American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/aiha20

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To cite this article: Thurman B. Wenzl (1997) Estimating Magnetic Field Exposures of Rail Maintenance Workers, American Industrial Hygiene Association Journal, 58:9, 667-671, DOI: 10.1080/15428119791012478

To link to this article: http://dx.doi.org/10.1080/15428119791012478

Published online: 18 Jun 2010.

Estimating Magnetic Field Exposures of Rail Maintenance Workers

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A measurement survey was undertaken to estimate exposures to 25 hertz (Hz) magnetic fields of maintenance workers on electrified rail lines near Philadelphia, Pa. Because of the mix of frequencies expected, a strategy was developed using a new instrument to capture magnetic field waveforms, which were then analyzed by fast Fourier transform for their frequency components. This instrument could only take spot measurements, so a personal monitor repeatedly measured magnetic fields in the ranges of 40–1000 Hz. To power trains in the mid-Atlantic region, electrical current flows from the overhead catenary to the locomotive and returns through the rails in a loop up to 10 miles long. This flowing current was the primary source of the magnetic field exposures when a train was near the maintenance work site being measured. A total of 93 spot measurements was taken at five locations. Peak magnetic flux densities ranged from 34 to 185 milligauss (mG) near a transformer, while medians at the five locations ranged from 6.5 to 40 mG. Time-weighted average personal exposures were estimated by combining spot measurements at occupied locations, with estimates of how much time was spent at each location. These averages were estimated to lie between 3.0 and 18 mG, depending on the location and how often trains passed the work site. Comparisons between the spot measurements in the 40–1000 Hz frequency range and summaries from the personal dosimeter showed reasonably good agreement. Further characterization of personal exposures in this region may be justified, since on-train workers and passengers may be more highly exposed.

Keywords: electromagnetic fields (EMF), magnetic fields, rail workers

APPLIED STUDIES

The National Institute for Occupational Safety and Health (NIOSH) was asked to investigate whether there might be an association between cancer among rail maintenance workers on the Northeast Corridor (NEC) and their exposure to magnetic fields from the overhead electrical currents supplying the trains. As part of investigating the feasibility of an epidemiologic study, a measurement survey was undertaken to estimate the range of magnetic field exposures likely to be experienced by these workers. Their tasks include repair of the tracks, roadbed, and overhead wiring. The NEC includes the rail lines between Washington, D.C., and New Haven, Conn., where passenger trains are electrically powered from overhead catenaries.

Evidence of harm from exposures to these magnetic fields continues to be uncertain. Epidemiologic studies with exposure measurements of electric utility workers have shown mixed results, with some showing a weak dose-response effect[1] and others no effect.[2] Some preliminary studies of rail workers on electrified systems in Europe and Japan have suggested elevated risks for brain cancer or leukemia,[3–5] but others have found no such elevations.[6]

In this geographical region overhead catenary wires deliver 25-hertz (Hz) electrical current to power the passenger trains, while a railway signaling line carries 100-Hz current. Power frequency (60-Hz) current is often present as well, usually in high-voltage transmission lines suspended above the rail lines. Figure 1 shows an example of a cross-sectional view of the various electrical circuits that may be present above the tracks.

When a train is present, magnetic fields are

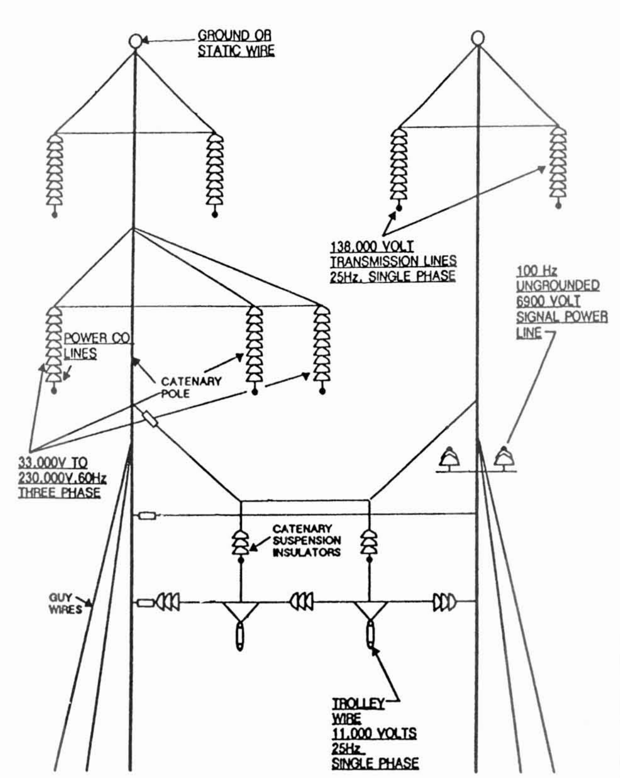

FIGURE 1. Example of wiring layout above tracks

generated by electric current flowing in two different but related circuits near the tracks. To power the train, 25-Hz current flows from the catenary to the train and returns through the rails, completing the circuit in a loop varying from 6 to 10 miles in length (Figure 2). Higher on the poles, other 25-Hz current flows continuously in the high-voltage transmission wiring, which supplies a much wider area.

