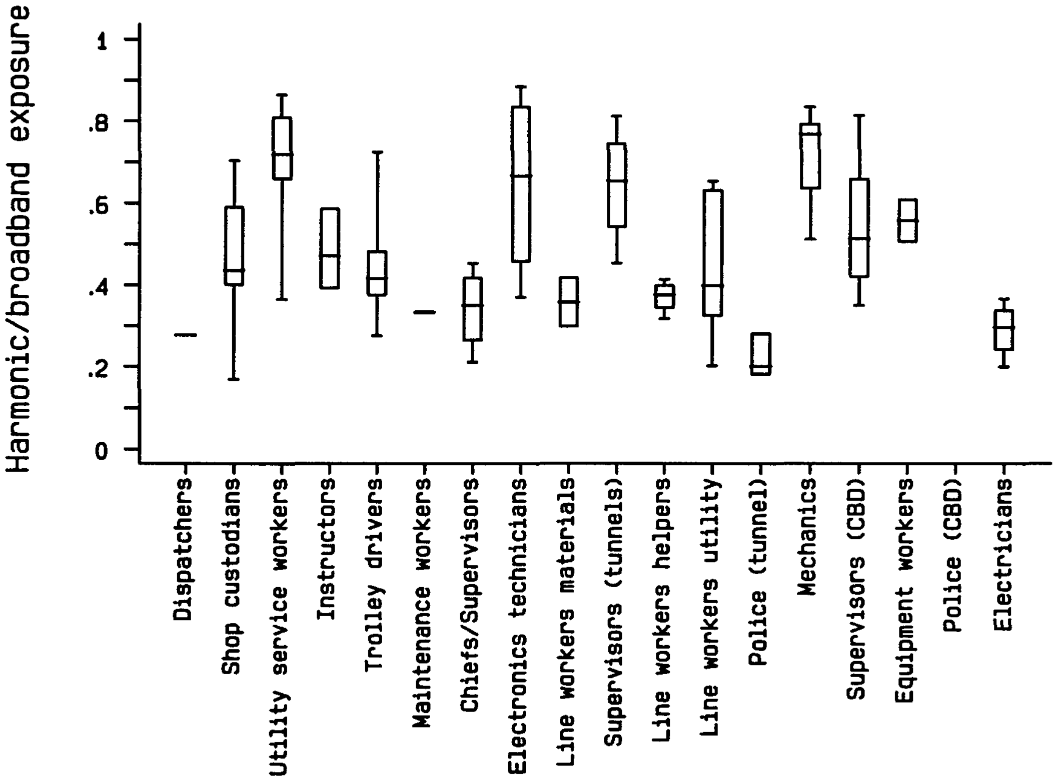

Figure 6. Modified box-and-whisker plot summarizing ratios of TWA harmonic to broadband personal exposures measured for each of 18 job titles.

Table 4. Statistics summarizing ratios of TWA personal harmonic (100–800 Hz) to broadband (40–800 Hz) magnetic-field exposures received during one shift by workers holding indicated job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)
Dispatchers	1	0.28	–
Shop Custodians	6	0.46	0.18
Utility Service Workers	5	0.68	0.19
Instructors	3	0.48	0.10
Trolley Drivers	13	0.45	0.11
Maintenance Workers	2	0.33	0.00
Chiefs and Supervisors	4	0.34	0.10
Electronics Technicians/Leads	4	0.65	0.23
Line Workers Materials	2	0.36	0.08
Supervisors (Tunnels)	4	0.64	0.15
Line Workers Helpers	4	0.37	0.04
Line Workers Utilities	5	0.44	0.20
Police (Tunnels)	3	0.22	0.05
Mechanics/Leads	8	0.72	0.11
Supervisors (Central Business District)	7	0.54	0.15
Equipment Service Workers/Leads	2	0.56	0.07
Police (Central Business District)	0	–	–
Electricians	4	0.29	0.07

- fraction of broadband measurements > 10 mG

Figure 7 and Table 5 summarize the first measure of peak exposure, the 90th percentile of the broadband magnetic-field exposure data collected during work shifts. (Examination of histograms of these data indicate that they are more nearly log normally than normally distributed.) The order in which data appears in Figure 7 and Table 5 is the same as previous figures and graphs, namely in order of increasing geometric-mean TWA broadband magnetic-field exposure. It is interesting that, sorted in this way, the data in Figure 7 still show a clear trend from lower to higher 90th percentile peak exposure. This trend is statistically significant ($p < 0.0001$, nonparametric trend test). In addition, job title is a significant grouping variable ($p < 0.0001$, Kruskal-Wallis test). Similar comments can be made regarding the 95th percentile measure of peak broadband exposure (data summarized in Figure 8 and Table 6). Note how prominently peak exposure for Electricians stands above peak exposures for the other job titles.

The other measure of peak exposure investigated in this study was the fraction of measurements during a work-shift recording that were greater than a threshold field intensity. Since the date were acquired with a constant sampling rate, this variable can also be interpreted as the fraction of time during the period of interest (i.e., the work shift) when the exposure level was greater than the specified threshold. Figure 9 and Table 7 summarize data, by job title, for this metric. We did not calculate geometric statistics for this metric because the data are closer to being normally distributed than the percentile metrics and because, for the higher thresholds, values of 0 were obtained.

The data in Figure 9 indicate the Police who worked in the central business district were more consistently exposed to fields > 2 mG in strength than Electricians, the job title that had highest exposures using all the metrics already discussed. This means that police were more consistently exposed to fields above 2 mG than the other job titles. Since these police patrolled throughout the central business district of Seattle, one can conclude that ambient magnetic fields in this environment are more consistently around or above 2 mG than in the other environments studied.

Figure 10 and Table 8 summarize the fractions of time exposures were > 5 mG. Interestingly, Equipment Service Workers have the largest exposure. Finally, Figures 11 and Tables 9 summarize exposure fractions > 10 mG. With this thresholds, Electricians stand well above

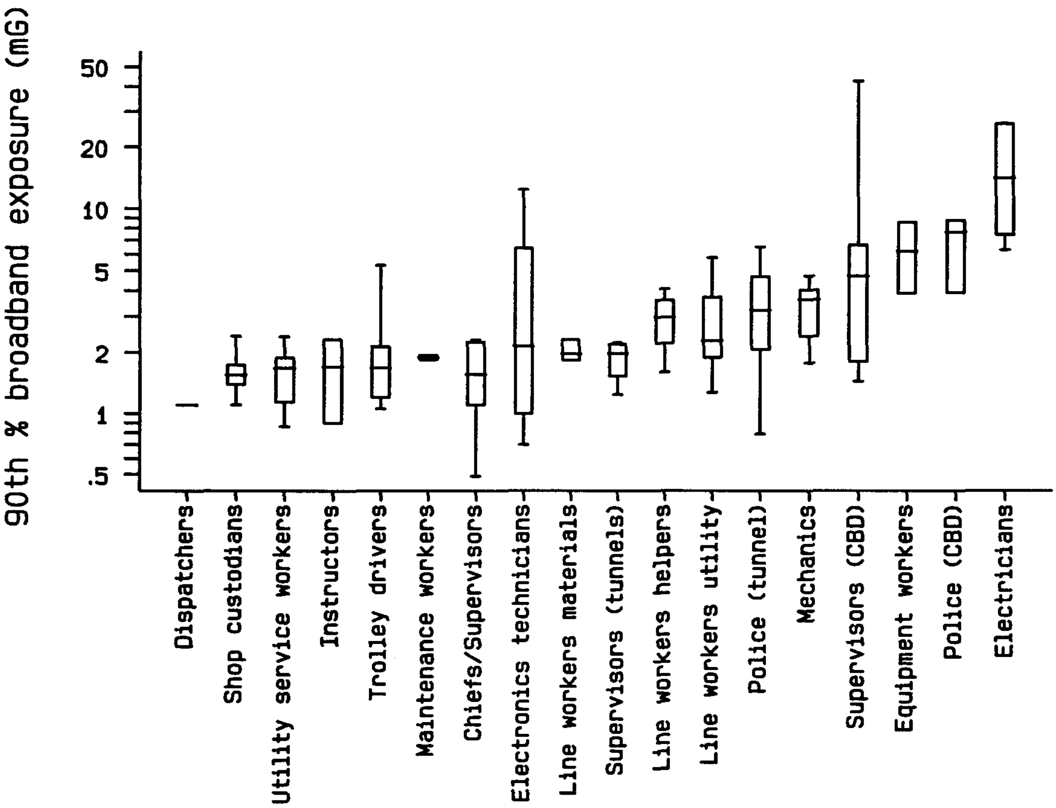

Figure 7. Modified box-and-whisker plot summarizing 90th percentile broadband magnetic-field exposure.

Table 5. Statistics summarizing 90th percentile broadband exposures to magnetic fields received during one shift by workers holding indicated job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D. (mG)
Dispatchers	1	1.10	–	1.10	–
Shop Custodians	6	1.62	0.45	1.57	1.30
Utility Service Workers	5	1.59	0.61	1.49	1.50
Instructors	3	1.64	0.71	1.52	1.62
Trolley Drivers	17	1.90	1.01	1.73	1.52
Maintenance Workers	2	1.89	0.07	1.89	1.04
Chiefs and Supervisors	7	1.52	0.66	1.36	1.72
Electronics Technicians/Leads	7	3.82	4.20	2.41	2.76
Line Workers Materials	3	2.03	0.24	2.02	1.12
Supervisors (Tunnels)	4	1.85	0.45	1.81	1.31
Line Workers Helpers	4	2.89	1.02	2.74	1.48
Line Workers Utilities	6	2.86	1.62	2.53	1.70
Police (Tunnels)	8	3.39	1.88	2.88	1.95
Mechanics/Leads	13	3.30	0.98	3.16	1.38
Supervisors (Central Business District)	7	9.24	14.52	4.57	3.20
Equipment Service Workers/Leads	2	6.17	3.28	5.72	1.75
Police (Central Business District)	3	6.73	2.51	6.37	1.54
Electricians	6	15.50	8.72	13.37	1.84

