Electric Power High-Voltage Transmission Lines: Design Options, Cost, and Electric and Magnetic Field Levels

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CONTENTS

ACKNOWLEDGMENTS	viii
NOTATION	ix
SUMMARY	1
1 INTRODUCTION	3
1.1 Purpose and Scope	3
1.2 Background	3
2 METHODS	6
2.1 Search of the Literature	6
2.2 Analysis of Sensitivity	6
2.3 Analysis of Cost versus Fields	7
3 RESULTS	8
3.1 Considerations for Planning and Design	8
3.1.1 Number of Lines	8
3.1.2 Voltage	8
3.1.3 Height of Conductors	8
3.1.4 Spacing of Phases	9
3.1.5 Positioning of Phases	9
3.1.6 Balance of Phases	9
3.1.7 Spacing and Location of Conductors	10
3.1.8 Size and Bundling of Conductors	10
3.1.9 Underbuilding	10
3.1.10 Width of Right-of-Way	10
3.1.11 Design Practices of Utilities	11
3.2 General Methods for Electric and Magnetic Field Reduction	11
3.2.1 Shielding	11
3.2.2 Cancellation	11
3.3 Specific Options for Electric and Magnetic Field Reduction	12
3.3.1 High-Voltage ac Transmission Lines	12
3.3.1.1 Configuration for 765-kV ac Transmission Lines	12
3.3.1.2 Configurations for 500-kV ac Transmission Lines	14
3.3.1.3 Configurations for 345-kV ac Transmission Lines	19
3.3.2 Direct-Current Transmission Lines	23
3.4 Costs	28
3.4.1 Florida Study	28
3.4.1.1 Proposed 230-kV Options	28
3.4.1.2 Proposed 500-kV Options	31
3.4.2 Rhode Island Study	35
3.4.2.1 Horizontal Configuration for 345-kV ac	36
3.4.2.2 Davit Arm Configuration for 345-kV ac	38

CONTENTS (Cont.)

3.4.2.3	Inverted-Delta Configuration for 345-kV ac	38
3.4.2.4	Split-Phase Configuration for 345-kV ac	38
3.4.2.5	Underground Delta Configuration for 345-kV ac	39
3.4.3	Washington State Study	39
3.4.3.1	Horizontal Configuration for 230-kV ac	41
3.4.3.2	Davit Arm Configuration for 230-kV ac	41
3.4.3.3	Delta Configuration for 230-kV ac	41
3.4.3.4	Split-Phase Configuration for 230-kV ac	42
3.4.3.5	Vertical Configuration for 230-kV ac	42
3.4.3.6	Underground Configuration for 230-kV ac	43
3.4.4	Bonneville Power Administration 500-kV Estimation Study	43
4	CONCLUSIONS	46
4.1	Sensitivity Study	46
4.2	Study of Cost versus Fields	47
5	REFERENCES	49
6	BIBLIOGRAPHY	50
	APPENDIX A: Sensitivity Calculations	51
	APPENDIX B: Design and Construction Cost Data	67

TABLES

1	Calculated EMF Strengths and Sensitivities for 765-kV ac Horizontal Configuration	13
2	Calculated EMF Strengths and Sensitivities for 500-kV ac Configurations	16
3	Calculated EMF Strengths and Sensitivities for 345-kV ac Configurations	21
4	Operating dc Lines in the United States	25
5	Calculated EMF Strengths and Sensitivities for ± 450 -kV dc Horizontal Configuration	28
6	Calculated EMF Strengths for Florida Base-Case and Proposed 230-kV Designs	30
7	Estimated Costs and Calculated EMF Strengths for 230-kV Designs from the Florida Study	33

TABLES (Cont.)

8	Calculated EMF Strengths for Florida Base-Case and Proposed 500-kV Designs	33
9	Estimated Costs and Calculated EMF Strengths for 500-kV Designs from the Florida Study	35
10	Calculated 345-kV EMF Strengths from the Rhode Island Study	37
11	Calculated 230-kV EMF Strengths from the Washington State Study	40
12	Comparative Construction Costs and EMF Strengths for Two 500-kV Low-EMF Transmission Line Designs	45
13	Sensitivity Analysis for Four 345-kV Configurations	46
14	Estimated Costs and Calculated EMF Strengths for Five 345-kV Power Line Configurations from the Rhode Island Study	47
A.1	Calculated EMF Strengths and Sensitivities for 765-kV ac Horizontal Configuration at 1,000 A per Phase	53
A.2	Calculated EMF Strengths and Sensitivities for 500-kV ac Horizontal Configuration at 1,000 A per Phase	54
A.3	Calculated EMF Strengths and Sensitivities for 500-kV ac Delta Configuration at 1,000 A per Phase	55
A.4	Calculated EMF Strengths and Sensitivities for 500-kV ac Vertical Configuration at 1,000 A per Phase	56
A.5	Calculated EMF Strengths and Sensitivities for 500-kV ac Davit Configuration at 1,000 A per Phase	58
A.6	Calculated EMF Strengths and Sensitivities for 500-kV ac Split-Phase Configuration at 1,000 A per Phase	59
A.7	Calculated EMF Strengths and Sensitivities for 345-kV ac Horizontal Configuration at 1,000 A per Phase	61
A.8	Calculated EMF Strengths and Sensitivities for 345-kV ac Delta Configuration at 1,000 A per Phase	62
A.9	Calculated EMF Strengths and Sensitivities for 345-kV ac Davit Configuration at 1,000 A per Phase	63

TABLES (Cont.)

A.10	Calculated EMF Strengths and Sensitivities for 345-kV ac Split-Phase Configuration at 1,000 A per Phase	65
A.11	Calculated EMF Strengths and Sensitivities for ± 450 -kV dc Horizontal Configuration at 1,000 A per Phase	66
B.1	Calculated EMF Strengths versus Construction Cost Data from the Florida Study for 230-kV Transmission Lines	68
B.2	Calculated EMF Strengths versus Construction Cost Data from the Florida Study for 500-kV Transmission Lines	70
B.3	Calculated Magnetic Field versus Construction Cost Data from the Rhode Island Study for 345-kV Transmission Lines	72
B.4	Calculated EMF Strengths versus Construction Cost Data from the Washington State Study	74

FIGURES

1	States that Impose Limits on Electric or Magnetic Fields for the Construction of New Power Transmission Lines	5
2	Tower for 500-kV ac Split-Phase Configuration	10
3	Tower for 765-kV ac Horizontal Configuration	13
4	Tower for 500-kV ac Horizontal Configuration	15
5	Tower for 500-kV ac Delta Configuration	17
6	Tower for 500-kV ac Vertical Configuration	18
7	Tower for 500-kV ac Davit Configuration	19
8	Tower for 345-kV ac Horizontal Configuration	19
9	Tower for 345-kV ac Delta Configuration	22
10	Tower for 345-kV ac Davit Configuration	22
11	Tower for 345-kV ac Split-Phase Configuration	23

FIGURES (Cont.)

