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Integrated Job Exposure Matrix for Electric Utility Workers

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EPRI Project Manager
R. Kavet

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

T. Dan Bracken, Inc

Robert M. Patterson

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CITATIONS

This report was prepared by

T. Dan Bracken, Inc.
P. O. Box 82695
Portland, Oregon 97282

Principal Investigator
T. D. Bracken

Robert M. Patterson
2031 Rittenhouse Square
Philadelphia, PA 19103

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PRODUCT DESCRIPTION

Results and Findings

This report identifies and includes all exposure factors in a prototype job-exposure matrix (JEM) to inform utility professionals, exposure assessment experts, and epidemiologists about exposures other than electric and magnetic fields that should be considered when assessing health and safety issues related to work near electric facilities. The nature of exposures to these factors, the ordinal exposure ranking for most of the factors, and the methodology for establishing such determining ordinal exposure levels should prove useful to those designing and conducting exposure assessments in electrical environments.

Challenges and Objectives

The report will enable industrial hygienists in electric utility companies to identify electromagnetic field (EMF) -related exposures that workers could encounter, based on their job description. Therefore, the report should interest those engaged in health and safety programs across a company.

Applications, Value, and Use

The approach and structure of this JEM can provide guidance on future exposure assessments and epidemiological studies in the electric utility and other industries. Furthermore, the information presented in this report can be folded into a comprehensive JEM for the utility industry that also includes chemical exposures and physical factors such as heat, noise, and vibration.

EPRI Perspective

This project developed a prototype job-exposure matrix that addresses exposure to all EMF factors, that is, electric fields, magnetic fields, nuisance shocks, contact currents, and electrical injuries. Although past studies have examined electric and/or magnetic field exposures, this is the first attempt to incorporate all EMF factors into an exposure matrix.

Approach

The objective of this investigation was to develop a prototype integrated JEM for electric utility workers that includes all electrical factors related to power-frequency currents and voltages found in electric utility work places. These factors consist of 60-Hz magnetic fields, 60-Hz electric fields, perceivable nuisance shocks, imperceptible contact currents, and electrical injuries (flash burns and electric shock/electrocution) and are referred to as *EMF factors*. Although exposure information for some EMF factors is incomplete, the development of a JEM that includes all of these factors can provide guidance on the design of future epidemiology studies of electric utility workers and beyond to workers in other industries with these exposures.

Keywords
Exposure assessment
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ABSTRACT

Electric utility workers may be exposed to any combination of magnetic fields, electric fields, nuisance shocks (from spark discharges and continuous currents), imperceptible contact currents, and electrical injuries. Collectively these exposures are referred to as "EMF Factors." Previous occupational exposure assessments have mainly characterized the magnetic field with less attention to the electric field. Nuisance shocks and electrical injuries, though palpable, have received little to no attention. This paper presents a prototype job-exposure-matrix that addresses exposure to all EMF Factors taking into account job category, primary work environment and occupied environment. Exposures for all factors were classified into three ordinal levels for 22 job categories. Electric and magnetic field exposures were classified by the geometric mean of daily average of personal exposure measurements. Although relatively sparse, survey data on nuisance shocks were adequate for exposure assignment by job category and indicate that the frequency of these exposures has diminished over time. The least information was available for imperceptible contact currents that are associated with electric-field exposures and small contact voltages. Data for electrical injuries by job category were derived from the Electric Power Research Institute Occupational Health & Safety Database with exposure assignments based on combined injury rates for flash burn and electric-shock/electrocution. The highest exposures for all EMF Factors are essentially limited to four job categories that work on or close to electrical equipment: cable splicers, electricians, line workers, and substation operators.

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INTRODUCTION

Electric utility workers experience exposure to electrical factors associated with the generation, transmission, distribution and use of electricity. Exposure assessments and epidemiological studies in the last two decades have developed job exposure matrices (JEM) for power-frequency magnetic fields and, to a lesser extent, electric fields for workers in electric utilities and in other industries.[1-8] The studies have commonly used job description as a surrogate for exposure.

Our objective was to develop an integrated JEM for electric-utility workers that includes 50/60-Hz magnetic fields, 50/60-Hz electric fields, perceivable nuisance shocks, imperceptible contact currents and electrical injuries (flash burns that result from electric arcs, electric shocks and electrocution). Collectively we call these "EMF Factors." Except for electrical injuries, no direct link has been established between these exposures and acute or chronic health outcomes. The JEM is intended to guide future epidemiology studies of electric utility workers, and of workers in other industries with similar exposures.

Appendix A describes surveys conducted to establish nuisance shock exposures among workers. Appendix B describes the clustering process to assign EMF factor exposures to job categories and compares the results when applied to different PE data sets.

2 JOB RELATED MATRIX ELEMENTS

Job Classifications

Job classification schemes linking job titles to magnetic- and electric-field exposure status have been developed for numerous exposure assessments and epidemiological studies. We evaluated four such classification schemes used for assigning magnetic-field exposures to US utility workers.[2, 3, 5, 9] A mortality study of a 5-utility cohort consolidated all jobs in the utility industry into 28 categories.[2] The result was a system that included workers involved in operation of the electrical system and non-operational personnel common to any large industry. Similarly a job classification scheme consisting of 20 job categories was developed for a cohort of employees at Southern California Edison (SCE).[3] The categories in the SCE study were drawn mainly from craft occupations in the work environments of generation, substations, transmission and distribution systems, and office personnel. A large scale exposure assessment of workers from 52 US and 3 foreign utilities – the Electric Power Research Institute (EPRI) EMDEX Study – used a job classification scheme with 13 job categories based on the primary work environment.[5] Finally, the EPRI Occupational Health Surveillance database (OHSD), which contains historical and contemporary injury rates for electrical and other injuries for employees in 16 US utilities, adopted the SCE classifications scheme with slight modification.[9, 10]

We employed the OHSD scheme with slight additional modifications because of its compatibility with job categories in studies with personal exposure (PE) data for electric and magnetic fields, the availability of shock data in the OHSD, and the ongoing maintenance of the OHSD as an active surveillance effort. Injury data have been collected annually since 1995, with 16 EPRI member utilities contributing data as of 2007. The resulting 22 OHSD job categories for the integrated JEM are listed in Table 2-1 along with sample job titles per category and the corresponding categories from the EMDEX Study.

Work Environments

The Primary Work Environment (PWE) is the principal work area or industry sector for a job category. The utility work environments having exposures to EMF Factors include: generation, transmission, substation, and distribution. Other PWEs are shop and office. Previous analyses of four large data sets indicated that PWE was a principal source of magnetic field PE variability within job category.[11] Furthermore, work location was cited as an important variable in assigning electric- and magnetic-field exposures in a Canadian epidemiology study.[8]

The Occupied Environment (OCCENV) is the actual environment(s) occupied by a worker during a day. The OCCENVs categories are identical to the PWEs. Workers with the same PWE but different job titles may distribute their time differently among OCCENVs.

Specific tasks, locations or work practices, such as climbing a transmission-line tower, can significantly increase exposures for both magnetic and electric fields. These peak exposures generally apply to a small number of workers for limited time periods and require description beyond PWE and/or OCCENV.

Table 2-1
Job Categories for Integrated Utility-Worker Job Exposure Matrix

Code	JEM Job Category	Sample Job Titles	Corresponding EMDEX Study Job Category
1	Administrative Support	Administrative Assistant, Secretary, Clerk, Computer Operator, Data Entry, Electronic Records, Receptionist, Sales Clerk	Clerical
2	Cable Splicers	Cableman, Cable Locator, Cable Splicer,	Electric power line installers with PWE = GEN, DIST, SUB
3	Coordinators	Coordinator, Planner, Scheduler	Professional and Technical
4	Custodians/Cooks/ Security	Attendant, Custodian, Gardener, Janitor, Fire Protection Specialist, Guard, Security Officer, Police Officer	Support services
5	Drivers/Deliverers/ Inspectors	Deliveryman, Driver, Inspector, Messenger, Truck Operator	Drivers and equipment operators
6	Electricians	Electrician, Electric Equipment Tester, Nuclear Electrician	Electricians
7	Engineers	Engineer, Chemical Engineer, Civil Engineer, Electrical Engineer, Mechanical Engineer, Nuclear Engineer, System Engineer	Professional and Technical
8	Foreman	Foreman, Superintendant (accompanies work crew)	Managers and Supervisors with PWE = GEN, TRANS, DIST, SUB
9	Line Workers	Aerial Lineman, Groundman, Lineman, Line Locator, Line Technician, Line Mechanic, Switchman, Tester and Installer	Electric power line installers
10	Machinists	Machinist, Nuclear Machinist, Machinist Welder, Machinist Mechanic	Other construction, field and craft occupations
11	Maintenance Workers	Building Services, Carpenter, Laborer, Repairman, Troubleperson, Painter, Pipefitter, Utilityperson, Yardman	Other construction, field and craft occupations
12	Managers	Manager, Treasurer, Comptroller, CEO, President, Program Manager	Managers and supervisors with PWE = OFFICE

Table 2-1
Job Categories for Integrated Utility-Worker Job Exposure Matrix (continued)

13	Materials Handlers/ Porters	Deckhand, Dock Worker, Material Handler, Material Processor, Stock Handler, Storekeeper, Warehouseman	Other construction, field and craft occupations
14	Mechanics	Airplane Mechanic, Auto Mechanic, Boiler Mechanic, Control Mechanic, Fleet Mechanic, Mechanic,	Generation facility mechanics
15	Meter Readers	Meterman, Meter Mechanic, Meter Reader, Meter Tester, Meter Technician, Meter Specialist, Field Service Representative	Outside customer service
16	Other Technicians	Communications Technician, Chemical Technician, Lab Analyst, Lab Technician, Technical Specialist	Other construction, field and craft occupations
17	Plant and Equipment Operators (generation)	Condenser Operator, Control Center Operator, Heavy Equipment Operator, Nuclear Specialist, Plant Operator, System Operator,	Generation operators and inspectors
18	Representatives	Customer Assistant, Customer Service Analyst, Customer Sales Associate, Representative	Professional and Technical; Clerical
19	Substation Operators	Substation operators; substation inspectors	Substation operators
20	Supervisors	Chief, Crew Leader, Supervisor, Superintendent, Team Leader	Managers and supervisors with PWE = OFFICE, SHOP
21	Technical Professional Support	Accountant, Administrator, Appraiser, Biologist, Chemist, Ecologist, Graphic Designer, Industrial Hygienist, Nurse, Scientist, Web Master	Professional and Technical
22	Welders	Apprentice Welder, Welder, Welder-Mechanic, Welding Engineer	Welders

3
EMF FACTOR EXPOSURE LEVELS

General Characteristics

The data quality and sources that characterize exposure to the EMF Factors vary greatly in documentation, accuracy and uncertainty necessitating a range of analyses techniques to determine exposures across job categories. Magnetic-field, electric-field and electric-shock exposures are parametric variables analyzed with standard techniques. Nuisance shock data are very limited, consisting of line worker survey responses and anecdotal reports. Data for contact currents are entirely lacking, and exposures to this factor were based on the environments and conditions conducive to exposure.

Analyses were performed using the R statistics package, version 2.6.2 (http://www.R-project.org).[12] Statistics computed for each job category, PWE (if data available) and OCCENV (if data available) included the arithmetic and geometric mean and standard deviation, and a range of quantiles.

Analyses included tests for lognormality (Shapiro-Wilkes) and log-probability plots. It was apparent that the distributions for magnetic and electric-field exposure within job category tended toward lognormality and that the geometric mean of the distributions of both workday means and workday 95th percentiles were appropriate for summarizing, respectively, central tendency and elevated exposures. Magnetic- and electric-field PE data tend to be highly skewed with a few extremely high values, with arithmetic means for daily exposures that tend to be dominated by a few high measurements.