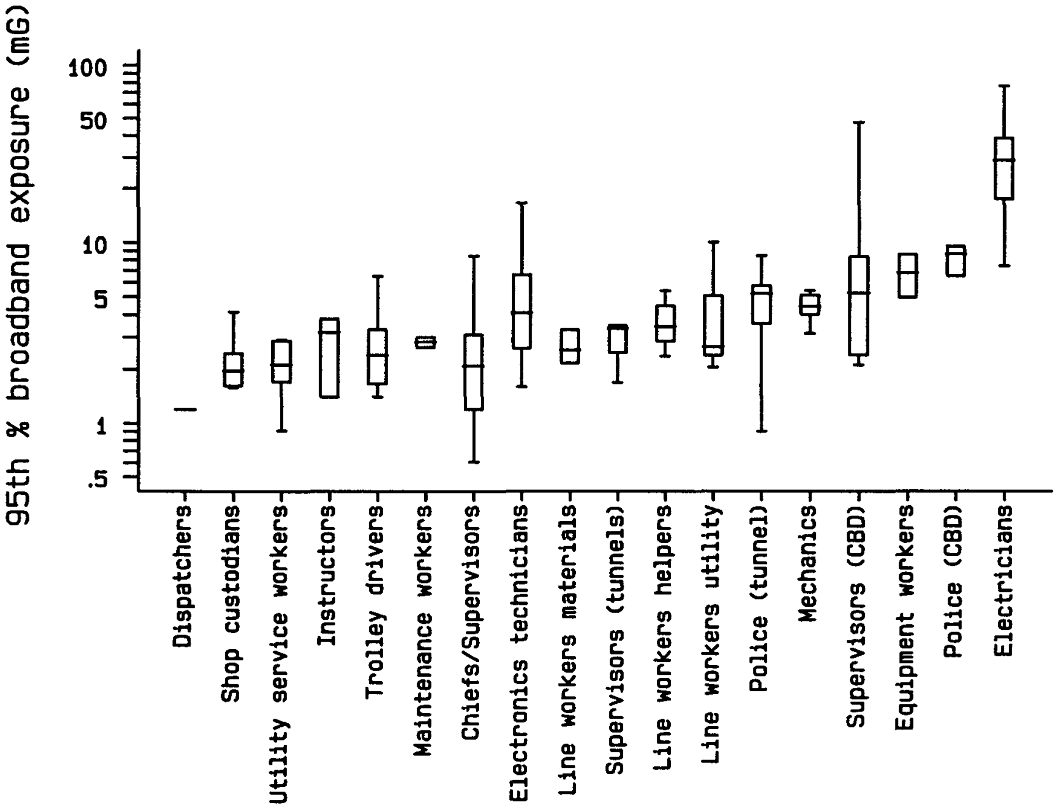

Figure 8. Modified box-and-whisker plot summarizing 95th percentile broadband magnetic-field exposure.

Table 6. Statistics summarizing 95th percentile broadband exposures to magnetic fields received during one shift by workers holding indicated job titles.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D. (mG)
Dispatchers	1	1.20	–	1.20	–
Shop Custodians	6	2.30	0.97	2.16	1.43
Utility Service Workers	5	2.11	0.84	1.95	1.62
Instructors	3	2.80	1.24	2.57	1.70
Trolley Drivers	17	2.76	1.42	2.48	1.59
Maintenance Workers	2	2.83	0.25	2.82	1.09
Chiefs and Supervisors	7	2.83	2.60	2.11	2.27
Electronics Technicians/Leads	7	5.74	5.06	4.44	2.10
Line Workers Materials	3	2.67	0.58	2.63	1.24
Supervisors (Tunnels)	4	2.97	0.86	2.85	1.42
Line Workers Helpers	4	3.65	1.27	3.50	1.40
Line Workers Utilities	6	4.14	3.08	3.47	1.83
Police (Tunnels)	8	4.78	2.26	4.08	2.01
Mechanics/Leads	13	4.46	0.81	4.39	1.21
Supervisors (Central Business District)	7	10.67	16.21	5.64	2.97
Equipment Service Workers/Leads	2	6.74	2.54	6.50	1.47
Police (Central Business District)	3	8.20	1.54	8.10	1.22
Electricians	6	32.46	23.47	25.75	2.19

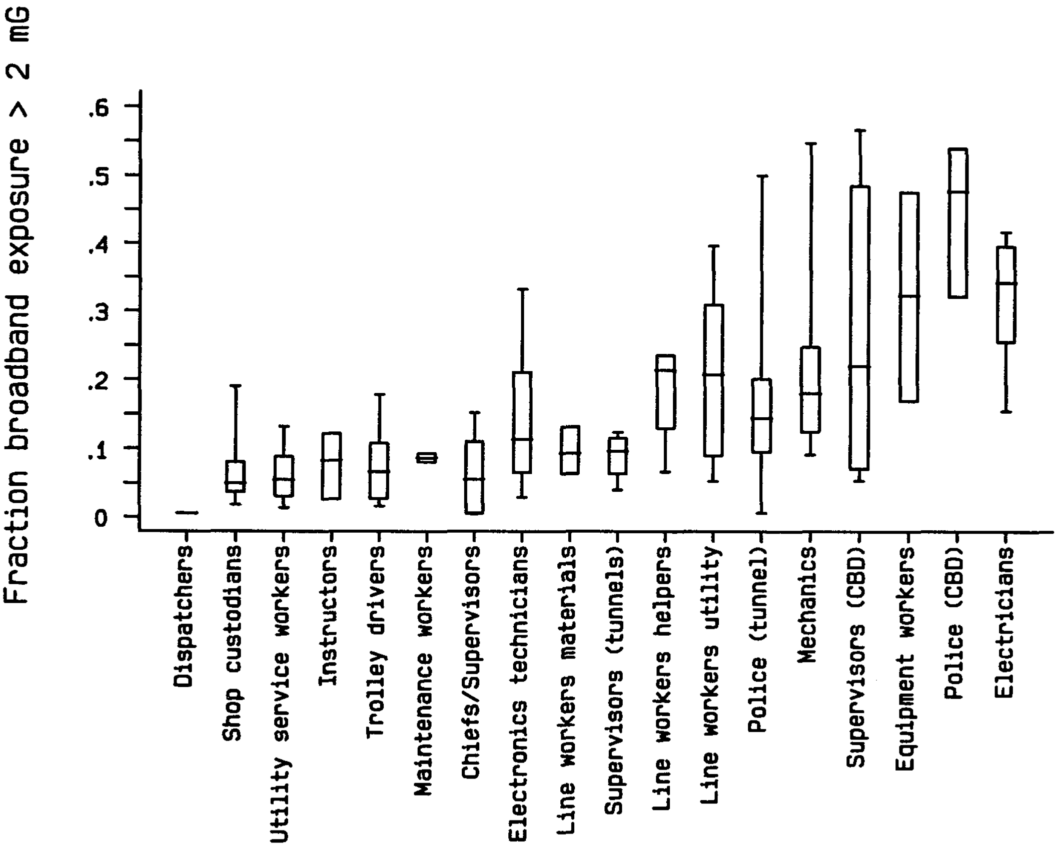

Figure 9. Modified box-and-whisker plot summarizing fractions of broadband magnetic-field exposure measurements during a work shift that were > 2 mG.

Table 7. Statistics summarizing fractions of broadband measurements made during work shifts that were > 2 mG.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)
Dispatchers	1	0.01	–
Shop Custodians	6	0.07	0.06
Utility Service Workers	5	0.06	0.05
Instructors	3	0.08	0.05
Trolley Drivers	17	0.08	0.05
Maintenance Workers	2	0.09	0.01
Chiefs and Supervisors	7	0.07	0.06
Electronics Technicians/Leads	7	0.14	0.10
Line Workers Materials	3	0.10	0.03
Supervisors (Tunnels)	4	0.09	0.04
Line Workers Helpers	4	0.18	0.08
Line Workers Utilities	6	0.21	0.13
Police (Tunnels)	8	0.17	0.15
Mechanics/Leads	13	0.23	0.15
Supervisors (Central Business District)	7	0.28	0.22
Equipment Service Workers/Leads	2	0.32	0.22
Police (Central Business District)	3	0.44	0.11
Electricians	6	0.32	0.10

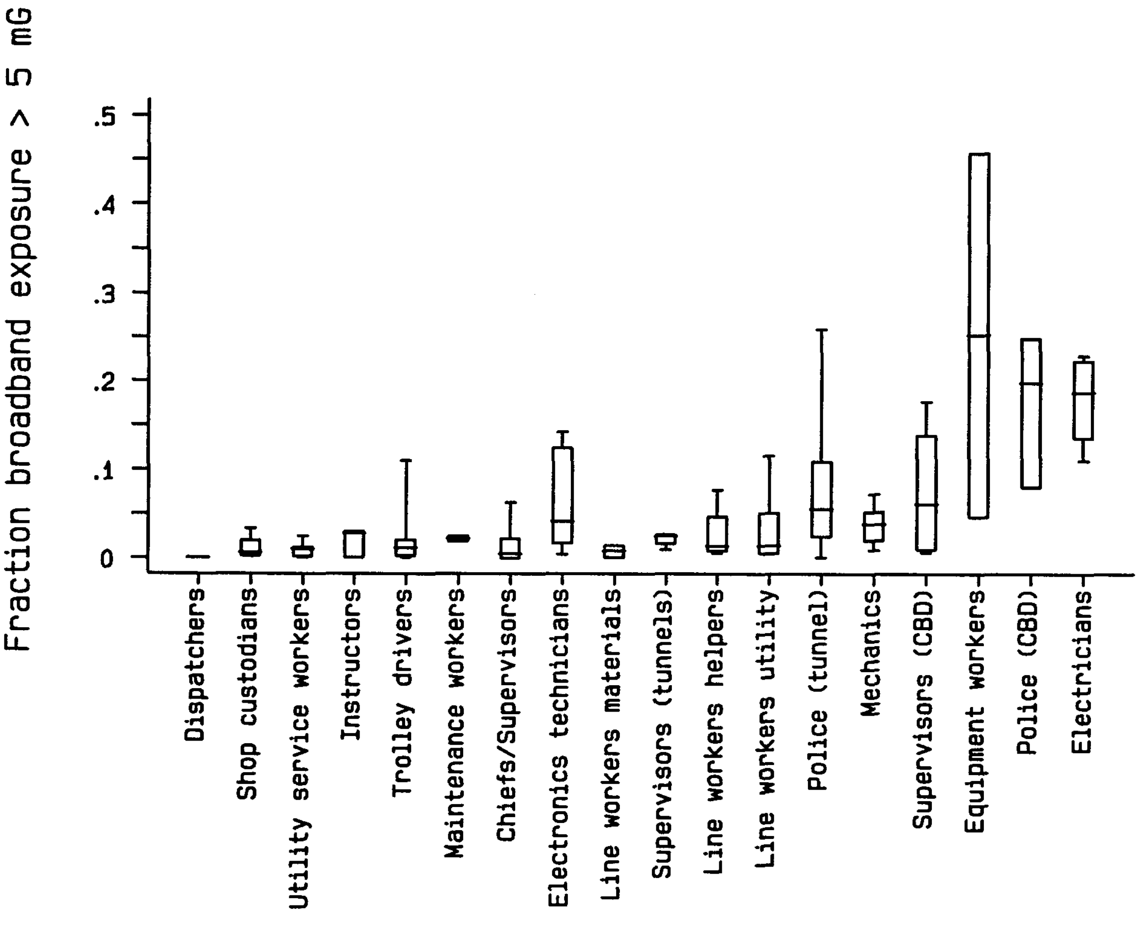

Figure 10. Modified box-and-whisker plot summarizing fractions of broadband magnetic-field exposure measurements during a work shift that were > 5 mG.

