



Hazard Surveillance for Industrial Magnetic Fields: I. Walkthrough Survey of Ambient Fields and Sources

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A walkthrough survey method was developed for measuring ambient magnetic fields (MFs) in industrial facilities as the first stage in hazard surveillance. This survey was designed to measure the mean and peak MF magnitudes at extremely low frequencies (ELFs), so that factories could be ranked by MF levels and prioritized for subsequent personal exposure monitoring. Sixty-two facilities from 13 Standard Industrial Classifications (SICs) with the highest monthly electric power usage were surveyed. To measure ambient MFs, a structured walkthrough survey with a special emphasis on workstations was conducted with an EMDEX-II meter in continuous operation, while MF sources were noted. The broadband MF data (40–800 Hz) for each facility were summarized with the geometric mean (GM) and the average of the five highest readings (Hi-5). The range of the GM magnetic field magnitude was 0.04–1.61 μT , where the maximum was measured at a steel mill operating large electric furnaces. Maximum values for specific sources were highly variable across and within facilities (Hi-5 range: 1.0–530 μT). Chemical and Allied Products (SIC 28) and Primary Metal Products (SIC 33) had facilities with GM and Hi-5 magnetic fields greater than any of the other industrial categories. However, the SIC categories were found to be poor predictors of the ambient MF in this sample of factories. A weak relationship was found between the facility-specific monthly electric power consumption and the GM magnetic field magnitude, but confidence limits were too broad to make meaningful exposure predictions from electric power data. Overall, 89% of the GMs were at or below 0.4 μT , consistent with most other studies that collected industrial MF exposure data. The walkthrough survey is a practical way of measuring ambient MFs in a large number of workplaces, and should be evaluated with personal measurements as a screening method for hazard surveillance. Published by Elsevier Science Ltd on behalf of British Occupational Hygiene Society.

Keywords: EMF; extremely low frequency; ELF; EMDEX

INTRODUCTION

The generation, transmission and distribution of electricity is inherently associated with electric and magnetic fields (EMF) at extremely low frequencies (ELF = 3–3000 Hz). These physical agents are ubiquitous in our industrialized society.

Recent epidemiologic research has suggested that occupational EMF exposures may be associated with increased risks of leukaemia (for example Floderus *et*

al., 1993; Theriault *et al.*, 1994), brain cancer (Savitz and Loomis, 1995), breast cancer (for example Coogan *et al.*, 1996), Alzheimer's disease (for example Sobel *et al.*, 1995), and amyotrophic lateral sclerosis (for example Davanipour *et al.*, 1997). Although *in vivo* studies have found no increase in either leukaemias or brain cancers from magnetic field exposures, such animal experiments have limitations as predictors of human carcinogenesis with environmental EMF (EMF RAPID Program, 1998). Based solely on epidemiologic associations with leukaemia, a recent US government review classified ELF magnetic fields (MFs) as a 'possible carcinogen' (Portier and Wolfe, 1998).

As more resources have been committed to MF

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health research over the past decade, surveillance has been undertaken, initially in residences (Zaffanella, 1993) and electric utilities (Bracken, 1990; London *et al.*, 1994; Sahl *et al.*, 1994; Theriault *et al.*, 1994; Kromhout *et al.*, 1995; Floderus *et al.*, 1996). The purpose of hazard surveillance with industrial MFs is to identify high exposure populations, target future research, and plan possible control efforts. Occupational MF exposures outside the electric utility industry have been surveyed systematically in offices (Breysse *et al.*, 1994a, b), a random sample of the adult population (Zaffanella, 1998), and a few industries in epidemiologic studies (for example Breysse *et al.*, 1994a, b; London *et al.*, 1994; Abdollahzadeh *et al.*, 1995; Wenzl *et al.*, 1997). The most comprehensive data on occupational MF exposures were collected by the National Institute of Occupational Health in Sweden for their case-control study of cancer in male workers from the general population (Floderus *et al.*, 1996). However, as products of epidemiologic studies, these data have gaps in their coverage of occupations, industries, and facilities. Thus, there is a need for systematic surveillance of industrial MFs beyond the electric utilities.

A first step in a complete surveillance effort is to prioritize industries in order of potential MF exposures for subsequent personal monitoring and source characterization. In this study, a walkthrough sampling method was developed so that industries and facilities with elevated ambient MFs could be identified. With the walkthrough survey, the average and peak magnitudes of potential MF exposures were measured in a sample of non-utility industrial facilities within the state of Ohio. These data were then used to test two surrogates for a facility's MF exposures that might be useful in prioritizing future surveillance measurements: (1) the monthly electric power consumption; and (2) the Standard Industrial Classification (SIC) at the two-digit level (US Department of Commerce, 1987).

