Abstract of EMF RAPID Program Engineering Project #8: Evaluation of Field-reduction Technologies

This project evaluates field-reduction techniques, with a goal of providing information to help decisionmakers consider questions centered on the potential for/ ways to reduce fields. The project examines field-reduction methods for a variety of magnetic-field sources, including transmission and distribution lines, substations, building wiring, appliances and machinery, and transportation systems.

The report evaluates five magnetic-field-reduction methods, including (1) minimizing magnetic fields when current-carrying conductors are matched with appropriate return conductors, (2) placing opposing current pairs as close together as possible, (3) splitting currents, (4) decreasing magnetic fields via distance from the sources, and (5) reducing current and thus reducing magnetic fields. Lifetime costs estimates were developed for reducing magnetic fields from six source types. The relative cost depends strongly on the source type and the selected field criterion.

Transmission lines: Costs are greater for rural designs than for suburban designs. Costs increase sharply with voltage level. Options are limited for 500-kV or 765-kV designs.

Distribution lines: Life-cycle costs increase significantly only for field limits of about 5 mG or less. Distribution-line cost multipliers increase with voltage.

Substations: Most of the magnetic field at a substation perimeter fence is from transmission and distribution lines entering the facility. The feasibility and cost of limiting public exposure to substation magnetic fields would depend heavily on modifications of those lines.

Customer-side power distribution: At 5 mG or less, all sources would require attention. Greatest impacts would occur if vaults, buses, and feeders had to meet a 5-mG or 2-mG exposure limit.

Appliances and machinery: Exposure limits defined for all points and near an appliance or machine could be extraordinarily difficult to achieve.

Electric railways: Power-frequency magnetic-field exposure limits could substantially affect electric railways. Edge-of-right-of-way limits would require changes like those for transmission lines. Defining exposure limits for passengers would be difficult.

Study limitations/Areas for future research

The investigators had access only to data on existing technologies and/or published research reports. Consequently, important work in progress under EPRI sponsorship and proprietary information were unavailable for consideration and inclusion.

The estimates of costs for powerline field management are based on standard right-of-way widths. Adjustments for land costs are available in Volume II of the report.
Incorporate recent work and new technologies into similar cost estimates.

EMF RAPID Program Engineering Project #8: Evaluation of Field-reduction Technologies

Purpose and Focus

This project evaluates field-reduction techniques with a goal of providing information to help decisionmakers consider essential questions centered on the potential for and ways to reduce fields. Until the proposed power-frequency magnetic-field health effects hypotheses are either proved or disproved, no scientific basis for defining safe human exposure thresholds will exist. Long-term planners must nonetheless ask whether it would be technically and economically possible to modify the use of electric power if magnetic fields were ever linked to adverse health.

Tasks and Approach

The project examines field-reduction methods for a variety of magnetic-field sources. These include the following:

- transmission lines,
- distribution lines,
- substations,
- building wiring,
- appliances and machinery, and
- transportation systems.

There are at least five magnetic-field-reduction methods. These include the following:

- minimizing magnetic fields when current-carrying conductors are matched with appropriate return conductors,
- placing opposing current pairs as close together as possible,
- splitting currents,
- decreasing magnetic fields via distance from the sources, and
- reducing current and thus reducing magnetic fields.

Within each category, magnetic-field-reduction methods are evaluated, based on their effectiveness, cost, environmental impact, and safety impact. The report focuses on power-frequency magnetic fields because these have been the focus of most of the recent health effects research.

One or more "problem" sources are identified that would be exceptionally difficult or expensive to modify into low-field versions if exposure limits were imposed. They include the following:

(1) transmission lines operating at voltages of 500 kV or above;
(2) unbalanced resultant (zero sequence) current on distribution lines;
(3) transmission line substation connections at 500 kV or above;
(4) vaults, buses, and feeders in buildings;
(5) industrial welding and metal melting processes; and

(6) most types of electric railway systems.

Transmission Lines

A case-study approach was used to compare magnetic fields, electric fields, and life cycle costs of various transmission line designs. Both "rural" and "suburban" designs were examined within each of four voltage categories (69 kV, 115 kV, 230 kV, and 345 kV). Rural-only designs were examined at 500 kV and 765 kV.

Several magnetic-field-reduction methods were considered. These included the following:

- compaction,
- phase splitting,
- higher voltage lines,
- shielding provided by underground pipe-type cables, and
- line-side passive cancellation loops.

The analysis showed that transmission-line life-cycle costs would increase sharply if magnetic-field exposure limits were set at 5 mG or 2 mG for publicly accessible areas.