Table 8. Statistics summarizing fractions of broadband measurements made during work shifts that were > 5 mG.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)
Dispatchers	1	0.00	–
Shop Custodians	6	0.01	0.01
Utility Service Workers	5	0.01	0.01
Instructors	3	0.02	0.02
Trolley Drivers	17	0.02	0.03
Maintenance Workers	2	0.02	0.00
Chiefs and Supervisors	7	0.02	0.02
Electronics Technicians/Leads	7	0.06	0.05
Line Workers Materials	3	0.01	0.01
Supervisors (Tunnels)	4	0.02	0.01
Line Workers Helpers	4	0.03	0.03
Line Workers Utilities	6	0.03	0.04
Police (Tunnels)	8	0.08	0.08
Mechanics/Leads	13	0.04	0.02
Supervisors (Central Business District)	7	0.08	0.07
Equipment Service Workers/Leads	2	0.25	0.29
Police (Central Business District)	3	0.17	0.09
Electricians	6	0.18	0.05

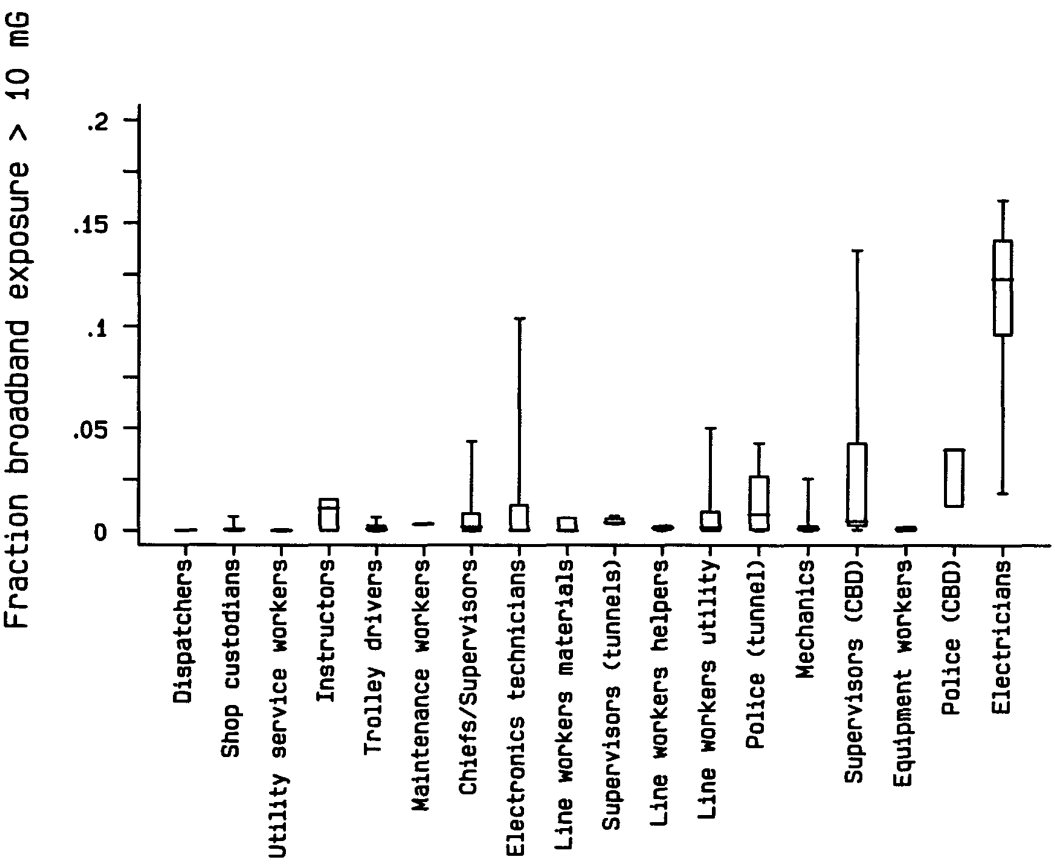

Figure 11. Modified box-and-whisker plot su7mmarizing fractions of broadband magnetic-field exposure measurements during a work shift that were > 10 mG.

Table 9. Statistics summarizing fractions of broadband measurements made during work shifts that were > 10 mG.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)
Dispatchers	1	0.00	–
Shop Custodians	6	0.00	0.00
Utility Service Workers	5	0.00	0.00
Instructors	3	0.01	0.01
Trolley Drivers	17	0.00	0.00
Maintenance Workers	2	0.00	0.00
Chiefs and Supervisors	7	0.01	0.02
Electronics Technicians/Leads	7	0.02	0.04
Line Workers Materials	3	0.00	0.00
Supervisors (Tunnels)	4	0.00	0.00
Line Workers Helpers	4	0.00	0.00
Line Workers Utilities	6	0.01	0.02
Police (Tunnels)	8	0.01	0.02
Mechanics/Leads	13	0.00	0.01
Supervisors (Central Business District)	7	0.03	0.05
Equipment Service Workers/Leads	2	0.00	0.00
Police (Central Business District)	3	0.03	0.02
Electricians	6	0.11	0.05

any other job titles. Evidently, these workers may be exposed to elevated magnetic fields only during parts of their shifts, but when they are exposed, the fields are quite strong.

IV.4. Temporal Variability in Exposure

The most direct way to examine the temporal structure of the exposures received by the workers sampled in this study is to simply examine graphs of broadband exposure magnetic field strength versus time. Figure 12 presents four examples of these graphs illustrating jobs whose exposures were characterized by relatively small and large levels of temporal variability.

The first two graphs in Figure 12 are for workers who had relatively low levels of temporal variability. These workers held the following job titles: Chief/Supervisor and Utility Service Worker. The bottom two graphs in Figure 12 illustrate relatively high levels of temporal variability. These exposures are for a Electronics Technician and an Electrician.

Figure 13 is a modified box-and-whisker plot that summarizes the corrected *RCM* data obtained to characterize the temporal variabilities of the exposures of the 104 workers sampled in the study. Table 10 lists summary statistics for this metric. Job title is a statistically significant grouping factor for *RCM* ($p = 0.016$, Kruskal-Wallis test). However, if Electricians are eliminated from the test, job title is no longer a significant factor ($p = 0.20$). Thus, one finding in Figure 13 is that the temporal variabilities of Electricians, as measured by the *RCM* metric, are significantly larger than all the other job titles.

The order of job titles presented in Figure 13 is from the smallest TWA broadband personal exposure (at the left end of graph) to the largest TWA broadband exposure. There is a statistically significant trend for increasing *RCM* moving from left to right in this graph ($p < 0.0001$, nonparametric trend test). The trend is still significant, even when Electricians are removed from the test ($p = 0.004$). However, as noted above, this trend may be due to the fact that *RCM* depends both on the temporal variability and *magnitude* of the field under study.

Figure 14 and Table 11 summarize RCM^* data for the 104 sampled workers. The appearance of the graph in Figure 14 is quite different from that for the *RCM* metric (Figure 13): In the latter (*RCM*) case, there is a trend towards increased *RCM* with increasing TWA broadband exposure, whereas in the RCM^* case, the trend appears to be toward decreasing RCM^* with

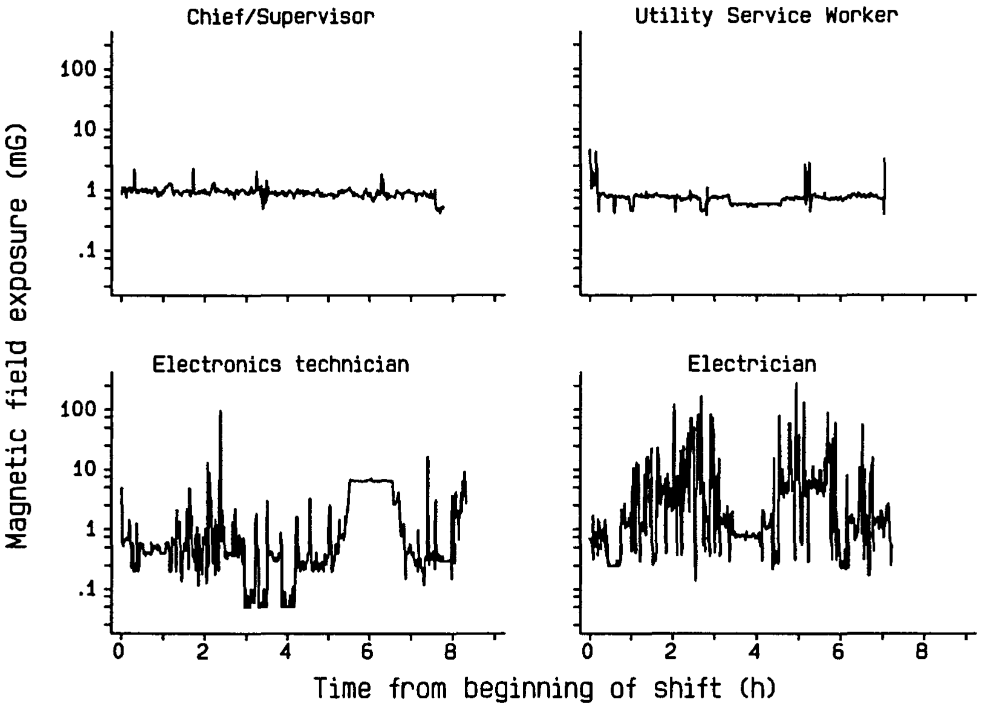

Figure 12. Plots of broadband magnetic-field exposure versus time for four selected workers illustrating low temporal variability (top two graphs) and high temporal variability.