12	Tower for ± 450 -kV dc Horizontal Configuration	24
13	Magnetic Fields Calculated with FIELDS 1.0 Program for the New England ± 450 -kV dc Transmission Line	25
14	Calculated Total Electric Field near Ground for ± 400 -kV dc Transmission Line	27
15	Presently Used Florida 230-kV Vertical Design	29
16	Proposed Florida 230-kV Inverted-Delta Design	31
17	Proposed Florida 230-kV Split-Phase Design	32
18	Existing Florida 500-kV Vertical Design	34
19	Proposed Florida 500-kV Davit Design	34
20	Proposed Florida 500-kV Delta Design	36
21	Horizontal Configuration for 230-kV ac	41
22	Davit Arm Configuration for 230-kV ac	41
23	Delta Configuration for 230-kV ac	41
24	Split-Phase Configuration for 230-kV ac	42
25	Vertical Configuration for 230-kV ac	42
26	Underground Configuration for 230-kV ac	44

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NOTATION

The following is a list of the acronyms, initialisms, and abbreviations (including units of measure) that appear in this document.

ACRONYMS, INITIALISMS, AND ABBREVIATIONS

ac	alternating current
ACSR	aluminum-core steel-reinforced
BPA	Bonneville Power Administration
dc	direct current
DOE	U.S. Department of Energy
EA	environmental assessment
EIS	environmental impact statement
ELF	extremely low frequency
EMF	electric and magnetic field
EPRI	Electric Power Research Institute
IEEE	Institute of Electrical and Electronics Engineers, Inc.
NESC	National Electric Safety Code

UNITS OF MEASURE

A	ampere(s)
°C	degree(s) Celsius
dB(A)	decibel(s) (A-weighted)
ft	foot (feet)
Hz	hertz
in.	inch(es)
kV	kilovolt(s)
m	meter(s)
MCM	kilo circular mil(s)
mG	milligauss
mi	mile(s)
MW	megawatt(s)

**Electric Power High-Voltage Transmission Lines:
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SUMMARY

The aim of this report is to provide background information about (1) the electric and magnetic fields (EMFs) of high-voltage transmission lines at typical voltages and line configurations and (2) typical transmission line costs to assist preparers and reviewers of the section on alternatives in environmental documents. This report will give the reviewing individual a better appreciation of the factors affecting EMF strengths near high-voltage transmission lines and the approaches that might be used to reduce EMF impacts on humans and other biological species in the vicinity of high-voltage overhead or underground alternating-current (ac) or direct-current (dc) transmission lines.

The EMF strengths at distances from 0 to ± 200 ft from the centerline were calculated for several configurations of high-voltage ac overhead transmission lines. The same calculations were made for a 345-kV ac and a 230-kV ac underground transmission line and for a ± 450 -kV dc overhead transmission line. The horizontal configuration was the only configuration of 765-kV ac overhead line considered. For the 500-kV ac overhead lines, the horizontal, delta, vertical, davit, and split-phase configurations were considered. For the 345-kV ac overhead lines, the horizontal, delta, davit, and split-phase configurations were considered. For 230-kV ac overhead lines, the vertical, inverted-delta, and split-phase configurations were considered.

The EMFs were then recalculated, first with the assumption that all conductor-to-conductor distances were decreased by 5 ft and again with the assumption that all conductor-to-ground distances were increased by 5 ft. The differences between the base-case EMFs and the decreased conductor-to-conductor (compacted) and raised-line (heightened) EMFs were then divided by 5 to derive a compacting and heightening sensitivity factor (sensitivity) that can be used to qualify the reduction (or increase) in EMFs that should occur when high-voltage transmission line conductors are moved closer together or raised. The unit of measurement of the computed sensitivity is percent per foot. The compacting and height sensitivities were then compared and reported, together with a discussion of the meaning and significance of the compared values.

Finally, estimated costs from other sources for the high-voltage transmission configurations and for the voltages that were considered in the calculations were collected; these estimated costs are presented and discussed so that the impact of using alternative strategies for reducing EMF strengths and the implications of implementing the strategies can be better appreciated.

1 INTRODUCTION

1.1 PURPOSE AND SCOPE

The purposes of this study are (1) to describe the potential for reducing electric and magnetic field (EMF) levels or strengths near high-voltage transmission lines by changing the configuration of the lines, raising the lines, and reducing the spacing between conductors and (2) to discuss the cost implications of such changes for the Office of Fuels Programs of the U.S. Department of Energy (DOE). The data are intended for use in environmental analyses associated with Presidential Permit applications and by others who prepare environmental assessments (EAs) and environmental impact statements (EISs). The scope of this study extends to transmission line configurations for 60-Hz (60 cycles per second) alternating-current (ac) transmission lines at 765, 500, 345, and 230 kV and for direct-current (dc) transmission lines at ± 450 kV.

1.2 BACKGROUND

Electric and magnetic fields occur naturally and as a consequence of human activity. Those created by human activity are produced by the use of electric and magnetic devices, including the generation, transmission, and application of electricity. Ambient levels of EMFs have increased dramatically as society has become more industrialized. Electric power system frequencies (60 Hz) are at the lower end of the range of frequencies of electromagnetic radiation and are sometimes referred to as extremely low frequencies (ELFs). Although considering the electric and magnetic forces together and collectively calling them electromagnetic fields is common, in the ELF range, the forces are two separate entities, both of which have unique interactions with living things. For power lines, electric fields are created whenever an electric voltage is applied to a conductor; whereas magnetic fields are created when current is running through a conductor (Waller and Geissinger 1992).

The environmental effects of power transmission lines have been under investigation for decades. Until recently, the research focused on efforts to protect the physical environment of the space used for transmission of power. In recent years, interest and concern about the potential health effects on biota (especially man) from exposure to EMFs has increased significantly because certain epidemiologic studies suggest a statistical association between exposure to EMFs and an increased risk of certain cancers.

A great deal of uncertainty surrounds the question of possible health effects from EMF exposure. Researchers are unsure about which aspect of exposure, if any, might be important in determining risk. The assumption has been made that frequency, magnetic field strength, electric field strength, currents induced in the body, time spent in the field, exposure to intermittent or switched fields, or other variables may be important. On the other hand, constant magnetic fields in the range of the earth's steady magnetic field of approximately 600 mG are considered benign. To date, data from biological tests provide conflicting results. To counter some of this uncertainty, the concept of "prudent avoidance"

has been introduced. This concept holds that individuals or society should take those measures to avoid magnetic field exposures that entail little or modest cost and that appear to be prudent, given the current level of scientific knowledge about health risks (Moore 1990).