A unique problem in MF hazard surveillance is determining what to measure, due in part to the fields' complex physical nature and numerous characteristics. Although biologically plausible measures for the EMF dose have been proposed, mechanistic research has yet to establish which dose metrics are disease risk factors (EMF RAPID Program, 1997). In most epidemiologic studies, the time-weighted average (TWA) of the root-mean-square (RMS) magnitude of the ELF-MF vector has been measured because it is convenient (Portier and Wolfe, 1998). However, many other EMF characteristics could also be important to the biological response if a plausible mechanism were available (for example frequency spectra, field orientation, waveform type).

This study (Part I) reports walkthrough measurements of the RMS magnitude of ELF magnetic fields with an EMDEX-II monitor, one of the instruments used in epidemiologic studies. An additional evalu-

ation (Bowman and Methner, 2000), identified other MF characteristics which were measured in a subset of facilities with a waveform capture instrument to address the exposure metric question.

MATERIALS AND METHODS

Identification of industries

Industrial categories were identified for walkthrough surveys by their average monthly electric power consumption (US Bureau of Census, 1992), which was employed as a surrogate for potentially elevated ambient MFs. Based on this information, the two-digit SICs were ranked according to electric power consumption and facilities were sought for measurements in the ten highest power-consuming industries (Range: 417 megawatt-hours (MW-h per month) for Apparel Products—SIC 23–12 250 MW-h per month for Primary Metal Smelting and Refining—SIC 33). For each SIC, five facilities were selected from a directory of Ohio industry (Harris Publishing, 1995). The initial goal was to conduct a random sampling effort but if a facility did not agree to participate, others within the same SIC were contacted and surveyed until data were gathered for five different sites. For some SICs, five different facilities were unattainable because of a lack of facilities within the defined geographical area. Overall, at least one facility was surveyed for each SIC where high power consumption was noted as summarized in Table 1.

Measurement methodology

All measurements during this survey were taken with an EMDEX-II portable monitor (Eneritech Consultants, Campbell, CA) which was mounted on a clipboard and carried by an industrial hygienist during the walkthrough survey at each facility. The EMDEX-II contains three orthogonal induction coils and electronic signal processing that measured the three RMS components of the MF vector in the 40–800 Hz frequency range. The EMDEX-II calculates the resultant of the three RMS components which yields the RMS vector magnitude of the ELF magnetic flux density in milligauss (mG). The conversion factor to obtain the SI units of microtesla (μT) is $10 \text{ mG} = 1 \mu\text{T}$. The EMDEX-II was set to run continuously and to record a measurement in its datalogger every 3 s. This sampling rate allowed the capture of MF data from all three of the EMDEX's filters: broadband, harmonic, and the fundamental power frequency (60 Hz). (See Bowman and Methner, 2000 for more discussion of EMDEX's filters.)

The walkthrough survey was conducted in the facility's production areas where there were workers and/or machinery. The industrial hygienist walked through all production areas in a systematic grid with

Table 1. Facility industrial process, floor area, and power usage

Facility ID	SIC code and industry description	Industrial process	Floor area (m ²)	Power usage (MW-h per month)	
47	20: Food and Kindred Products	Washing, grading, packaging eggs	600	77	
50		Distribution of refrigerated coffee creamer	1400	42	
60	20: Food and Kindred Products	Mfg salad dressing/food condiments	6000	430	
52		Brewing and packaging of malt beverages	3300	380	
54	23: Apparel Products	Mfg cotton undergarments	14 000	400	
45	24: Lumber and Wood Products	Retail lumber yard	1000	15	
11	26: Paper and Allied Products	Pulp and paper mill	33 000	9450	
12		Pulp and paper mill	17 000	7500	
13		Mfg aluminium-framed filters	6000	6	
30		Mfg recycled paperboard	23 000	2700	
31		Mfg paperboard using pulp and paper	11 600	2000	
32		Mfg corrugated paperboard shipping boxes	15 770	816	
33		Mfg corrugated sheets (paperboard)	6500	210	
34		Converter of paper	5000	52	
35		Recycle paper mill, including paperboard	20 000	1387	
44		27: Printing, Publishing	Offset printing	510	10
17		28: Chemicals and Allied Products	Raw air separation, distillation, liquefied gases	5000	12 500
18			Fill industrial gases (cryogenic and acetylene)	1000	87
19	Raw air separation plant (N ₂ , O ₂ , Ar)		10 000	10 000	
20	Raw air separation plant (C, H, He, O ₂ , N ₂ , Ar)		10 000	27 797	
21	Fill industrial gases (from raw separation plants)		1000	15	
22	Repackaging of gases/acetylene production		600	15	
23	Mold, cut, shape, form polystyrene		4200	28	
24	Convert plastic monomers—polymers, extrusion		13 160	135	
25	Plastic toll compounders, extrusion process		21 900	40	
26	Produce chlorine and potassium hydroxide		5000	149	
27	Chemical distributor, mfg bleach/alkali products		14 000	145	
28	Mfg bleach		10 000	130	
29	Produce alkali and organic chemicals		10 000	14	
48	Pharmaceutical production		23 000	50	
49	Mfg granular fertilizers		20 000	167	
53	Oral drug delivery—pharmaceutical mfg	1820	62		
14	29: Petroleum Refining	Oil recycling, hydropulping, filter, centrifugation	N/A	N/A	
15		Preparation of oils and greases for industrial use	15 000	80	
16	30: Rubber Products	Fuel refinery	40 000	30 561	
46		Mfg tyre repair kits, mix raw rubber	6330	150	
55	32: Stone, Clay, Glass and Concrete Products	Mfg auto weatherstripping	10 000	870	
36		Excavate/crush rock, produce cement powder	30 000	5000	
51	33: Primary Metal Smelting and Refining	Produce sound-proofing materials	2000	19	
1		Crushing, screening, blending of aluminium	7000	80	
2		Aluminium smelting, casting, and heat treating	1600	200	