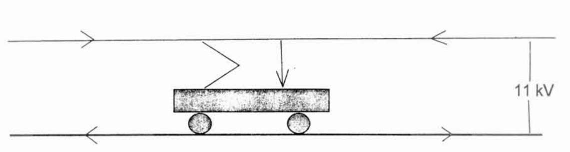

FIGURE 2. Catenary-rail loop, showing current flow when train is present

The goal of this survey was to estimate the range of magnetic field exposures of the maintenance workers at both 25 Hz and at higher frequencies. Additionally, frequency-specific spot measurements were compared with personal monitor measurements to learn how much information may have been lost by the frequency limits of the personal monitor, which responds poorly below 40 Hz.

METHODS

To measure 25-, 60-, and 100-Hz magnetic fields simultaneously, the Multiwave System II (Electric Research and Management Inc., State College, Pa.) was used for spot measurements. This instrument uses 3 orthogonal fluxgate sensors and was set up to capture 1024 sequential measurements in a single 0.2 sec interval each time a spot measurement was taken. Each of these recorded waveforms was then analyzed with fast Fourier transform (FFT) software to determine the different frequencies contained within that waveform. Such a complex device was needed because the more widely used personal magnetic field monitors with data loggers, developed for the studies of 60-Hz fields, do not respond accurately to fields below 40 Hz.

Spot measurement readings of 25- and 60-Hz magnetic flux densities were manually recorded from the Multiwave in the field, with notations on location and sources, including whether a train was nearby. The data were also stored and downloaded to diskettes at the conclusion of each measurement day. From these downloaded files, FFT analyses were carried out to evaluate all the frequency components making up the magnetic fields present. This instrument thus allowed the measurement of fields at the odd harmonic frequencies of 25 Hz (i.e., 75, 125, and 175 Hz), as well as 60 and 100 Hz.

Most measurements were taken at the waist height of someone working on or adjacent to the tracks. To reduce motion of the sensor, in most cases it was held against the waist while standing still each time a spot measurement was taken. This technique was necessary to reduce movement within the earth's static magnetic field, which this instrument can detect and interpret as a time-varying field. Readings were also taken at the operator's position on equipment where maintenance workers would typically work. These included a small crane, a modern track ballast-leveling machine, and a personnel lift elevated on a station platform to near catenary height (18 feet above the tracks).

Spot measurements (n = 93) were taken at five locations where a variety of typical rail maintenance activities were under way, and summaries are presented subdivided by location. At some locations the magnetic field exposure was measured for workers who were using modern maintenance equipment to level the track by adjusting and packing down the ballast under the ties. In other locations workers were using old technology, such as manually removing spikes with bars in preparation for replacement of rails and ties. Measurements were made in rural (n = 27) and urban (n = 56) settings, during high-traffic day (n = 41) and low-traffic (n = 52) night operations. The number of tracks in operation at any single location varied from 3 to 11. One location was not at the tracks, but nearby where a substation transformer was being rebuilt by members of this maintenance work force. Locations measured thus included sites where each of the track, electrical, and building maintenance crafts worked. As a result, a cross section was gained of the exposure patterns of rail maintenance workers in this region.

Personal monitoring of worker exposures was not attempted, because the frequency response of the available instruments was not appropriate to capture the expected 25-Hz fields. Also, the logistics and timing of the field visits prevented the distribution of personal monitors to the workers.

However, the industrial hygienist using the Multiwave did wear a small personal magnetic field monitor (Emdex Lite, Enertech Inc., Campbell, Calif.) while performing the spot measurements. Though this instrument could not accurately measure the 25-Hz fields, it could collect sequential readings more detailed than could the Multiwave. The personal monitor was set up to record three-axis measurements every 4 sec. These exposure data were downloaded, and average exposures were computed for each of the five work locations. This allowed the gathering of an independent and a much more dense collection of data on field strength between 40 and 1000 Hz. For example, at the last of the 5 locations, 22 spot measurements were taken, but 518 sequential Emdex measurements were recorded. Averages, medians, and ranges from this personal monitor, computed for each location visited, were then compared with the Multiwave results in the personal monitor's effective frequency range (40–1000 Hz). This was possible because the Multiwave's FFT software calculated flux densities at each multiple of 5 Hz (Figure 3), and these were then combined for that frequency range.