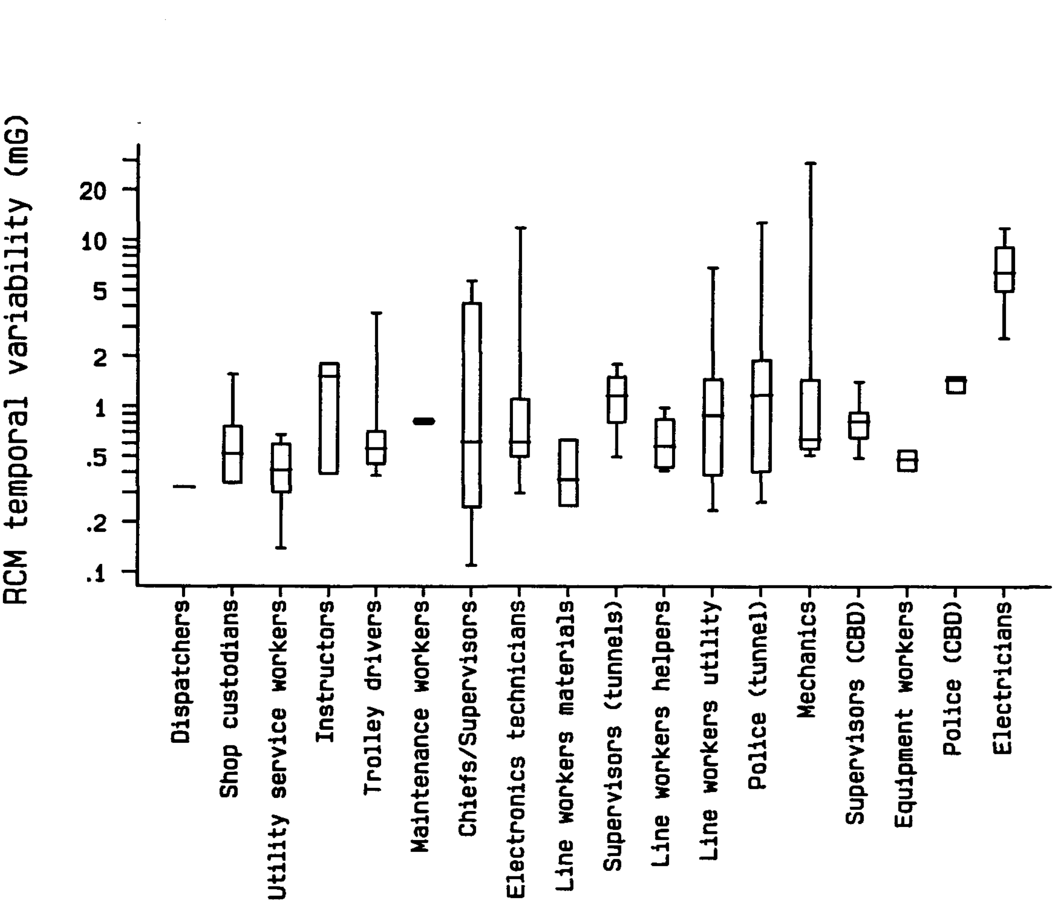

Figure 13. Modified box-and-whisker plot summarizing the temporal variability data as gauged by the *RCM* metric.

Table 10. Statistics summarizing *RCM* metric characterizing temporal variabilities of magnetic fields to which Metro Transit workers were exposed during one shift.

Job Title	N	Arithmetic mean (mG)	Arithmetic S.D. (mG)	Geometric mean (mG)	Geometric S.D. (mG)
Dispatchers	1	0.33	–	0.33	–
Shop Custodians	6	0.67	0.46	0.57	1.81
Utility Service Workers	5	0.43	0.22	0.37	1.88
Instructors	3	1.24	0.75	1.03	2.30
Trolley Drivers	17	0.78	0.76	0.64	1.72
Maintenance Workers	2	0.82	0.04	0.82	1.05
Chiefs and Supervisors	7	1.96	2.23	0.85	4.62
Electronics Technicians/Leads	7	2.21	4.23	0.87	3.36
Line Workers Materials	3	0.41	0.19	0.38	1.58
Supervisors (Tunnels)	4	1.15	0.53	1.04	1.71
Line Workers Helpers	4	0.63	0.26	0.60	1.50
Line Workers Utilities	6	1.77	2.52	0.89	3.45
Police (Tunnels)	8	2.48	4.18	1.12	3.47
Mechanics/Leads	13	4.52	9.21	1.25	3.98
Supervisors (Central Business District)	7	0.84	0.29	0.80	1.39
Equipment Service Workers/Leads	2	0.48	0.09	0.47	1.21
Police (Central Business District)	3	1.39	0.15	1.38	1.11
Electricians	6	6.85	3.26	6.15	1.71

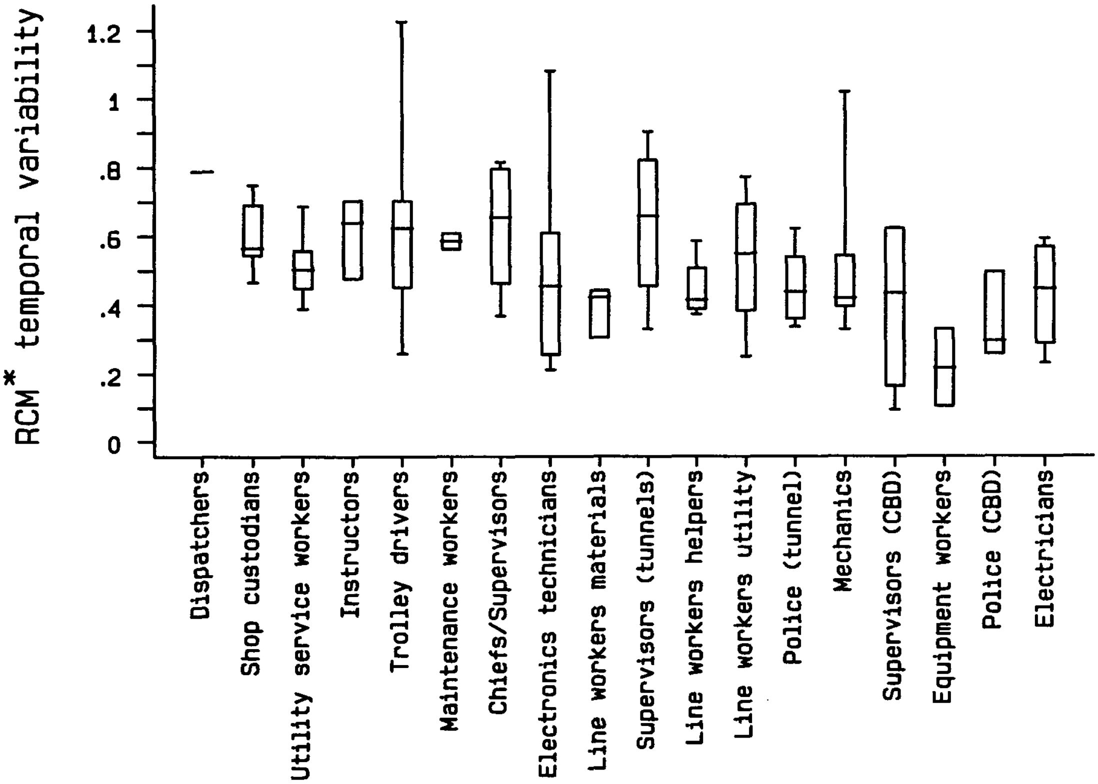

Figure 14. Modified box-and-whisker plot summarizing the temporal variability data as gauged by the *RCM** metric.

Table 11. Statistics summarizing *RCM** metric characterizing temporal variabilities of magnetic fields to which Metro Transit workers were exposed during one shift.

Job Title	N	Arithmetic mean	Arithmetic S.D.	Geometric mean	Geometric S.D. (mG)
Dispatchers	1	0.79	–	0.79	–
Shop Custodians	6	0.60	0.10	0.59	1.19
Utility Service Workers	5	0.52	0.11	0.51	1.24
Instructors	3	0.61	0.12	0.60	1.22
Trolley Drivers	17	0.62	0.23	0.59	1.44
Maintenance Workers	2	0.59	0.03	0.59	1.06
Chiefs and Supervisors	7	0.63	0.17	0.61	1.35
Electronics Technicians/Leads	7	0.50	0.29	0.44	1.74
Line Workers Materials	3	0.39	0.07	0.38	1.22
Supervisors (Tunnels)	4	0.64	0.24	0.60	1.55
Line Workers Helpers	4	0.45	0.09	0.44	1.22
Line Workers Utilities	6	0.53	0.20	0.50	1.54
Police (Tunnels)	8	0.45	0.10	0.44	1.26
Mechanics/Leads	13	0.51	0.20	0.48	1.39
Supervisors (Central Business District)	7	0.39	0.22	0.33	2.07
Equipment Service Workers/Leads	2	0.22	0.16	0.19	2.25
Police (Central Business District)	3	0.35	0.13	0.34	1.41
Electricians	6	0.38	0.14	0.36	1.45

increasing broadband exposure ($p < 0.0001$, nonparametric trend test). On a percentage basis, workers in environments characterized by larger TWA broadband personal exposures to magnetic field experience less field fluctuations than do workers in other environments.

IV.5. Relation Between Exposure Metrics

The following metrics have been used to describe the occupational exposures to magnetic fields of the 104 workers sampled from Metro Transit's electric trolley operations:

1) TWA broadband personal exposure
2) TWA harmonic personal exposure
3) 90th percentile broadband personal exposure
4) 95th percentile broadband personal exposure
5) Fraction of broadband measurements > 2 mG
6) Fraction of broadband measurements > 5 mG
7) Fraction of broadband measurements > 10 mG
8) *RCM* temporal variability metric
9) RCM^* temporal variability metric

The purpose of this section is to examine correlations between these alternative methods of characterizing occupational magnetic-field exposure. Table 12 list Pearson correlation coefficients for these metrics. However, Pearson correlations may not be the best choice for this application because they tend to be strongly influenced by values in the tails of the distributions. As an alternative, Table 13 list Spearman (rank) correlation coefficients. This choice seems particularly appropriate because exposure is usually categorized in studies of magnetic-field exposure and human health.

Tables 12 and 13 show that there is a high degree of correlation between many of the metrics used in this study, indicating that they do not all provide independent information about exposure. As far as the author knows, there is no real consensus as to the level of correlation between two measures of exposure required to conclude that one is redundant. It seems, though, that a redundant measure should explain at least 50% of the between-subject variability (ranking) explained by the measure, which corresponds to a Pearson (Spearman) correlation coefficient of 0.707. If we apply this criteria to Table 13 and regard TWA broadband personal exposure as a primary measure, we see that TWA harmonic exposure, 90th and 95th percentile exposure, and the fractions of measurements >2 mG and >5 mG are all redundant. This leaves the fraction of measurements >10 mG, *RCM*, and RCM^*. The fraction

Table 12. Pearson correlation coefficients between 9 exposure metrics used to describe occupational magnetic-field exposures received by 104 workers employed in Metro Transit's electric trolley operations.