(Continued on next page)

Table 1. (continued)

Facility ID	SIC code and industry description	Industrial process	Floor area (m ²)	Power usage (MW-h per month)
3		Aluminium foundry general machining	5000	125
4		Custom aluminium extruder and anodizer	8000	25
5		Reheat steel billets and hot roll into bar product	4500	315
6		Coil processing: slit coils, precision levelling	11 000	80
7		Steel mill, processing of steel billets and bar	50 000	90 000
8		Tension levelling of steel rolls	3100	150
9		Steel processing, levelling, slitting, heat treat	28 200	2000
39		Aluminium and iron foundry and machining	20 000	900
40		Gray iron foundry	1300	100
41		Gray iron foundry	35 000	135
42		Gray iron foundry	35 000	225
43		Gray iron foundry	10 000	178
62		Cold and hot rolled steel processing	8000	200
56		Mfg auto brake lines/steel tubing	17 500	1900
57		Secondary lead smelter (battery reclamation)	7000	2900
58	34: Fabricated Metal Products	Mfg of brass hinges	15 100	1800
37	36: Electronic Equipment	Printed circuit board assembly and testing	3300	68
38		Produce cadmium semiconductor solar panels	1800	30
59	38: Measuring/Analysing/Controlling Instruments	Mfg and test missile guidance systems	300 000	4460
61		Mfg endoscopic surgery instruments	30 000	1000

the EMDEX in continuous operation. On the clipboard with the EMDEX was a data sheet where the industrial hygienist recorded information about specific work areas and/or processes, as well as MF sources. The industrial hygienist stopped at MF sources near workstations and other areas where workers spend substantial amounts of time, and took five EMDEX measurements (15 s total measurement time) with the monitor 0.3 m from the sources. At each source, the industrial hygienist pressed the EMDEX's 'event marker' button, and recorded the event number on the data sheet in order to link source information with the MF measurements during the analysis.

Upon completion of each survey, data were downloaded to a portable computer and then copied to a computer diskette for storage and retrieval. A calibration coil (Model 147, Electric Field Measurements, Stockbridge, MA) was used to check the broadband mode of all EMDEX-II units before and after each survey. No significant changes in calibration (done originally by the EMDEX's manufacturer) were detected over the course of the study.

Data analysis

Descriptive statistics of the MF data were reviewed for each facility. The data from the fundamental power frequency and harmonic modes indicated that the harmonic content (100–800 Hz) of the ambient MFs was not of sufficient magnitude to warrant separate analyses. Therefore, all data analyses used the broadband MF data (40–800 Hz).

Skewed distributions were observed for the broadband MF measurements at all facilities. Therefore, the geometric mean (GM) was employed as the exposure metric for the central tendency at each facility because it is more robust under the influence of skewed data. A new statistic, the 'Hi-5' (mean of the five highest measures) was calculated to provide an indication of the magnitude at the highest sources and peak exposure potential at each facility. Summary statistics and cumulative distributions were calculated for both exposure metrics. The arithmetic mean values of the facility-specific data were similar in appearance to the GM data presented here (data not shown).

The two surrogates for MF exposure, power consumption and the SIC codes, were both tested as pre-

dictors of the GM magnetic fields. The relationship between GM magnetic fields and facility-specific monthly power consumption was tested by regression and correlation analysis. Since both data sets are skewed, the Spearman correlation was used, and the regression was performed after log transformation of the data. The relationship between magnetic fields and two-digit SICs was tested graphically and by a multiple means test, using the log-transform of the SIC-specific geometric mean of the facility-specific GMs.

RESULTS

A total of 62 facilities were surveyed, which resulted in the collection of 61 000 MF data points. The total number of measurements per facility ranged from 160 to 4592. The duration of each facility survey ranged from 8 to 228 min, depending on the size of the facility. The 8 min survey was at a small printing shop while the 228 min survey was at a large oil refinery. Table 1 presents facility data: the two-digit SIC, facility processes, floor area (range: 510–300 000 m²) and facility-specific monthly power consumption (range: 0.01–90 MW-h per month).