The concerns for citizens living, working, or attending school close to power lines have compelled a number of state governments to consider or to adopt regulations or standards for EMFs. Seven states have imposed limits on electric or magnetic field strengths (or both) for the construction of new transmission lines within their borders (Figure 1). In other states, the need for regulation is still under consideration. Over the next few years, more states are likely to adopt EMF exposure standards, limits, or other measures as projected increased demand for electricity creates the need for new and upgraded transmission and distribution line capacity.

The DOE has been working with other federal agencies, states, researchers, the public, and the private sector to establish a comprehensive and coordinated National Electric and Magnetic Fields Research and Communication Program. Research activities include assessments of exposure and the development of options for field management and mitigation. In support of this broad-based program and to fulfill its own research needs regarding the health and safety effects of international electric transmission lines, the DOE Office of Fuels Programs has commissioned this study of the designs and costs of possible alternatives for EMF mitigation.

A utility must apply for and obtain a Presidential Permit before connecting a new transmission line to a foreign utility at the border of Canada or Mexico. The DOE Office of Fuels Programs reviews the utility applications for Presidential Permits. As part of its responsibility to comply with implementing procedures for the National Environmental Policy Act, an environmental impact analysis is conducted on the project. The impacts of each project and possible mitigative measures relative to construction and operation of the proposed transmission line system are evaluated before the Presidential Permit is issued. The practicality and effectiveness of various options for mitigation are compared with the costs of those options. The environmental review culminates in the preparation of an EA or EIS, in which the proposed project is described and discussed.

2 METHODS

This study was done in three phases: (1) a search of the literature, (2) a sensitivity analysis, and (3) a cost comparison. Most of the time and effort were spent in the sensitivity analysis, which required a considerable number of calculations of EMF levels and sensitivity factors.

2.1 SEARCH OF THE LITERATURE

A search of the literature was conducted to obtain information on EMF mitigative strategies, particularly strategies for modifying transmission line design and for reducing EMF strengths. Utility industry research groups that provide technical support to utilities or public utility commissions (or both) and representative major utility companies were contacted to obtain more current information. The published results of several recent large-scale research studies on EMF mitigation (Commonwealth Associates, Inc. 1992; Waller and Geissinger 1992; Oppel and Stewart 1993) were also reviewed. Data from these reports are presented in this report. These and other research studies were the basis for this comparison study of EMF reduction and costs for high-voltage transmission lines. Transmission line designs from the *Transmission Line Reference Book* (General Electric Co. 1982), published by the Electric Power Research Institute (EPRI), were used as the basis for the calculations performed in the sensitivity-analysis phase of the study.

2.2 ANALYSIS OF SENSITIVITY

The second part of the study consisted of an analysis to qualify the near-ground EMF strengths associated with several common high-voltage transmission line configurations at several common transmission line voltages and to calculate the changes of EMF strengths when the conductor-to-conductor (phase-to-phase) spacing is decreased or the conductor-to-ground (phase-to-ground) distance is increased.

The phase-to-phase analysis consisted of calculating both the EMF strengths of points located 3 ft above the ground and on the centerline of the transmission line and at several distances within ± 200 ft from the centerline. (The height of 3 ft above ground was selected because it represents a reasonable height above ground for the middle body organs of a human adult and a reasonable height above ground for most organs and the heads of quadrupeds or the upper organs and heads of human children.) After calculating the field strengths for several common line configurations and several common transmission voltages a first time, recalculations were made for each voltage and configuration, except that all phase-to-phase distances were reduced (compacted) by 5 ft. Thus, two values of the electric field strengths and two values of the magnetic field strengths, a normal value and a compacted value, were derived for each point. By subtracting the two values and dividing by five times the normal value, factors called the compacting sensitivity were developed. These values have units of percent per foot and indicate the average change of EMF level caused

by moving the lines closer together by 5 ft. The fact that the EMF levels would be increasingly attenuated as the lines get closer together indicates that the average compacting sensitivity value that is derived is different from what one can expect for smaller changes of phase spacing. Consequently, the compacting sensitivity merely qualifies, not quantifies, the changes of EMF levels.

The phase-to-ground analysis consisted of calculating both the EMF strengths of points located 3 ft above the ground and on the centerline of the transmission line and points at several distances within ± 200 ft from the centerline. (The height of 3 ft above ground was selected for the same reasons noted previously.) After calculating the field strengths for several common line configurations and several common transmission voltages a first time, recalculations were made for each voltage and configuration, except that all phase-to-ground distances were increased (heightened) by 5 ft. Thus, two values of the electric field strengths and two values of the magnetic field strengths, a normal value and a compacted value, were derived for each point. By subtracting the two values and dividing by 5 times the normal value, factors called the height sensitivity were developed. These values have units of percent per foot and indicate the average change of EMF level caused by raising the lines by 5 ft. The fact that the EMF levels may not be attenuated in a linear manner as the lines are raised indicates that the derived value for height sensitivity may be different from what one would expect for smaller changes of conductor height. Consequently, the height sensitivity merely qualifies, not quantifies, the changes of EMF levels.

A positive value of either the compacting sensitivity or the height sensitivity indicates a decrease in EMF strength. Because of the numerous physical and environmental factors and the variability of conditions in the field, the calculated EMFs will probably be different from values derived by experiment or by actual field measurements (or by both). All EMF calculations were done by using the FIELDS 1.0 computer program developed by Southern California Edison Co.

2.3 ANALYSIS OF COST VERSUS FIELDS

The third part of this study focuses on the costs of mitigating EMFs. The analysis was performed by comparing estimated costs from other sources for various sized lines, configurations, and tower dimensions in Rhode Island, Florida, and Washington.

3 RESULTS

3.1 CONSIDERATIONS FOR PLANNING AND DESIGN

Of primary importance in the planning and design of a power system is the need to provide continuous and reliable electric power, regardless of the power demand. Power systems are designed to incorporate a network or "grid" of interconnected substations. Generally, the more redundant the interconnection, the higher the reliability. To maintain reliability, transmission (and distribution) lines are designed to be able to carry more current than they are expected to carry on a daily basis (Waller and Geissinger 1992). Although reliability and continuity are of primary importance, a number of considerations that relate specifically to EMFs also go into the planning and design of power systems. The following discussion addresses some of these considerations.

