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The Possible Role of Contact Current in Cancer Risk Associated With Residential Magnetic Fields

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Residential electrical wiring safety practices in the US result in the possibility of a small voltage (up to a few tenths of a volt) on appliance surfaces with respect to water pipes or other grounded surfaces. This "open circuit voltage" (V_{OC}) will cause "contact current" to flow in a person who touches the appliance and completes an electrical circuit to ground. This paper presents data suggesting that contact current due to V_{OC} is an exposure that may explain the reported associations of residential magnetic fields with childhood leukemia. Our analysis is based on a computer model of a 40 house (single-unit, detached dwelling) neighborhood with electrical service that is representative of US grounding practices. The analysis was motivated by recent research suggesting that the physical location of power lines in the backyard, in contrast to the street, may be relevant to a relationship of power lines with childhood leukemia. In the model, the highest magnetic field levels and V_{OC}s were both associated with backyard lines, and the highest V_{OC}s were also associated with long ground paths in the residence. Across the entire neighborhood, magnetic field exposure was highly correlated with V_{OC} ($r = 0.93$). Dosimetric modeling indicates that, compared to a very high residential level of a uniform horizontal magnetic field (10 μT) or a vertical electric field (100 V/m), a modest level of contact current (~18 μA) leads to considerably greater induced electric fields (> 1 mV/m) averaged across tissue, such as bone marrow and heart. The correlation of V_{OC} with magnetic fields in the model, combined with the dose estimates, lead us to conclude that V_{OC} is a potentially important exposure with respect to childhood leukemia risks associated with residential magnetic fields. These findings, nonetheless, may not apply to residential service used in several European countries or to the Scandinavian studies concerned with populations exposed to magnetic fields from overhead transmission lines. Bioelectromagnetics 21:538–553, 2000.

Key words: magnetic fields; childhood leukemia; power lines; open circuit voltage

INTRODUCTION

Background

The question of whether residential exposure to power frequency (50 and 60 Hz) magnetic fields is a risk factor for childhood leukemia remains unresolved [NIEHS Working Group, 1998; NIEHS, 1999]. Early epidemiological studies conducted in Denver and Los Angeles reported associations between electric utility line wiring configurations and childhood leukemia [Wertheimer and Leeper, 1979; London et al., 1991] or all childhood cancer [Savitz et al., 1988], with a suggestion of increased leukemia risk in the latter. As developed initially by Wertheimer and Leeper [1979, 1982] with subsequent refinements by others [Barnes et al., 1989], the wiring configurations were the basis of a categorical exposure surrogate, referred to as the "wire code". The positive relation between wire code and magnetic field [reviewed in Kheifets et al., 1997], as well as suggestive associations between measured fields and relative risk estimates [Savitz et al., 1988; London et al., 1991], appeared consistent with the hypothesis that the residential magnetic field was the causal agent in these studies.

In a recent re-analysis of the Denver and Los Angeles studies, Ebi et al. [1999] report that in both data sets, risk associated with wire code was concentrated in residences served by backyard distribution lines, as opposed to distribution lines in the street. This observation motivated the analysis presented in this paper, which is concerned with (a) the relationship

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between the physical features of residential electric service and exposures to magnetic fields and currents; (b) the correlation among specific electric and magnetic exposure parameters; and (c) the dosimetric implications of these relationships with respect to childhood leukemia risk. We introduce an exposure called the "open circuit voltage" (V_{OC}), which is a small power frequency voltage (up to a few tenths of a volt) that may appear on electrical equipment. V_{OC} can cause a "contact current" to flow directly into a person in manual contact with the appliance. The findings presented in this paper suggest that contact current due to V_{OC} may be an exposure variable that could hold the key to clarifying the reported associations of power line environments with childhood leukemia. We first review the relevant aspects of residential electrical service.

Residential Electrical Service

The major features of electrical service in US distribution systems are illustrated in Figure 1 and further elaborated in its caption. Electrical service to the residence occurs via the "service drop", which connects the distribution transformer secondary located outside on a utility pole or underground, to the "service panel", where the occupant has access to circuit breakers and/or fuses. The service drop consists of three cables: two 120 volt (V) alternating current (ac) "hot legs", which provide the load currents for lights, appliances, etc., and the neutral, through which current may return to the substation.

For safety purposes, e.g., electric shock and fire prevention, residential electrical wiring in the US provides multiple pathways for current to return to the substation [NESC, 1992]. Under normal conditions, the current returns via both the utility's service drop neutral and an alternative pathway, which in many cases is a conductive residential plumbing line connected to the municipal water main in the street. The connection to the plumbing is established with a "ground wire" bonded electrically to the utility neutral at the service panel and strung at some length to a convenient (exposed) water line. For cases in which conductive water pipes are not available, houses will have driven ground rods to establish a strong alternative ground connection. The amount of current that each pathway takes has an inverse relationship to each pathway's electrical resistance.

The "net load current" is the algebraic sum of the current in the two supply conductors. The "net current" in the utility service drop equals the net load current to the residence minus the current in the service drop neutral. Net current equals the current that flows in the alternative ground pathways, which we refer to as the "ground current" (see Figure 1). Thus, the service drop to ground wire pathway becomes a magnetic field source in the residence. The source strength depends on the current magnitude and the pathway's geometry. In residences located away from overhead utility distribution or transmission lines, Kavet et al. [1999] report that, compared to other predictor variables, the net service drop current (i.e., the ground current) correlates most strongly with magnetic fields measured in the residence. In communities with conductive water service and water mains, a fraction of ground current generated in one residence may flow to another residence's ground.

Since the ground wire has a resistance, though small, the current flowing in it produces a voltage difference between the service neutral and the plumbing connection. This voltage equals the ground wire current multiplied by the wire's resistance (assuming no additional resistance due to poor bonding at the wire's termini). To prevent shock, electrical appliances have their metallic chassis connected, either through their neutral wire or their third wire, to the utility neutral bonding point in the service panel (Figure 1). Through this connection, the chassis carries the voltage generated in the ground wire, which we refer to as the "open circuit voltage" or V_{OC}. As indicated by the open switch in Load 3 in Figure 1, V_{OC} is present on an appliance even when in the "off" position, so long as it is plugged in.

V_{OC} can serve as a source of contact current into a person who touches the chassis, and, through either the other hand or the feet, completes an electrical circuit back to the house's ground. This circuit is shown schematically in Figure 2. The resistance of the ground wire, R_{GW}, is usually very small (around 0.1 ohm (Ω) for a 30 m length) compared to the resistance in the rest of the contact current pathway, which consists of R_P, the resistance of the individual, in series with R_G, the resistance from the feet back to ground. R_P is on the order of several thousand ohms [Reilly, 1998], but varies depending on skin moisture and other factors; R_G depends on footware, floor material, and housing materials. Thus, since $R_{GW} \ll R_P + R_G$, contact current is essentially equal to V_{OC} divided by the sum of R_P and R_G. If the other hand comes in contact with a water fixture, which is usually at house ground potential, then the contact current would likely take the hand-to-hand route as the path of lower resistance.