	TWA broadband	TWA harmonic	90th % broadband	95th % broadband	Fraction > 2 mG	Fraction > 5 mG	Fraction > 10 mG	RCM
TWA harmonic	0.81[a]							
90th % broadband	0.75[a]	0.82[a]						
95th % broadband	0.84[a]	0.71[a]	0.87[a]					
Fraction > 2 mG	0.61[a]	0.80[a]	0.59[a]	0.48[a]				
Fraction > 5 mG	0.62[a]	0.73[a]	0.59[a]	0.53[a]	0.77[a]			
Fraction > 10 mG	0.82[a]	0.70[a]	0.85[a]	0.88[a]	0.52[a]	0.57[a]		
RCM	0.62[a]	0.48[a]	0.22[d]	0.29[c]	0.22[d]	0.22[d]	0.36[b]	
RCM[*]	*-0.36*[b]	*-0.35*[b]	*-0.38*[b]	*-0.35*[b]	*-0.42*[a]	*-0.40*[a]	*-0.31*[c]	*0.16*

[a] $p < 0.0001$ [b] $p < 0.001$ [c] $p < 0.01$ [d] $p < 0.05$

Table 13. Spearman correlation coefficients between 9 exposure metrics used to describe occupational magnetic-field exposures received by 104 workers employed in Metro Transit's electric trolley operations.

	TWA broadband	TWA harmonic	90^{th} % broadband	95^{th} % broadband	Fraction > 2 mG	Fraction > 5 mG	Fraction > 10 mG	RCM
TWA harmonic	0.77[a]							
90^{th} % broadband	0.90[a]	0.69[a]						
95^{th} % broadband	0.86[a]	0.70[a]	0.94[a]					
Fraction > 2 mG	0.86[a]	0.69[a]	0.96[a]	0.91[a]				
Fraction > 5 mG	0.82[a]	0.69[a]	0.84[a]	0.93[a]	0.81[a]			
Fraction > 10 mG	0.70[a]	0.53[a]	0.58[a]	0.65[a]	0.55[a]	0.72[a]		
RCM	0.70[a]	0.59[a]	0.60[a]	0.64[a]	0.58[a]	0.69[a]	0.82[a]	
RCM*	-0.37[b]	-0.20	-0.48[a]	-0.51[a]	-0.46[a]	-0.43[a]	-0.18	0.13

[a] $p < 0.0001$ [b] $p < 0.001$ [c] $p < 0.01$ [d] $p < 0.05$

of measurements > 10 mG and *RCM* are strongly correlated, so one or the other is redundant. Dropping the latter leaves us with the following list of "independent" exposure measures: TWA broadband personal exposure, fraction of measurements > 10 mG, and RCM^*.

IV.6. Spectral Measurements

To complement the personal-exposure data presented in the earlier sections of this chapter, we also made spectral measurements using a Multiwave II Waveform Capture system. In total, 410 individual Multiwave II samples were acquired during the course of the study. The remainder of this section presents typical spectra measured for several types of jobs. We have suppressed the static (dc) component of the magnetic field in all of these graphs since its large size ($\approx$ 500 mG) would have obscured all other details.

Figure 15 presents six frequency spectra. The top left spectrum in this graph was acquired in the area where Dispatchers work. Note the prominent magnetic-field peaks at 60 Hz, 180 Hz, and 300 Hz. This pattern is very characteristic of most environments, where magnetic fields produced by 60-Hz electric power currents are dominant. The 180-Hz and 300-Hz components are odd harmonics of 60 Hz, present because the currents that produce them are distorted from a pure 60-Hz sinusoid.

The remaining five graphs in Figure 15 were all taken in areas where Electronics Technicians work. The first two were taken while an Electronics Technician worked on a fare-box used on all trolleys in Seattle. In the first of these two, the technician was cleaning parts; note that the overall field was relatively small. In the second, he was testing the mechanism that collects and sorts coins. Exposure associated with this test was substantially increased. In the next two graphs, an electronics technician was working at the bench, the most common location where electronics technicians work. Field levels at this location were relatively low, but exhibited some frequency components below 60 Hz. The final spectrum in Figure 15 was taken while a technician worked at the rear of a trolley which was not energized (i.e., not connected to a source of electric power).

Figure 16 presents six magnetic-field spectra taken in the work areas of Mechanics. The first spectrum was taken as a Mechanic worked on a de-energized trolley. Note that the overall magnetic field was very small at this location, and that the most prominent frequency component was at 180 Hz rather than at 60 Hz. We cannot definitively explain this, but one

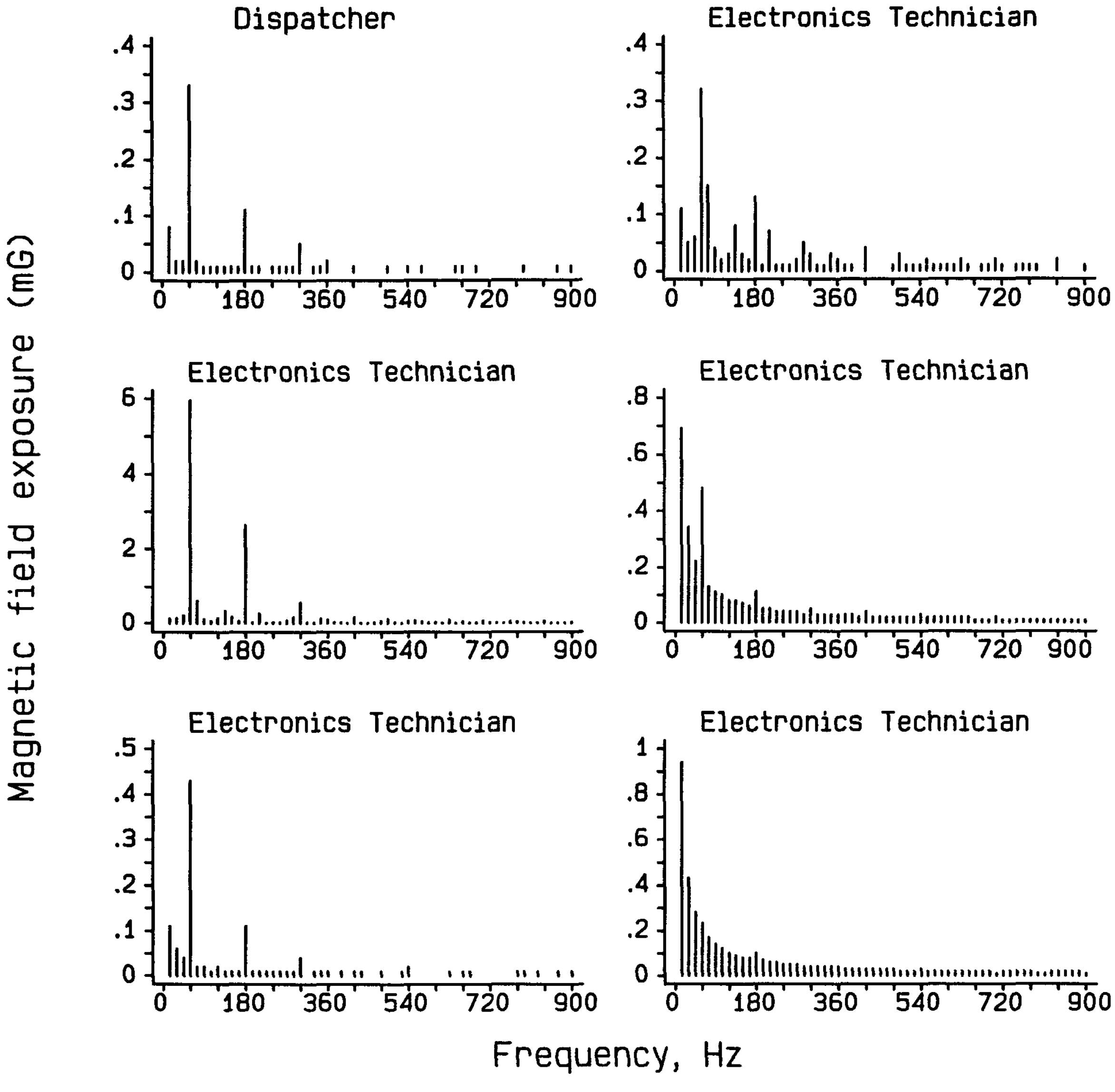

Figure 15. Frequency spectra of magnetic fields measured in work areas of Dispatchers and Electronics Technicians