In January 1992, P. Waller and L. Geissinger, members of the Electric Transmission Research Needs Task Force of the State of Washington, authored the report *Electric and Magnetic Field Reduction: Research Needs*. They concluded that planning and design for EMF reductions should include consideration of the number of lines, line voltage, conductor height, phase spacing, phase positioning, phase balance, conductor configuration, conductor size and bundling, underbuilding, right-of-way width, and utility practices. All of these design considerations are discussed in that report (Waller and Geissinger 1992).

3.1.1 Number of Lines

If existing portions of a network cannot reliably supply the anticipated power demand, the addition of one or more lines may be necessary to provide adequate reliability. The more lines serving an area, the more the current flow can be shared between lines, thus reducing the current flow in each line and the magnetic fields adjacent to each line.

3.1.2 Voltage

Voltage is probably the largest single factor affecting the strength of an electric field produced by a transmission line. Because the power delivered is proportional to the product of voltage and current, high voltages are used for power transmission to keep current-related line losses at economically viable levels. Similarly, magnetic fields (which are related to current level) are reduced when higher voltages and lower current transmission are used.

3.1.3 Height of Conductors

Generally, EMF strength is inversely related to the height of the transmission line conductors. As one moves away from the centerline, the increased distance will also reduce the EMFs; however, at points 120 ft and 200 ft from the centerline, data for some

transmission line configurations show negative values (increasing EMFs) when conductor height is increased.

3.1.4 Spacing of Phases (or Conductors)

Alternating-current power is transmitted via one or more sets of three parallel conductors. The peak voltage of each conductor is, nominally, one-third or 120° out of phase with the voltages of the other conductors. Consequently, ac power lines operate in a three-phase mode. The earth acts as the second or return line for each phase. Direct-current power is also transmitted via three parallel conductors. The peak voltage of two of the conductors is constant but reversed. The third conductor acts as a return (ground) conductor. Consequently, dc power lines operate in a two-phase mode. Air provides the required insulation between conductors, as does air between the conductors and ground. Air and specially designed insulators provide insulation between the conductors and the towers. The higher the voltage, the larger the spacing and insulator length are required to be. All air spacing and insulators must be able to withstand voltage surges caused by lightning or switching, as well as allow sufficient insulating space for utility personnel to carry out their work safely during live-line maintenance activity. If placing all three phase conductors in the same physical space were electrically possible, the electric fields from the conductors would completely cancel each other out. Although close or compact placement reduces field strength, the ability of designers to achieve such reductions is limited because of the clearances required for insulation and the practice of performing live-line maintenance.

3.1.5 Positioning of Phases

Although the direction of currents in a single circuit line produces currents that oppose one another, the direction of currents in a double circuit line (such as the split-phase configuration shown in Figure 2) can be arranged so that currents oppose one another to an even greater extent. This arrangement results in significant reduction in magnetic field strength.

3.1.6 Balance of Phases

The ideal situation for minimum magnetic field strength is equal (balanced) phase currents. In practice, though, fluctuations in power demand between phases cause current differences in the individual phases, creating a condition known as phase unbalance. Although currents in each phase of most transmission lines are nearly balanced, the currents are never in perfect balance.

3.1.7 Spacing and Location of Conductors

Conductors can be physically arranged in ways that will change the EMFs produced at a given current or voltage. Some of the more common configurations are defined later in this report.

3.1.8 Size and Bundling of Conductors

Conductor(s) must be large enough to carry the current without overheating, even during peak-load conditions. The choice of conductor diameter usually depends on a balancing of the installed cost of the line versus the cost of lost power over the lifetime of the line. Other considerations include the environmental and cost impacts caused by the corona effect (i.e., ionization of the air at the surface of a conductor caused by the voltage of the conductor, which produces related audible noise, radio frequency interference, and power losses). Corona effects decrease when the diameter of the conductor is increased. Corona effects can also be reduced by using two or more conductors per phase (bundling).

FIGURE 2 Tower for 500-kV ac Split-Phase Configuration

3.1.9 Underbuilding

Underbuilding is the practice of placing distribution lines or lower voltage transmission lines on the same towers beneath the primary transmission line. This practice can decrease magnetic fields at ground level, but the extent of the decrease is dependent on the voltages, currents, and phase arrangements of each circuit.

3.1.10 Width of Right-of-Way

The width of the right-of-way for power lines is typically determined by the cost of the land and the amount of space required for construction, operation, and maintenance of the line. Because EMF strength generally decreases with lateral distance from the centerline, the wider the right-of-way, the weaker the field strengths are at the edge.

3.1.11 Design Practices of Utilities

Each utility employs design practices that are tailored to its particular needs. Regional variations in topography, weather, environmental factors, population density, service area size, and other factors all play a role in the design of a power transmission system.

3.2 GENERAL METHODS FOR ELECTRIC AND MAGNETIC FIELD REDUCTION

The primary methods for reducing EMFs from electric transmission lines are shielding and cancellation.

3.2.1 Shielding

Nearly any physical object will distort and reduce the electric field. Although shield wires are common above transmission lines to provide lightning protection, shield wires can also be used under power lines to reduce the electric field strength at ground level.

Shielding for magnetic fields requires that the fields be blocked by a shield made of iron or other magnetic material. Shielding against magnetic fields produced by power lines is very difficult and expensive to achieve because effective magnetic shields are large and heavy. A common misconception is that placing power lines underground achieves magnetic field reduction by earth shielding; however, such field reductions actually are caused by cancellation because the conductors are insulated and are placed very close together.

3.2.2 Cancellation

Cancellation in a double-circuit configuration (as shown in Figure 2) involves positioning out-of-phase conductors from each circuit close to each other so that the magnetic field from each conductor tends to cancel the field of the others. This cancellation becomes increasingly effective as one moves away from the tower's centerline perpendicular to the line.

Numerous tower designs and circuit configurations are employed by utilities for three-phase high-voltage power transmission. Different conductor spacing and phase arrangements usually produce very different magnetic field levels. Until recently, the choice of design was dependent primarily on such operational criteria as a line's capacitance and reactance or on such environmental criteria as aesthetics or corona effects (audible noise or radio frequency interference).

3.3 SPECIFIC OPTIONS FOR ELECTRIC AND MAGNETIC FIELD REDUCTION

Specific design options that can both satisfy operational criteria and reduce EMFs are presented in the following sections. Different conductor configurations that will be discussed include horizontal, vertical, delta, davit, split-phase, and underground pipe configurations. The configurations, which will be defined as they are discussed, are compared with respect to cost, EMF strengths, and phase-spacing sensitivity.