Organizations concerned with EMF exposure guidelines [e.g., International Commission on Non-Ionizing Radiation Protection (ICNIRP)] and appliance safety [e.g., Underwriters Laboratories (UL)] have published limits for contact or "leakage"

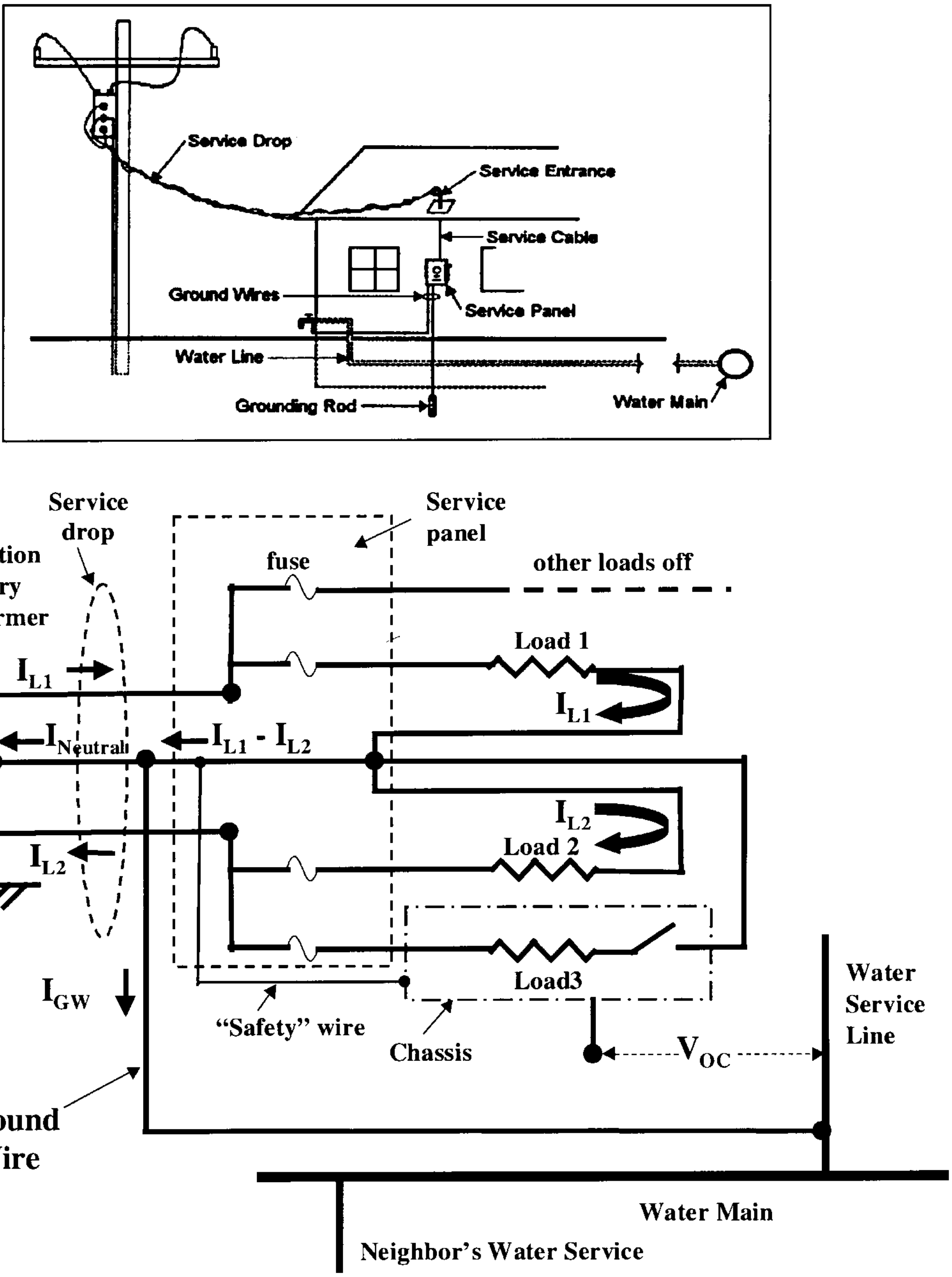

Fig. 1. Residential Electric ServiceTypical of "Multi-grounded Neutral" Systems used in the US and Origin of Open Circuit Voltage (V_{OC}). Top inset is a "real world" view of electrical service to a single-unit residence. Bottom graphic is a schematic of the electrical relationships in the service and internal wiring. Two 120-V conductors (hot legs) from the distribution secondary transformer, 180 degrees out of phase with each other, supply currents I_1 and I_2 to Load 1 and Load 2, respectively. The center tap of the transformer is grounded at the street pole or underground transformer location. The "net load current" on the service drop is the amount of current returning to the substation at any point in time and, in the figure, equals $I_{L1}-I_{L2}$. Current returns via two basic pathways: (a) the service drop neutral cable or (b) an alternate ground path, which in the figure consists of a ground wire connected to a conductive water line. The net load current equals the sum of the currents in these two pathways, $I_{Neutral}+I_{GW}$. The "net current" in the service drop equals net load current minus the current in the neutral, or $I_{Net}=(I_{L1}-I_{L2})-I_{Neutral}$. The current in the ground wire, I_{GW}, equals I_{Net}. I_{GW} and I_{Net} are sources of magnetic field in the residence. Because the ground wire has a finite resistance, R_{GW} (not pictured), a voltage is developed across its length equal to $I_{GW} \times R_{GW}$, which we refer to as the open circuit voltage (V_{OC}). Load 3, plugged in but in the off position (open switch), has a safety wire that connects the load's chassis to the service panel neutral. The chassis is, thus, at a voltage V_{OC} with respect to the grounded water system. In this model, V_{OC} represents the largest voltage potentially present prior to contact between a person and an appliance chassis or between a person and metallic structures (e.g., hot water heaters, steam radiators) connected to residential water pipes. Ground currents may be shared among residences.

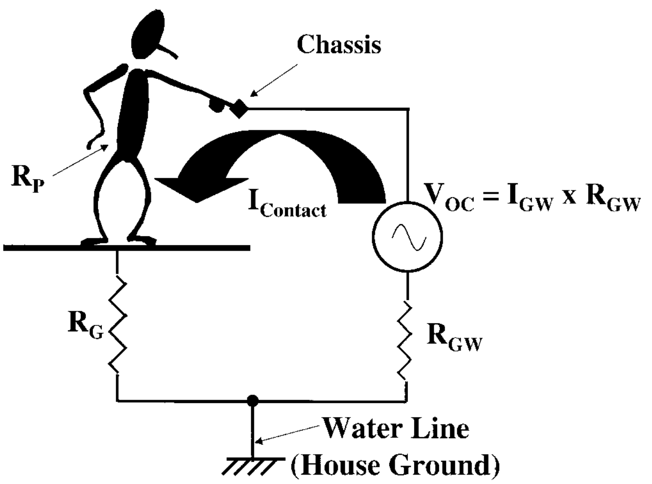

Fig. 2. Contact Current. A person contacting a chassis is exposed to V_{OC}, which can drive current into that person, depending on the nature of his/her connection to the chassis and to the ground. Moist extremities decrease a person's electrical skin resistance, while insulating footwear or poorly conductive housing materials will sharply limit current. The figure shows hand-to-feet contact, but if the second hand is in touch with a grounded object, the current will take a hand-to-hand route.

currents. These limits are designed to avert hazardous startle and adverse perceptual effects. Below 2.5 kHz, ICNIRP [1998] specifies 0.5 mA and 1.0 mA contact current limits for the general public and workers, respectively. UL lists 0.5 mA and 0.75 mA as startle limits for portable and fixed appliances, respectively [reviewed in Reilly, 1998]. The National Electric Safety Code [NESC, 1992], which specifies safety practices for overhead transmission line construction and operation, limits to 5 mA steady-state whole body current that may result from electric field induction on large objects (e.g., trucks) in physical contact with a person in the right-of-way of overhead high-voltage transmission lines.

Study Overview

We constructed a computer model of a 40 house neighborhood to address how specific physical features of residential electrical service affect magnetic field and V_{OC} exposures within the residence. The software running the model has been previously validated against measurements taken in a test residence under various grounding conditions [Zaffanella et al., 1997]. The features we examined are line location—backyard or street, relative length of the ground return pathway—short or long, and service line type—overhead or underground. The quantities modeled include the 60 Hz and 180 Hz magnetic fields at the center of each room, the time-weighted-average fields experienced by a child as a result of a day's occupancy of the residence, and the V_{OC}. The neighborhood wiring follows practices applicable to the US, although we recognize that such practices vary among countries [Rauch et al., 1992]. Despite the stochastic nature of the residential loading imposed on the neighborhood, the model itself is completely deterministic, and the statistical treatment of the data is intended to clarify relationships among exposure and source variables, rather than to achieve inferential support as occurs in population studies.