The facility-specific GM and Hi-5 statistics for the broadband MF are shown in Table 2. Facilities were rank-ordered by their GM values, which has a median of 0.15 μ T and a range of 0.04–1.61 μ T. The GM values were affected by the number of sources as well as the source's magnitude. Overall, 89% of the facilities had GM values below 0.4 μ T, which is noted in the cumulative frequency distribution presented in the left portion of Fig. 1. This point (approximately equal to the 90th percentile) may be a useful cut-off for determining facilities that are a higher priority for additional study, but this needs to be validated by personal monitoring.

Table 2 also presents a brief description of sources emitting the highest MF magnitudes, as measured by the Hi-5 statistic for each facility. The Hi-5 for different sources (measured 0.3 m from sources) varied widely across facilities, with a median of 205.2 μ T and a range from 1 to 530 μ T. The maximum Hi-5 was measured next to an induction furnace used to melt steel, and in fact exceeded the EMDEX-II upper detection limit of 530 μ T. A convenient reference point for the Hi-5 was 100 μ T, which is just over the 90th percentile as shown in the right portion of Fig. 1. The vast majority of high magnitude sources were electric motors, transformers and furnaces.

Figure 2 shows the Spearman correlation ($r = 0.46$) between the facility GM and the Hi-5 value. When these metrics were categorized with the 90th percentile cut-offs (0.4 μ T for GMs and 100 μ T for Hi-5s), eleven facilities (17.7%) exhibited discordance between these two metrics (Fig. 2). Four facilities had large Hi-5 values but relatively low GM fields (Table 2), consisting of three iron foundries

(SIC 33) and a solar panel manufacturer (SIC 37). In these facilities, a few strong MF sources (such as induction furnaces or xenon lamp power supply) were found among generally low ambient fields.

The opposite discordance (large GM and low Hi-5) was found in four chemical plants (SIC 28), an iron foundry (with Hi-5 close to the cut-off at 92.5 μ T), and a plant that tension-levelled steel rolls (SIC 33). In these facilities, many moderate MF sources have created high ambient fields and a greater potential for worker exposure. We therefore used the GM metric for the analysis of the MF surrogates since the Hi-5 is less likely to indicate overall worker exposures in a facility.

The monthly electric power consumption was also tested as a surrogate for a facility's ambient MF magnitudes (Fig. 3). The Spearman correlation coefficient between these two variables was 0.39. When the monthly power consumption was divided by the floor area, there was still little correlation with the GM magnetic field measured at each facility (data not shown). A regression on the log transform of the power consumption and the GM did show a significant linear relationship (P from F -test = 0.0011), but the confidence limits were very broad (Fig. 3). At the power consumption's 90th percentile (7500 MW-h per month), for example, the predicted GM is 0.26 μ T with a 95% confidence interval of 0.06–1.05 μ T, which equates to 10th–98th percentile of the measured GMs (Table 2). Therefore, a MF prediction from power consumption is too uncertain for surveillance purposes.

To test whether industrial categories are a surrogate for magnetic field exposures, the data were collapsed into two-digit SIC codes and graphically displayed to determine if any new trends emerged. Figure 4 presents results of this analysis and indicates that similar intra-industry variability continued to exist between facilities. The industry-specific geometric means and 95% confidence intervals are presented in Table 3. Of the three industries that were sampled most extensively, SIC 28 (Chemicals and Allied Products) and SIC 33 (Primary Metal Products) had geometric means for GM magnetic field that were higher than SIC 26 (Paper Products) although the elevation was not significant ($P > 0.5$).

DISCUSSION

The results of this walkthrough surveillance effort provide new information on ambient MF magnitudes in diverse industrial settings. Of the 13 industrial categories surveyed, high MFs were most prevalent in Primary Metal Smelting and Refining (SIC 33) and Chemicals and Allied Products (SIC 28). The survey also identified a variety of MF sources, such as the expected electric power supplies, furnaces, and motors, but also high-intensity lamps, fabric cutters, and chart recorders.