3.3.1 High-Voltage ac Transmission Lines

From a design standpoint, 765-, 500-, and 345-kV transmission lines are considered to be extra-high-voltage or high-voltage transmission lines. The field strengths for the various design configurations that are reported here are the computer-calculated (not measured) field strengths. No minimum phase-to-phase distance is recommended in the National Electric Safety Code (NESC) (Institute of Electrical and Electronics Engineers, Inc. [IEEE] 1990); however, in the EPRI *Transmission Line Reference Book*, the normal high-voltage configurations are identified, and typical phase-to-phase and phase-to-ground distances are provided (General Electric Co. 1982). The minimum distances listed in the *Transmission Line Reference Book* were used to calculate the field strengths that are presented in the tables of this report.

3.3.1.1 Configuration for 765-kV ac Transmission Lines

The only 765-kV configuration described in the EPRI *Transmission Line Reference Book* (General Electric Co. 1982) is the horizontal configuration. A typical horizontal-configuration tower is shown in Figure 3. The 765-kV voltage is advantageous for long-distance transmission because the higher voltage allows reduced current and minimizes line losses; however, the higher voltages need greater phase spacing to minimize corona effects. The horizontal configuration is generally used at 765 kV because of the large distances required between the phases, because other designs require increased height, and because wind stress increases with tower height. A current of 1,000 A per phase was assumed for all 765-kV calculations.

A review of 765-kV transmission line designs in the EPRI *Transmission Line Reference Book* (General Electric Co. 1982) shows that existing systems use 40-54 ft of minimum (point of maximum line sag between towers) phase-to-ground clearance. (The tower in Figure 3 shows typical dimensions for mountainous terrain.) This 40- to 54-ft distance is somewhat higher than the 35-ft minimum ground clearance recommended by the NESC. The EPRI-listed phase-to-phase spacing for 765-kV conductors is 40-50 ft.

Detailed data on the calculated field strengths and sensitivities for the 765-kV horizontal configuration are presented in Table A.1 in Appendix A. The height sensitivity data in Table 1 indicate that increasing the line height is not very effective (0.25%/ft) for reducing the magnetic field of a 765-kV transmission line at a distance of 200 ft from the centerline. Moreover, this design change would increase cost because the taller towers would require stronger and, therefore, more costly structures to withstand the increased wind stress.

FIGURE 3 Tower for 765-kV ac Horizontal Configuration

TABLE 1 Calculated EMF Strengths and Sensitivities for 765-kV ac Horizontal Configuration

Field	Magnetic			Electric		
	Field (mG)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)	Field (kV/m)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
Maximum	137 at 20 ft ^a	0.82	2.6	5.67 at 40 ft ^a	0.51	3.2
120 ft from centerline ^b	30.9	2.9	0.69	1.23	2.8	-0.58
200 ft from centerline ^b	11.4	2.7	0.25	0.279	2.3	-1.6

^a Distance from centerline.

^b Centerline of tower.

The data on compacting sensitivity in Table 1 indicate that, at 60 ft or more from the centerline, decreasing the phase-to-phase distances (compaction) reduces both the electric and magnetic fields by about 3%/ft because of the field cancellation effect. The decreased compacting sensitivity at distances less than 60 ft can be attributed to the calculated point being closer to one of the phases and farther away from the other two phases.

Increasing the height of the lines reduces both the magnetic and electric field strengths under the lines because of the inverse proportionality of field strength to distance. Increasing the height has the opposite effect on the electric field strengths (-1.5%) farther from the centerline (>120 ft) because the increased height of the conductors reduces the shielding effect of the adjacent conductor.

3.3.1.2 Configurations for 500-kV ac Transmission Lines

Many different 500-kV ac configurations exist. For the purposes of discussion, the following design configurations were chosen to be representative of the group:

- Horizontal,
- Delta,
- Vertical,
- Davit, and
- Split phase.

At the 500-kV level, the NESC minimum (sag point) phase-to-ground clearance is 30 ft. The EPRI listing of existing systems contains examples that have a 28-ft clearance for worst-case (maximum current and air temperature) conductor sag. The EPRI examples have phase-to-phase distances of 28-40 ft. For these sensitivity calculations, the minimum clearances were assumed to be 30 ft for conductor to ground and 35 ft between phases. A current of 1,000 A per phase was assumed for all 500-kV calculations.

Horizontal Configuration for 500-kV ac. For purposes of calculation, the ac horizontal design (Figure 4) was assumed to have two grounded shield wires 27 ft above and 26 ft on either side of the center transmission line. The 70- to 160-ft heights shown in Figure 4 are typical heights used in mountainous terrain.

Because minimal tower height is obtained with the horizontal-configuration tower, wind and line forces are minimized. Consequently, the horizontal configuration is generally least costly to build; however, the design has unbalanced line spacing (i.e., the phases are not equidistant from one another), so the horizontal-configuration tower has the highest EMFs.

Table 2 lists the calculated magnetic field strength as 28.7 mG at 120 ft from the centerline and as 10.1 mG at 200 ft. The compacting sensitivity at 200 ft is 3.0%/ft.

At 200 ft from the centerline, the calculated height sensitivity of 0.16%/ft is only 5% of the compacting sensitivity. Clearly, raising the lines to reduce magnetic field strength is not as efficient as compacting the lines at 200 ft from the centerline. On the other hand, the height sensitivity of 3.6%/ft is 6 times (600%) the compacting sensitivity at 20 ft from the centerline.

**FIGURE 4 Tower for 500-kV ac
Horizontal Configuration**

Delta Configuration for 500-kV ac. Figure 5 shows the delta-configuration tower. For purposes of calculation, the distance between phases A and C (the lower, horizontally aligned conductors) was assumed to be 30.7 ft, and the height of the B conductor above the A and C conductors was 29 ft. This arrangement results in a distance of 32.8 ft between phases A or C and B. Shield wires were assumed to be 12 ft on either side and 17 ft above the top conductor. Again, Figure 5 shows typical ground-to-conductor heights of towers in mountainous terrain. The delta-configuration tower is somewhat higher than the horizontal-configuration tower but is lower than the towers of the other configurations that will be discussed because the triangular spacing allows equal phase-to-phase distance in a smaller vertical height.

The calculated values of magnetic field strength are lower at all distances for the delta configuration than those for the horizontal configuration. For the delta configuration, the compacting sensitivity and height sensitivity at both 120 ft and 200 ft from the tower centerline are almost the same as those of the horizontal configuration; however, near the centerline, the compacting and height sensitivities of the delta configuration are about 320% and 130% more effective than the respective sensitivities for the horizontal configuration. The field can be reduced by 3.2% (at 200 ft from the centerline) for each foot that the phases are compacted. The height sensitivities show the delta configuration to be a more effective design than the horizontal configuration for reducing magnetic fields near the centerline but show negligible improvement at the greater lateral distances.