Electric field exposure data provide an additional complication. Conducting objects, including the human body, perturb the field making PE measurements of the unperturbed field impractical. The fields recorded at the body surface depend on the anatomical location of the PE meter, the worker's grounding and orientation with respect to the source and field uniformity. Such conversions involve considerable uncertainty.[13] Thus measurements can only be used to assign exposures in a relative rather than an absolute sense.

The diverse sources of data for the factors, the relative nature of electric field PE data, and the absence of quantitative data for nuisance shocks and contact currents prompted the use of an ordinal scale for ranking exposures to all five factors. Ordinal rankings are often used for classifying exposures in epidemiological studies, especially with uncertainties in estimating historical exposures. Exposures were characterized as Low (L), Medium (M), or High (H) by job category.

To develop the ordinal exposure levels for the parametric exposure variables, the geometric mean exposures by job category were sorted in ascending order and divided into three groups by a clustering procedure, the Partitioning Around Medoids (PAM) method found in the R package Cluster. The PAM method selects clusters that minimize the within-cluster distances among cluster members. The dividing points between clusters were determined by the mean of the center of adjacent clusters.

A peak exposure category was identified by task if there were measurements or other sources demonstrating circumstances of especially high exposures.

Magnetic fields

Power-frequency magnetic-field exposures in the electric utility and other industries vary widely and have been documented.[14] There is no agreement on what magnetic-field attribute or collection of attributes (magnitude, duration, phase, polarization, etc.) might be associated with health effects, if any. The magnetic-field exposure metrics selected for the JEM reflect the magnitude of the magnetic field experienced over three different temporal domains. Depending on the locations and tasks performed, *average* daily exposures can range from about 0.1 to above 1 μT; *elevated* exposures ((≥100s of μT) lasting from minutes to hours can occur while performing specific tasks; and *peak* exposures can exceed 10 mT over very short times (seconds to minutes) during very specialized tasks. The metrics selected for these time periods were computed from time-series PE data. The geometric mean of the average daily exposures within a job category served as the average metric and the geometric mean of the 95th percentiles of the daily measurements characterized elevated exposure. Peak exposures were ascertained from specific task- or location-related PE measurements.

Even within a single utility, exposure variability within and between workers in the same job category can be substantial. Consequently, many measurement days are preferable for characterizing exposures within job categories. Large data sets of time-series magnetic-field PE data were available from the SCE and EMDEX studies to produce quantitative exposure metrics for average, elevated and peak exposures in μT by job category.[3, 5] The magnetic-field and electric-field PE data collected during the EMDEX Study were used for exposure estimates in the JEM.

Magnetic field data from the EPRI EMDEX Study consist of 4411 days of measurements from 52 US and three foreign utilities.[5] Using the linkage between the EMDEX job categories and those used in the JEM shown in Table 2-1, the summary files for workday exposures were analyzed to develop statistical descriptors of central tendency and quantiles by job category. The default exposure metrics for a job category were computed from all days having at least 4 hours of data for that category. Summary metrics within job categories were also computed for workdays with a given PWE or OCCENV.

The geometric mean of the daily 95th percentiles was selected as the metric of elevated exposure. This descriptive statistic was also calculated within job categories when there were at least 20 days with at least 4 hours of data in selected PWEs and OCCENVs.

Previous analyses of the EMDEX Study magnetic- and electric-field exposure data demonstrated strong correlation between mean daily and mean 90th percentile daily exposures for individual work days and for job categories.[15] This suggested that an average exposure metric was sufficient to characterize both central tendency and elevated exposures. In fact, product-moment and rank-order correlation coefficients between the default average and elevated magnetic-field exposures by job category were greater than 0.99 and 0.95, respectively. Consequently, the ordinal rankings of the average exposure metrics were considered representative of those of the elevated exposure metrics. Only the former are shown in Table 3-1. Similar results were found for electric fields.

The PAM clustering process was applied to the magnetic-field exposures for OHSD job categories derived from EMDEX Study data. The resulting clusters of job categories for Low, Medium and High exposures are shown in Table 3-1. These clusters are compared in Section 5 with those generated when the exposures for the OHSD job categories are derived from other PE data sets.

Electric fields

Sixty-hertz electric-field exposure levels generally refer to the unperturbed field, i.e., the field without a worker present, and are expressed in units of V/m or kV/m. Electric fields in utility workplaces may range from 10 V/m or less in office settings, to 10 kV/m or more on the ground in substations and under transmission lines, and up to 30 kV/m at some work locations in 500- and 765-kV transmission-line towers.[16] Lower voltage transmission and distribution facilities have correspondingly lower electric-field exposure levels.

As with magnetic fields, there is no agreement on what, if any, electric-field attribute constitutes a potential risk to worker health. Consequently, the metrics for electric field exposure were determined the same as for magnetic fields.

Electric-field PE meters measure the field incident on the surface of the body. However, characterization of electric-field exposure is more complicated than for magnetic fields, because the human body perturbs the electric field, and acts as a shield if the body is between the meter and the electric-field source. For example, in a uniform vertical field the field at the top of the head will be increased about 18 times the unperturbed value, while fields at the arm will be enhanced by about 8 times.[17] Also, the exposure level registered on a PE meter depends on the grounding status of the wearer: The surface field is higher on a grounded person than on one who is insulated from ground.

Thus, the field measured at the PE meter is affected by factors other than the magnitude of the unperturbed field. Consequently, the field measured as a worker moves about is not a constant multiple of the unperturbed field, and it cannot be linked to an absolute exposure value in V/m or kV/m. Therefore comparisons between electric-field PE measurements are considered relative with the assumption that the effects of meter location, posture and orientation average out equally over all subjects during the course of activities. Normal variability of electric fields in the workplace plus the variability added by the measurement process lead to considerable uncertainty in electric-field PE measurements. Thus, as with magnetic fields, it is desirable to have a large sample of PE data to characterize electric-field exposures within job categories.

Table 3-1
Average Daily Magnetic-Field Exposure by Job Category

Code	Job Category	GM of Daily Means, μT	Exposure Category
12	Managers	0.11	Low • 0.23 μT
20	Supervisors	0.11	
1	Administrative Support	0.12	
15	Meter Readers	0.14	
5	Drivers/Deliverers/Inspectors/Patrol	0.14	
18	Representatives	0.16	
10	Machinists	0.16	
3	Coordinators	0.17	
7	Engineers	0.17	
21	Technical/Professional Support	0.17	
11	Maintenance Workers	0.19	
13	Material Handlers	0.19	
16	Other Technicians	0.19	
4	Custodians/Cooks/Security	0.26	Medium • 0.51 μT
2	Cable Splicers	0.27	
22	Welders	0.28	
8	Foremen	0.29	
9	Line Workers	0.30	
14	Mechanics	0.34	
17	Plant Operators	0.37	
6	Electricians	0.54	High
19	Substation Operators	0.72	

The electric-field PE measurements in the EMDEX Study provided estimates of average and elevated exposures.[18] This data set contains 2082 days of electric-field PE data collected by a subset of the magnetic-field cohort. The same methodology described above for magnetic fields was used to rank average and elevated electric field exposures (Table 3-2)

Table 3-2
Average Daily Electric-Field Exposure by Job Category.

Code	Job Category	GM of Daily Mean[A], V/m	Exposure Category
20	Supervisors	3.4	Low • 6.1 V/m
12	Managers	3.4	
22	Welders	3.5	
14	Mechanics	4.6	
10	Machinists	4.8	
17	Plant Operators	5.2	
3	Coordinators	5.3	
7	Engineers	5.3	
21	Technical/Professional Support	5.3	
18	Representatives	5.4	
8	Foremen	5.5	
1	Administrative Support	5.6	
15	Meter Readers	6.3	Medium • 10.8 V/m
11	Maintenance Workers	6.8	
13	Material Handlers	6.8	
16	Other Technicians	6.8	
4	Security	6.9	
5	Drivers	9.4	
2	Cable Splicers	13.6	High
19	Substation Operators	14.9	
6	Electricians	14.9	
9	Line Workers	17.6	

[A] Note: Values are perturbed electric field measured at the waist. These are suitable only for establishing relative exposures.

Nuisance shocks

Nuisance shocks occur when a voltage difference exists between the worker and a contacted object. If the voltage is small but nonetheless large enough to cause the dielectric breakdown of air then a perceptible spark discharge can occur as contact is being made. The voltage difference can either be induced on an ungrounded object by an electric field or be due to a potential difference between the conductor and the subject. If contact is made either without breakdown or after breakdown occurs, then a continuous, perceptible or imperceptible, current flows. For our purpose, spark discharges and perceptible continuous currents are both considered nuisance shocks, since it is difficult to distinguish between the two when they occur. This choice limits the definition of contact-current exposures only to those continuous currents that are not perceived (discussed below).

Nuisance shocks have long been recognized as an unpleasant, and possibly adverse, effect that can occur near high voltage sources due to electric fields and in other utility environments where direct contact with low voltage conductors is possible. There have been evaluations of the thresholds for spark discharges in terms of charge transfer between object and person, unperturbed electric field, and voltage between object and person.[17, 19] For continuous current exposure, thresholds have been estimated for graded responses from relatively harmless perception, through aversion, to let-go inhibition, to cardiac fibrillation.[20] More recently results have been published of computations of dose to tissue in terms of the local electric field from exposure to spark discharges and continuous currents.[21, 22] The possibility of inadvertent physical responses to both spark-discharge and continuous-current nuisance shocks is recognized in electric-field exposure guidelines which advise limiting exposures to avoid such responses.[23-25]

Even with the recognition of potential adverse effects from nuisance shocks, only limited data characterizing the prevalence and severity of these shocks among utility workers are available. Line workers provided daily reports of the presence of nuisance shocks during an electric-field exposure assessment.[26] A more recent survey of workers' experiences with nuisance shocks was conducted as part of ongoing efforts to characterize electrical exposures in electric utility environments and to develop this JEM. In both these studies only perceivable shocks would have been reported and no distinction was made between spark discharges and continuous currents.

Nuisance-shock exposures for the JEM were based primarily on the results of these two limited surveys of primarily transmission and distribution line workers. Results of these surveys are discussed in Appendix A. Nuisance shocks in job categories absent from the two surveys were inferred from the work environments and electrical conditions necessary to produce exposure.

High, Medium and Low were assigned to the JEM job categories based on the two surveys and on possible access to low-voltage (< 600V) contacts. The latter determinant was based on knowledge of utility work environments and job titles within job category. High exposures were assigned to categories consistently reporting nuisance shocks in both surveys combined with work in high electric fields. Medium exposures were assigned to those categories that reported some nuisance shocks and/or worked in areas where they could encounter high electric fields or could access low voltages, such as on service wiring or in control cabinets. Low exposures were assigned to job categories representing workers who were very unlikely to enter environments with electric fields or unguarded low voltages. Categorizing nuisance shocks was necessarily less precise than for factors with PE measurements.

Contact currents

Like spark discharges, imperceptible continuous contact currents have long been recognized as present in the utility workplace either from induced currents or from touch voltages across the body. For this JEM, contact currents are defined as below the median perception level for adult males (between approximately 200 and 400 µA). Continuous currents above this level, but below the electric-shock level (roughly lower than 2 and 8 mA, depending on the individual), are classified as nuisance shocks because they are not likely to cause physical harm except through inadvertent movement, and because it would be difficult to distinguish them from annoying spark discharges. Interest in contact currents has increased because they are suggested to be an alternative explanation for the apparent association between childhood leukemia and residential magnetic-field levels.[27]

Electric-field induced currents are an important source of contact currents to utility workers, and likely the most prevalent. If a worker is ungrounded, current is induced within an exposed person and capacitively coupled currents to ground are distributed over the surface of the body. If the worker touches a grounded object then the induced current flows to ground as a contact current, which is referred to as the short-circuit current. The short circuit current for a 1.75-m person standing upright and grounded in a uniform vertical electric field is approximately 18 µA/(kV/m).[17] Peak electric fields found under high-voltage transmission lines range from a about 1 kV/m to above 10 kV/m depending on voltage. Such fields produce short-circuit currents of from 20 to 200 µA through the grounded extremity of an upright person. Larger induced currents for utility workers can occur when climbing towers.[16] At the high field levels found under higher voltage lines and on towers, it is likely that a spark discharge would occur before establishing contact with ground.