Table 2. Magnetic field metrics and source information for each facility

Facility ID	Industry (two-digit SIC)	Magnetic field metrics (μT)		Highest magnitude source (measured 0.3 m from source)
		GM (95% C.I.)	Hi-5	
7	33	1.61 (1.26–2.07)	521.9	Electric furnaces
26	28	0.93 (0.83–1.04)	18.7	Reaction cell area
49	28	0.74 (0.65–0.85)	26.8	Transformer
19	28	0.63 (0.56–0.72)	49.8	Compressor motor
8	33	0.57 (0.48–0.67)	22.4	Welding station
17	28	0.43 (0.38–0.50)	49.3	Compressor motor
43	33	0.43 (0.36–0.52)	92.5	Induction furnace
90th percentile for GM				
39	33	0.38 (0.35–0.42)	140.8	Electric furnaces
35	26	0.37 (0.35–0.40)	13.4	Transformer
61	38	0.35 (0.33–0.37)	34.1	Transformer
11	26	0.28 (0.26–0.30)	37.2	Generator
20	28	0.27 (0.25–0.29)	36.9	Electric heater
41	33	0.26 (0.23–0.31)	275.2	Electrogalvanizing tank (rectified DC)
38	36	0.26 (0.23–0.30)	108.6	Coreless style induction furnace
58	34	0.26 (0.24–0.27)	93.5	Xenon lamp power supply
45	24	0.25 (0.21–0.30)	14.7	Hand-held drill
12	26	0.23 (0.21–0.26)	27.9	Evaporator pump motor
30	26	0.23 (0.21–0.25)	11.6	Transformer
37	36	0.21 (0.19–0.23)	3.4	Infrared oven
56	33	0.20 (0.19–0.21)	99.2	Electric heaters
52	20	0.19 (0.18–0.21)	5.1	Ammonia condenser control
31	26	0.19 (0.18–0.21)	4.3	Refrigeration compressor
44	27	0.19 (0.18–0.21)	0.9	Electrical service panel
25	33	0.19 (0.17–0.21)	24.7	Mixer motor
60	20	0.19 (0.18–0.20)	24.5	Transformer
23	28	0.18 (0.15–0.21)	7.4	Slicer
57	33	0.17 (0.16–0.18)	25.1	20 HP pump motor
4	33	0.17 (0.14–0.20)	69.2	Electric heater
48	20	0.17 (0.16–0.18)	1.3	Vortex mixer
47	28	0.17 (0.15–0.18)	36.9	DC rectifier
54	23	0.15 (0.14–0.16)	31.7	Hand-held fabric cutter
3	33	0.14 (0.13–0.17)	18.5	Extrusion drive motor
24	28	0.14 (0.14–0.15)	33.4	Electroplater
59	38	0.14 (0.14–0.15)	15.1	Transformer
14	29	0.14 (0.13–0.15)	25.1	Electric heater
5	33	0.14 (0.12–0.15)	4.4	Compressor motor
51	32	0.14 (0.12–0.15)	2.5	20 HP drive motor
33	26	0.13 (0.12–0.15)	10.6	25 A drive motor
9	33	0.13 (0.11–0.14)	42.4	Transformer
15	29	0.12 (0.11–0.13)	25.7	Processing pump motor
53	28	0.12 (0.10–0.14)	10.9	Batch mixer motor
36	32	0.11 (0.11–0.12)	39.9	Pump motor
13	26	0.11 (0.11–0.12)	3.8	Electric oven
2	33	0.11 (0.10–0.12)	26.8	7.5 HP mixer motor
55	30	0.11 (0.10–0.11)	2.8	50 HP induction motor
29	28	0.11 (0.10–0.12)	32.1	Heated press
62	33	0.10 (0.08–0.12)	11.9	Transformer
10	26	0.10 (0.09–0.11)	6.5	Halogen inspection lamp
16	29	0.09 (0.08–0.10)	65.2	4160 V induction motor
42	33	0.09 (0.08–0.10)	10.6	TIG welding station
46	30	0.09 (0.08–0.10)	7.6	Chart recorder
28	28	0.07 (0.07–0.08)	2.7	Solenoid
22	28	0.07 (0.07–0.08)	3.3	Hydrocarbon analyser
40	33	0.07 (0.06–0.08)	532.4	Box style induction furnace
1	33	0.07 (0.06–0.08)	1.6	125 HP drive motor
32	26	0.07 (0.06–0.08)	5.9	Coiling line drive motor
6	33	0.07 (0.06–0.08)	28.7	Dust collection fan motor
21	28	0.07 (0.06–0.07)	1.5	Dryer motor
34	26	0.06 (0.05–0.07)	6.1	25 HP drive motor
18	28	0.06 (0.05–0.07)	1.4	Electronic scale
27	28	0.05 (0.05–0.06)	8.1	Steam boiler motor
50	20	0.04 (0.03–0.04)	8.2	Transformer

(Continued on next page)

Table 2. (continued)

Facility ID	Industry (two-digit SIC)	Magnetic field metrics (μT)		Highest magnitude source (measured 0.3 m from source)
		GM (95% C.I.)	Hi-5	
Summary statistics:		N=62		
	Arithmetic mean	0.22	46.8	
	Geometric mean	0.16	16.7	
	GSD (unitless)	2.08	4.14	
	Minimum	0.04	0.9	
	10th percentile	0.07	1.5	
	25th	0.10	6.1	
	50th (median)	0.15	20.5	
	75th	0.25	36.9	
	90th	0.43	93.4	
	Maximum	1.61	532.4	