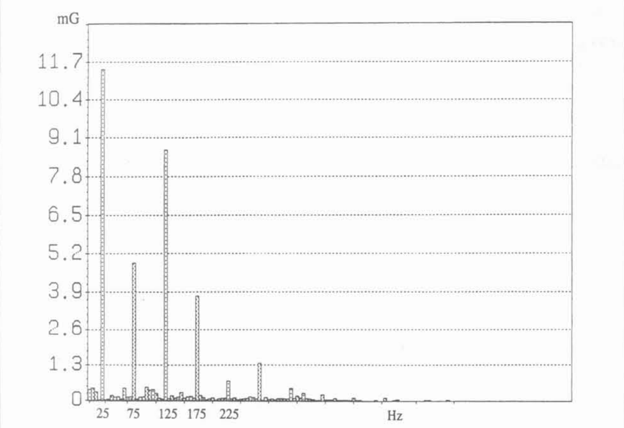

FIGURE 3. Example of a frequency spectrum available from FFT analysis

A limitation of this measurement strategy was that some of the specific measurement sites were chosen to estimate the broad range of possible exposures. So, some site selection was nonrandom and depended on expected exposure. To some extent, locations were more likely to have been measured if they were close to sources. Sometimes a measurement was taken because a train had passed by recently, which would have increased the current and thus the magnetic flux density. Therefore, the spot measurements could not be directly interpreted as either area averages or as personal exposures. Such a method would be biased toward higher values, since the data were not collected at a random sample of locations or of times of day. On the other hand, typical personal average exposures were estimated by making realistic judgments about how much time was usually spent by workers at various locations.

RESULTS

A total of 93 spot measurements was made with the Multiwave instrument at five rail maintenance work locations along the NEC in Maryland and Pennsylvania. The number of measurements taken at each general location ranged from 8 to 27, depending on the number of workers and the variety of tasks. The work underway included removal and replacing of rails, leveling of ballast under the ties, repair of a station platform, and rebuilding of a substation transformer.

Magnetic flux densities showed a wide range of values at 25 Hz, the principal frequency of the rail current present near the maintenance work sites. Figure 4 shows an example of a waveform captured by one of the single-axis fluxgate sensors at one spot measurement. Negative values appear because the sensor detected the direction as well as the magnitude of the field, and the earth's DC field was filtered out. These waveforms from each of the three orthogonal sensors were the input for the FFT software, which determined the frequency components present. Figure 3 shows an example of a frequency spectrum from this FFT analysis. In some cases relatively strong fields were detected at the odd harmonic frequencies of the expected 25-Hz fields (i.e., 75, 125, and 175 Hz).

Table I summarizes by location the 93 spot measurements

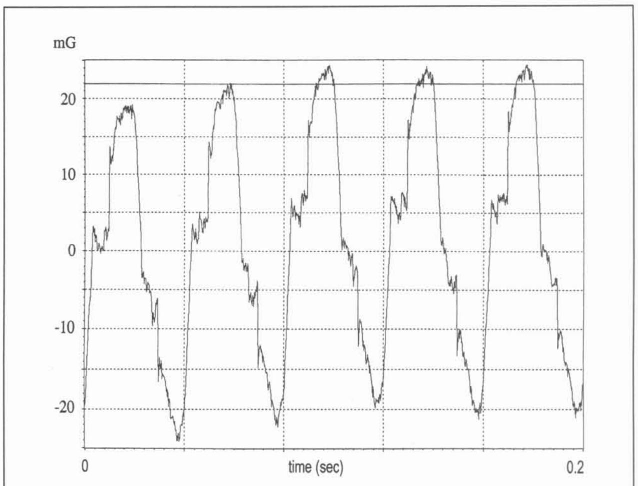

FIGURE 4. Example of a waveform captured by one fluxgate sensor

made with the Multiwave system. In each case the root-mean-squared magnitude of the magnetic field is reported for both 25-Hz and the extremely low frequency (ELF) range. Artifacts below 20 Hz, due to slight motion of the sensor in the earth's field, have been removed. Statistics were computed separately for each of the five locations visited, where measurements were taken at a variety of typical work sites. Medians and ranges are presented to summarize the variability, since the spot measurements were not taken randomly nor at evenly spaced intervals.