METHODS

Modeling Software

The modeling software calculates magnetic fields resulting from currents on arbitrary arrays and configurations of electric transmission lines, primary and secondary distribution lines, and ground and neutral return pathways. The program conducts network analyses of ground/neutral currents in neighborhoods based on user-specified residential loads and impedances. Local dipole sources, such as appliances, are not included in the field calculation. As mentioned above, the program has been previously validated against measured fields and known ground currents [Zaffanella et al., 1997].

Modeling Objective

This paper is concerned exclusively with magnetic fields and V_{OC}s resulting from currents in the service drop (i.e., secondary distribution current) and in the ground path (Figure 1). Wertheimer-Leeper wire code categories do not play a role in the model as configured for the analyses here. In fact, for the neighborhood loading used here, primary loads and their return currents had a negligible effect on residential magnetic fields and V_{OC}. However, the neighborhood was provided with a full range of distribution wiring configurations representative of the Wertheimer-Leeper wire code, should further development of the neighborhood (e.g., downstream connections to other load centers) be warranted. The appendices contain a detailed description of the neighborhood's electrical infrastructure.

Neighborhood Description

Briefly, the study neighborhood (Figure 3) consists of four streets containing 40 two-story houses, each 10.7 m by 7.6 m (35 × 25 ft) with the long dimension parallel to the street. Each house has eight equal-size rooms, four per floor. For each house, the service drop arrives at a corner and then goes to the electrical panel. All houses have copper-pipe water service that provides a conductive ground path to the

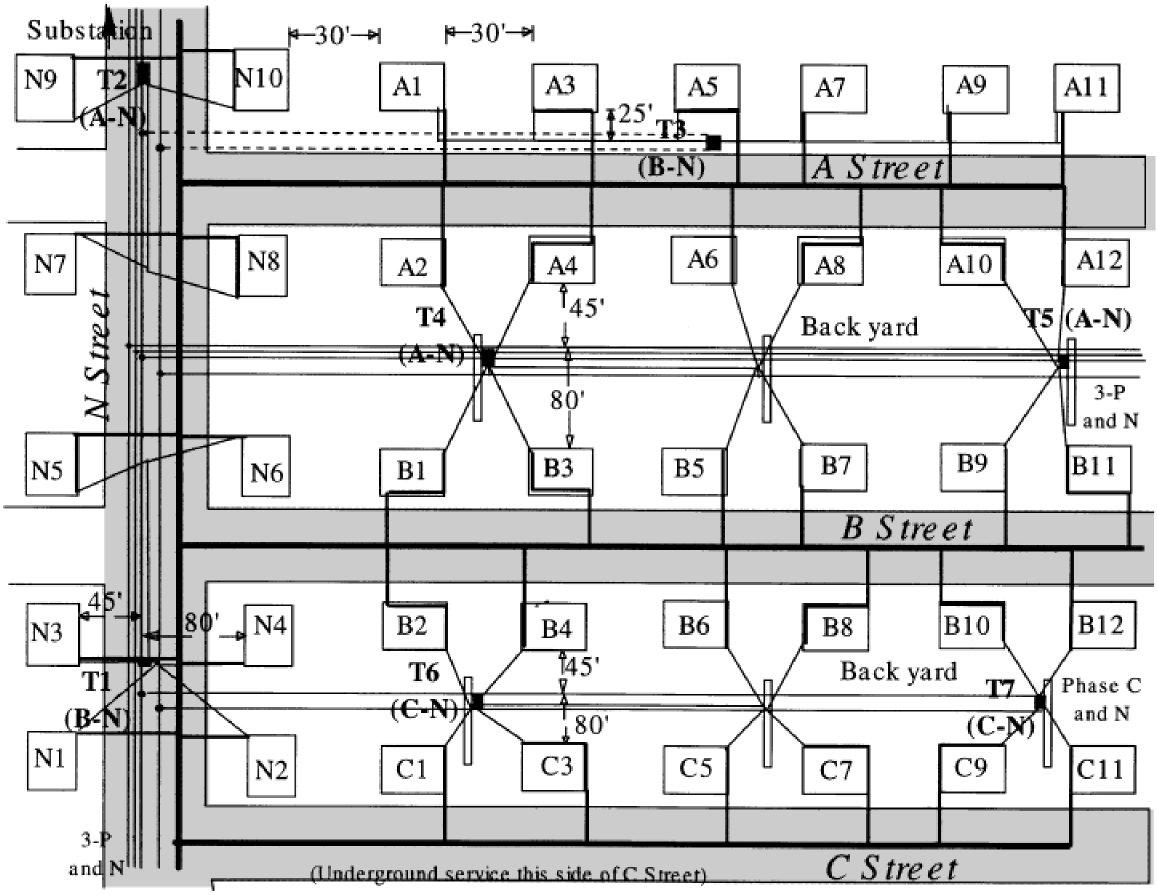

Fig. 3. Model neighborhood (see text and Appendix).

water main. All water mains were located in the middle of the street.

With the exception noted below, all combinations of the following attributes were represented: line location—backyard or street; relative length of the ground return pathway—short or long; and service line type—overhead or underground. Underground lines were not situated in the backyard, as this is a less common feature of residential electric distribution systems. Figure 4 illustrates the "length of ground path" dichotomous variable: Type 1 is the shorter possible path for overhead street lines, overhead backyard lines, and underground street lines (top to bottom in Figure 4); Type 2 is the longer possible path for overhead street lines, overhead backyard lines, and underground street lines (top to bottom in Figure 4).

Loading

As discussed above and shown in Figure 1, the net load is the parameter that defines the electrical load of the house with regard to ground current. The "1,000-home study" [Zaffanella, 1993] developed a database of electrical parameters, including the 24 h statistical distribution of the net load for each house. These data suggested using a net load for each house randomly extracted from a log-normal distribution with a median value of 4.34 ampere (A) and a geometric standard deviation of 1.87. The model was run 100 times, each time with a net load randomly allocated to each house. To account for possible ground current interactions between residences, the sign of the net load was also randomly chosen. The load currents were all at the power frequency of 60 Hz with a 15% third harmonic. The value chosen for the third harmonics corresponded to the average value recorded during the 1000 home survey [Zaffanella, 1993].

RESULTS

General Statistical Description of Sample

The parameters selected for study are listed in Table 1, and their descriptive statistics across the entire neighborhood are shown in Table 2. The variables displayed continuous, smooth distributions, although

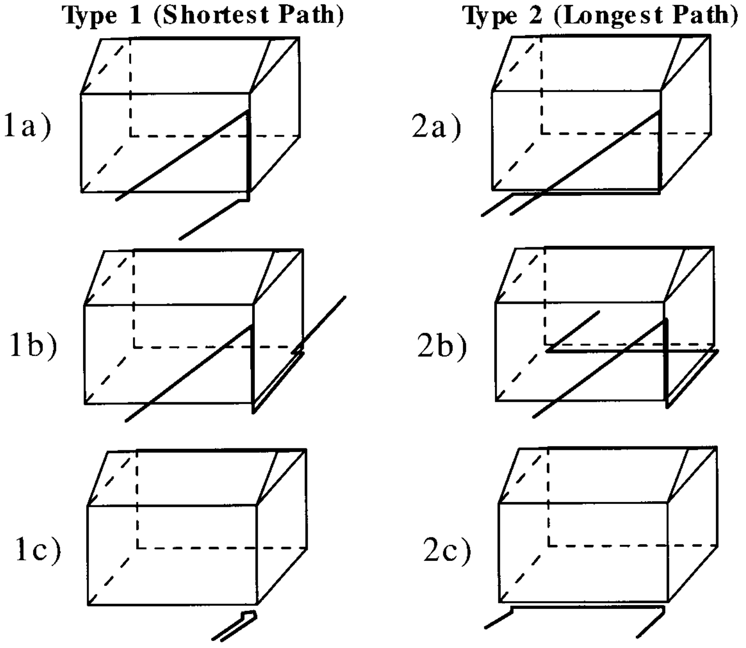

Fig. 4. Net and ground current paths: 1a) Overhead street line, short path; 1b) Overhead backyard line, short path; 1c) Underground street line, short path; 2a) Overhead street line, long path; 2b) Overhead backyard line, long path; 2c) Underground street line, long path.