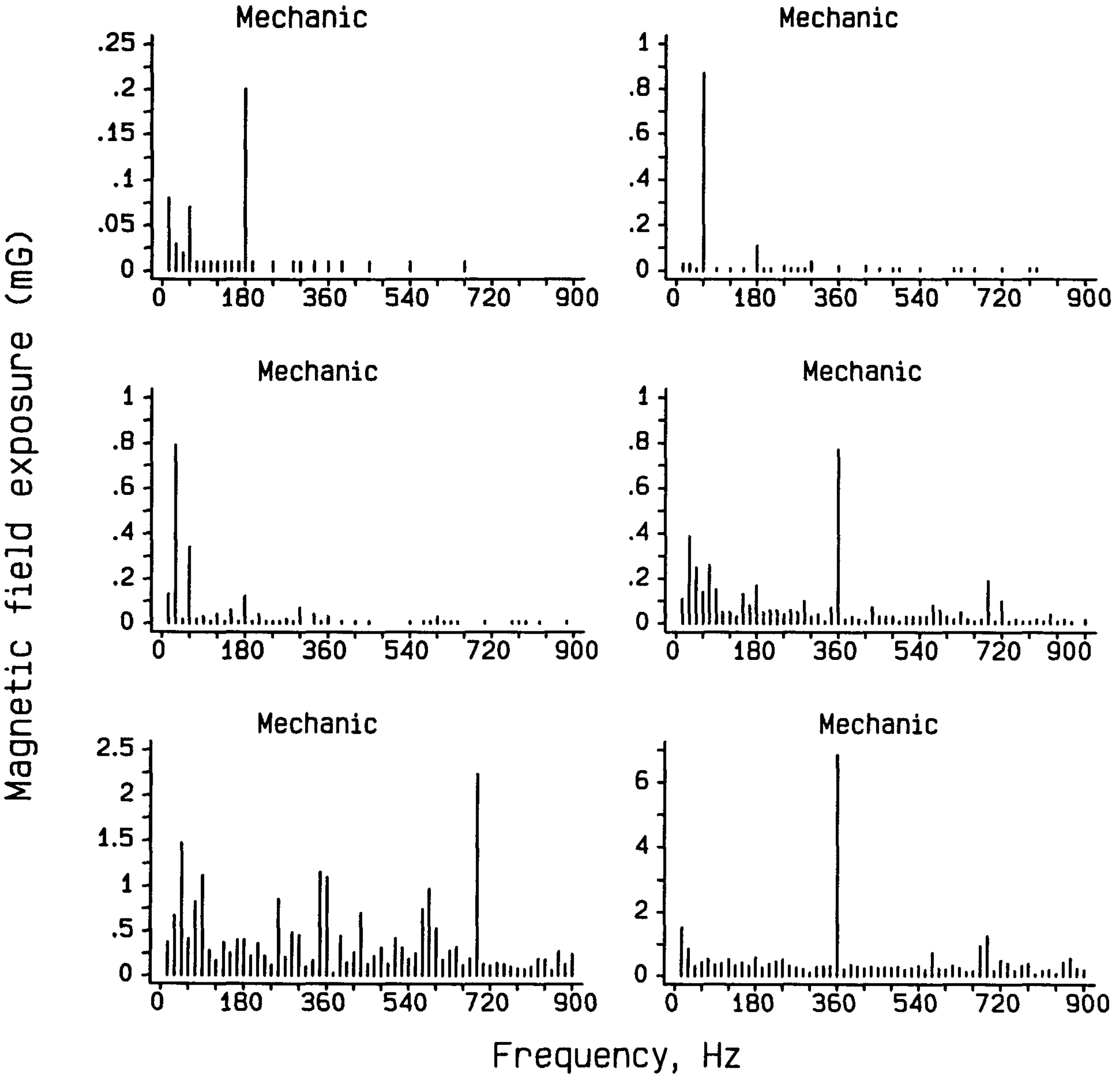

Figure 16. Frequency spectra of magnetic fields measured in work areas of Mechanics

possibility is that the major source of fields at this location was ground currents, which are often rich in harmonics. The second spectrum in Figure 16 was taken near an operating ventilation hood in the paint shop. The third spectrum was taken as a mechanic used a drill press. Note the strong peak at about 30 Hz in the latter spectrum.

The fourth, fifth, and sixth spectra in Figure 16 were all taken while a mechanic worked near the electronics section of an energized trolley. The fourth and sixth spectra show pronounced peaks near 360 Hz, while the fifth spectrum shows a peak just below 720 Hz. These frequencies are generated by the power electronics used to control the speed of trolleys. The first two spectra in Figure 17 were also taken in the work areas of Mechanics near energized trolleys and exhibit similar structures, with prominent magnetic fields at frequencies of 180 Hz and higher.

The last two spectra in Figure 17 were taken in a substation that Metro Transit operates to supply power to trolleys. The first of these was taken as an Electrician inspected a battery charger. The spectrum is somewhat different from the other ones in Figures 15–17 because it exhibits prominent even-harmonic peaks at 120 and 240 Hz. We believe this is most likely a result of the operation of a single-phase rectifier used to supply dc for battery charging. The last spectra in Figure 17 was taken near the ac side of the substation and exhibits the 60-Hz and odd-harmonic frequency structure characteristic of most 60-Hz powered systems.

IV.7. Estimate of Industry-Wide Average Exposure

We now use our data to approximately characterize the entire workforce employed in the electric trolley operations of Metro Transit. Suppose that the j^{th} job title is held by W_j workers and that we sampled S_j of these workers. Starting with the sampled data set, we should weight each sample by the factor W_j/S_j in order to reconstruct from the sample to complete data set. We accomplished this by replacing each observation in the data set with W_j/S_j copies of itself. (Actually, to minimize the effects of rounding W_j/S_j to the nearest integer value, we replaced each sampled value with $100W_j/S_j$ copies of itself, resulting in a data set with 125,297 observations.) The resulting data set was used to calculation statistics characterizing the complete population of airline workers. The results are given in Table 14.

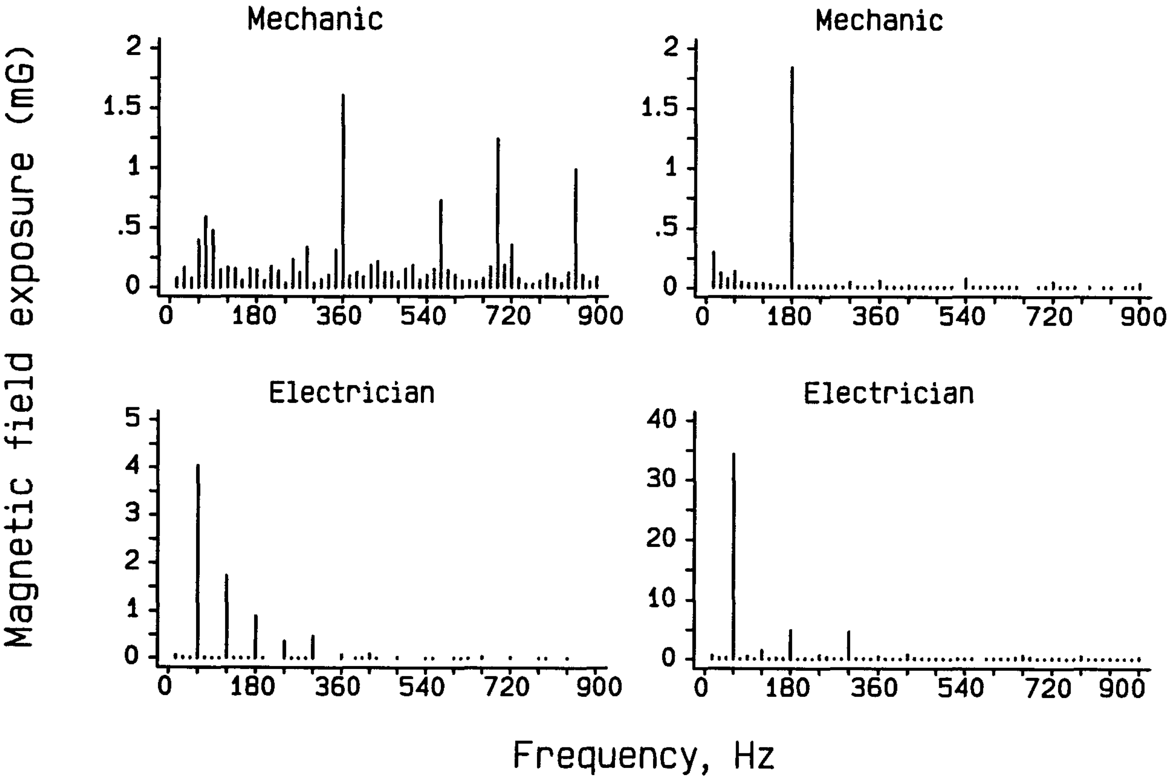

Figure 17. Frequency spectra of magnetic fields measured in work areas of Mechanics and Electricians.

Table 14. Average magnetic-field exposures for population of electric trolley workers employed by Seattle Metro Transit.

Exposure metric	Population statistics Arithmetic mean	Arithmetic SD	Geometric mean	Geometric SD
TWA broadband personal exposure	1.52 mG	1.63 mG	1.18 mG	1.84
TWA harmonic personal exposure	0.66 mG	0.59 mG	0.51 mG	1.90
90th percentile personal exposure	3.2 mG	4.1 mG	2.4 mG	1.96
Fraction of time exposure > 2 mG	0.14	0.13	0.09	2.69
Fraction of time exposure > 5 mG	0.05	0.09	0.02	4.7
Fraction of time exposure > 10 mG	0.007	0.023	0.001	5.8
Temporal variability *RCM* metric	1.8 mG	4.6 mG	0.80 mG	2.50
Temporal variability *RCM** metric	0.55	0.23	0.50	1.62

V. SUMMARY AND CONCLUSIONS

V.1. Summary

This study characterized the occupational exposures to magnetic fields of workers employed in the electric trolley operations of Metro Transit, which operates the public transportation system in the City of Seattle. The first step of the project was to generate a list of job titles and the numbers of workers holding each (Table 1). From this list, a sampling plan was developed that tended to select job titles for sampling in proportion to the numbers of workers holding each. In the end, 18 job titles were sampled.

Volunteer workers were asked to wear Emdex II or Emdex Lite magnetic-field meters at a waist location for one work shift. Emdex II meters were set to record the broadband (40–800 Hz) and harmonic (100–800 Hz) magnetic fields sampled every 3 s. Emdex Lite meters were programmed to record the broadband (40–1000 Hz) magnetic field every 4 s. From the resulting data the following nine exposure metrics were calculated:

1) Time-weighted-average broadband personal magnetic-field exposure
2) Time-weighted-average harmonic personal magnetic-field exposure
3) 90th percentile broadband personal magnetic-field exposure
4) 95th percentile broadband personal magnetic-field exposure
5) Fraction of broadband measurements > 2 mG
6) Fraction of broadband measurements > 5 mG
7) Fraction of broadband measurements > 10 mG
8) Temporal broadband magnetic-field variability using the *RCM* metric
9) Temporal broadband magnetic-field variability using the RCM^* metric

Most of these quantities were more nearly log normally than normally distributed (Figure 3).

The geometric means of the time-weighted-average (TWA) broadband magnetic-field exposures varied from a low of 0.59 mG for Dispatchers to a high of 6.01 mG for Electricians (Table 2). Other job titles with TWA broadband exposures above 2 mG were Equipment Service Workers, Police who worked in the central business district, and Electricians.

It is interesting that both of the jobs that involve work in the central business district of Seattle (Supervisors and Police) had relatively large TWA broadband exposures. Since these jobs involve considerable walking on city streets, one must conclude that magnetic-field levels in these areas, no matter what the source, are elevated relative to other areas.

In many cases, measured exposures for jobs were considerably lower than we expected on the basis of earlier area magnetic-field measurements (Kaune, 1994). For example, the earlier study showed that Electronics Technicians can be exposed to quite strong fields while performing certain high-power electronic tests. Yet, the geometric mean of the TWA broadband exposures of this group was, on the whole, very modest at 1.05 mG.