TABLE I: Spot Measurement Results for Magnetic Flux (MF) Density, from Multiwave System II

Location, Description	Number	Night (N)/ Day (D)	ELF MF Median (mG)	25-Hz Median (mG)	25-Hz Range (mG)
Rural, 3 tracks	27	N	28.8	16.7	4–185
Urban industrial, 4 tracks	14	N	24.9	22.3	9.1–34.3
Urban, large station, 11 tracks	22	D	8.15	6.54	1.5–69.8
Urban power substation	8	D	43.2	40.3	3.7–178
Urban, 6 tracks	22	D	22.6	16.7	6.2–72.1

Magnetic flux densities exhibited both temporal and spatial variability. Temporal variability was influenced by the presence or absence of trains, since the catenary-rail loop carries current only when a train is nearby. This loop varies from 6 to 10 miles in length. For example, at one rural track location, 25-Hz fields with intensity of 12 mG increased to 80 mG as a train approached. The term "background exposure" will be used here to refer to those exposures that do not depend on the presence of a nearby train; these varied from 1.5 to 12 mG at typical work locations.

Spatial variability in field strength was also present. At most work sites, exposures varied greatly depending on distance from a source. At the substation, where field strength was very high close to a transformer, the intensity decreased to background levels within 20 feet. The highest 25-Hz fields behind the large passenger station were near a circuit breaker on the line supplying power to a catenary wire. Locations with transmission lines sharing the catenary poles had a relatively steady 60-Hz component, while exposures varied more at locations where only rail power was present.

The full-shift average exposures for the maintenance workers were estimated by combining spot measurements of magnetic flux density at typical locations with the approximate time a worker might spend at each site (Table II). Site A and B background levels, with no train nearby, were chosen to be representative of magnetic fields at the most commonly occupied work sites. These background exposures may include both 25- and 60-Hz components, depending on which types of transmission lines are present. Passenger train schedules were used to estimate the approximate number of briefly elevated exposures that would result from the increased current flow in the catenary each time a train passed. (On these lines freight is pulled only by diesel locomotives, though electric freight locomotives were used in the past.) Typical exposure values were selected for this calculation based on measurements at those locations observed to be most commonly occupied by maintenance workers. Most measured peak values (from Table I) were not chosen since some of those were taken at locations rarely occupied by a maintenance worker.

TABLE II: Example: Estimating Full-Shift Personal Exposure from Spot Measurements and Approximate Durations of Work Activity

Location/Source	Exposure[A] (mG)	Duration (hr)	Product (mG/hr)
Site A (background)	4	5	20
Site B (background)	12	2	24
10 Trains passing for 6 min each[B]	50	1	50
Total		8	94

[A]Estimated average exposure: 94/8 = 11.8 mG
[B]When a train is near the work site, current is flowing in the catenary-rail loop (6–10 miles long), increasing work site magnetic field exposure substantially.

By varying the estimates for durations, measured exposures, and frequency of trains passing, the calculated full-shift averages were estimated to lie typically between 3 and 18 mG. Occasionally, exposures might be above this range for locations with high background levels from transmission lines, or with very many trains passing on that day. The 60-Hz component of the total exposure may be somewhat larger at those locations where utility company transmission lines are suspended on the catenary poles.

Since one investigator carried a small personal monitor to measure fields continuously between 40 and 1000 Hz, the more detailed measurements allowed the computation of average 40–1000 Hz exposures for the time spent by NIOSH investigators at each of the five locations. The Emdex averages ranged from 3.4 to 17 mG and agreed reasonably well with the summaries of the Multiwave measurements (Table III) at the comparable frequencies (above 40 Hz). The maxima from the two instruments did not correspond exactly, since the spot measurements (each with duration 0.2 sec) may have come between the Emdex measurements, which were automatically taken every 4 sec. The response of the Emdex personal monitor is also not entirely flat across its frequency range, dropping off at the lower and higher ends of the range.