TABLE 1. Parameters Reported on in Results[a]

Parameter	Description
AvgRoomB	Temporal average of the 60 Hz magnetic field in the center of each room 1 m above the floor averaged across all eight rooms
Avg180HzB	Temporal average of the 180 Hz magnetic field in the center of each room 1 m above the floor averaged across all eight rooms. Typical values of harmonic loads are assumed [Zaffanella, 1993]
AvgPerimB	Temporal average of the magnetic field sampled every 5 m around the house periphery, 1 m from the house, and 1 m off ground
AvgChildB	Temporal average of the field across the entire indoor space, from floor to four feet above the floor. The field is calculated at all points of a three-dimensional grid with one foot (0.305 m) grid size. For each floor of a 10.7 m by 7.6 m (35 × 25 ft) house, there are 4680 calculation points in the "child" space
10%ChildB	The upper 10th percentile value of child's exposure within a house
AvgGC	The temporal average of the current in the residential ground path; same as average net current in the service drop
10%GC	The upper 10th percentile value of GC within a house
AvgV_{OC}	Temporal average of the open-circuit voltage between appliance chassis and the water line at the point where it is connected to the conductor that grounds the electric service neutral
10%V_{OC}	The upper 10th percentile value of V_{OC} within a house

[a]Within each residence parameters are calculated for each of 100 loads randomly assigned. Thus, for example, AvgGC for a residence is the ground current averaged over 100 values; 10%GC for a residence is the value exceeded for 10% of the calculations.

most were not normally distributed according to the Shapiro-Wilk test.

Stratification of Sample

By design (see Methods), only the currents in the service secondaries, service neutral, and ground pathways influenced the electrical quantities computed for each residence. Thus, all one-, two-, and three-phase primary lines were collapsed into one "overhead" (OH) category, with the remainder classified as "underground" (UG). The basic geometric differences between OH and UG are evident in Figure 4.

Table 3 shows summary statistics for several key exposure variables, stratified by engineering factors. Visual inspection suggests that the highest field exposure quantities were associated with backyard, overhead lines, the highest ground currents were associated with overhead lines, and the highest V_{OC}s were associated with overhead, backyard lines with long ground paths.

TABLE 2. Descriptive Statistics for Selected Exposure Variables for the Entire Neighborhood Sample ($N = 40$ Houses)

Statistic	AvgRoom B (μT)	Avg180Hz B (μT)	AvgPerim B (μT)	AvgChild B (μT)	10%Child B (μT)	AvgGC (A)	10%GC (A)	AvgV$_{OC}$ (mV)	10%V$_{OC}$ (mV)
Mean	0.077	0.014	0.118	0.097	0.169	1.44	2.82	54.4	107.1
SD	0.046	0.009	0.096	0.052	0.103	0.64	1.22	34.2	67.6
Median	0.088	0.016	0.085	0.095	0.169	1.23	2.47	53.2	105.2
Upper 10%	0.135	0.025	0.264	0.177	0.320	2.53	4.79	90.8	187.5
Lower 10%	0.012	0.002	0.011	0.021	0.008	0.79	1.53	10.4	20.0
Shapiro-Wilk *P*-value	<0.05	<0.01	<0.01	>0.1	>0.3	<0.01	<0.01	<0.05	<0.05

TABLE 3. Summary Statistics for Selected Exposure Measures Broken Down by System Characteristics

Line type	Location	Ground type	*N*	AvgRoomB (μT) Median	AvgRoomB (μT) Min–Max	AvgChildB (μT) Median	AvgChildB (μT) Min–Max	AvgGC (A) Median	AvgGC (A) Min–Max	AvgV$_{OC}$ (mV) Median	AvgV$_{OC}$ (mV) Min–Max
OH	Backyard	Short	12	1.12	0.12–1.64	1.05	0.61–1.83	1.49	0.88–2.60	52.0	30.7–91.0
OH	Backyard	Long	12	0.99	0.54–1.63	1.12	0.80–2.14	1.09	0.78–2.10	74.5	53.7–144.0
OH	Street	Short	6	0.72	0.41–1.09	0.73	0.34–1.01	2.13	0.98–2.80	20.9	9.6–27.6
OH	Street	Long	4	0.53	0.14–1.03	1.05	0.34–1.42	1.46	0.48–1.98	64.6	21.1–87.7
UG	Street	Short	4	0.10	0.04–0.15	0.17	0.14–0.21	1.01	0.83–1.22	10.0	8.2–12.0
UG	Street	Long	2	—	0.18–0.18	—	0.25–0.40	—	0.51–0.79	—	22.4–35.1

Regression Model

A linear regression model was used to clarify the dependencies between the three factors (line type, location, and ground type) and the nine computed exposure variables:

$$\begin{aligned}\text{Exposure} = {} & \beta_1 * (\text{Line Type}) + \beta_2 * (\text{Location}) \\ & + \beta_3 * (\text{Ground Type}) + \varepsilon\end{aligned}$$

The results of the regression analysis are summarized in Table 4. The computed *P*-values shown cannot be taken too literally because the residual “errors” are not random and because if the number of houses and number of temporal samples were increased, all the *P*-values would necessarily become smaller. In general, exposure values were increased for residences served by backyard OH lines. Not surprisingly with their lower resistance, short ground paths increased ground current, and the long ground path increased V$_{OC}$.

The results in Table 4 were generally consistent with subgroup models that included OH lines only ($N = 34$; Location and Ground Type predictors); backyard lines only ($N = 24$; Ground Type predictor only); and street lines only ($N = 16$; Line Type and Ground Type predictors).

Correlation of Exposure Variables

Table 5 shows the Pearson correlation among the six average exposure parameters under study. The nonparametric Spearman test produced essentially the same results. The nearly perfect correlation between AvgRoomB and Avg180HzB is not surprising as sources for both exposures and methods for field calculation are tightly linked.

We note a very high correlation ($r = .93$ or about 87% explained variance) between AvgChildB and AvgV$_{OC}$. The correlations between these two parameters and the other exposure variables were relatively weaker. The reasons for this difference are (1) the way AvgChildB was computed, compared to the other field quantities (see Table 1), and (2) the relation between ground current (GC) and both AvgChildB and V$_{OC}$, as compared to the other field quantities. First, AvgChildB was computed across the entire floor space of the residence and thus it controls for asymmetric service and ground wiring patterns among residences. AvgRoomB, which represents the average field from only the center of each house's rooms, does not completely control for asymmetry, nor does AvgPerimB taken at selected points outside the residence.