The calculated electric field strengths for the 500-kV delta configuration are below 6 kV/m at the tower centerline but drop to 0.27 and 0.09 kV/m at 120 ft and 200 ft, respectively, from the centerline. Increasing conductor height has a similar effect on the electric field strength of both the delta and horizontal configurations (i.e., the field decreases near the centerline and increases at the outer distances).

TABLE 2 Calculated EMF Strengths and Sensitivities for 500-kV ac Configurations

Configuration and Field	Magnetic			Electric		
	Field (mG)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)	Field (kV/m)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
Horizontal						
Maximum	226 at 20 ft ^a	0.59	3.6	6.83 at 40 ft ^a	2.1	4.1
120 ft from centerline ^b	28.7	3.3	0.49	0.57	3.6	-2.0
200 ft from centerline ^b	10.1	3.0	0.16	0.12	3.1	-2.7
Delta						
Maximum	181 at 0 ft ^a	1.9	4.7	5.80 at 20 ft ^a	1.9	4.4
120 ft from centerline ^b	13.3	3.3	0.56	0.27	2.6	-1.1
200 ft from centerline ^b	4.86	3.2	0.21	0.09	2.5	-0.23
Vertical						
Maximum	152 at 0 ft ^a	1.3	4.2	6.53 at 0 ft ^a	0.94	4.0
120 ft from centerline ^b	18.7	2.7	0.58	0.26	0.78	3.3
200 ft from centerline ^b	7.75	3.0	0.26	0.16	2.1	1.3
Davit						
Maximum	152 at 0 ft ^a	0.72	4.04	5.75 at 20 ft ^a	1.7	4.5
120 ft from centerline ^b	14.1	2.4	0.47	0.37	2.9	-0.05
200 ft from centerline ^b	5.37	2.4	0.19	0.12	3.6	-0.17
Split phase						
Maximum	158 at 0 ft ^a	2.5	5.1	5.12 at 20 ft ^a	2.7	4.9
120 ft from centerline ^b	8.60	5.3	0.87	0.27	5.1	1.5
200 ft from centerline ^b	2.28	5.7	0.39	0.08	5.4	1.0

^a Distance from centerline.^b Centerline of tower.

FIGURE 5 Tower for 500-kV ac Delta Configuration

Vertical Configuration for 500-kV ac. For purposes of calculation, the vertical configuration (Figure 6) has phase-to-phase spacings of 30 ft and 60 ft and a grounded shield wire at 33 ft above the top conductor and displaced 9 ft toward the tower. This design is the most costly tower design for 500-kV lines because larger or stronger components would be needed to withstand increased wind and line load stresses caused by the taller towers.

Table 2 shows that the calculated magnetic field strengths for the vertical configuration are lower than those for the horizontal configuration but are higher, except for the fields directly under the line, than those for the other configurations. The sensitivities are comparable to those of the other configurations except for the split-phase configuration. The electric field strength is highest at the centerline and decreases as the distance to the centerline increases.

Davit Configuration for 500-kV ac. The davit configuration (Figure 7) is basically a rotated delta configuration. For purposes of calculation, the vertical base of the triangle was 25 ft, and its horizontal measurement (height of the triangle) was about 35 ft. This configuration yielded phase-to-phase distances of 25 ft or about 37.2 ft. Two grounded shield wires were assumed at 18 ft 7 in. above the top conductor and displaced about 7 ft toward the centerline from both the base conductors and the peak conductor.

The davit configuration is comparable in height to the delta configuration and therefore is subject to comparable wind and line loads on the tower. The cost of davit towers, therefore, should be comparable to the cost of delta towers.

Calculations show that the maximum magnetic field strength for the davit configuration was reduced when compared with those of the horizontal and delta configurations, but the strength for the delta configuration at the 200-ft distance from the centerline is about 10% lower than that for the davit configuration. Magnetic field strengths for the vertical configuration are comparable near the centerline but are higher than the field strengths for the davit configuration at greater distances from the centerline (44% higher at 200 ft).

The magnetic field compacting sensitivity for the davit configuration was 0.72%/ft at the centerline, showed an increase to 3.1%/ft at 60 ft, and then declined to 2.4%/ft at both 120 ft and 200 ft. The height sensitivity was 4.0%/ft at the centerline, rose to 4.3%/ft at 20 ft, and then steadily declined to 0.19%/ft at 200 ft from the centerline.

The electric field strengths, which were calculated to be less than 6 kV/m at all points from the centerline to 200 ft from the centerline, are generally higher for the davit configuration than those for the delta configuration, except at the centerline.

FIGURE 6 Tower for 500-kV ac Vertical Configuration

Split-Phase Configuration for 500-kV ac. The split-phase configuration (Figure 2) contains two parallel circuits, one on each side of the tower. These circuits are in opposite sequence to each other (i.e., if one side has an A-B-C sequence from top to bottom, the other side will have a C-B-A sequence from top to bottom). For purposes of calculation, the spacing for the split-phase configuration was as shown in Figure 2. Because the currents were also assumed to be 1,000 A per phase, the transmission line power level is twice (200%) that of the other configurations. One grounded shield wire was assumed at 35 ft above the top conductors on the transmission line centerline. This configuration is the most costly because of both the tower height and the extra hardware and conductors required for the double circuits.

The calculations yielded higher magnetic fields at the centerline for the split-phase configuration than those for the davit and vertical configurations but lower than those for the horizontal and delta configurations. The split-phase configuration also has the highest calculated compacting sensitivity (over 5%/ft) for distances greater than 100 ft. The electric fields compare favorably with those of the other configurations and were 3.3 kV/m at the centerline, increased to a maximum of 5.1 kV/m at 20 ft, and then gradually decreased to 0.08 kV/m at 200 ft.

3.3.1.3 Configurations for 345-kV ac Transmission Lines

The study of the compacting and height sensitivities for 345-kV transmission lines considered the following configurations from the EPRI *Transmission Line Reference Book* (General Electric Co. 1982):

- Horizontal,
- Delta,
- Davit, and
- Split phase.

For purposes of calculation, currents of 1,000 A per phase were assumed for all configurations.

Horizontal Configuration for 345-kV ac. For purposes of calculation, the horizontal configuration was assumed to be as shown in Figure 8. Two grounded shield wires were assumed at 18 ft above and 18 ft 7 in. on either side of the tower's centerline.

FIGURE 7 Tower for 500-kV ac Davit Configuration

FIGURE 8 Tower for 345-kV ac Horizontal Configuration

Table 3 lists the calculated magnetic field strengths of 17.7 mG at a point 120 ft from the transmission line centerline and 6.43 mG at a distance of 200 ft. Calculations indicate that phase compacting can reduce the magnetic field by about 4.5%/ft at distances of 120-200 ft from the centerline.