Flux densities specifically at 60 Hz varied much less, since the major source was transmission lines suspended above the rail circuits on the same poles (Figure 1). Magnetic fields at 100 Hz were generally found to be very weak with occasional peaks. This is consistent with the use of 100 Hz only for communications and signaling. Table IV presents summaries of these magnetic fields. As

TABLE III: Comparison of Multiwave Spot Measurements to Emdex (Personal Monitoring) Results

Location	Emdex[A] Duration (min)	Emdex Median (mG)	Emdex Average (mG)	Emdex Range (mG)	Multiwave 40–1000 Hz Median (mG)	Multiwave 40–1000 Hz Range (mG)
Rural	40	18.2	16.7	1.9–43.5	20.2	2.7–46.2
Industrial	25	7.3	7.9	3.4–12.9	9.87	6.5–21.8
Passenger station	81	2.6	3.4	0.8–21.8	4.56	1.4–12.6
Electrical substation	33	6.6	11.4	1.6–105	11.6	2.3–50.6
Urban	66	12.6	13.1	7.6–49.2	13.0	9.6–21.3

[A]Effective frequency range of this magnetic field dosimeter: 40–1000 Hz

expected, the highest and most consistent 60-Hz fields were found where 60-Hz transmission lines were on the catenary poles (at the industrial and urban locations).

TABLE IV: Magnetic Flux Densities at 60 and 100 Hz from Multiwave Spot Measurements (mG)

Location	60 Hz Median (Range)	100 Hz Median (Range)
Rural	0.62 (0.18–1.1)	0.96 (0.18–2.4)
Industrial	6.8 (5.1–8.6)	0.61 (0.13–3.2)
Passenger station	0.87 (0.15–5.3)	0.91 (0.03–10.7)
Electrical substation	4.4 (1.7–22)	0.18 (0.05–1.62)
Urban	8.9 (7.8–13.8)	0.91 (0.49–5.9)

In addition to fields at these expected frequencies, spectra from the FFT analyses showed that fields were present at various odd harmonics of the dominant 25-Hz frequency, for example at 75, 125, and 175 Hz. Figure 3 is an example of such a spectrum for one of the three axes during a single spot measurement.

The falloff in field strength with distance from the source was rapid, and source strength varied, depending on whether the principal source was transmission or catenary current. In the rural work site visited at night, this transmission background exposure was about 5 mG. In one urban work location, it reached 25 mG during the day, showing a much greater influence of transmission currents in that location.

DISCUSSION

Magnetic field exposures for these rail maintenance workers are somewhat elevated compared with those of other workers, with time-weighted averages estimated to range between 3 and 18 mG based on measured magnetic fields at typical locations. These values are in the same range as those of some electric utility workers. One report of utility cable splicers' average exposures showed a skewed distribution with geometric mean of 4 mG and arithmetic mean of 15 mG.[7] These rail workers are exposed to a wider range of frequencies (including the odd harmonics of 25 Hz), while the utility workers were primarily exposed to 60-Hz fields.

These rail maintenance estimates can also be compared with average exposures among the general population, which were estimated from the nonwork exposures of another group of utility workers.[8] That survey reported a median of 0.7 mG and the 75th percentile of average daily exposures to be about 1.3 mG. In a case control study's exposure measurement survey across many Swedish industries, 90% of the workers had average exposures below 4 mG.[9]

Rail workers on board the trains may have higher personal exposures to magnetic fields than those maintaining the tracks, based on similar measurements on passenger trains in this same region. Other investigators have taken evenly spaced consecutive measurements on NEC trains and found average exposures at 25 Hz in passenger cars between 110 and 130 mG.[10] This suggests that conductors' average personal exposures may also be in this range. Also, based on 40 min of repeat measurements in an electric locomotive, engineers' exposures averaged about 35 mG.[10] In a brief NIOSH pilot study on the 60-Hz portion of the NEC, a personal dosimeter found average exposures in passenger cars between 14 and 44 mG for trips varying from 37 to 67 min. These higher values are consistent with the principles of magnetic field generation. On-train workers and passengers are always in the energized catenary-rail loop, while the maintenance workers are close to this energized circuit only when a train is nearby.

Swedish investigators have recently carried out personal dosimetry on board electrified locomotives, using a modified instrument believed to be accurate at the 16.67-Hz frequency used there.[11] They found average exposures in newer locomotives to be between 20 and 30 mG, but these results may have been influenced by the motion through the earth's field.

Recommendations

Further estimation of personal exposures is needed for electrified rail systems, since surveys have so far been incomplete. Since new personal monitors have become available to measure fields below 40 Hz, improved description of rail exposures is now possible.[11] If on-train exposures can be more completely described, it may be possible to make progress with magnetic field epidemiology by studying the large populations of rail passengers.

Acknowledgments

William Murray, Christopher Reh, and Paul Mills are to be thanked for their assistance in the planning and carrying out of these measurements. Furthermore, employees of Amtrak, the Federal Railway Administration, and the Brotherhood of Maintenance of Way Employees assisted with gaining safe access to active work sites. William Gish of Electric Research and Management Inc. was very helpful in assisting with the operation of the Multiwave instrument and software.

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