Second, linear regression allows us to observe that, within both Backyard ($N = 24$) and Street ($N = 16$) strata, the following model accounts for 100% of the variability in both AvgV$_{OC}$ and AvgChildB (of course, the value of the α coefficients are different for AvgV$_{OC}$ and AvgChildB):

$$\begin{aligned}\text{AvgV}_{OC} \text{ or AvgChildB} = {} & \alpha_1 * (AvgGC) \\ & + \alpha_2 * (\text{Ground Type}) \\ & + \alpha_3 * (\text{Ground Type})^*(AvgGC) + \varepsilon\end{aligned}$$

TABLE 4. Summary Results of Regression Analysis of Full Sample ($N = 40$)

	Predictor variables		
Exposure variable	Line type (OH or UG)	Location (Backyard or Street)	Ground type (Short or Long)
AvgRoomB	OH, < 0.01	Backyard, < 0.05	> 0.2
180HzAvgB	OH, < 0.05	Backyard, < 0.01	> 0.2
AvgPerim	> 0.2	Backyard, < 0.01	> 0.2
AvgChildB	OH, < 0.01	Backyard, < 0.01	> 0.2
10%ChildB	OH, < 0.01	Backyard, < 0.01	Long, < 0.05
AvgGC	OH, < 0.01	> 0.2	Short, $= 0.01$
10%GC	OH, < 0.01	> 0.2	Short, < 0.01
AvgV$_{OC}$	< 0.2	Backyard, < 0.001	Long, < 0.001
10%V$_{OC}$	< 0.2	Backyard, < 0.001	Long, < 0.001

Table shows P-value associated with regression coefficients of predictor variable; $P < 0.2$ means $0.10 < P < 0.2$; $P < 0.1$ means $0.05 < P < 0.1$; $P < 0.05$ means $0.01 < P < 0.05$; $P < 0.01$ means $0.001 < P < 0.01$. In one case $P = 0.01$.
Table also shows which predictor causes exposure to rise for all cases when $P < 0.05$, e.g., AvgGC increases with Short Ground Type, compared to Long, and AvgRoomB increases with OH Line Type, compared to UG.

TABLE 5. Pearson Correlation of Average Exposure Parameters (N = 40)

	180HzAvgB	AvgPerimB	AvgChildB	AvgGC	AvgV$_{OC}$
AvgRoomB	0.99	0.84	0.78	0.54	0.68
180HzAvgB	—	0.84	0.80	0.50	0.73
AvgPerimB		—	0.74	0.47	0.66
AvgChildB			—	0.65	0.93
AvgGC				—	0.37

The Ground Type main term (the α_2 term) contributes negligibly to explaining AvgV$_{OC}$ or AvgChildB. In other words, within each Location stratum (Backyard or Street) both AvgV$_{OC}$ and AvgChildB in our model are determined solely by ground current plus ground current as modified by the length of the ground path. For AvgRoomB, the same model explains 45% of the variance for Backyard and 72% of the variance for Street; for AvgPerimB, the model explains 47% of the variance for Backyard and 46% of the variance for Street. For neither AvgRoomB nor AvgPerimB were the main Ground Type or interaction terms statistically significant. Thus, across the full population of our model neighborhood, V$_{OC}$ and the child's magnetic field exposure classify each other better than any of the other field or ground current quantities.

Comparative Dosimetry

Finally, we compare dosimetric quantities averaged within the bone marrow and across the heart of an adult male resulting from magnetic field exposure, electric field exposure, and contact current, all 60 Hz. Although an important focus of these comparisons concern children, more precise modeling data are available for adults than for children. For this comparison, a uniform magnetic field of 10 μT, oriented perpendicular to the front of the body was chosen; the electric field chosen was 100 V/m, vertical and uniform when unperturbed; two electric field results are presented, one for a grounded subject and one for a subject in free space (off ground). These values represent extremely high residential fields that do not occur away from appliances. Contact current was estimated from the upper 10% average V$_{OC}$ value of 90 mV (see Table 2). Assuming a total body resistance (R$_P$) of 2.5 kΩ (see Reilly, 1998) and the same value back to the circuit ground (R$_G$), for a total resistance of 5 kΩ, we calculated a contact current of 18 μA, more than ten times below the median perception threshold for adult males (0.36 mA) [IEEE, 1985]; based on limited data for children in IEEE [1985], we estimated that the perception threshold for a child would be about 35–50% of the value listed for adult males (on the order of 0.15 mA). Of course, for hand-to-feet contact, current would double in a very well-grounded person, but would be much less, or even zero, for an individual wearing well-insulated footwear or standing on an insulated floor surface.

TABLE 6. Comparative Dosimetry from Magnetic Field, Electric Field, and Contact Current Exposure[a]

			Bone marrow		Heart		
Factor	Configuration	60 Hz exposure	E (mV/m)	J (mA/m^2)	E (mV/m)	J (mA/m^2)	Reference
Magnetic field	Uniform, horizontal, perpendicular to front of body	10 μT	1.6×10^{-1}	8.0×10^{-3}	1.4×10^{-1}	1.4×10^{-2}	Dawson and Stuchly, 1998
Electric field	Uniform, vertical, grounded model	100 V/m	3.2×10^{-1}	1.6×10^{-2}	1.3×10^{-1}	1.3×10^{-2}	Stuchly et al., 1998
Electric field	Uniform, vertical, free space model	100 V/m	1.0×10^{-1}	5.0×10^{-3}	6.6×10^{-2}	6.6×10^{-3}	Stuchly et al., 1998
Contact current	Current injection into shoulders	18 μA (total)	3.5×10^{0}	1.8×10^{-1}	1.9×10^{0}	1.9×10^{-1}	Dawson et al., in press[b]

[a] The electric fields and current density values are averaged across the tissue.

[b] This reference reports dosimetry relevant to pacemaker interference only; tissue average values for this table provided by M. Stuchly (personal communication).

σ(heart) = 0.1 S/m

σ(marrow) = 0.05 S/m

The induced average electric fields and current densities (Table 6) were derived from values published by Stuchly and colleagues (references listed in table). These investigators used the scalar potential finite difference and finite-difference time-domain methods to calculate induced electric fields and current densities from fields and injected currents in anatomically correct models of adult males subdivided into cuboidal voxels 3.6 mm on a side, with tissue-specific conductivity, as estimated from published sources.

Table 6 reports that 18 μA injected current produces an electric field of 3.5 mV/m averaged across bone marrow and 1.9 mV/m averaged across heart tissue, more than an order of magnitude higher than from the field levels selected for comparison.

DISCUSSION

Our initial objective was to explore a possible engineering basis for the result of Ebi et al. (1999) that, in two previous studies of power lines and childhood cancer [Savitz et al., 1988; London et al., 1991], risk was related to the backyard location of lines, in contrast to street location. To that end, we developed a virtual neighborhood of 40 single-dwelling houses with different combinations of residential electric service attributes, including line location, line type, and ground length, as described above in detail. We report higher power-frequency and harmonic fields associated with overhead lines located in the backyard, higher ground currents associated with overhead lines and short ground paths, and higher open circuit voltage (V_{OC}) associated with backyard lines and long ground paths. Further, we find (a) V_{OC} is highly correlated with the magnetic field across the residential floor area (AvgChildB) in the neighborhood model; and (b) compared to magnetic or electric fields, V_{OC} can produce a higher electric field in target tissue. As further discussed below, these last two results suggest that V_{OC} is a potentially relevant, though overlooked, exposure in prior studies concerned with the relationship of electric power line environments to health.

Correlation of Magnetic Fields With V_{OC}

The correlation of magnetic fields with V_{OC} in our virtual neighborhood reflects their fundamental electrical relationship. Both result from electrical current, the former from any current source near or in a residence and the latter from current in the ground. The high correlation of V_{OC} with AvgChildB for the neighborhood indicates that, in locations with similar electrical characteristics, the magnetic field measured across a residential area would serve as a marker or surrogate for V_{OC}. In actual neighborhoods, a poorer correlation is likely to occur. For example, currents on primary distribution lines that do not contribute to a given residence's ground current will nonetheless contribute to the residential field. Likewise, the correlations reported here do not extend to magnetic fields calculated for residences near overhead transmission lines based on historical load data, as was done for several Scandinavian epidemiology studies [reviewed in NIEHS Working Group, 1998]. Without further investigation, however, we would not categorically dismiss the possibility of contact potentials resulting from magnetic induction on long conductive paths within and between residences abutting rights-of-way.