Another potential source of contact currents in the workplace is small voltage differences of less than a few volts between conductors or between a conductor and ground. Minimal data are available on the frequency of occurrence and intensity of contact-current exposures resulting from such sources. However, their prevalence is expected to be minimal because of the necessity for grounding in electrical facilities. Exploratory measurements of contact currents were performed with a sample of utility workers who did not work with energized equipment.[28] Results indicated that the majority of tested workers (68 of 76) experienced spark discharges but not contact currents. The average contact currents were small and well below perception thresholds: 10 µA for arm-to-arm currents and 26 µA for torso currents. Similar measurements of contact-current exposures among sewing machine operators suggested that exposure was more likely with poorly grounded equipment.[29]

Contact currents below perception levels are not easily measured or modeled. Exposure data for contact currents in utility workplaces are very sparse except for short-circuit current measurements in electric fields under and near transmission lines.[17, 26] Exposure to sub-perception contact currents of approximately 0.2 mA or less can occur in environments with contact voltages less than a few volts.[20] Sub-perception contact currents from higher voltage sources can occur if a high impedance pathway limits current and spark discharges are absent. These latter conditions arise from electric-field induced voltages on humans and objects, as well as from direct contacts with sources.

Thus, the presence of electric fields and/or access to small voltage differences between contact points determined whether a job category could be associated with contact-current exposure. High contact-current exposure rankings were assigned to job categories with high electric-field exposures and to welders (arc, not gas) because of their work with electrical equipment. For job categories without high electric-fields, Medium contact-current exposures were assigned to categories with Medium electric-field exposure and with access to low-voltage contacts. The lack of information about exposure sources and the absence of measurements made these assignments less certain than those for the other EMF Factors.

Electrical injuries (electrocution, electric shock, flash burns)

Electrical accidents that result in injury or death are rare among utility workers. But they can occur when a worker comes in contact with an energized conductor or when an electric fault causes a rise in voltage on an otherwise grounded piece of equipment. Exposure to an electric current can result in an injury or electrocution depending on the amount of current and its pathway through the body. Flash burns occur when a worker is burned by an electrical arc in close proximity to unprotected skin.[10] Data on electrical injuries to utility workers (1995-2006) are contained in the EPRI OHSD.[9]

For electrical injuries the data accumulated in the OHSD from 1995 to 2006 were analyzed. The database contains only lost-time and “recordable” injuries. The latter are defined by the Occupational Safety and Health Administration (OSHA) to include injuries that required medical attention or involved loss of consciousness.[9]

The number of flash burn and electric-shock/electrocution events in the data base is small (468) with about 40% flash burns and 60% electric shock/electrocution. To estimate the annual probability of an electrical injury the aggregated injury-rate data for flash burns and electric shock/electrocution by job category were used.

The injury rates for “recordable” events in the OHSD were small, ranging from 0 to ~35 injuries/10,000 employee-years across job categories. The average rate for all electric utility workers was ~5 injuries/10,000 employee-years. Thus, the probability of a worker experiencing an electrical injury during a year is very small: 5 out of 10,000 or 0.0005.

If direct interviews are not possible, one possible measure of exposure is the probability of experiencing an electric shock over a career. For such small annual rates, the probability of occurrence over n years in the same job category is approximately the product of n and the annual probability for that job category. For multiple job categories in a career, the probability of occurrence would be the sum of such products over all job categories.

The OHSD database does not include first-aid only or “record only” events: such events may involve an incident report but do not necessarily entail an injury.[9] Information on occurrence of these less severe shocks also may not be available through direct interviews or utility records at the worker level. For the purposes of the JEM these shocks, which may be above the nuisance level but not recorded in the OHSD, are conservatively assumed to be an electrical injury with the same relative rates of occurrence within job category as the more severe events recorded in the OHSD. This assumption allows generation of ordinal rankings that apply to all electrical injuries.

4
EMF FACTOR EXPOSURE BY JOB CATEGORY

Magnetic fields

The three ordinal exposure levels of Low, Medium and High for the default average magnetic-field metric based on all workdays are shown in Table 3-1. The levels for elevated exposures are approximately three times larger than the average levels. (Linear regression of the elevated-exposure against the average exposure yielded an offset of 0.07 µT and slope of 2.9 with $R^2 = 0.98$).

Average and elevated exposures were also computed for exposures associated with a job category and a PWE or OCCENV. These values were then compared with the default cutpoints to assess if presence in a PWE or OCCENV changed the exposure level from the default level for the job category.

Any adjustments to the default value associated with a PWE or OCCENV are indicated in the PWE or OCCENV columns of Table 4-1. A blank entry in a Job Category-PWE cell indicates there were insufficient data. As an example, the daily exposure of an engineer with a PWE of substation would increase from the default value of Low to High, while an electrician with a PWE of generation would drop from the default value of High to Medium.

Peak magnetic-field exposures occur during performance of live-line tasks on transmission and distribution lines and during tasks performed by cable splicers in network vaults.[30, 31]

Table 4-1
Average Magnetic-Field Exposure Rankings by Job Category, Primary Work Environment and Occupied Environment

Code	Job Category	Central Tendency Default	Primary Work Environment[A]				Occupied Environment[A]			
			GEN	TRNS	DIST	SUB	GEN	TRNS	DIST	SUB
1	Administrative support	Low								
2	Cable splicers[B]	Medium			0	0			0	+
3	Coordinators	Low	+			++	+			++
4	Custodians/Cooks/Security	Medium								
5	Drivers/deliverers/inspectors/ patrol	Low			0					
6	Electricians	High	-		0	0	0			0
7	Engineers	Low	+			++	+			++
8	Foreman	Medium	0		-	+	0			
9	Line workers[C]	Medium		0	0	0		+	0	+
10	Machinists	Low								
11	Maintenance workers	Low	+			+	+			++
12	Managers	Low								
13	Material handlers/porters	Low	+			+	+			++
14	Mechanics	Medium	0				0			
15	Meter readers	Low								
16	Other technicians	Low	+			+	+			++
17	Plant and equipment operators	Medium	0				0			
18	Representatives	Low	+			+	+			++
19	Substation operators	High				0				0
20	Supervisors	Low								
21	Technical/professional support	Low	+			++	+			++
22	Welders	Medium	0				0			

Key:

Symbol	Impact of PWE or OCCENV
0	No change from Default exposure level
-	Decrease of one exposure level from Default exposure
+	Increase of one exposure level from Default exposure
++	Increase of two exposure levels from Default exposure
Blank	No data for cell.

[A] GEN = Generation; TRNS = Transmission; DIST = Distribution; SUB = Substation
[B] Peak magnetic-field exposures for Cable splicers include tasks in network vaults.
[C] Peak magnetic-field exposures for Line workers include live-line work with bare-hand techniques on transmission lines and live-line work on distribution lines with rubber-glove techniques.

Electric fields

The electric field levels refer to the average local electric field measured at the waist and used to compare the relative magnitude of electric field exposure among job categories. They cannot be used for comparison with absolute unperturbed values such as those given in exposure guidelines.[21-23]

Default rank-ordered average perturbed electric-field exposures by job category with cutpoints are given in Table 4-2. This table also represents the ordinal exposure rankings for elevated exposures by job category.

The default ordinal rankings by job category and adjustments to the exposure rankings for job categories associated with a specific PWE or OCCENV are shown in Table 4-2. Default High exposures occur for workers in job categories associated with high electric-field environments: cable splicers in the distribution environment, line workers in the transmission and distribution environments, and electricians and substation operators in the substation environment. The influence of work PWE and OCCENV on electric-field exposures within job category is much less than on magnetic-field exposures. Only two job categories have changes in exposure associated with PWE or OCCENV: electricians' exposures decrease in the generation environment and foremen's exposures increase when in generation or substation environments.

Peak electric-field exposures occur for line workers working at or near minimum safe working distances from energized 500- and 765-kV conductors. For example, the unperturbed electric-field averaged over the body can reach 30 kV/m when climbing and/or working in 500- and 765-kV towers.[16] Peak electric-field exposures can presumably occur for electricians working on energized equipment in substations of these same voltage classes. However, the authors know of no computations or measurements characterizing unperturbed field exposures in such instances.

Table 4-2
Average Electric-Field Exposure Rankings by Job Category, Primary Work Environment and Occupied Environment

Code	Job Category	Central Tendency Default	Primary Work Environment[A]				Occupied Environment[A]			
			GEN	TRNS	DIST	SUB	GEN	TRNS	DIST	SUB
1	Administrative support	LOW								
2	Cable splicers	HIGH			0	0			0	
3	Coordinators	LOW	0				0			
4	Custodians/Cooks/Security	MEDIUM								
5	Drivers/deliverers/inspectors/ Patrol	MEDIUM								
6	Electricians	HIGH	-			0	-			0
7	Engineers	LOW	0				0			
8	Foremen	LOW	+			+	+			
9	Line workers [B]	HIGH		0	0	0		0	0	
10	Machinists	LOW								
11	Maintenance workers	MEDIUM					0			
12	Managers	LOW								
13	Material handlers/porters	MEDIUM					0			
14	Mechanics	LOW	0				0			
15	Meter readers	MEDIUM								
16	Other technicians	MEDIUM					0			
17	Plant and equipment operators	LOW	0				0			
18	Representatives	LOW	0				0			
19	Substation operators	HIGH				0				0
20	Supervisors	LOW								
21	Technical/professional support	LOW	0				0			
22	Welders	LOW								

Key:

Symbol	Impact of PWE or OCCENV
0	No change from Default exposure level
-	Decrease of one exposure level from Default exposure
+	Increase of one exposure level from Default exposure
++	Increase of two exposure levels from Default exposure
Blank	No data for cell.

[A] GEN = Generation; TRNS = Transmission; DIST = Distribution; SUB = Substation
[B] Peak electric field exposures for Line Workers include climbing and working on 500- and 765-kV towers.

Nuisance shocks

Nuisance-shock exposure levels assigned to the OHSD job categories are shown in Table 4-3 along with the three determinants used to estimate nuisance-shock exposures: survey responses, electric-field exposure, and possible access to low voltage contacts.

With a few exceptions the nuisance-shock exposures are in the same ordinal categories as electric-field exposures. The High exposure job categories all reported nuisance shocks in the surveys and have High electric-field exposure. Some job categories with Medium electric-field exposure were assigned Low nuisance-shock exposure because no information was available to support a higher exposure (e.g, maintenance workers and material handlers). Welders were assigned a Medium exposure for nuisance shocks to reflect their work with electrical equipment and their High reported rate of electrical injuries.

The occurrence of nuisance shocks has decreased over the last several decades due to changes in work practices and equipment, and an emphasis on safety (Appendix A). No adjustment has been made to account for this in assigning exposures. Instead it is assumed that there has been a uniform decrease in nuisance shocks across the workplace over time and that the relative exposure ratings among job categories have remained constant.

It is not possible to identify scenarios where peak exposure to nuisance shocks might occur. Specific conclusions about the location, frequency and severity of nuisance shocks for all job categories require more extensive and broad based data.

Table 4-3
Nuisance-Shock Exposure Rankings By Job Category

Code	Job Category	Exposure Determinants			Nuisance–shock Exposure[A]
		Survey Response	Electric-Field Exposure	Access to Low Voltage	
1	Administrative support		L		L
2	Cable splicers	Yes	H	Yes	H
3	Coordinators		L		L
4	Custodians/Cooks/Security		M		L
5	Drivers/deliverers/inspectors/patrol		M		L
6	Electricians	Yes	H	Yes	H
7	Engineers		L		L
8	Foreman[B]	Yes	L/M	Yes	M
9	Line workers	Yes	H	Yes	H
10	Machinists		L		L
11	Maintenance workers		M		L
12	Managers		L		L
13	Material handlers/porters		M		L
14	Mechanics		L		L
15	Meter readers	Yes	M	Yes	M
16	Other technicians		M	Yes	M
17	Plant and equipment operators		L	Yes	M
18	Representatives		L		L
19	Substation operators	Yes	H	Yes	H
20	Supervisors		L		L
21	Technical/professional support		L		L
22	Welders		L	Yes	M

[A] Exposure levels were estimated from utility-worker survey responses, electric field exposure, and possible access to low voltages.
[B] Foremen have Medium electric field exposures in generation and substation environments.