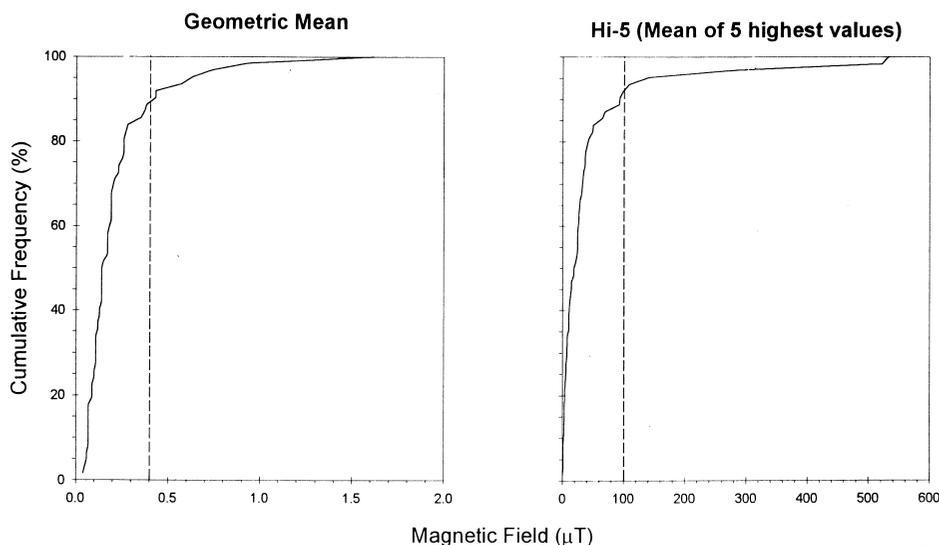


Fig. 1. Cumulative distributions of GM and Hi-5 magnetic fields showing our proposed 90th percentile cut-points for further exposure measurements.

The surveillance data presented here can be compared with other MF exposure assessments in industrial facilities (Table 4). These studies all took personal measurements, mainly in a few facilities that were part of epidemiologic studies. Magnetic field surveillance over a wider sample of industrial facilities was undertaken initially for electric utilities (Bracken, 1990), but surveys of general industry have been attempted as well (Skotte, 1994). In Table 4, personal MF data reported by these industrial studies (office work excluded) have been re-analysed to obtain central-tendency metrics such as the GM of TWAs, which are roughly comparable to the walkthrough GM. With the exception of the high exposure jobs from Skotte (1994), the central tendencies from the personal monitoring studies fall within the range of the facility-specific GMs from our walkthrough surveys (Fig. 1 and Table 2).

Facility-specific electric power consumption (Fig. 2) was found to be a poor predictor of the average facility MF magnitude. The reliability of this conclusion is limited by the non-random selection of industrial facilities, focusing on the industrial categories with the highest electric consumption. This relationship was also examined in a survey at three paper mills (Barroetovena *et al.*, 1994). Although the raw data suggest a correlation between MFs and a mill's power usage, the paper workers spent less time in areas with strong fields. We have also noted cases where industrial employees seldom worked by equipment with heavy power consumption and high MFs, for example power panels and large, noisy motors. In addition, MF correlation with power usage is weak in residences (Kaune *et al.*, 1987). These poor correlations can be explained by the complicated relationship between electric power and MFs, which is

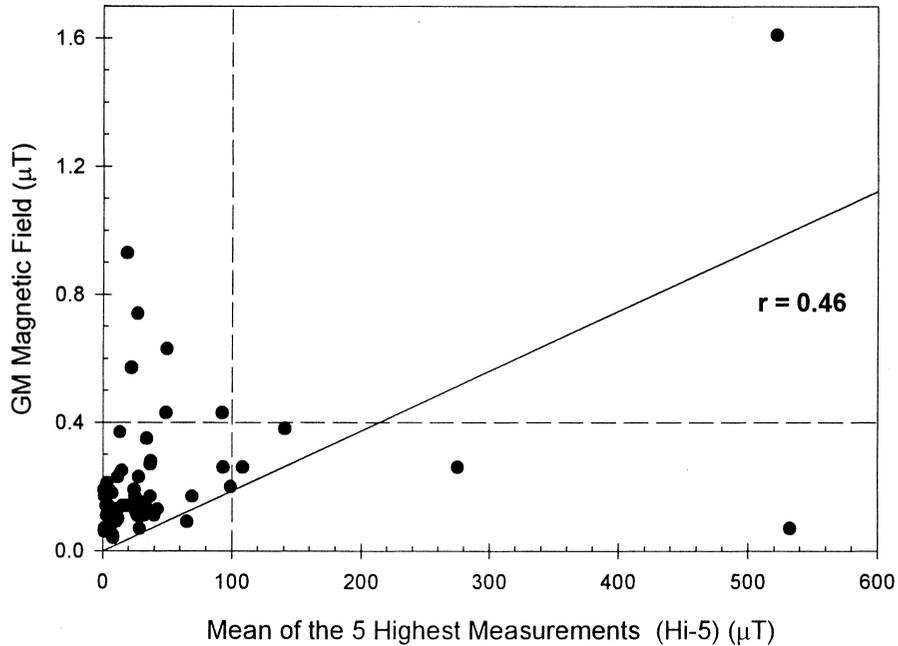


Fig. 2. Geometric mean (GM) magnetic field magnitudes compared with the average of the five highest measurements (Hi-5).