The geometric mean of the TWA harmonic magnetic-field exposure varied from 0.16 mG for Dispatchers to 1.51 mG for Electricians (Table 3). Interestingly, the ratios of TWA harmonic to broadband exposures (Table 4) did not exhibit the same relation to job title as TWA broadband exposure. For example, this ratio was relatively small for Electricians (0.29) which had the largest TWA broadband and harmonic exposures, and was largest for Mechanics. In general, the largest ratios were observed for those workers whose jobs involve close proximity to the power electronics and traction motors located in the rears or middles of trolleys. Such jobs include Utility Service Workers (who clean trolleys), Electronics Technicians, Supervisors who work in the transit tunnel under downtown Seattle, and Mechanics.

Five different metrics were used to capture peak magnetic-field exposure (Tables 5–9). The geometric means of the 90th percentile exposure ranged from 1.10 mG for Dispatchers to 13.4 mG for Electricians. Corresponding statistics for the 95th percentile exposure were 1.20 mG to 25.8 mG, respectively. The ordering of job titles, from smallest to largest 90th (or 95th) percentile exposure was similar to that for TWA broadband exposure. The only job title that was substantially misplaced by TWA broadband exposure was Electronics Technicians, which had considerably larger 90th (or 95th) percentile exposures than expected.

Peak exposure was also assessed using three threshold measures, fraction of measurements > 2 mG, fraction > 5 mG, and the fraction > 10 mG. The fraction of measurements > 2 mG varied from 0.01 for Dispatchers to 0.44 for Police who worked the central business district. Evidently, ambient magnetic fields in the central business district are fairly consistently above 2 mG in strength. The pattern of exposure is rather different when the fraction of measurements > 10 mG is used as a metric. Here, all job titles are low, below 0.03, except for Electricians which are at 0.11. These two results indicate that the magnetic field to which electricians are exposed is usually relatively small, but is significantly above 10 mG for substantial blocks of time.

Temporal variability of the broadband exposure magnetic field was assessed using two metrics, the so-called *RCM* and RCM^* metrics. The first is sensitive to both the temporal structure of the field, expressed as a percentage of the average field strength, and the size of the field. On the other hand, the second metric (RCM^*) depends only on the temporal structure of the magnetic field under study (again expressed as a percentage of the average field strength). The *RCM* metric varied from 0.33 mG for Dispatchers to 6.15 mG for Electricians. Interestingly, the *RCM** metric shows an almost inverse relation with job titles. Dispatchers have the largest exposures (0.79) while Electricians have one of the lower exposures (0.36).

Investigation of the correlations between exposure as measured with the various metrics used in this study showed that most were fairly closely related. By throwing out metrics whose correlations with other metrics was greater than 0.70, a minimal list of reasonably independent metrics would consist of three: TWA broadband personal exposure, fraction of personal exposure measurements > 10 mG, and the second rate-of-change metric, RCM^*.

V.2. Accuracy of Results

Extensive experience has shown that magnetic-field data acquired using Emdex II and Emdex Lite meters, such as that presented in this report, are consistently accurate. We checked the performance of these meters regularly throughout the course of the field work, and found no problems with any of them.

In a field study involving personal exposure measurements, one is always dependent on the cooperation of the subjects. Since we had as many as 11 meters deployed at any one time, it was not possible to directly observe that subjects were always following the protocol. Our belief from talking to subjects when the meters were collected is that the level of protocol adherence was high.

As mentioned earlier, some of the electronics used to condition the power flowing to the traction motors in electric trolleys produce magnetic fields with complex frequency spectra that can extend to several thousand Hz (Kaune, 1994). Thus, it is possible that the meters used for personal exposure measurements may have failed to respond to some of the higher frequency magnetic-field components to which some workers were exposed. Consequently, the TWA personal broadband personal exposure data we present in this report may understate true magnetic-field exposure.

By comparing the broadband and harmonic data acquired with the Emdex II meters, we can obtain some sense of how important frequency components in the 100–800 Hz range were. Let B_{LO} be the strength of the magnetic field that falls in the bandwidth from 40 to 100 Hz and would, thus, be detected by Emdex II meters only when operating in the broadband mode. Let B_{HI} be the strength of the magnetic field in the bandwidth 40–800 Hz. Then, since Emdex II meters incorporate rms detectors, the strengths of the broadband (B_b) and harmonic (B_h) fields measured by an Emdex II can be written

$$\begin{aligned} B_b &= \sqrt{B_{LO}^2 + B_{HI}^2} \\ B_h &= B_{HI} \end{aligned} \qquad (13)$$

By simple algebraic manipulations, we obtain the following equation for the ratio of B_{HI} to B_{LO}:

$$\frac{B_{HI}}{B_{LO}} = \frac{B_h}{\sqrt{B_b^2 - B_h^2}}. \qquad (14)$$

This formula was applied to all of the measurements taken with Emdex II meters. The results are presented in Figure 18. For most of the job titles, we see that the ratio in Eq. (14) is around 0.5 or less. That is, the magnetic fields to which workers holding these job titles were exposed consisted primarily of fields with frequencies in the 60–100 Hz bandwidth. It is reasonable to expect for these jobs that contributions from magnetic fields with frequencies above 800 Hz would have been very small. However, some jobs had values of this ratio ranging from 1 to nearly 2. These jobs were Utility Service Workers, Electronics Technicians, Supervisors who worked in the tunnel under the downtown area of Seattle, and Mechanics. All of these jobs, except for the Supervisor, involve activities which will, at times, require the workers to be close to the electronics used in trolleys for power control. (We do not know why Supervisors working in the tunnel scored high on this parameter.)

Unfortunately, the data obtained in this study are not sufficient to enable a more quantitative estimate of the errors associated with the use of Emdex II and Emdex Lite meters in magnetic-field environments characterized by relatively broad frequency spectra. However, data gathered in the earlier study at Metro Transit (Kaune, 1994) can be used for this purpose. Table 15 reproduces Table 15 from the earlier report. From this table, we see that estimated errors associated with the use of Emdex II and Emdex Lite meters range from a few percent to as high

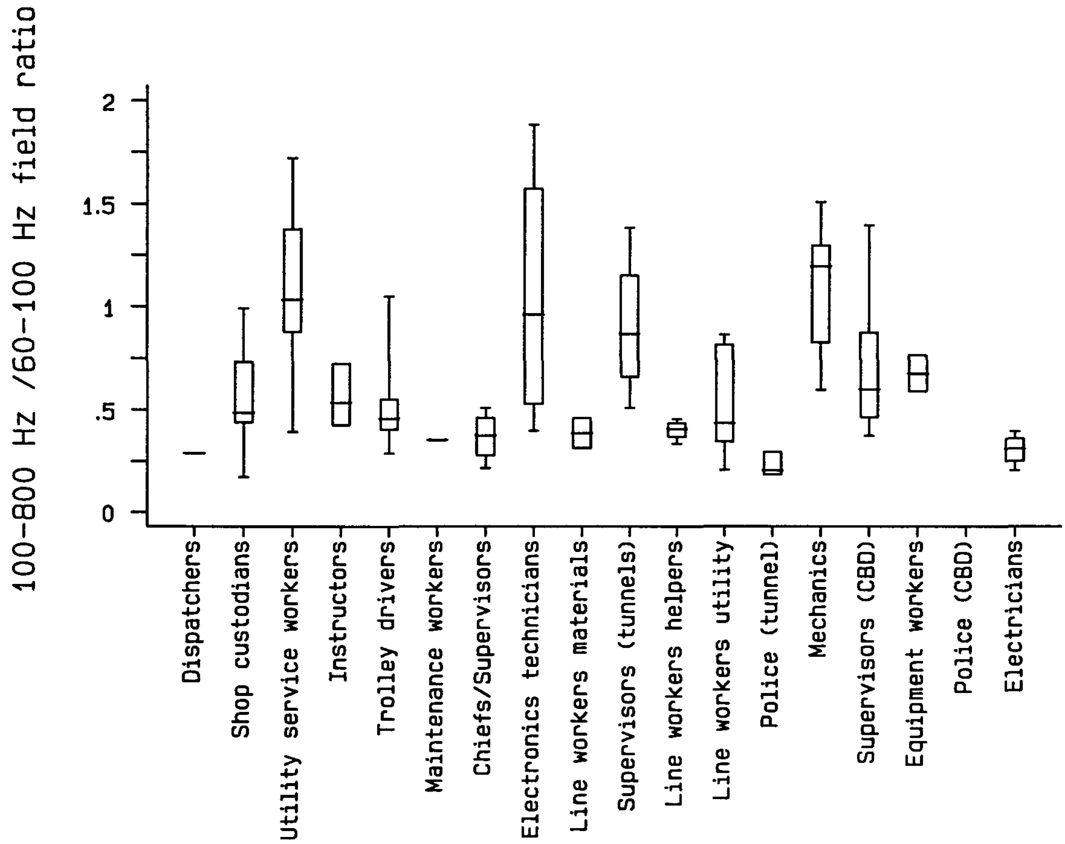

Figure 18. Modified box-and-whisker plot summarizing the ratios of the 100–800 Hz magnetic-field to the 60–100 Hz magnetic-field components.

Table 15. Reproduction of Table 15 in Kaune [1994], summarizing estimated errors associated with the use of an Emdex II meter to measure magneic fields in various occupational environments in Metro Transit facilities.