Contact currents

The estimated contact-current exposure by Job Category is shown in Table 4-4 along with the two primary determinants of exposure: electric-field exposure and possible access to low voltage contacts.

The exposure level for contact-currents was essentially determined by electric-field exposure with the exception of welders (arc, not gas), where their use of electrical equipment and possible access to low-voltage contacts increased their exposure to High. In other job categories, the possible access to low-voltage contacts was not considered sufficient to increase the contact-current exposure from that based on electric field alone.

There is insufficient knowledge about contact currents to identify peak exposure scenarios.

Electrical injuries (electrocution, electric shock, flash burns)

Electrical-injury rates by job category were derived from the OHSD and are shown in Table 4-5 as the annual probability of an electrical injury. The results were sorted by electrical-injury rate and ordinal exposures assigned through a cluster analysis. The exposure-level breakpoints were annual probabilities of 0.0007 for Low-to-Medium and 0.0024 for Medium-to-High. Line workers and welders were in the High exposure category with probabilities of occurrence of "recordable" electric shocks above 0.003/employee-year. Six job categories were in the Medium exposure category: foreman, maintenance, cable splicer, substation operator, electrician, and meter reader. These exposure levels are assumed to represent the probabilities of occurrence for all electrical injuries, including those not recorded in the OHSD.

The probabilities in Table 4-5 combined with years in a job category can be summed over all job categories to obtain the risk over an individual's career. The quantitative total probability of exposures can then be compared with other similarly constructed exposures to obtain ordinal exposures within a group of workers.

Table 4-4
Contact-Current Exposure Rankings by Job Category

Code	Job Category	Exposure Determinants		Contact-Current Exposure
		Electric Field	Access to Low Voltage	
1	Administrative support	L		L
2	Cable splicers	H	Yes	H
3	Coordinators	L		L
4	Custodians/Cooks/Security	M		M
5	Drivers/deliverers/inspectors/pa trol	M		M
6	Electricians	H	Yes	H
7	Engineers	L		L
8	Foreman	L/M	Yes	M
9	Line workers	H	Yes	H
10	Machinists	L		L
11	Maintenance workers	M		M
12	Managers	L		L
13	Material handlers/porters	M		M
14	Mechanics	L		L
15	Meter readers	M	Yes	M
16	Other technicians	M	Yes	M
17	Plant and equipment operators	L	Yes	L
18	Representatives	L		L
19	Substation operators	H	Yes	H
20	Supervisors	L		L
21	Technical/professional support	L		L
22	Welders	L	Yes	H

Table 4-5
Electrical-Injury Exposure Probabilities and Rankings by Job Category

Code	Job Category	Probability of Electric Injury[A], $\times 10^{-5}$	Relative Exposure Level
1	Administrative Support	1.8	L
2	Cable Splicer	128	M
3	Coordinators	17.6	L
4	Custodians/Cooks/Security	6.4	L
5	Drivers/Deliverers/Inspectors/Patrol	29.5	L
6	Electricians	172	M
7	Engineers	7.8	L
8	Foreman	109	M
9	Line Workers	302	H
10	Machinists	46.8	L
11	Maintenance Workers	119	M
12	Managers	0	L
13	Mechanics	44.1	L
14	Materials Handlers	0	L
15	Meter Readers	189	M
16	Other Technicians	56.7	L
17	Plant and Equipment Operators	47.4	L
18	Representatives	3.6	L
19	Substation Operator	161	M
20	Supervisors	12.8	L
21	Technical/Professional Support	6.2	L
22	Welders	355	H

[A] Probability is over one year period for a recordable electrical injury, including flashburns and electric-shock/electrocution.

Summary

Table 4-6 summarizes across all factors by job category. Only the default average exposure metrics are given for magnetic and electric-field exposures. The ordinal exposures for default elevated field exposures were the same as those for the average exposures except for the electric-field exposure for the Administrative Support job category. Adjustments to the default magnetic and electric-field exposures for PWE and OCCENV are given in Tables 4-1 and 4-2. With one exception, the High exposures for all EMF Factors were limited to four job categories that work on or very close to electrical equipment: cable splicer, electrician, line worker and substation operator. The exception was High contact-current and electric-shock exposures for welders.

Table 4-6
Exposure Rankings for All EMF Factors by Job Category

Code	Job Category	GM of Daily Means[A]		Nuisance Shocks	Contact Currents	Electric Shocks
		Magnetic Field	Electric Field			
1	Administrative support	L	L	L	L	L
2	Cable splicers	M^{+}	H	H	H	M
3	Coordinators	L^{++}	L	L	L	L
4	Custodians/Cooks/Security	M	M	L	M	L
5	Drivers/deliverers/inspectors/ patrol	L	M	L	M	L
6	Electricians	H^{-}	H^{-}	H	H	M
7	Engineers	L^{++}	L	L	L	L
8	Foremen	M^{+-}	L^{+}	M	M	M
9	Line workers	M^{+}	H	H	H	H
10	Machinists	L	L	L	L	L
11	Maintenance workers	L^{++}	M	L	M	M
12	Managers	L	L	L	L	L
13	Material handlers/porters	L^{++}	M	L	M	L
14	Mechanics	M	L	L	L	L
15	Meter readers	L	M	M	M	M
16	Other technicians	L^{++}	M	M	M	L
17	Plant and equipment operators	M	L	M	L	L
18	Representatives	L^{++}	L	L	L	L
19	Substation operators	H	H	H	H	M
20	Supervisors	L	L	L	L	L
21	Technical/professional support	L^{++}	L	L	L	L
22	Welders	M	L	M	H	H

$^{+,++}$ Default exposures may increase by one (+) or two (++) categories or decrease by one (-) category depending on PWE and OCCENV. See Tables 4-1 and 4-2.

5 DISCUSSION

Limitations

The integrated JEM demonstrates methodologies that address occupational exposures to EMF Factors beyond magnetic and electric fields by also including nuisance shocks, contact currents, and electrical injuries. The following possibly limiting factors are noted.

The PE data used to generate magnetic- and electric-field exposures were from one (albeit large) study and though representative of the industry as a whole, may not apply to a specific cohort study without further investigation.

Limited days of PE data left many job-category-by-PWE and job-category-by-OCCENV exposure cells vacant in Tables 4-1 (magnetic fields) and 4-2 (electric fields). Many of these empty cells could be completed from observations of exposures for other job categories by PWE and OCCENV.

The identification of peak field exposures relied on PE measurements or past computer modeling of exposure groups who perform tasks easily recognized as being near high-current or high-voltage sources. There may be other tasks in high-field environments that have not been identified, because very few workers perform them infrequently.

Nuisance-shock exposures in job categories other than line worker were inferred qualitatively from the presence of electric fields or reports from a few workers of nuisance shocks in the PWE associated with the job category. Another complication for assigning nuisance-shock exposures was the apparent change in their rate of occurrence over time. Additional information from an expanded set of job categories is needed to confirm the reduction in nuisance shocks and to better quantify the frequency of their occurrence.

The principal source of uncertainty in the contact-current exposures in the JEM was a lack of information on the presence and magnitude of voltage differences in the workplace that could produce contact currents. If potential voltage sources are better identified, then observations of worker activity could be used to estimate the frequency of occurrence.

Both nuisance-shock and contact-current exposures are strongly associated with electric fields, which makes it difficult to differentiate these three factors in an exposure assessment without surveying participants or measuring contact voltages.

Exposure estimates for electrical injuries were based on the combined injury rates for flashburn and electric-shock/electrocution from the EPRI OHSD. Combining these rates provided the maximum number of incidents to establish probability of occurrence for electrical injuries by job category. Because the two injury types represent different physical mechanisms, they could be enumerated separately, which would result, however, in smaller numbers of incidents and a corresponding increase in their uncertainties.

The severe injuries recorded in the OHSD presumably occurred at higher voltages than the unrecorded less-severe injuries. At lower voltages the ratio of flashburns to electric shocks could decrease since flashburns require an arc. Therefore extrapolation of electrical-injury rates from the OHSD to an all-injury rate may have somewhat overestimated the rate for unrecorded flashburns and the rate for all injuries.

Exposures to all EMF Factors vary over time as technology and work practices evolve. For example, the use of conducting suits while performing bare-hand live-line maintenance on transmission lines has allowed peak magnetic-field exposures without a concomitant increase in electric-field exposures. Similarly, the worker surveys indicated a reduction in nuisance shocks over time attributable in part to new work practices and an emphasis on safety. Such changes have not been included in the prototype integrated JEM, and further research would provide contemporary assignments.

Consistency of Exposure Assignments Across PE Data Sets

Initial selection of the EMDEX Project data for assigning exposures by job category was based on familiarity with and availability of the data, plus the demonstration nature of the current JEM. However, the consistency of assigning electrical exposures is ultimately of interest in developing such a JEM.

To examine the consistency of assigning magnetic-field exposures to job categories exposure levels for the OHSD job categories were derived from the PE data collected during the US Utility Workers Study[2] , the SCE Workers Study[3], and a survey of workers at Hydro Quebec[32] (HQ) in Canada, as well as from the EMDEX Study[5]. The job categories from these other three studies were collapsed into the OHSD categories. Weighted means, either arithmetic or geometric, were computed from the data from the original job titles in each category. The results of cluster analyses for exposures in each of the three studies are shown in Table 5-1 along with those based on the EMDEX Study data, shown previously in Table 3-1.

The quantitative exposures for the three studies cannot be compared directly because of different instrumentation and protocols. For example the US Utility Workers Study employed a simple meter that integrated magnetic field exposure over the course of a workday, while the EMDEX and SCE studies collected time series magnetic-field data at 10- and 1.5-second intervals, respectively and averaged them over a work day. The HQ study employed a PE meter that recorded magnetic and electric field exposures at one-minute intervals and reported mean exposures for a work week. Therefore only the exposure rankings from PE data by job category and the qualitative exposure levels obtained from clustering were compared across data sets.

Table 5-1
Magnetic-field Exposures for OHSD Job Categories by Personal-exposure Data Source

Data Source	EMDEX Study[5]		US Utility Workers Study[2]		SCE Worker Study[3]		Hydro Quebec Study[32]	
Exposure Category	**OHSD Code**	**OHSD Job Category**	**OHSD Code**	**OHSD Job Category**	**OHSD Code**	**OHSD Job Category**	**OHSD Code**	**OHSD Job Category**
LOW	1	Admin. support	1	Admin. support	1	Admin. support	1	Admin. Support
	3	Coordinators	4	Custodians/security	3	Coordinators	3	Coordinators
	5	Drivers	7	Engineers	4	Custodians/security	4	Custodians/security
	7	Engineers	11	Maint. workers	7	Engineers	5	Drivers
	10	Machinists	12	Managers	9	Line workers	7	Engineers
	11	Maint. workers	13	Mat'l handlers	12	Managers	8	Foremen
	12	Managers	14	Mechanics	15	Meter readers	9	Line workers
	13	Mat'l handlers	18	Representatives	16	Other technicians	10	Machinists
	15	Meter readers	20	Supervisors	18	Representatives	12	Managers
	16	Other technicians	21	Tech./prof. support	20	Supervisors	13	Mat'l handlers
	18	Representatives			21	Tech./prof. support	15	Meter readers
	20	Supervisors					18	Representatives
	21	Tech./prof. support					20	Supervisors
							21	Tech./prof. support
MEDIUM	2	Cable splicers	10	Machinists	10	Machinists	11	Maint. workers
	4	Custodians/security	16	Other technicians	11	Maint. workers	14	Mechanics
	8	Foremen	17	Plant/equip. oper.	14	Mechanics	16	Other technicians
	9	Line workers	19	Sub. operators	17	Plant/equip. oper.	17	Plant/equip. oper.
	14	Mechanics	22	Welders	22	Welders	19	Sub. operators
	17	Plant/equip. oper.						
	22	Welders						
HIGH	6	Electricians	2	Cable splicers	2	Cable splicers	2	Cable splicers
	19	Sub. operators	6	Electricians	6	Electricians	6	Electricians
			9	Line workers	19	Sub. operators		

Table 5-2
Spearman Rank-order Correlation Coefficients Between Magnetic-field (upper right) and Electric-field (lower left) Exposures for OHSD Job Categories by Personal Exposure Data Source

Data Source	EMDEX Study[5]	US Utility Workers Study[2]	SCE Workers Study[3]	HQ Workers Study[32]
EMDEX Study		0.75	0.72	0.63
US Utility Workers Study	N/A		0.73	0.44
SCE Workers Study	N/A	N/A		0.68
HQ Workers Study	0.51	N/A	N/A	

A visual inspection of the rank-order of exposures by job category indicated a relatively strong relationship between the exposure rankings for the four data sets. As shown in Table 5-2, Spearman rank-order correlation coefficients for the magnetic-field exposure rankings by job-category for the four data sets ranged from 0.63 and 0.75, except for between the US Utility Workers and HQ studies, where the coefficient was 0.44. These latter studies had the most disparate methods for characterizing exposures among the four studies.