We designed the neighborhood according to the ‘‘multi-ground neutral’’ practice required in the US, in which the chassis wire, the ground wire, and the utility neutral are electrically connected with each other at the service panel. As a consequence, current in the ground will create a voltage source of magnitude V_{OC} at the chassis, which can drive a small "leakage" or contact current into an individual who contacts it (Figure 2). Several European countries, have used grounding practices that keep the chassis wire separate from the ground return pathway, leaving a much lower possibility for contact current [Rauch et al., 1992].

It is important to observe that V_{OC} is a characteristic of the residence itself, as determined by its electrical supply and grounding characteristics. Thus, all plugged-in devices with a conductive exterior surface will carry an equivalent V_{OC}, regardless of location in the residence. In contrast, high magnetic fields are often confined to "hot spots" associated with service drops, ground return pathways, or unusual wiring. Such hot spots may be away from areas that are normally occupied.

Dosimetry

As shown in Table 6, contact currents far below perception thresholds produce electric fields in tissue that exceed those due to ambient residential magnetic fields (away from appliances). We compared a contact current due to time-averaged V_{OC} within the upper tail of this parameter's distribution across the neighborhood to a uniform magnetic field (10 μT) larger by a factor of at least 10–20 than the highest space and/or time-averaged residential magnetic fields measured in many US studies [reviewed in Kavet, 1995]. Near appliances the fields may be even higher than 10 μT, but they are highly nonuniform in space falling off usually with the cube of distance from the device.

The dosimetric contrasts shown in Table 6 for adults would likely be accentuated for child-size subjects. As Kaune et al. [1997] have shown in analytical solutions of simple ellipsoidal models, induced electric fields and current densities from the same electric and magnetic fields as above would be lower due to reduced coupling to the smaller body size. With the dimensions Kaune et al. [1997] used, coupling in children was about 30% lower for both magnetic and electric fields. For contact potentials, although total body impedance is higher for children (approximately 40–50%, see Reilly [1998]), their reduced cross sectional area (roughly half or less of an adult) results in larger induced quantities. Further, the marrow dose for contact current shown in Table 6 was based on bilateral current injection into the shoulders [to analyze pacemaker interference (Dawson et al., in press)]. The tissue levels shown in the table are averaged across the body even though, for shoulder injection, the current through the arm is negligible. Thus, for hand-to-feet conduction, the current would pass through the long bones of a single arm, which has a smaller cross section than the leg, the net effect of which would be higher induced quantities in the exposed upper extremity.

In addition to these relative aspects of dose, the absolute (as well as modest) level of contact current modeled (18 μA) produces average electric fields in tissue along its path that exceed 1 mV/m. At and above this level, the NIEHS Working Group [1998] accepts that biological effects relevant to cancer have been reported in "numerous well-programmed studies". The effects the Working Group cites are "increased cell proliferation, disruption of signal transduction pathways, and inhibition of differentiation". The NIEHS endorses this conclusion in its final EMF RAPID report [1999].

Nonetheless, it remains important to compare electric fields induced in tissue due to environmental exposure to the magnitude and spectra of fields due to endogenous electrical activity. Hart and Gandhi [1998] report that the average 40–70 Hz endogenous electric field in cardiac tissue is between 8 and 25 mV/m, depending on computational method. The cardiac signal decreases with distance to neighboring tissue and is negligible in the brain. Natural electrical activity in the central nervous system (CNS), as recorded on the electroencephalogram, may be several millivolts per meter (see NIEHS, 1997), peaks below 30 Hz and has little spectral power beyond 40 Hz.

Bone marrow, target tissue for leukemia, is located directly adjacent to bone tissue, which when physically loaded, experiences "streaming potentials" of up to 0.1–1 V/m [MacGinitie, 1995; reviewed in NIEHS Working Group, 1998]. In general, the spectral power of these potentials is mainly below 10 Hz [McLeod et al., 1998]. The extent to which these fields extend to the marrow is not known precisely, although they tend to be radially oriented and would not be expected to produce marrow fields that exceed 1 mV/m. Although cartilage has streaming potentials even higher than bone, the physical and electrical relations of cartilage to bone marrow are also likely to result in only small fields in the marrow [K. McLeod, personal communication]. Finally, active skeletal muscle produces local extremely-low-frequency (ELF) electric fields due to ongoing action potential activity. However, given the relative resistance of muscle and bone, the resulting fields normal to the bone are expected to remain confined to the muscle layer itself with little effect inside the marrow; some penetration of the component parallel to bone will occur due to boundary effects, but is likely to be attenuated in the marrow. Thus, the marrow of the long bones, site of hematopoiesis and leukemogenesis in humans, is most likely electrically silent with respect to natural ELF signals in the heart and CNS (due to distance), and based on first principles, quite likely "quiet" due to bone and muscle activity nearby. However, further microdosimetric research will be required to clarify the natural electric field environment inside bone marrow.

Epidemiological Implications

In a pooled analysis of all "qualifying" worldwide studies concerned with residential magnetic fields and childhood leukemia published through 1998, Greenland et al. (submitted) report a summary relative risk of 1.8 (95% CI: 1.1–2.9) associated with fields greater than 0.3 μT, compared to < 0.1 μT, with no evidence of heterogeneity across studies or across continents. In contrast, the risks associated with high wire categories (relevant to US studies only) were not consistent across studies.

Since the pooled analysis was completed, two studies of leukemia among children in Canada have been published, with neither reporting excess risk associated with wire code. McBride et al. [1999] reported little indication of an association of leukemia with personally monitored fields, while Green et al. [1999a] showed elevated odds ratios associated with fields measured within the residence and around the residence perimeter, as well as with the exposures recorded on personally-worn monitors [Green et al., 1999b]; these elevated risks were concentrated among younger children. A study across England, Wales, and Scotland [UKCCSI, 1999] reported no excess risks of childhood leukemia (or other cancers) associated with measured residential magnetic fields. How these more recent results may affect the pooled analysis has not been determined.

The immediate application of our results to specific studies in the EMF childhood leukemia literature is limited. The neighborhood was configured to represent residential electric service scenarios found in the Denver [Savitz et al., 1988] and Los Angeles [London et al., 1991] studies to address findings unique to those data sets [Ebi et al., 1999].

To that end, the neighborhood model incorporated realistic housing dimensions and realistic distances from the residence to street facilities (utility line and water main) and to backyard lines. The loads on the service drop conductors and 3rd harmonic generated from residential electricity usage were based on data acquired in a large-scale survey of nearly 1000 homes in the US [Zaffanella, 1993]. The power lines serving the neighborhood, however, were not loaded in accordance with their current-carrying capacity, nor were transformers more heavily concentrated on three-phase primaries, as compared to the other primaries in the model. Accordingly, the model neighborhood's power delivery system analyzed in this paper did not (and was not intended to) simulate the Wertheimer-Leeper wiring configurations, as they have been used in many epidemiological and exposure assessment studies.

In our simulated neighborhood, in which overhead distribution currents played no role in producing residential fields, the Spearman correlation of AvgGC with RoomAvgB was 0.52; in a sample of 333 nationwide residences whose magnetic fields were minimally affected by overhead power lines [see Kavet et al., 1999], the Spearman correlation of 24 h average ground current with spot measurements averaged across the residence was 0.41 [Kavet, unpublished observation]. Whereas the latter correlation was with respect to a field measurement taken at one point of time during the day in the real world, compared to a time averaged room measurement computed in a simulated neighborhood, the correspondence of these two correlation values is reassuring with regard to the neighborhood's representativeness of service drop/ground electrical properties.

V_{OC} is an exposure variable that we believe could explain the marginal association of measured field with leukemia in the Denver study (odds ratio (OR) of 1.93, 95% confidence interval (CI) 0.67–5.56; $\geq 0.2\,\mu T$ spot-measured field compared to $< 0.2\,\mu T$), and in the Los Angeles study (OR of 1.48, 95% CI 0.66–3.29; $\geq 0.268\,\mu T$ 24 h bedroom average compared to $< 0.68\,\mu T$). Both of these studies also reported positive associations between Wertheimer-Leeper wire code and leukemia risk, as well as positive associations between wire code and measured fields. As Ebi et al. [1999] reported, the wire code/leukemia associations in both studies were confined to backyard lines. Here, we report that both magnetic fields and V_{OC} are higher in residences with backyard lines.