Environment	Magnetic-field strength (mG) dc	range ac[a]	median ac[a]	Average Emdex II measurement errors[b]	Frequency structure
Trolley substations, peak-loading conditions	200-1,600	0-100[d] 0-30[e]	≤10[d] ≤3[e]	(1 ± 1)% near ac section, (15 ± 10)% near dc section, values to 70%	60, 180, 300 Hz near ac section; <60 Hz, 60 Hz, 360 Hz near dc section
Near overhead trolley wires	-[c]	0-200	≈4	-[c]	-[c]
AMG 900 trolley, near electrical equipment	60-1,000	0-125	≤2	(30 ± 20)%, values to 65%	sometimes 200 Hz and harmonics, other times < 60 Hz
MAN 4000 trolley, near electrical equipment	50-600	0-250	≤5	(20 ± 12)%, values to 70%	Very complex. Occasional peaks at 500 Hz or near 60 Hz or <60 Hz
Breda 5000 trolley, near electrical equipment	200-500	0-600	≤4	(25 ± 25)%, values to 90%	Complex, often <60 Hz, sometimes peak near 60 Hz or broad peak near 500 Hz,
Atlantic Base Facility, general work areas	-[c]	0-14	0.5	Not measured but probably small	Not measured but certainly 60, 180 and 300 Hz
Test of Breda Parizzi converter	300-1,100	0-6	≤3	(30 ±20)%	Strong peaks at about 1600 Hz or 500 Hz
Test of Breda inverter module	≈250	0-15	≤2	(24 ± 11)%	Continuous spectrum from 0 through 3,000 Hz

[a] Corrected for reduced bandwidth of Emdex II meters [b] Mean ± standard deviation [c] Not measured

[d] Inside substation fence [e] Outside but near substation fence

Table 15. Continued

Environment	Magnetic-field strength (mG) dc	range ac[a]	median ac[a]	Average Emdex II measurement errors[b]	Frequency structure
Test of AMG Chopper module	≈ambient	0-450	≤6	(22 ± 3)%	Complex discrete spectra with 200 Hz and harmonics or about 40 Hz and harmonics
Test of AMG Field Regulator	≈ambient	0-27	≤3	(13 ±12)%	Almost continuous spectra with peaks largest fields below 100 mG
Test of AMG Converter	400-500	0-20	≤3	≈40%	Discrete spectra with peaks at largest peaks at 900-1200 Hz and small satellite peaks above and below
Passenger areas of International District Station	-[c]	0-6	≤1	Not measured but probably < 10%	Not measured
Fan room alley area of International District Station	-[c]	1-4	≤2	Not measured but probably < 10%	Not measured
Fan room alley area of International District Station	-[e]	0-13	≤4	Not measured but probably < 10%	Not measured

[a] Corrected for reduced bandwidth of Emdex II meters [b] Mean ± standard deviation [c] Not measured

[d] Inside substation fence [e] Outside but near substation fence

as 30% for measurements in various locations in and near trolleys. There is little doubt that the measurements taken in this earlier study tended to emphasize environments where magnetic fields were larger, so the 30% value is very likely a substantial overstatement of the true error in the personal exposure measurements.

In addition, the spectral measurements we made in this project (Figures 15–17) show little evidence of substantial frequency components outside the 40–800 Hz bandwidth of an Emdex II. In fact, of the 16 spectra displayed in these figures, there is only two (lower left spectrum in Figure 16 and upper right spectrum in Figure 17) that exhibit significant magnetic-field components with frequencies above 700 Hz. Based on all of these data, the best judgment of the authors is that the personal exposure measurements reported here probably understate true broadband magnetic-field exposure by no more than about 10% for jobs involving significant amounts of work near the power electronics used in trolleys. The jobs we expect would be most affected by this error are Utility Service Workers, Electronics Technicians, Supervisors who worked in the tunnel under the downtown area of Seattle, and Mechanics

V.3. Final Conclusions.

The average TWA broadband personal exposure to magnetic fields for workers employed in the electric trolley operations of Seattle's Metro Transit Division is 1.5 mG (Table 14), a value which is only modestly elevated relative to the typical U.S. residence (Zaffanella, 1993). Based on our measurements, the predicted numbers of the 705 individuals employed in the electric trolley operations of Metro Transit that have TWA broadband occupational personal exposures > 2 mG and > 5 mG are about 97 and 24, respectively. (These estimates were obtained from the data set described in Section IV.7.) These numbers are clearly not sufficient to support an epidemiological study with the goal of detecting associations between TWA broadband exposure and human disease.

The average TWA harmonic personal exposure of magnetic fields for Metro Transit employees is 0.63 mG, a value that is about 4 times typical residential ambient levels (Zaffanella, 1993). Insufficient residential data are available to enable us to compare any of the other exposure metrics in Table 14 to typical residential levels, but it seems possible that some of them, such as the two rate-of-change metrics, might be elevated. Thus, the Metro Transit population would seem to be a better choice to study the health effects of some of the more exotic attributes of magnetic fields. However, even then, the numbers do not seem sufficient to support such a study.

VI. REFERENCES

Barnes F, Wachtel H, Savitz D, Fuller J. 1989: Use of wiring configuration and wiring codes for estimating externally generated electric and magnetic fields. *Bioelectromagnetics 10*:13-21.

Caola RJ, Deno DW, Dymek VSW. 1984: Measurements of electric and magnetic fields in and around homes near a 500 kV transmission line. *IEEE Transactions on Power Apparatus and Systems PAS-102*:3338-3347.

Chatfield C. 1989. *The Analysis of Time Series–An Introduction.* New York: Chapman & Hall.

Davanipour Z., Sobel E, Bowman JD, Quan Z, Will AD. 1997. Amyotrophic lateral sclerosis and occupational exposure to electromagnetic fields. *Bioelectromagnetics 18*:28-035.

Dietrich FM, Papas PN, Feero WE, Jacobs WL, Steiner GA. 1993a. *Safety of High Speed Guided Ground Transportation Systems: Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System. Volume I--Analysis.* Report DOT/FRA/ORD-93/05.1, National Technical Information Service, Springfield, VA 22161.

Dietrich FM, Papas PN, Jacobs WL, Feero WE. 1993b. *Safety of High Speed Guided Ground Transportation Systems: Magnetic and Electric Field Testing of the Washington Metropolitan Transit (WMATA) System. Volume I--Analysis.* Report DOT/FRA/ORD-93/04.1, National Technical Information Service, Springfield, VA 22161.

Dietrich FM, Feero WE, Jacobs WL. 1993c). *Safety of High Speed Guided Ground Transportation Systems: Comparison of Magnetic and Electric Fields on Conventional and Advanced Electrified Transportation Systems.* Report DOT/FRA/ORD-93/07, National Technical Information Service, Springfield, VA 22161.

ERM. 1993). *User's Manual: MultiWave System II.* Electric Research & Management, State College, PA.

Feychting M, Ahlbom A. 1993. Magnetic fields and cancer in children residing near Swedish high-voltage power lines. *American Journal of Epidemiology 138*:467-481.

Floderus B, Persson T, Stenlund C, Wennberg A, Ost A, Knave B. 1993. Occupational exposure to electromagnetic fields in relation to leukemia and brain tumors. A case-control study in Sweden. *Cancer Causes and Control 4*:465-476.

Kaune W T. 1994. *Scoping Study of Magnetic Fields Associated with the Electric Trolley System Operated by Municipality of Metropolitan Seattle.* Report submitted to Seattle Metro Transit, Seattle WA.

Kromhout H, Loomis DP, Milhan GJ, Peipins LA, Kleckner RC, Iriye R, Savitz DA. 1995. Assessment and grouping of occupational magnetic field exposure in five electric utility companies. Scand. J. Work Environ Health 21:43-50.

Linet MS, Hatch EE, Kleinerman RA, Robison LL, Kaune WT, Friedman DR, Severson RK, Haines CM, Hartsock CT, Niwa S, Wacholder S, Tarone RE. 1997. Residential exposure to magnetic fields and acute lymphoblastic leukemia in children. *The New England Journal of Medicine 337*:1-7.

London SJ, Thomas DC, Bowman JD, Sobel E, Cheng T-C, Peters JM. 1991. Exposure to residential electric and magnetic fields and risk of childhood leukemia. *American Journal of Epidemiology 9*:923-937.

London SJ, Bowman JD, Sobel E, Thomas DC, Garabrant DH, Pearce N, Bernstein L, Peters JM. 1994. Exposure to magnetic fields among electrical workers in relation to leukemia risk in Los Angeles County. *American Journal of Industrial Medicine 26*:47-60.

Milham S. 1982. Mortality from leukemia in workers exposed to electrical and magnetic fields. *New England Journal of Medicine 307*:249.

NIEHS. 1998. *Assessment of Health Effects from Exposure to Power-Line Frequency Electric and Magnetic Fields.* NIH Publication No. 98-3981, National Institute of Environmental Health Sciences, U.S. National Institutes of Health, Research Triangle Park, NC 27709.

Olsen JH, Nielsen A., Schulgen G. 1993. Residence near high voltage facilities and risk of cancer in children. *British Journal Medicine 307*: 891-895.

Sahl JD, Kelsh MA, Greenland S. 1993. Cohort and nested case-control studies of hematopoietic cancers and brain cancers among electric utility workers. *Epidemiology 4*:104-114.

Savitz DA, Loomis DP. 1995. Magnetic field exposure in relation to leukemia and brain cancer mortality among electric utility workers. *American Journal of Epidemiology 141*:123-134.

Savitz DA, Wachtel H, Barnes FA, John EM, Tvrdik JG. 1988. Case-control study of childhood cancer and exposure to 60-Hz magnetic fields. *American Journal of Epidemiology 128*:21-38.

Sobel E, Davanipour Z, Sulkava R, Erkinjuntti T, Wikstrom J, Henderson VW, Buckwalter G, Bowman JD, Lee P.J.. 1995. Occupations with exposure to electromagnetic fields: A possible risk factor for Alzheimer's Disease. *American Journal of Epidemiology 142*:515-524.

Sobel E, Davanipour Z. 1996. Electromagnetic field exposure may cause increased production of amyloid beta and may eventually lead to Alzheimer's disease. *Neurology 47*:1594-1600.

Sokal RR, Rohlf FJ. 1995. *Biometry–The Principles and Practice of Statistics in Biological Research.* New York: W.H. Freeman and Company, Third Edition.

Stevens RG. 1987. Electric power use and breast cancer: A hypothesis. *American Journal of Epidemiology 125*:556-561.

Theriault G, Goldberg M, Miller AB, Armstrong B, Guenel P, Deadman J, Imbemon E, To T, Chevalier A, Cyr D, Wall C. 1994. Cancer risks associated with occupational exposure to magnetic fields among electric utility workers in Ontario and Quebec, Canada, and France: 1970-1989. *American Journal of Epidemiology 139*:550-572.

Verkasalo PK, Pukkala E, Hongisto MY, Valjus JE, Jarvinen PJ, Heikkila KV, Koskenvuo, M. 1993. Risk of cancer in Finnish children living close to power lines. *British Journal of Medicine 307*:895-899.

Weaver JC, Astumian RD. 1990. The response of living cells to very weak electric fields: The thermal noise limit. *Science 247*:459-462.

Wertheimer N, Leeper E. 1979. Electrical wiring configurations and childhood cancer. *American Journal of Epidemiology 109*:273-284.

Wilson BW, Lee GM, Yost MG, Davis KC, Heimbigner T, Buschbom RL. 1996. Magnetic field characteristics of electric bed-heating devices. *Bioelectromagnetics 17*:174-179.

Zaffanella LE. 1993. *Survey of Residential Magnetic Field Sources. Volume 1: Goals, Results, and Conclusions*. Report TR-102759-V1, Electric Power Research Institute, Palo Alto, CA.