The rank-order correlation coefficients indicating comparability between exposures derived from the four data sets is borne out by the results of the PAM clustering process as shown in Table 5-1. Consistently high exposure rankings were exhibited by electricians, substation operators and cable splicers, while low rankings prevailed across data sets for job categories associated with work in an office or other setting removed from electrical transmission, distribution and generation facilities. However, one notable exposure classification difference between the data sets was the Line Worker job category, which is often associated with high magnetic field exposures. This job category was assigned High and Medium exposure by the US Utility Workers and EMDEX Studies, respectively, while the SCE and HQ studies assigned lineworkers to the Low exposure category.

Similar analysis for two sets of electric-field PE data are shown in Table 5-3, where the exposure clusters derived for OHSD job categories using electric-field PE data from the HQ Study is compared with those derived from the EMDEX Study data[18, 32]. The Spearman rank-order correlation coefficients for these two data sets was 0.51 as shown in Table 5-2. The large uncertainty in measuring electric field exposures contributes to this weaker association than observed for magnetic-field exposures from the same studies.

Table 5-3
Electric-field Exposures for OHSD Job Categories by Personal-exposure Data Source

Data Source	EMDEX Study[18]		Hydro Quebec Study[32]	
Exposure Category	**OHSD Code**	**OHSD Job Category**	**OHSD Code**	**OHSD Job Category**
LOW	1	Admin. support	1	Admin. support
	3	Coordinators	2	Cable splicers
	7	Engineers	3	Coordinators
	8	Foremen	4	Custodians/security
	10	Machinists	5	Drivers
	12	Managers	7	Engineers
	14	Mechanics	8	Foremen
	17	Plant Operators	10	Machinists
	18	Representatives	12	Managers
	20	Supervisors	14	Mechanics
	21	Tech./prof. support	15	Meter readers
	22	Welders	16	Other technicians
			17	Plant/equip. oper.
			18	Representatives
			20	Supervisors
			21	Tech./prof. support
MEDIUM	4	Security	6	Electricians
	5	Drivers	11	Maint. workers
	11	Maint. workers	13	Mat'l handlers
	13	Mat'l handlers	19	Sub. operators
	15	Meter readers		
	16	Other technicians		
HIGH	2	Cable splicers	9	Line workers
	6	Electricians		
	9	Line workers		
	19	Sub. operators		

As the Spearman rank order correlation coefficients indicate, rankings for job categories for magnetic- and electric-field exposures in the different data sets agree reasonably well: that is, the general trends from low to high exposure values for the different job category are similar. However, when the data are separated into clusters, differences between data sets become immediately apparent. For example, five job categories are in different magnetic-field exposure levels in the SCE Study compared to the EMDEX Study, while seven differ between the US Utility Workers Study and the EMDEX Study.

Two sources of the variation in clustering by job category are differences in data collection and reduction between studies, and differences in the actual exposures assigned to job categories. An example of the first source of variation is that instruments with different recording rates were used in the studies. Also the data were reduced ultimately to geometric means in the EMDEX and SCE data sets, and to arithmetic means in the US Utility Workers and HQ studies. Because the data tend to be lognormally distributed, it is quite possible that the rank order of job-category-based exposures would differ depending on whether the arithmetic or geometric mean was used. This in turn could put a given job category in a different cluster. The particular central tendency metric employed could also change the relative quantitative spacing between job-category exposures even if the rank order remained the same, which in turn could affect assignments in the clustering process.

Differences in exposure assignments to job categories can arise from several factors. The first is erroneous assignment of job category. With the exception of the shock data, all job titles/ job categories of each data set were merged into the OHSD categories. This process could easily lead to differences in exposure assignment between studies. Differences in the actual tasks and work locations for similar job categories could also contribute to variability in measured exposures. across data sets. This is admittedly a more subtle aspect of the first, but it is important, as it can occur independent of the first. Differences in exposures due the use of different work practices for performing the same task could also contribute to variations between data sets.

All of these factors—data collection and reduction methods; and job category assignment, work activities, and work practices – need to be studied further to identify their effects in whole and in part on exposure assignments. This prototype JEM provides the methodological foundation to guide such study and to adapt the findings into a next generation JEM.

6 CONCLUSIONS

The structure of an integrated JEM for electrical utility workers has been developed that includes exposures to magnetic and electric fields, nuisance shocks, contact currents, and electrical injuries.

The job classification scheme for all EMF Factors is closely linked to that used by the EPRI Occupational Health and Safety Database, an ongoing exposure surveillance effort for electric utility workers.

Exposures for all factors were assigned by job category to an ordinal scale of Low, Medium or High exposure. For magnetic and electric fields, data are sufficient to populate the matrix; for electrical injuries, the prospect of refining our estimates is excellent with the expanding EPRI OHSD. Data quality is less optimal for nuisance shocks and contact currents, for which more study is required to validate our matrix entries.

With one exception, the High exposures for all EMF Factors are limited to four job categories that work on or very close to electrical equipment: cable splicer, electrician, line worker and substation operator. Estimated contact-current and electrical-injury exposures for welders were also High, although data were only available from one data set.

Future epidemiologic and exposure assessment investigations of electric utility workers should consider including all EMF Factors, rather than examining a single exposure. With the further development of chemical JEMs for this population, the research community will be in a position to approach electric utility workers from a holistic perspective.

7
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A
NUISANCE SHOCK SURVEYS

Transmission-Line Worker Survey (1982-1984)

Utility workers participating in an electric-field exposure assessment at the Bonneville Power Administration were asked to report whether they had experienced nuisance shocks on the day(s) they wore an electric-field personal exposure (PE) meter.[1, 2] The respondents included both non-electrical and electrical workers, with the latter only working on or near transmission equipment. The study was conducted in three stages: 2232 days of exposure data that included the nuisance shock surveys were collected during Phases I and II when both line and substation workers were included; 146 days of data were collected during Phase III when only line workers were monitored. Participants wore an electric–field PE meter for an average of ten days during the study. Electrical worker job categories in this study included Substation Operator, Substation Maintenance Electrician, Construction (Electricians, Heavy-equipment Operators), Line Crew (Lineman, Line Equipment Operator, Groundman), and Power System Control/System Protection and Maintenance Craftsmen.

Electrical workers reported experiencing nuisance shocks on 8 to 10 percent of days during Phases I and II. The highest percentage of days with nuisance shocks (25%) was reported for exposures near 500-kV equipment. The prevalence of days with nuisance shocks when near 115-kV and 230-kV was lower, ranging from 6 to 16% depending on the phase of the study during which data were collected. When only transmission line workers were monitored (Phase III), the frequency of days with nuisance shocks present increased to 39%. Surprisingly in this case the reported prevalence was higher for working near 115-kV equipment (48%) than near 500-kV equipment (24%). (There were no days near 230-kV equipment during this phase of the study.)

In addition, respondents were asked to characterize the number of nuisance shocks experienced as Few (•10) or Many (>10). In phases I and II which included both line and substation workers, of the 194 days when nuisance shocks were experienced only 7% involved Many (>10) nuisance shocks. During Phase III with only line workers the frequency of days with Many nuisance shocks increased to 28 of the 57 days (49%). Respondents were not asked to characterize the intensity of the shocks.

Even though these results are self-reported and reflect working conditions over 20 years ago, they indicate that overhead transmission line workers have high exposures to nuisance shocks compared to other job categories. Furthermore transmission substation workers, including operators, electricians and craftsmen, experience fewer nuisance shocks than line workers, but nevertheless are an exposed group.

Utility Worker Survey (2006)

In a recent effort to better characterize nuisance-shock exposure among utility workers a survey was administered to 87 male workers at two utilities. Participants were asked to recall their experience with nuisance shocks over their careers, including the task being performed, frequency of occurrence, intensity, location, weather conditions, and whether the frequency of nuisance shocks had changed over time. The final survey instrument was limited to perceivable nuisance shocks and could be completed quickly (< 15 minutes). Since the survey recorded no personal identification, an Institutional Review Board exemption was requested and granted.

Survey respondents reported their job titles and the tasks they were performing when they experienced nuisance shocks. Self-reported job titles were aggregated into common job categories. Most of the 41 participants at one utility were line workers who worked on distribution lines. However, respondents also included workers with experience on transmission lines, at substations and at generation plants. The 46 respondents at the other utility were almost all distribution line workers.

The average length of time employed as an electrical worker was 16.2 years for the 76 volunteers who provided this information. The 50 current and past electrical workers with more than 10 years' experience were defined as "long-time" electrical workers for purposes of analysis. Ninety-one percent of all long-time workers reported receiving nuisance shocks at some time in their careers, while 81% of present workers did. About 40% of present workers reported that they were still experiencing nuisance shocks.

When the survey was administered in 2006, nuisance shocks appeared to occur very infrequently: about 80% of reporting workers reported that they occurred less than monthly. (About 30% of participants who still experience nuisance shocks provided no estimate of shock frequency.) Only one response out of 24 indicated that they occurred daily. The frequency of nuisance shocks reported by distribution line workers in the 2006 survey was well below that reported by transmission line workers more than 20 years earlier. When asked whether nuisance shocks have been reduced by actions taken in the workplace, nearly 90% of all respondents said yes.

At each utility the administrators of the survey and their colleagues assigned a work environment to each job category. Participants identified a total of 123 tasks (including duplicates across workers) that were associated with nuisance shocks. The distributions across work environments of workers reporting nuisance shocks and of tasks involving nuisance shocks are shown in Table A-1.

The vast majority of the tasks from this sample of workers were linked to work environments associated with line work: Distribution Line or the combined Transmission & Distribution Lines. (At one utility line workers commonly work on both transmission and distribution lines.) Most of the reported tasks with nuisance shocks were reported by workers in the Line Worker job category: 65% at the first utility and 88% at the second utility.

The sample composition and size of this survey were not adequate (mostly line workers at only two utilities) to allow estimates of the distribution of nuisance shocks across job categories, conditions for occurrence, frequency, or severity of nuisance shocks. However, the survey provided insight into the characteristics of nuisance shocks experienced by distribution line workers and their variation over time. The specific task descriptions indicated that most nuisance shocks in this sample were at distribution voltages of 34.5 kV or less. Most contemporary workers (25 out of 33) reported that they experienced nuisance shocks less than monthly. If experienced at all, the number of shocks per day was generally much less than ten. The intensity of shocks was fairly evenly distributed across categories from Noticeable to Painful. The level of nuisance shocks has decreased substantially over the last decade.