For the magnetic field, calculations show that, at a distance of 200 ft from the centerline, the height sensitivity is 1/30th of the compacting sensitivity. Clearly, raising the lines to reduce the magnetic field is not very effective at 200 ft. On the other hand, raising the lines is about three times more effective than compacting the lines for reducing magnetic fields at the centerline of the transmission line.

Calculations for the horizontal configuration yield a maximum electric field of 3.65 kV/m at 20 ft from the transmission line centerline and fields of 0.23 kV/m at 120 ft from the centerline and 0.05 kV/m at 200 ft. The electric fields at 345 kV are lower than those at 500 kV because of the lower operating line voltage.

Compacting is reasonably effective for reducing the electric field at greater distances from the centerline; raising the line is not; however, at the more distant points, increasing the height has the effect of decreasing the cancellation effect among the three phases and causes an increase in the electric field. This increase is indicated by the negative sensitivities at 120 and 200 ft from the centerline.

Delta Configuration for 345-kV ac. For purposes of calculation, the delta configuration was assumed to be as shown in Figure 9, except the worst-case (sag point) phase-to-ground clearance was assumed to be 30 ft. Two grounded shield wires were assumed at 8 ft 8 in. above the top conductor and 8 ft on either side of the top conductor's centerline.

For magnetic fields, compacting the 345-kV delta configuration is reasonably effective for reducing fields away from the transmission line centerline. In this case, the field can be reduced by 4.0%/ft and 3.9%/ft at 120 and 200 ft, respectively. Raising the power line is an effective method of reducing the magnetic field near the centerline but quite ineffective at 120 and 200 ft from the centerline.

The electric field strengths are under 4 kV/m under the power lines and are less than 0.2 kV/m at distances greater than 120 ft from the centerline. As with the horizontal configuration, increasing the lines' heights decreases the electric field near the centerline but increases the field at the longer distances from the centerline.

Davit Configuration for 345-kV ac. The davit configuration (Figure 10) is a rotated delta. For purposes of calculation, the vertical base of the davit configuration was assumed to be 23 ft and its horizontal height 18 ft. One grounded shield wire was located on the centerline and 22 ft above the topmost conductor.

TABLE 3 Calculated EMF Strengths and Sensitivities for 345-kV ac Configurations

Configuration and Field	Magnetic			Electric		
	Field (mG)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)	Field (kV/m)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
Horizontal						
Maximum	207 at 0 ft ^a	1.38	3.83	3.65 at 20 ft ^a	1.03	4.85
120 ft from centerline ^b	17.7	4.6	0.43	0.23	4.4	-2.3
200 ft from centerline ^b	6.43	4.5	0.15	0.05	3.9	-3.1
Delta						
Maximum	168 at 0 ft ^a	2.5	4.9	3.68 at 20 ft ^a	2.5	4.46
120 ft from centerline ^b	10.7	4.0	0.43	0.15	3.3	-1.85
200 ft from centerline ^b	3.87	3.9	0.16	0.04	3.8	-1.0
Davit						
Maximum	112 at 0 ft ^a	2.8	4.7	2.97 at 20 ft ^a	3.4	3.86
120 ft from centerline ^b	9.42	4.6	0.55	0.20	3.5	0.61
200 ft from centerline ^b	3.43	4.6	0.21	0.07	3.8	0.27
Split phase (at 500 A)						
Maximum	147 at 0 ft ^a	3.1	5.1	3.18 at 20 ft ^a	3.8	5.24
120 ft from centerline ^b	6.94	5.6	0.77	0.13	3.6	0.15
200 ft from centerline ^b	1.87	5.2	0.30	0.03	3.3	0

^a Distance from centerline.^b Centerline of tower.

**FIGURE 9 Tower for 345-kV ac Delta Configuration
(shown with angled guy wires used to support tower)**

The davit configuration is comparable in height to the delta configuration and therefore imposes the same wind and line loads on the tower. Consequently, the costs for the delta and davit configurations should be comparable.

Magnetic fields for the davit configuration were less at all distances from the centerline than those of the horizontal and delta configurations. The magnetic field compacting sensitivity was 2.8%/ft at the centerline but increased to 4.6%/ft at distances of 80-200 ft from the centerline. The magnetic field height sensitivities show a maximum of 4.7%/ft at the centerline but decreased with increasing distance from the centerline.

Compared with those for the delta configuration, the magnetic fields for the davit configuration are 33% lower at the centerline and are about the same at distances greater than 100 ft from the centerline. The electric fields are less than 3 kV/m under the power line and are less than 1 kV/m at distances of 60 ft and greater from the centerline.

**FIGURE 10 Tower for
345-kV ac Davit
Configuration**

Split-Phase Configuration for 345-kV ac. The split-phase design (Figure 11) contains two circuits, one on each side of the tower, and in opposite phase sequence to each other. Currents of 1,000 A per phase were assumed. Therefore, this configuration would also carry twice (200%) the power of the other configurations. For purposes of calculation, the configuration spacing was assumed to be as shown in Figure 11. Two grounded shield wires were assumed at 24 ft above the top conductor and 20 ft on either side of the centerline. This configuration is the most costly of those considered because of the greater tower height and the double circuits.

For the split-phase configuration, the magnetic fields near the centerline are greater than those of the davit configuration but lower than those of the horizontal and delta configurations. At distances greater than 100 ft, the split-phase configuration has the lowest magnetic fields of the configurations that were considered. The split-phase configuration also has the highest magnetic field compacting sensitivities at all distances. The electric field strengths are comparable to those of the other configurations. The maximum electric field was 3.2 kV/m at 20 ft, but the field strengths dropped to less than 1 kV/m at distances of 60 ft and greater from the centerline.

FIGURE 11 Tower for 345-kV ac Split-Phase Configuration

3.3.2 Direct-Current Transmission Lines

For purposes of calculation, the dc line consisted of a two-conductor tower ($\pm$ polarities) with a dedicated buried return conductor connected to each tower. Figure 12 shows a typical ± 450 -kV dc horizontal-configuration transmission tower.

Transmission of high-voltage dc power has received the attention of the electric utility industry since the 1930s but, because of technology limitations, did not become operational until 1954 in Sweden. The introduction of mercury-arc converters that could handle 100 kV and 1,000 A in 1961 allowed a wider commercial application of dc lines in power transmission. From 1961 to 1975, the worldwide increase in the use of dc lines grew at the rate of 400 MW per year.