- At 69 kV and 115 kV, life-cycle costs could increase by as much as 20% to meet a 20-mG standard and could double or triple to meet a 2-mG standard.
- At 230 kV, costs could increase by as much as 50% for 20 mG and triple or quadruple for a 2 mG limit.
- Costs for a 345-kV line would triple or quadruple to meet a 20-mG exposure limit. (See Table A-12, below.)
- No 500-kV options were identified that could meet a 50-mG or lower exposure limit; no 765-kV options were found that could meet a 100-mG or lower limit on the right-of-way. A series-capacitor-compensated cancellation loop might be effective for 500-kV and 765-kV edge-of-right-of-way field limits, however.

Table A-12: Transmission-line Magnetic-field-reduction Summary (selected cases)

Voltage	<50 mG Type	Live-Cycle Cost Multiplier	<20 mG Type	Life-Cycle Cost Multiplier	<5 mG Type	Life-Cycle Cost Multiplier	<2 mG Type	Life-Cycle Cost Multiplier
69 kV (72 MVA) Rural	Split-6	1.13	Split-6	1.13	Split-6 Suburban	1.48	UG HPGF Pipe	2.67
69 kV (72 MVA) Suburban	Delta	1.00	Split-6	1.23	Split-6	1.23	UG HPGF Pipe	2.21
115-kV (120 MVA) Rural	Delta Cpct.	0.96	Split-6 Cpct.	1.18	Split-6 Cpct. Suburban	1.56	UG HPGF Pipe	2.78

Voltage	**<50 mG Type**	**Live-Cycle Cost Multiplier**	**<20 mG Type**	**Life-Cycle Cost Multiplier**	**<5 mG Type**	**Life-Cycle Cost Multiplier**	**<2 mG Type**	**Life-Cycle Cost Multiplier**
115 kV (120 MVA) Suburban	Delta	1.00	Delta Cpct.	0.97	Split-6 Cpct.	1.24	UG HPGF Pipe	2.22
230 kV (239 MVA) Rural	Split-6 Cpct.	1.16	Split-6 Cpct. Suburban	1.48	UG HPFF Pipe	3.80	UG HPFF Pipe	3.80
230 kV (239 MVA) Suburban	Delta	1.00	Split-6 Cpct.	1.18	UG HPFF Pipe	3.01	UG HPFF Pipe	3.01
345 kV (717 MVA) Rural	230 kV Split-6 Cpct. Suburban	1.54	UG HPFF Pipe	3.88	UG HPFF Pipe	3.88	UG HPFF Pipe+?	3.88+?
345 kV (717 MVA) Suburban	230 kV Split-6 Cpct.	1.19	UG HPFF Pipe	2.98	UG HPFF Pipe	2.98	UG HPFF Pipe+?	2.98+?

Underground pipe-type cables provide the lowest transmission-line magnetic fields, but are not commercially available for line voltages exceeding 345 kV. Their use would almost certainly be required to meet 2-mG standards. Six-wire and five-wire split-phase lines (the lowest-field overhead conductor designs) could probably meet 5-mG standards at 115 kV and below. The taller towers and shorter spans of the suburban overhead transmission lines studied at 345 kV and below offered much lower peak magnetic and electric fields than their rural counterparts. The effect was less significant outside the right-of-way.

Unbalanced resultant (zero sequence) currents are usually the most significant magnetic-field source outside a transmission line right-of-way. If low magnetic-field levels were mandated, unbalanced current would have to be minimized throughout the transmission network. This action would entail balancing the line loading at transmission substations, transposing transmission line conductors, and adding low-impedance shield wires to “attract” zero sequence current.

Distribution Lines

The magnetic fields, electric fields, and life cycle costs of various distribution-line designs were also examined during the project. Both “rural” and “suburban” designs were modeled for 7.6-kV single-phase, 13.2-kV three-phase, and 34.5-kV three-phase categories. Several magnetic-field reduction concepts were evaluated, including compaction, phase splitting, and the use of higher voltage (same load) to reduce current.

For balanced phase-current conditions, low-field distribution line life-cycle costs were predicted to increase significantly only for presumed exposure limits of about 5 mG or less. Costs increased as much as 40% for a 2-mG limit at 7.6 kV and 13.2 kV, for which tall compact and split-phase

Hendrix cable designs could be used. Life-cycle costs for 34.5 kV lines were predicted to increase by 50% to 100% to meet a 2-mG limit, accomplished with a split-phase Hendrix cable design. Heavily loaded distribution lines would have to be shielded, perhaps by underground conduit, to meet a 2-mG limit.

Underground duct and direct burial designs produced the highest magnetic fields at 13.2 kV and 34.5 kV. The underground duct designs nearly triple the baseline design life-cycle costs. See Table A-13, below.