The two surveys indicate that both transmission and distribution line workers were, and continue to be, exposed to relatively high levels of nuisance shocks compared to most other electrical workers.

Figure A-1
Distributions of Nuisance Shock Reports by Work Environment

Work Environment	Number of Workers[A]	Number of Nuisance-Shock Tasks[B]	Sample Job Titles
Transmission Line	5	0	Hot Washer, Lineman, Sys. Operator
Distribution Line	61	61	Apparatus Tech., Foreman, Lineman/Line mechanic, Troubleman
Distribution/Transmission Line	47	34	Lineman/Splicer, Foreman
Distribution Underground (UG)	2	0	Splicer, UG contractor
Transmission Substation	11	4	Sub. Electrician, Sub. Operator
Distribution Substation	1	0	Electrician
Generation	2	0	Electrician, Test Technician
Other	12	0	Field service Rep., Safety Specialist
Unknown	24	24	Fiber Optic Skywrap, Supervisor, Sys. Operator
Total	165	123	

A Includes all workers who spent time in job title associated with the PWE. Some workers reported experience in multiple job titles.

B If a reported task could not be linked to a specific job title, it was assigned to the longest held job title by the electrical worker.

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B
CLUSTER ANALYSES FOR THE JEM

Cluster Analysis For The JEM

Robert M. Patterson

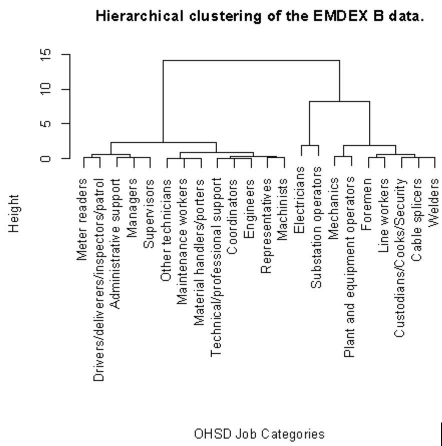
1 Magnetic Fields

Table 1 shows the magnetic field data – geometric means in mG from the EMDEX and SCE studies, and arithmetic means in μT from the Hydro Quebec (HQ) and US Utility Workers (USUW) studies.

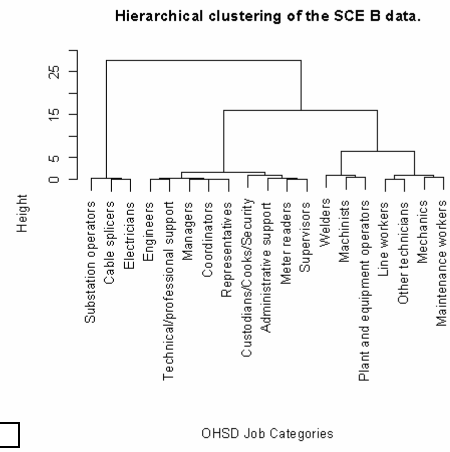
Job Category	EMDEX (mG)	SCE (mG)	HQ (μT)	USUW (μT)
Administrative support	1.22	1.57	0.16	0.25
Cable splicers	2.70	9.22	1.86	3.12
Coordinators	1.68	1.81	0.09	
Custodians/Cooks/Security	2.63	0.90	0.15	0.41
Drivers/deliverers/inspectors/patrol	1.42		0.15	
Electricians	5.39	9.28	2.13	2.18
Engineers	1.68	1.94	0.16	0.23
Foremen	2.90		0.28	
Line workers	2.98	3.20	0.39	1.59
Machinists	1.62	5.82	0.15	0.72
Maintenance workers	1.90	3.96	1.01	0.24
Managers	1.08	1.83	0.16	0.14
Material handlers/porters	1.90		0.39	0.25
Mechanics	3.44	3.62	0.77	0.31
Meter readers	1.35	1.50	0.17	
Other technicians	1.90	3.24	1.19	0.63
Plant and equipment operators	3.72	6.29	1.09	0.64
Representatives	1.56	1.81	0.45	0.12
Substation operators	7.23	9.35	1.46	0.80
Supervisors	1.12	1.51	0.16	0.21
Technical/professional support	1.68	1.94	0.14	0.36
Welders	2.75	5.31		0.80

Table 1: Table of Magnetic Field Data From Four Studies. EMDEX and SCE values are geometric means in mG. HQ and USUW values are arithmetic means in μT. Job categories/titles follow the OHSD database.

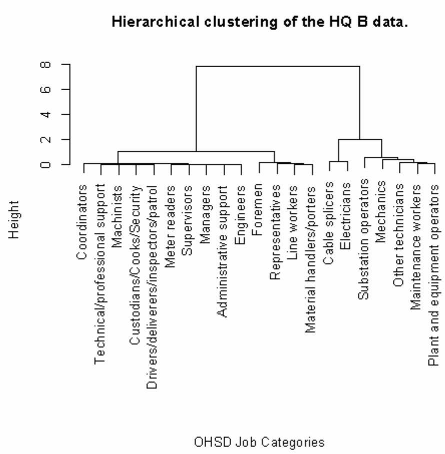
Dendrograms show graphically how the data group together and indicate what the cluster choices might be. The hierarchical clustering shown in the dendrograms begins by assuming each point is a cluster, shown at the bottom of each figure, and then combines them moving upward. Clusters can be chosen by making horizontal cuts through the dendrogram. Heights represent the distances between data (objects) being connected – greater height means more dissimilar data being combined in a group, smaller height means the data are closer together. The following figures are dendrograms for the four available magnetic-field exposure data sets – the EMDEX data, the SCE data, the HQ data, and the USUW data.



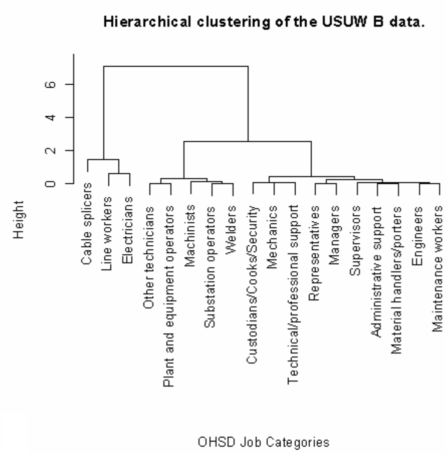
(a) EMDEX



(b) SCE



(c) HQ



(d) USUW

Figure 1: Dendrograms showing hierarchical clustering of the data sets.

While the dendrograms show the overall clustering of the data, plots of silhouettes are more useful to show the optimal number of clusters to group the data efficiently. As an example, the plot below shows silhouettes for the EMDEX data in two clusters. The closer a silhouette (and the average silhouette) is to 1.0 the better. The OHSD job categories belonging to each cluster are shown.

The silhouette widths, $s(i)$, are calculated as follows: For each observation i, put $a(i)$ = average dissimilarity between i and all other points of the cluster to which i belongs (if i is the *only* observation in its cluster, $s(i) = 0$). For all *other* clusters C, put $d(i, C)$ = average dissimilarity of i to all observations of C. The smallest of these $d(i, C)$ is $b(i) = \min_C d(i, C)$, and can be seen as the dissimilarity between i and its "neighbor" cluster, i.e., the nearest one to which it does *not* belong. Finally,

$$s(i) = \frac{b(i) - a(i)}{max(a(i), b(i))}$$

Observations with a large $s(i)$ (almost 1) are very well clustered, a small $s(i)$ (around 0) means that the observation lies between two clusters, and observations with a negative $s(i)$ are probably in the wrong cluster.

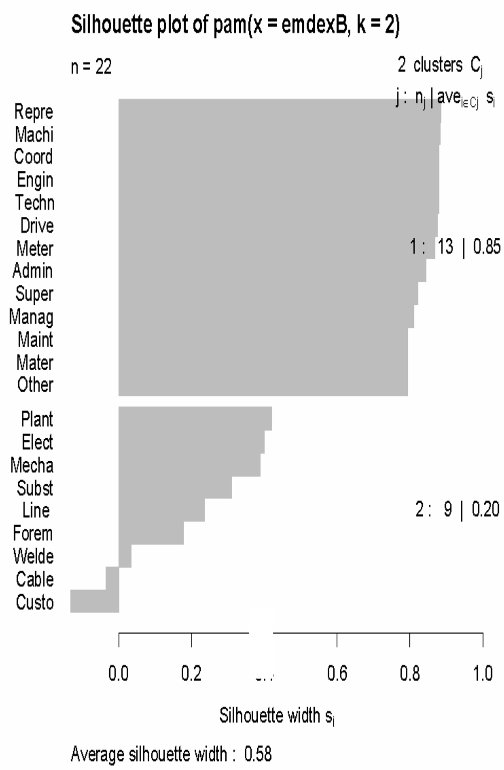
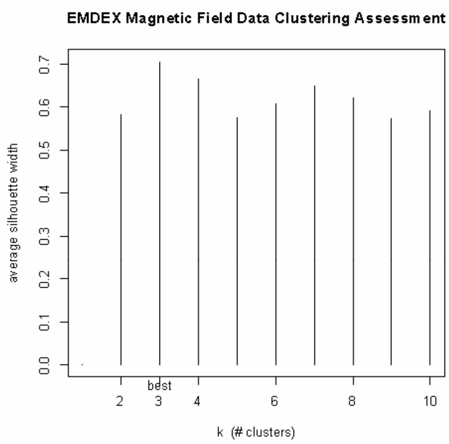
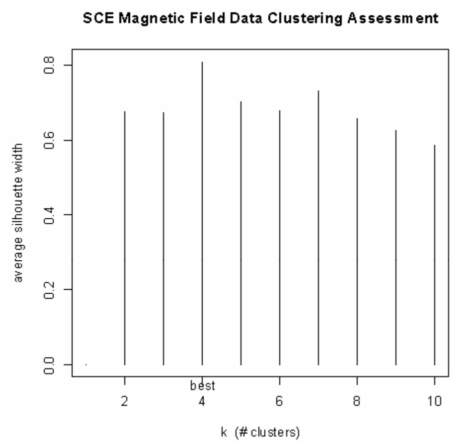


Figure 2: Silhouette plot for EMDEX data with two clusters.

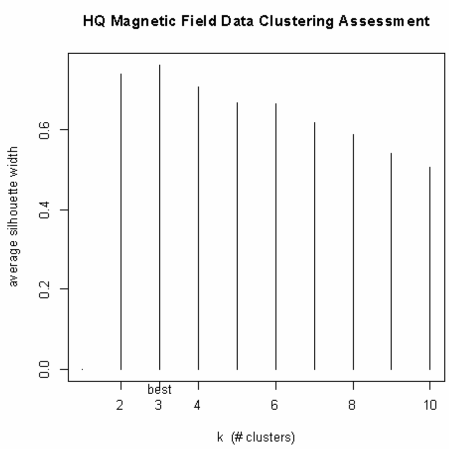
We can calculate and plot the average silhouette width for a range of numbers of clusters for each of the data sets. From these, we can pick the number of groups that gives the best clustering of the data for each. These plots are shown in Figure 3.