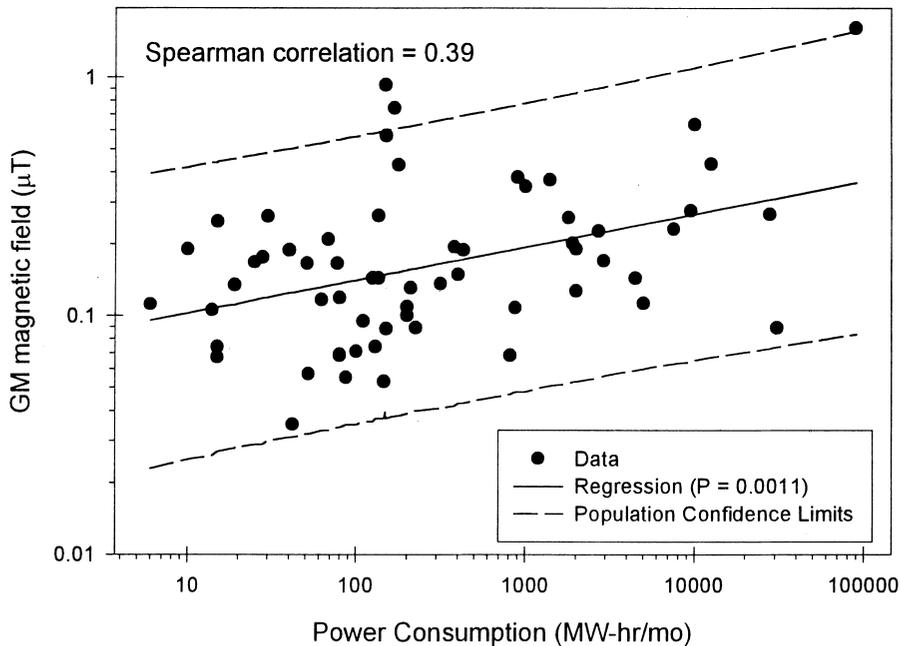


Fig. 3. Facility power consumption versus the GM magnetic fields with a log-transformed linear regression.

strongly modified by the source's voltage and wiring configuration.

Industrial categories represented by the SIC codes also did not prove to be a good predictor of facilities with high levels of MFs (Fig. 3). This was most likely due to the wide variation in industrial processes and source types within and across the small number of

facilities sampled. These conclusions are tentative because the selection of facilities for the survey was not random and systematic with only one facility sampled for some industries. Therefore, the results obtained are not a representative sample of an industry as a whole and should be interpreted with some caution.

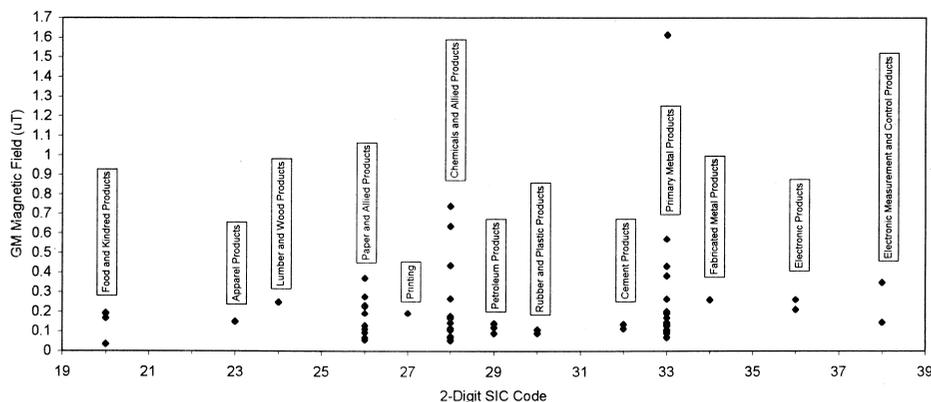


Fig. 4. GM magnetic fields by industrial categories (two-digit SIC).

Table 3. Means of the GM magnetic field metric by industry

Industry (two-digit SIC)	N	GM magnetic field metric (μT)	
		Geometric mean	95% C.I.
38	2	0.23	(0.03–0.43)
36	2	0.23	(0.18–0.28)
34	1	0.26	–
33	18	0.18	(0.01–0.35)
32	2	0.12	(0.10–0.15)
30	2	0.10	(0.09–0.12)
29	3	0.11	(0.09–0.14)
28	15	0.17	(0.03–0.31)
27	1	0.19	–
26	10	0.15	(0.04–0.26)
24	1	0.25	–
23	1	0.15	–
20	4	0.12	(0.05–0.19)
All	62	0.16	(0.04–0.69)

Given the failure of power usage and SICs to explain substantial portions of the variability of MFs, other explanatory variables should be investigated. One MF predictor that appears feasible for industrial settings is the source density (that is the number of pieces of electrical equipment per unit area of each facility).