Unbalanced resultant (zero sequence) current is often the most significant source of distribution-line magnetic fields. If very low magnetic-field exposure limits were mandated, control of zero sequence current would be necessary at every point in the distribution network. This significant challenge would require rethinking not only line-design methods, but also broader network-scale issues such as grounding methods, distribution voltage selection, and transformer sizing.

Table A-13: Distribution-line Magnetic-field Reduction Summary (selected cases)

Voltage	<50 mG Type	Life-Cycle Cost Multiplier	<20 mG Type	Life-Cycle Cost Multiplier	<5 mG Type	Life-Cycle Cost Multiplier	<2 mG Type	Life-Cycle Cost Multiplier
7.6 kV (0.76 MVA) Rural	Standard	1.00	Standard	1.00	Tall Cpct.	1.12	Tall	1.12
7.6 kV (1.52 MVA) Suburban	Standard	1.00	Standard	1.00	UG Direct Bury	1.08	Cpct.	1.12+?
13.2 kV (6.86 MVA) Rural	Cross Arm	1.00	Cross Arm	1.00	Split-6 Cross Arm	1.15	Tall Cpct.+?	1.38
13.2 kV (13.7 MVA) Suburban	Cross Arm	1.00	UG Direct Bury	1.05	Split-6 Hendrix	1.32	Split-6 Hendrix	1.32
34.5 kV (17.93 MVA) Rural	Cross Arm	1.00	Delta	1.05	Hendrix Cable	1.31	Split-6 Hendrix	1.55
34.5 kV (35.85 MVA) Suburban	Cross Arm	1.00	Delta	1.08	Split-6 Hendrix	1.45	?	?

<u>Substations</u>

Most of the magnetic field at a substation perimeter fence stems from transmission and distribution lines entering or leaving the facility. The need to build low-field transmission- and distribution-line segments at the station entrance would heavily influence the feasibility and cost of reducing substation magnetic fields. Field-reduction methods and life-cycle costs of these line segments would be similar to those listed for transmission and distribution lines. Few, if any, methods are available to allow 500-kV and 765-kV lines to meet exposure limits below 100 mG.

The cost of a "low-field" substation design would also include the cost of expanding the perimeter fence or wall, if needed. More difficult to predict would be the cost of reducing substation worker exposures. Potential methods for reducing worker exposures include shielding, especially with metal-clad switchgear or gas-insulated substation buses, and remote operation and maintenance.

Customer-side Power Distribution

Many magnetic-field sources are found on the customer side of the electric-utility service connection. These include customer-owned power-distribution equipment such as transformers, switchgear, buses, feeders, service panels, and general wiring. Grounding methods at and beyond the service connection can also affect magnetic fields if stray return current paths are created. Residential and small commercial environments use mostly single-phase sources. Larger commercial and industrial environments use mostly three-phase sources.

Field-reduction methods include rewiring to correct on-premises stray return currents and current loops; installing net current control devices to stop off-premises stray currents; and using rigid metal conduit or flat plate shielding for buses, feeders, branch circuits, lighting panels, and transformer vaults.

Only a few sources, such as transformer vaults and heavily loaded buses and feeders, would require attention if a 100-mG exposure limit were specified. At 5 mG or less, all sources would require attention. The greatest cost impacts would occur if vaults, buses, and feeders had to meet a 5-mG or 2-mG exposure criterion. Such installations could at least double in cost. Some office-building owners have already spent tens to hundreds of thousands of dollars to reduce computer display interference problems by installing magnetic-field shielding.

Appliances

The primary sources of magnetic fields from end-user appliances are resistive heating elements, motors, transformers and coils, and power cords and wiring. Field-reduction methods for these include use of split return or bifiliar heating elements, replacement of inexpensive motors with heavier-duty motors, use of toroidial transformers and coils, installation of shielding for most sources, and conductor compaction for wiring,

The lowest existing magnetic-field emission guideline was established for computer video display terminals (VDTs) by the Swedish government in 1991. That standard, called MPR2, requires VDT magnetic fields to be less than 250 nT (2.5 mG) 50 cm (20 in) from the monitor in the 5 Hz-2 kHz frequency range and less than 25 nT (0.25 mG) in the 2 kHz-400 kHz frequency range. Most new computer monitors are designed to meet the MPR2 standard, since manufacturers have found it possible to meet the standard with little added cost. See Table A-14, below.

No magnetic-field guidelines apply to electric blankets, but some manufacturers have altered their designs to reduce magnetic fields. No other low-field appliance examples are known.