In a separate follow-up analysis of the Savitz et al. (1988) Denver data set, Wertheimer et al. [1995] reported that increased all-cancer risks were associated with conductive plumbing, as well as with a metric they termed "elevated non-vertical" (ENV) fields, a marker of magnetic fields due to ground currents. These ENV fields may well have served as markers for V_{OC} according to the engineering relationships presented in this paper. No similar data were explicitly reanalyzed for Los Angeles, although Bowman et al. [1999] created a predictive model for residential magnetic fields in that data set which was used to confirm an association of leukemia risk with magnetic fields [Thomas et al., 1999]. These investigators conclude that the predicted fields cannot entirely account for the wire code association with leukemia reported by London et al. [1991], and that ''the most likely hypothesis is that an unidentified exposure metric involving the ELF magnetic field plays a role in carcinogenesis''. Although the investigators are likely alluding to alternate field metrics (perhaps transients), we believe that in a broader context, a ''metric involving the ELF magnetic field'' could also include contact current.

In the nine-state National Cancer Institute (NCI) childhood leukemia study [Linet et al., 1997], excess risk was reported for fields above 0.3 μT ''blended'' time-average field relative to <0.065 μT (OR 1.7; 95% CI 1.0–2.9); in the 0.4–0.5 μT stratum, the OR peaked at 3.3 (95% CI 1.2–9.4). At higher fields the OR fell. We can only conjecture that the absence of a monotonic risk function in this study is due to the fact that the highest fields in the NCI data are caused by sources, such as nearby high voltage transmission lines, which do not contribute current to the residential ground path and thus to V_{OC}, whereas risk peaked among residences with high fields created by ground currents with correlated increases in V_{OC}. The NCI study reported no relationship of leukemia risk with Wertheimer-Leeper wire code category.

As mentioned above, the model here does not in any obvious way, adequately explain positive associations of cancer with overhead high voltage transmission lines, as reported in Sweden by Feychting et al. [1993]. However, we note the absence of a positive association in the study of childhood leukemia across the United Kingdom [UKCCSI, 1999], where residential wiring practices may preclude contact currents of the magnitude prevalent in residential electrical systems in the US.

Limitations

At this time there are no data that describe (a) the distribution of V_{OC} across residences, both single dwelling and multioccupancy, (b) the extent of physical contact with energized equipment or other conductive objects in the home that could produce contact current, or (c) the currents that actually result from such contacts. Factors that affect the magnitude of current from such contact include a residence's service/ground configuration and time-varying net load, alternative current paths (hand-to-hand and hand-to-feet), and variable impedance back to ground.

In addition, other situations can lead to either high V_{OC} or V_{OC} on unintended surfaces. For example, a poor connection in the service drop neutral will increase current through the ground wire, which will increase V_{OC}. Although all water pipes were assumed at ground in the model, a poorly conductive joint in a water line can produce V_{OC} on water fixtures if the ground wire is bonded upstream of that joint.

We need to address the data gaps identified above from a historical, as well as contemporary, perspective. Historical, to understand previous epidemiology studies of cases that occurred up to decades ago, when appliance construction, home wiring practices, and water service were different than they are today. More appliances today have a plastic exterior compared to metal exterior surfaces prevalent years ago; three-hole and two-hole polarized sockets are standard today as opposed to the unpolarized two-wire sockets used previously; and water service has evolved from copper pipe to plastic pipe, resulting in more alternative grounding practices. Contemporary, because if V_{OC} is an important exposure parameter with respect to health risks, then the knowledge of exposure characteristics as they now occur is critical to the design of new epidemiology studies. Obtaining reasonable estimates of the magnitude and temporal quality (likely to be highly intermittent) of residential contact current exposures, both historically and contemporarily, will also assist in designing laboratory studies to determine if appropriate cell or animal models of leukemia respond to exposures representative of the real world.

Another factor concerns exposures in apartment buildings, in which individual units are served through separate electric meters served from the same service drop. About one-quarter of all housing units in the US are apartments [US Census Bureau, 1999]. Depending on the wiring in the building, V_{OC} in one apartment may be dependent, to some extent, on net loads serving the others.

Other potentially relevant aspects of residential distribution systems have not been addressed here. These would include possible effects from loads downstream of the neighborhood in terms of fields from the primaries associated with those loads, and ground return currents that can insinuate themselves into the neighborhood's grounding system. All of the grounding in the neighborhood was through conductive water pipe through a conductive water main. The analysis here did not address redistribution of return current due to alternate grounding methods, such as driven ground rods or the effect of unintentional faults in the grounding system.

CONCLUSION

We have identified contact current due to V_{OC} as a factor potentially responsible for the association between residential magnetic fields and childhood leukemia. The studies of childhood leukemia risks in

EMF environments, which were of case-control design, encompass diverse combinations of base populations, control selection methods, transmission and distribution systems, and methods for assessing historical exposure relevant to a proposed etiologic period. Although alternate environmental exposures, including local vehicular traffic density [Pearson et al., 1999], viral contact [Sahl, 1994], and water quality [Kavet, 1995] have been proposed as possible explanations, none have risen to an acceptable level of plausibility. In addition, no bias with respect to case-control selection or response has been identified that would rationalize the positive associations in any unifying way [NIEHS Working Group, 1998]. The NIEHS Working Group's report [1998] and the NIEHS EMF RAPID report [1999] both concluded that significant uncertainty remains with respect to childhood leukemia risk in magnetic field environments.

In the virtual neighborhood analyzed here, which models residential service for single dwelling homes across much of the US and Canada, V_{OC} is strongly associated with the magnetic field, and is capable of delivering biologically significant dose to target tissue. Our conclusion regarding V_{OC} is more difficult to rationalize for those studies reporting positive associations in an overhead transmission line environment, although exposed caseloads were extremely small in number and magnetic induction effects cannot be ruled out automatically. The pooled analysis by Greenland et al. (submitted) suggests increased childhood leukemia risk above 0.3 μT, indicative of large currents in and around the residence. In our model, large currents in the ground are also capable of generating high V_{OC}. Interestingly, there has been no trace of positive association of childhood leukemia with residential electric fields [Savitz et al, 1988; London et al., 1991; McBride et al., 1999], which may be present regardless of current flow.

Two-year bioassays, as well as shorter-term model-specific bioassays for magnetic field carcinogenicity, and leukemia in particular, have been almost entirely negative [McCann et al., 1997, 2000] and have created a conceptual obstacle for drawing inferences regarding magnetic fields as a possible leukemogen [NIEHS, 1999]. If a toxicologically significant dose (induced electric field) is required in the fore- and hindlimbs to promote leukemia in a rodent model, then a magnetic field, even the high fields used in the bioassays, may be ineffective because of poor coupling to those sites.

To date there is no accepted biophysical mechanism that would explain leukemogenic effects of residential-strength magnetic fields, which are < 1 μT away from appliances [Valberg et al., 1997; NIEHS Working Group, 1998]. Contact currents due to V_{OC}s of the magnitude estimated for the residences in our neighborhood model produce electric fields in tissue that do not strain the question of biological plausibility to this extent, and in fact, produce doses with the potential to trigger biological effects.

Many unknowns about contact currents resulting from V_{OC} remain with respect to biological effects in appropriate laboratory models, the extent of exposure across the population now and historically, and the relevant associations of exposure with health endpoints. Finally, contact current is an exposure that likely occurs in the workplace in association with energized equipment. Occupational exposures to contact current merit as much attention as do residential exposures.