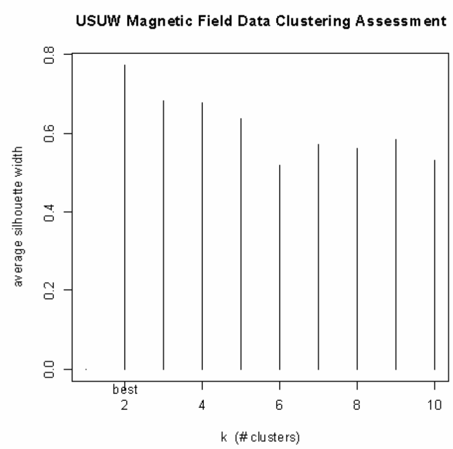
(a) EMDEX



(b) SCE



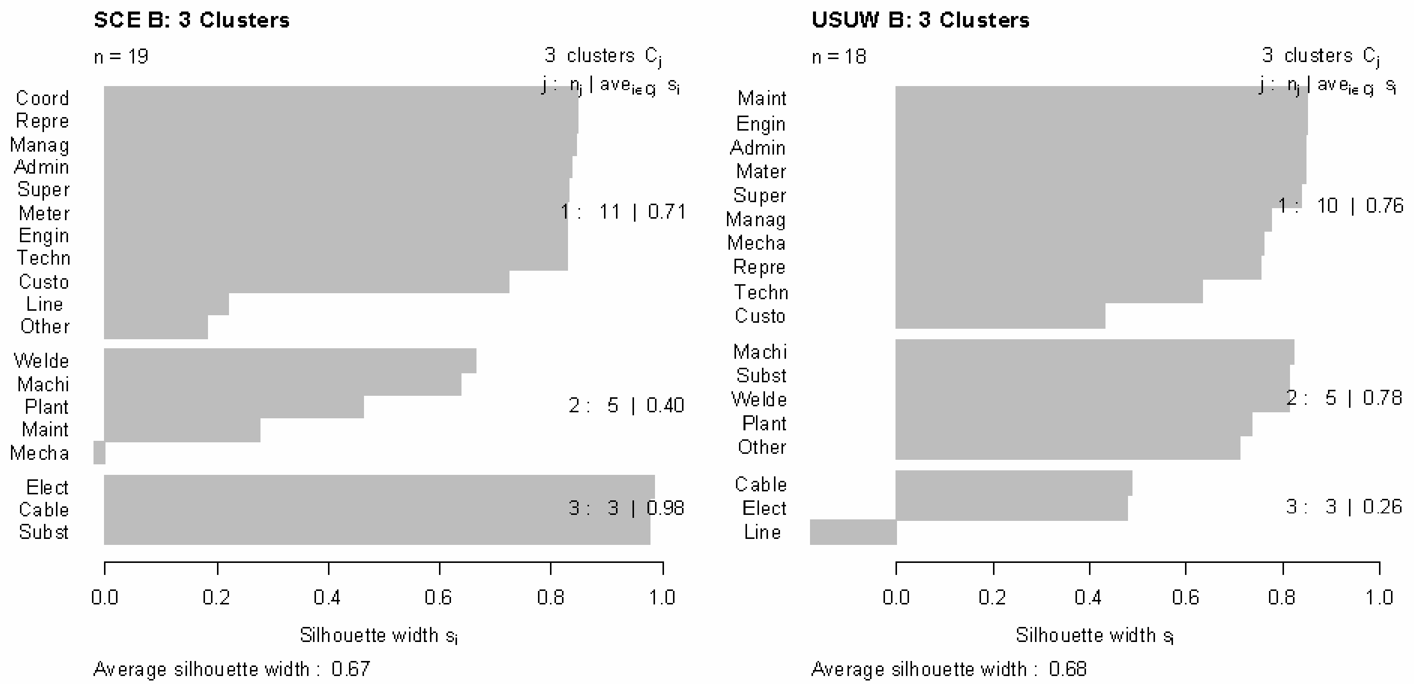
(c) HQ



(d) USUW

Figure 3: Silhouette widths of the clustered data sets by number of clusters. The best number of clusters is shown for each.

The "best" clustering for the EMDEX and HQ data is in three groups, while the SCE data cluster best with four groups and the USUW data are best with two. The next figure shows silhouette plots of the data sets using their best number of clusters. Silhouettes for the SCE and USUW data are then shown



(a) SCE: 3 Clusters

(b) USUW: 3 Clusters

Figure 5: Silhouette plots of the SCE and USUW magnetic field data using three clusters.

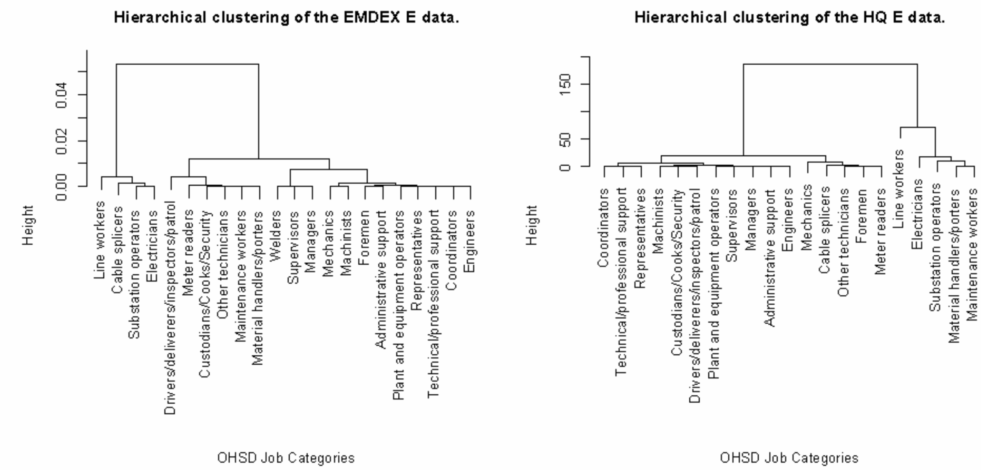
2 Electric Fields

Electric field data are available from the EMDEX and HQ studies. The data for central tendency by OHSD job categories are tabulated here. Because of factors affecting the collection of electric field data, discussed in the body of the report, values should be considered relative within each data set.

Job Category	EMDEX	HQ
Administrative support	0.0056	5.7600
Cable splicers	0.0136	10.1600
Coordinators	0.0053	3.1600
Custodians/Cooks/Security	0.0069	5.0200
Drivers/deliverers/inspectors/patrol	0.0094	5.0200
Electricians	0.0149	43.3700
Engineers	0.0053	5.7600
Foremen	0.0055	7.9300
Line workers	0.0176	81.1500
Machinists	0.0048	5.0200
Maintenance workers	0.0068	32.0500
Managers	0.0034	5.7600
Material handlers/porters	0.0068	31.9000
Mechanics	0.0046	14.4600
Meter readers	0.0063	8.0300
Other technicians	0.0068	7.3900
Plant and equipment operators	0.0052	5.4600
Representatives	0.0054	4.0900
Substation operators	0.0149	23.9100
Supervisors	0.0034	5.7600
Technical/professional support	0.0053	3.7900
Welders	0.0035	

Table 2: Table of Electric Field Data From The EMDEX and HQ Studies. Data should be considered as relative values within each data set.

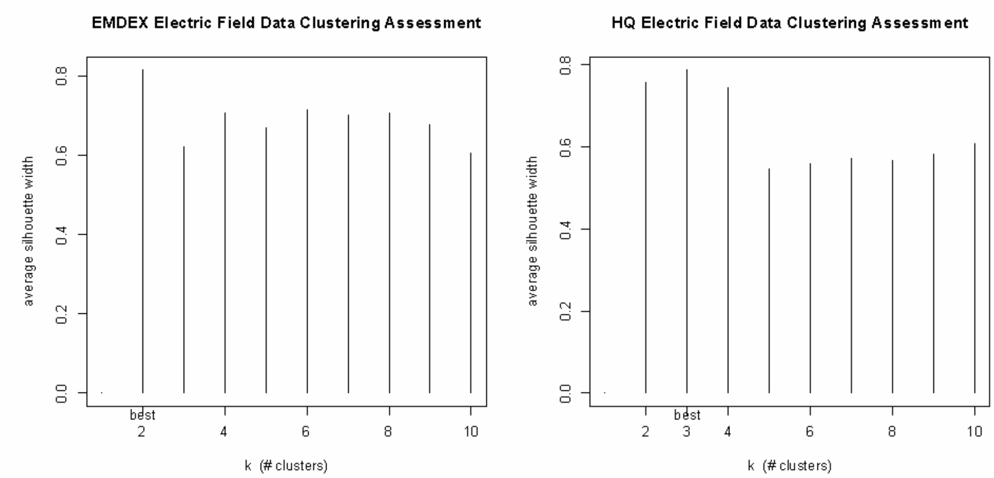
The dendrograms show the hiera chical clustering behavior of the data.



(a) EMDEX (b) HQ

Figure 6: Dendrograms showing hierarchical clustering of the electric field data sets.

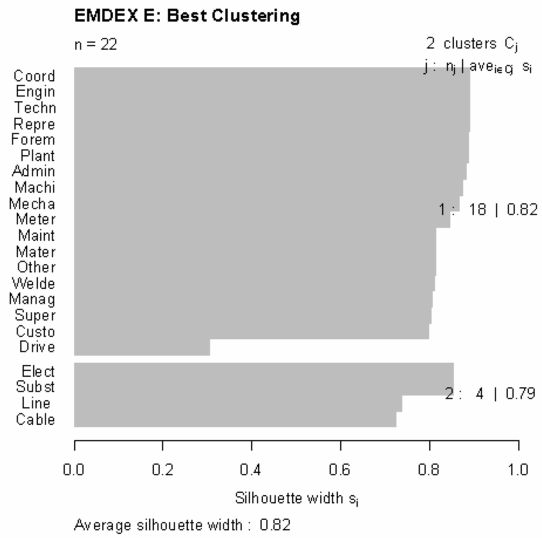
The next plots show the best number of groups to cluster the data in each set.



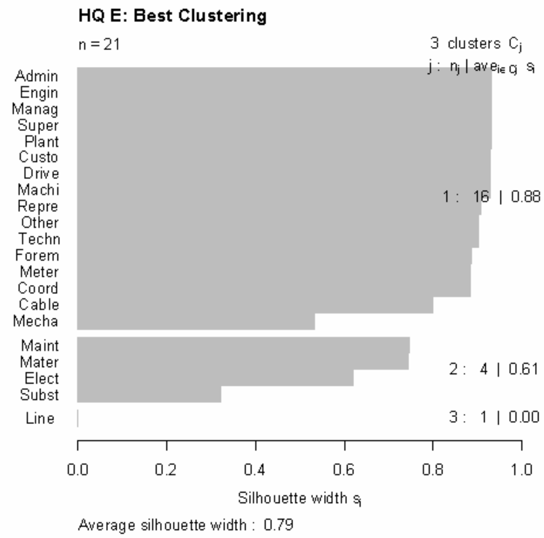
(a) EMDEX (b) HQ

Figure 7: Plots of average silhouette width by number of clusters for the electric field data.

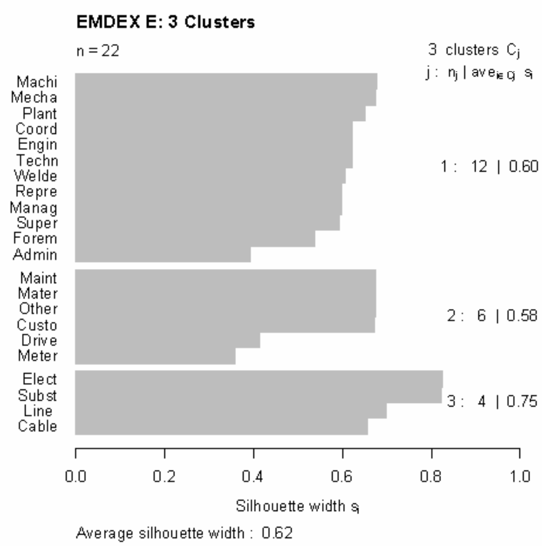
The silhouettes using the best number of clusters, and using three clusters for the EMDEX electric field data, are shown in the next figure.



(a) EMDEX: Best Clustering



(b) HQ: Best Clustering



(c) EMDEX: 3 Clusters

Figure 8: Silhouette plots of the electric field data sets using the best number of clusters for each, and using three clusters for the EMDEX data.