The experience of video-display manufacturers shows that some appliances and machines can be modified at little cost to meet low magnetic-field exposure limits. How far this low cost trend extends to other appliances and machines is unknown, because almost no effort has been expended in this area. Without question, however, some industrial welding and electrically heated metal melting processes would present extraordinary design and cost challenges if low field limits were imposed.

Table A-14: Appliance and Machinery Magnetic-field Reduction Summary

Source Type	<50 mG Method	Est. Cost Multiplier	<20 mG Method	Est. Cost Multiplier	<5 mG Method	Est. Cost Multiplier	<2 mG Method	Est. Cost Multiplier
Appliance Resistive Heating Elements	No Change	1.00	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50
Industrial Resistive Heating Elements	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar+?	1.00-1.50+?	Split Return or Bifiliar+?	1.00-1.50+?
Inexpensive Fractional HP Motors	Shield or Replace	1.00-2.00	Shield or Replace	1.00-2.00	Shield or Replace	1.10-2.00	Shield or Replace	1.10-2.00
Heavier-Duty Motors	No Change	1.00	Shield or Upgrade	1.00-1.50	Shield or Upgrade	1.00-1.50	Shield or Upgrade	1.00-1.50
Appliance Transformers and Coils	No Change	1.00	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50
Industrial Transformers and Coils	Shield or Toroid if needed	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50
Appliance Power Cords and Wiring	No Change	1.00	No Change	1.00	Conductor Twisting/ Spacing	1.00-1.10	Conductor Twisting/ Spacing	1.00-1.10
Industrial Power Cords and Wiring	No Change	1.00	Conductor Twisting/ Spacing	1.00-1.10		1.00-1.10		1.00-1.50

High-Field Industrial Machines (Arc Furnaces, welding, etc.)	Remote Operation ?	1.50+?	Remote Operation ?	1.50+?	Remote Operation ?	1.50+?	Remote Operation ?	1.50+?

Transportation Systems

Power-frequency magnetic-field exposure limits could substantially affect electric railways and other transportation systems. For electric railways, edge-of-right-of-way exposure limits would require changes like those required for transmission and distribution lines. Exposure limits defined for rail passengers would be much more difficult to meet.

Magnetic-field reduction methods might include the following:

- use of DC currents,
- use of third rail or dual overhead trolley bus type feed systems for lower-speed trains,
- use of single-ended autotransformer feeds for high-speed trains,
- use of higher voltages, and
- use of shielding.

The uncertain life-cycle costs of these options would have to be weighed against the costs of abandoning electrification in favor of high-speed diesel or turbine motive power.

Summary

Lifetime cost estimates were developed for reducing magnetic fields from six source types. The relative cost depends strongly on the source type and the selected field criterion.

Transmission lines: Low-field rural transmission line costs increase more than low-field suburban costs. Transmission life-cycle costs increase sharply at 5 mG and 2mG for 69-kV, 115-kV, and 230-kV designs. 345-kV line costs increase significantly below 20 mG for suburban designs and below 100 mG for rural designs. No 500-kV options are available for 50 mG or less; no 765-kV options are available for 100 mG or less.

Distribution lines: Low-field distribution line life-cycle costs increase significantly only for field limits of about 5 mG or less. Distribution-line cost multipliers increase with voltage. No 34.5-kV suburban design option was available for the 2-mG threshold.

Substations: Most of the magnetic field at a substation perimeter fence is from transmission and distribution lines entering the facility. The feasibility and cost of limiting public exposure to substation magnetic fields would be heavily influenced by the need to build low-cost transmission/distribution-line segments at the station entrance. More difficult to predict would be the cost of reducing substation worker exposures. Potential methods for reducing worker exposures include shielding (e.g., metal-clad switchgear or gas-insulated substation buses), and remote operation and maintenance.

Customer-side power distribution: Meeting a standard with new construction would be easier than retrofitting an existing installation. Only a few sources (e.g., transformer vaults and heavily loaded buses and feeders) would require attention if a 100-mG exposure limit were specified. At 5 mG or less, all sources would require attention. The greatest cost impacts would occur if vaults, buses, and feeders had to meet a 5-mG or 2-mG exposure criterion.

Appliances and machinery: Magnetic-field limits would depend on limit values and how exposure limits were defined. Most appliances and machinery magnetic fields drop off quickly. However, exposure limits defined for all points and near an appliance or machine could be extraordinarily difficult to achieve.

Electric railway: Power-frequency magnetic-field exposure limits could substantially affect electric railways and other transportation systems. Impact would depend on values and definition, as with appliances. Edge-of-right-of-way limits would require changes like those for transmission lines. Exposure limits defined for rail passengers would be more difficult to meet.