The walkthrough sampling method provided a systematic method to rank industrial MF environments, which permitted surveys to be conducted in a wide variety of industries/facilities where MF levels have not been previously documented. Also, the survey collected important qualitative information about sources that helped explain the MF measurements. Another advantage was that workers could not influence the data collected (for example by placing the meter near electrical equipment). Also, the survey was easily conducted using only one sampling technician and did not appear to disturb workers or any production processes. Finally, the walkthrough survey

allowed all sources, processes and departments to be monitored for high potential exposure.

An important future goal would be to relate results from walkthrough surveys with personal measurements. However, this may be different because the GM and Hi-5 from walkthrough surveys cannot be compared directly with the TWA magnetic field magnitudes measured by personal monitoring. Another source of error for the walkthrough method is sources that operate intermittently (for example on/off duty cycle), thus varying the MFs over time. In addition, workers may move in and out of the MFs, thus varying their personal exposure. These limitations also make the walkthrough results difficult to compare with other MF exposure assessment and surveillance studies, which generally measure personal TWA exposures (Table 4). A possible solution to these problems would be to have workers wear EMDEXs for a partial or full work shift after the walkthrough method identifies areas with elevated ambient levels or sources. Kromhout *et al.* (1995) developed a method of mailing MF monitors to randomly selected workers which may be adapted to industrial surveillance.

In addition, this study collected little information about the number of workers potentially exposed because many workers move from area to area and do not regularly occupy a fixed workstation. In order to improve these walkthrough surveys, consideration should be given to recording the number of people working in each area.

Finally, the survey technique is also limited by the specifications of the EMDEX-II, which has a bandwidth of 40–800 Hz and a dynamic range from 0.01–530 μT and will not accurately record the magnitude of fields outside this range. Furthermore, the EMDEX-II meter only measures the RMS vector magnitude of the ELF magnetic field and not other field characteristics, potentially important to biology (Bowman *et al.*, 1995; Valberg, 1995). To characterize harmonic frequencies, high frequency transi-

Table 4. Summary of magnetic field exposures at industrial facilities (office work excluded)^a

Industry (SIC)	Study	No. of workdays	Central-tendency metric	Magnetic field (μ T)	
				Mean	(SD)
Semiconductor manufacturing (3674)	Abdollahzadeh <i>et al.</i> (1995)	192	AM of TWAs GM of TWAs ^b	0.566 0.475	(0.365)
Electric utilities (4911)	Bracken (1990)	2082	GM of TWAs	0.210	
Telecommunications (4813)	Breysse <i>et al.</i> (1994a, b)	204	GM of GMs AM of TWAs GM of TWAs ^b	0.161 0.323 0.225	(0.334)
Auto transmission manufacturing (3714)	Wenzl <i>et al.</i> (1997)	83	AM of medians ^b	0.188	(0.256)
Pulp and paper making (2611 and 2621)	Barroetovena <i>et al.</i> (1994)	132 ^c	GM of TWAs	0.16	
General industry	Skotte (1994)		Median of spot measurements GM of TWAs	0.16	
Normal exposure ^d		30		0.10	
High exposure ^e		24		6.00	

^aAM = arithmetic mean, SD = standard deviation, TWA = time - weighted average (AM over time).

^bEstimated from: $GM = AM^2 / (AM^2 + SD^2)$ which applies to log-normal distributions.

^cNumber of spot measurements. (Other studies used personal monitoring.)

^dAuto repair shop, plating shop, machine shop, laboratory, and telecommunications equipment manufacturing.

^eWelders, electric furnace workers, electricians in steel mill, electric railroad engineer, and spectrophotometer technician.

ents, and equipment operating at frequencies outside the range of the EMDEX instrument, a companion survey is needed with a waveform-capture instrument (see Bowman and Methner, 2000).

Given the above limitations, MF surveillance data cannot be used at the present time to guide exposure control efforts, the traditional role of hazard surveillance (Griefe *et al.*, 1995). Laboratory and/or epidemiologic studies have not yet determined hazardous levels of exposure or even the best dose measure (Portier and Wolfe, 1998). However, the surveillance data can identify MF sources, and provide guidance for the design and analysis of future epidemiologic studies.

CONCLUSIONS

The walkthrough sampling method was effective in accomplishing what was originally planned: developing a systematic method to rank industrial MF environments for future personal exposure monitoring and epidemiologic studies. For each facility, the ambient MFs were summarized by two statistics: the GM, which should be a predictor of average worker exposure across the facility, and the Hi-5, which is an indicator of potential exposures to peak levels. The MF levels obtained during the survey varied widely due to differences in processes and equipment that are often operated intermittently. The GM values were affected by the number of sources as well as their magnitude, and varied widely within all industries studied. The GM magnetic field did not correlate with either the facility's electric power consumption nor its industrial category (SIC code), so no simple surrogate currently exists for predicting MF exposures from industry-wide data sources. When walkthrough surveys are possible, the GM and the Hi-5 provide convenient rankings of the ambient MF levels in industrial facilities for planning future studies.

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