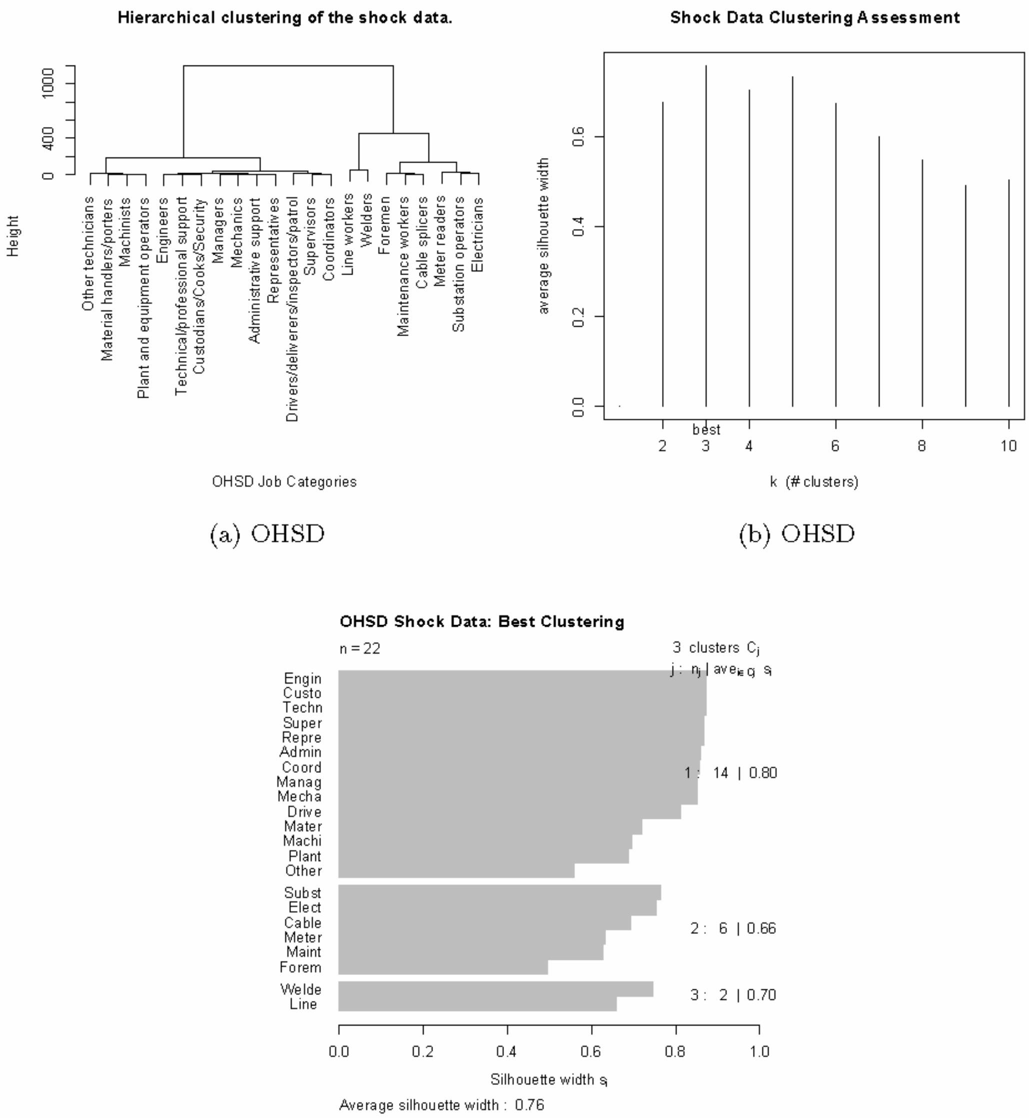
3 Shocks

The shock data available from the OHSD study/database are listed in the table below.

Job Category	OHSD
Administrative support	1.80
Cable splicers	128.00
Coordinators	17.60
Custodians/Cooks/Security	6.40
Drivers/deliverers/inspectors/patrol	29.50
Electricians	172.00
Engineers	7.80
Foremen	109.00
Line workers	302.00
Machinists	46.80
Maintenance workers	119.00
Managers	0.00
Material handlers/porters	44.10
Mechanics	0.00
Meter readers	189.00
Other technicians	56.70
Plant and equipment operators	47.40
Representatives	3.60
Substation operators	161.00
Supervisors	12.80
Technical/professional support	6.20
Welders	355.00

Table 3: Table of Shock Data From The OHSD Study.

The dendrogram, the plot of average silhouette widths by number of clusters, and the plot of silhouettes are in the next figure.



(a) OHSD

(b) OHSD

(c) OHSD: Best Clustering

Figure 9: Hierarchical clustering, best number of clusters, and silhouette plots of the OHSD shock data.

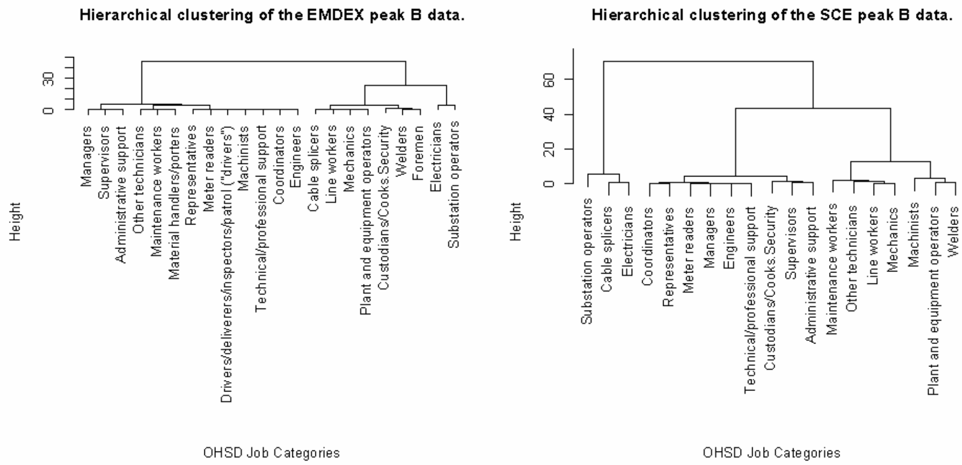
4 Magnetic Fields – Peak Values

Measures of peak values (geometric means of 95th percentiles) using the OHSD job categories are available for the EMDEX and the SCE data and are listed here. Values are in mG.

Job Category	EMDEX (mG)	SCE (mG)
Administrative support	2.59	3.61
Cable splicers	8.57	25.44
Coordinators	3.65	4.29
Custodians/Cooks.Security	6.50	2.22
Drivers/deliverers/inspectors/patrol ("drivers")	3.73	
Electricians	15.26	26.14
Engineers	3.65	4.62
Foremen	7.79	
Line workers	9.41	9.11
Machinists	3.59	12.53
Maintenance workers	4.66	10.48
Managers	2.38	4.67
Material handlers/porters	4.66	
Mechanics	8.96	9.36
Meter readers	3.90	4.56
Other technicians	4.66	8.12
Plant and equipment operators	9.10	14.55
Representatives	3.39	4.29
Substation operators	19.85	21.46
Supervisors	2.54	3.20
Technical/professional support	3.65	4.62
Welders	7.62	14.96

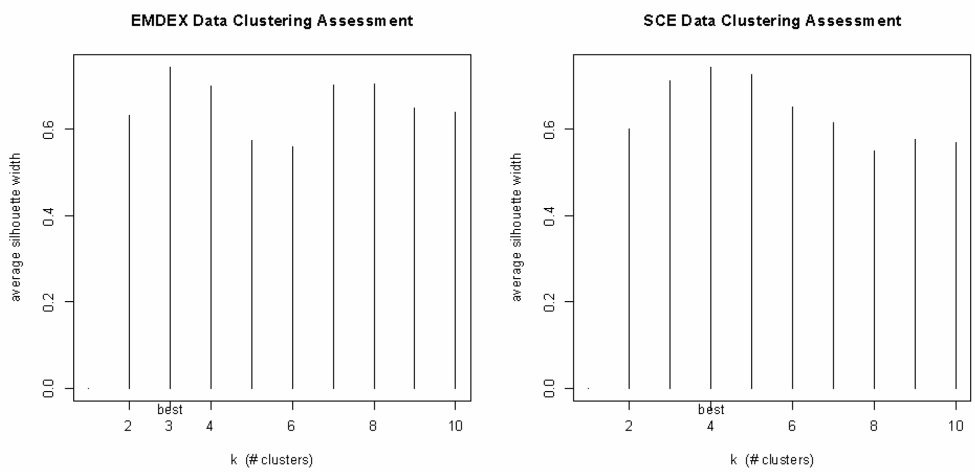
Table 4: Table of Peak Magnetic Field Data From EMDEX and SCE Studies. Values are geometric means of 95th Percentiles in mG.

As for the data on central tendency, ıe best clustering for the peak EMDEX data is in three groups, while the SCE peak data cluster best with four groups. Silhouette plots of the two data sets using their "best" groupings are shown, as is a silhouette plot of the SCE peak data using three groups. Note that this analysis provides an objective reason for using 3 clusters for the EMDEX data.



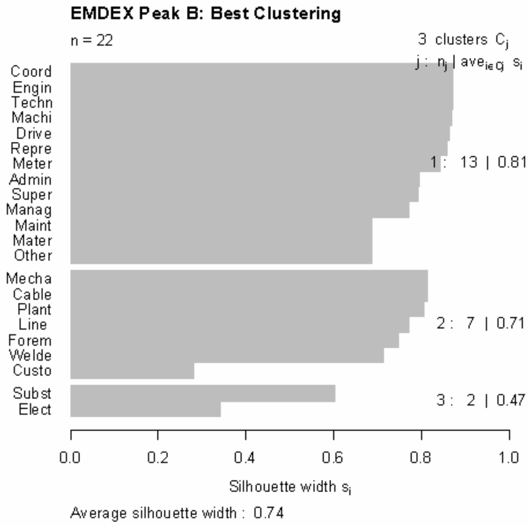
(a) EMDEX (b) SCE

Figure 10: Dendrograms showing hierarchical clustering of the data sets.

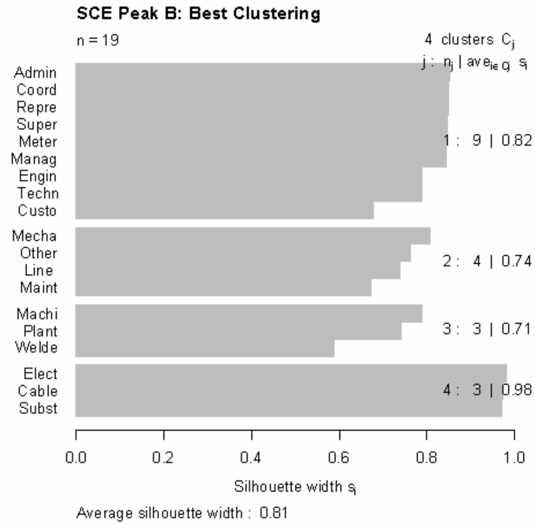


(a) EMDEX (b) SCE

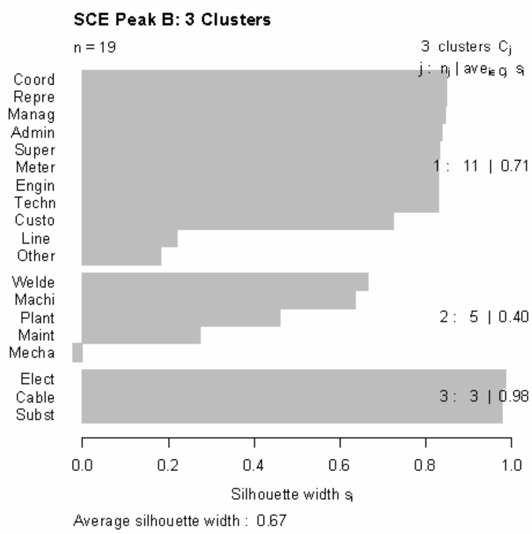
Figure 11: Silhouette widths of the ered data sets by number of clusters. The best number of clusters is shown.



(a) EMDEX: Best Clustering



(b) SCE: Best Clustering



(c) SCE: 3 Clusters

Figure 12: Silhouette plots of the peak magnetic field data sets using the best number of clusters for each, and using three clusters for the SCE data.

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com