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APPENDIX 1

Detailed Neighborhood Description

1. Four streets and 40 houses comprise the model (Figure 3). A Street, B Street, and C Street run West to East, and N Street runs South to North. A Street and C Street are cul-de-sac, with 12 houses in A Street and six in C Street included in the study. B Street and N Street are through streets. Twelve houses in B Street and 10 in N Street are included in the study. A Street, B Street, and C Street are 12.2 m (40 feet) wide. N Street is 19.8 m (65 feet) wide. Houses are set back 9.1 m (30 feet) from the street.
2. A three-phase overhead distribution line, with thick wires (the term, "thick", was used by Wertheimer and Leeper [1979] to describe lines with high potential loading), is running along N Street. Another three-phase overhead distribution line, with thick wires, is running in the backyards of houses between A and B Streets. An overhead distribution line with a single-phase primary is running in the backyards of houses between B and C Streets. An underground distribution line serves the houses on the North side of A Street. The height of the neutral above ground is 10.1 m (33 feet). The distances between houses and lines are shown in Figure 3 and are listed in Appendix 2.

3. Seven different distribution transformers (T1 to T7) serve different groups of houses as shown in Figure 3. The transformers are connected between one phase of the primary and the neutral. For instance, transformer T6 is connected between Phase C and the neutral and serves eight houses: four houses directly connected to the transformer and four houses connected at the end of a secondary line.
4. The segments of the ground current circuit are indicated with thicker lines. They include water mains, water service lines connecting houses to the main, and the conductors connecting the electrical service neutral to the water service line inside the houses (“grounding wires”). The water mains are located in the middle of the street, 1.1 m (3.6 feet) below street level. Two types of ground current paths are considered inside each house: type 1 and type 2 (Figure 4). Type 1 is the shorter possible path for overhead street lines, overhead backyard lines, and underground street lines (top to bottom in Figure 4). Type 2 is the longer possible path for overhead street lines, overhead backyard lines, and underground street lines (top to bottom in Figure 4). For each house, the service drop arrives at a corner and then goes to the electrical panel. The attachment points of overhead service drops at the houses are 5.3 m (17.4 feet) above street level. The distance between service drop and inside wall of the house is 0.5 m (20 inches). The grounding wire is 0.3 m (10 inches) below the first floor. The water service line from the main is perpendicular to the street and arrives at 0.3 m (1 foot) from a house corner at a depth of 1.1 m (3.6 feet) below street level.
5. The class (1 = thick 3-phase primary, 3 = first span secondary, 6 = end pole, 7 = underground), distance, and wire code of the residences, the type of line (street or backyard), and the type of ground current path (Type 1 or Type 2) are listed in Appendix 2. Using Wertheimer-Leeper wire code terminology, there are 11 Very High Current Configuration (VHCC) houses, 13 Ordinary High Current Configuration (OHCC) houses, two Ordinary Low Current Configuration (OLCC) houses, and 14 Very Low Current Configuration (VLCC) houses, six of which have underground service.
6. The same dimensions are assigned to all houses: two-floor houses with a rectangular floor plan 10.7 m by 7.6 m (35 × 25 ft), with the longest dimension parallel to the street. The first and second floors are at 0.5 m (1.6 feet) and 3.3 m (10.8 feet) above street level, respectively. Each house contains eight equal size rooms, four per floor.
7. The electrical parameters of the conductors of the ground current circuit are given in Appendix 3. The values of these parameters were chosen to represent values encountered in practical situations. The termination impedances (to ground) simulating the extension of water mains and primary neutrals beyond the immediate neighborhood are listed in Appendix 3. The primary loads and their return currents had a negligible effect on residential magnetic fields and ground currents, and, therefore, were not taken into account in the neighborhood analysis presented in the Results.

APPENDIX 2

Characteristics of Neighborhood Houses

House	Class	Distance m (feet)	Residence code	Line type	Line location	Ground type
A1	7	7.6 (25)	VLCC	UG	Street	1
A2	1	13.7 (45)	VHCC	3-Phase	Backyard	1
A3	7	7.6 (25)	VLCC	UG	Street	2
A4	1	13.7 (45)	VHCC	3-Phase	Backyard	2
A5	7	7.6 (25)	VLCC	UG	Street	2
A6	1	13.7 (45)	VHCC	3-Phase	Backyard	1
A7	7	7.6 (25)	VLCC	UG	Street	1
A8	1	13.7 (45)	VHCC	3-Phase	Backyard	2
A9	7	7.6 (25)	VLCC	UG	Street	1
A10	1	13.7 (45)	VHCC	3-Phase	Backyard	2
A11	7	7.6 (25)	VLCC	UG	Street	1
A12	1	13.7 (45)	VHCC	3-Phase	Backyard	1
B1	1	24.4 (80)	OHCC	3-Phase	Backyard	2
B2	6	13.7 (45)	VLCC	1-Phase	Backyard	2
B3	1	24.4 (80)	OHCC	3-Phase	Backyard	2
B4	3	13.7 (45)	OHCC	1-Phase	Backyard	1
B5	1	24.4 (80)	OHCC	3-Phase	Backyard	1
B6	3	13.7 (45)	OHCC	1-Phase	Backyard	1

House	Class	Distance m (feet)	Residence code	Line type	Line location	Ground type
B7	1	24.4 (80)	OHCC	3-Phase	Backyard	1
B8	6	13.7 (45)	VLCC	1-Phase	Backyard	2
B9	1	24.4 (80)	OHCC	3-Phase	Backyard	1
B10	6	13.7 (45)	VLCC	1-Phase	Backyard	2
B11	1	24.4 (80)	OHCC	3-Phase	Backyard	2
B12	6	13.7 (45)	VLCC	2-Phase	Backyard	1
C1	6	24.4 (80)	VLCC	2-Phase	Backyard	1
C3	3	24.4 (80)	OLCC	2-Phase	Backyard	2
C5	3	24.4 (80)	OLCC	2-Phase	Backyard	1
C7	6	24.4 (80)	VLCC	2-Phase	Backyard	2
C9	6	24.4 (80)	VLCC	2-Phase	Backyard	2
C11	6	24.4 (80)	VLCC	2-Phase	Backyard	1
N1	1	13.7 (45)	VHCC	3-Phase	Street	1
N2	1	24.4 (80)	OHCC	3-Phase	Street	1
N3	1	13.7 (45)	VHCC	3-Phase	Street	1
N4	1	24.4 (80)	OHCC	3-Phase	Street	1
N5	1	13.7 (45)	VHCC	3-Phase	Street	2
N6	1	24.4 (80)	OHCC	3-Phase	Street	1
N7	1	13.7 (45)	VHCC	3-Phase	Street	1
N8	1	24.4 (80)	OHCC	3-Phase	Street	2
N9	1	13.7 (45)	VHCC	3-Phase	Street	2
N10	1	24.4 (80)	OHCC	3-Phase	Street	2

APPENDIX 3

Electrical Parameters of the Ground Current Circuit Conductors[a]

	Resistance (mΩ/m)	Geometric mean diameter (m)
Primary neutral	0.494	0.008
Secondary neutral (overhead line)	0.494	0.008
Secondary neutral (underground line)	0.336	0.009
Service drop neutral (overhead)	0.494	0.008
Service drop neutral (underground)	0.84	0.005
Grounding wire	3.25	0.0025
Water line	0.206	0.023
Water main[b]	0.32	0.01
Ground rod at service entrance	50 Ω	
Water main terminations	0.002 Ω	
Primary neutral terminations	0.002 Ω	

[a] The values in the table are based on personal experience of one of the authors (LEZ), who managed the EPRI high voltage facility in Lenox, MA, was the principal investigator of the "1000-home study" [Zaffanella, 1993], and developed the algorithms for the ground current network analysis used in the modeling software.

[b] Geometric mean diameter (GMD) is a function of a conductor's physical dimensions and impedance characteristics. The water main has a smaller GMD than the water line, even though it is physically larger.

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