In 1989, worldwide, 44,000 MW of total installed dc transmission capacity was divided among 52 electrical power systems. Nineteen of these 52 systems were located in the United States and Canada. Table 4 lists the larger operating dc lines in the United States (Lee et al. 1993).

The following summary addresses design and cost considerations in planning dc transmission lines. Information supporting these conclusions was obtained from several references.

1. *For distances over 250 mi, where intermediate tap-offs are not necessary, dc lines are more efficient than ac lines when both construction and operating costs are considered.*

The operating savings include the absence of the ac skin losses. These losses are caused by ac-induced forces that push the ac current to the conductor's surface (skin) and thereby reduce its effective area. Equivalent skin-effect resistance ranges from 5 to 10% of the conductor's dc resistance (Fink and Carroll 1969). Additionally, the dc line has only two conductors, instead of three; hence, power delivery is achieved with 67% of the cable resistance losses of the three-phase ac system.

The costs of ac-to-dc converters make short lines (or long lines with ac taps) too expensive for reasonable cost recovery. On the other hand, a long-distance ac line would require costly series compensation capacitors to transmit the power in a reasonably efficient manner. The estimated construction costs for a ± 450 -kV dc transmission line in northern New England, according to Oppel and Stewart (1993), are as follows:

- a. A 2,000-MW transmission line costs about \$1 million/mi.
 - b. Each 2,000-MW ac-to-dc converter station costs about \$200 million.
2. *Where concern exists about 60-Hz magnetic fields, the dc line offers an absence of ac magnetic and electric fields.* The dc line has no 60-Hz fields, but static (dc) magnetic and electric fields are present. The earth also has a static magnetic field on the order of 500-600 mG. The magnetic field caused by a typical ± 450 -kV ac transmission line at 1,000 A in a worst-case scenario is equal to the earth's field and falls away to 2% (12 mG) of the earth's static field at 200 ft from the center of the line. Figure 13 shows the magnetic fields calculated with the FIELDS 1.0 program (Southern California Edison Co.) for a typical ± 450 -kV transmission line at 1,000 A.

FIGURE 12 Tower for ± 450 -kV dc Horizontal Configuration

TABLE 4 Operating dc Lines in the United States

Transmission Line	Year Installed	Voltage Level (kV)	Length (mi)
Square Butte	1977	± 250	465
CU Project	1979	± 400	440
Pacific Intertie upgrade	1984	± 500	850
Intermountain	1986	± 500	490
Comerford	1986	± 450	105
New England	1991	± 450	930

FIGURE 13 Magnetic Fields Calculated with FIELDS 1.0 Program for the New England ± 450 -kV dc Transmission Line

3. *For situations where controlling the power flow between ac systems is a priority, dc connection is an option.* The dc power system is inherently more stable than an ac power system because of the ability of the dc power system to control the power flowing through it. In situations where two ac grids are not synchronous (i.e., weakly coupled and not exactly in phase), dc coupling may be the most practical solution. This solution was used for a New England (United States/Canadian) ± 450 -kV transmission line interconnection. System analysis indicated that an ac tie would be subject to large current flows if loading changed abruptly on either side of the border (Lee et al. 1993).
4. *The electric field strengths from dc lines are, in general, higher than those from ac lines.* Figure 14 shows the results of a study of electric fields below a ± 400 -kV dc line (Bracken et al. 1978). The results indicate that the electric field below the line is enhanced by the presence of ionized air and by atmospheric conditions.

Tests have demonstrated that current induced in a human body because of such dc field levels is far below the threshold of perception. The perception of dc-induced current is several orders of magnitude less than that for the ac-induced current from fields of equal strength.

5. *Ionized air caused by dc transmission lines has been cited as a health concern.* Air ions are molecules with either an extra electron (negative) or a missing electron (positive). Because of the high voltage, dc lines always produce corona discharges. Therefore, air ions are constantly being produced. Research (Lee et al. 1993) indicates that levels of production of ionized air fall within the lower range of values associated with causing subtle effects on biological systems. The effects of exposure to ionized air are very small and would be difficult to detect outside the laboratory because the symptoms of exposure are within the range of normal physiological and psychological symptoms caused by other environmental stresses.
6. *Audible noise caused by the corona effect is a design consideration.* Audible noise is greatest for ac transmission lines during heavy rain or wet conductor conditions. For dc lines, radio and audible noise generally decreases in wet weather, when ionization of the air around the conductor is the greatest. The intense ionization surrounds the conductor with a space charge region that reduces the electric field at the surface of the conductor. This region, in turn, suppresses the intensity of the corona pulses, and both the audible and radio noises are reduced. The level of audible noise produced by a dc line is 40 decibels (A-weighted) (dB[A]), which is less than the 50 dB(A) from an ac line (Oppel and Stewart 1993).

FIGURE 14 Calculated Total Electric Field near Ground for ± 400 -kV dc Transmission Line (RH = relative humidity) (Source: Bracken et al. 1978 [© IEEE])

The EMF strengths at ground level for dc lines are dependent on the phase-to-phase distance and the phase-to-ground distance. Table 5 lists the calculated values of the fields at various points relative to the centerline of the transmission lines.

Although the dc magnetic field strength at the centerline is higher than those of the 500-kV ac configurations, the dc field is constant (like the earth's magnetic field) and is less than 50% of the earth's magnetic field. Because of their constant nature and low strength relative to the earth's field, the magnetic fields from the dc lines are less controversial than the lower but fluctuating fields from ac transmission lines.

The calculated electric field is only provided here for completeness. Because of the effects of ionization, actual electric field strengths will vary substantially. This factor has been discussed previously.

TABLE 5 Calculated EMF Strengths and Sensitivities for ± 450 -kV dc Horizontal Configuration

Field	Magnetic			Electric		
	Field (mG)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)	Field (kV/m)	Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
Maximum ^a	232 at 0 ft ^b	0.92	4.2	11 at 20 ft ^b	0.9	5
120 ft from centerline ^c	18	2.6	0.41	0.66	2.4	-2.2
200 ft from centerline ^c	6.5	2.5	0.15	0.15	2.3	-2.8

^a Maximum field inside of 160-ft right-of-way.

^b Distance from centerline.

^c Centerline of tower.

3.4 COSTS

3.4.1 Florida Study

Power Technologies, Inc., conducted a study of 230-kV and 500-kV transmission systems (Oppel and Stewart 1993) for the Florida Department of Environmental Regulation "to analyze options and propose designs to further reduce the magnetic fields beyond the present Florida designs" (Oppel and Stewart 1993, chap. 1, p. 1). Specific information on the report is presented in Section B.1 of Appendix B. As a result of the study, two 230-kV and two 500-kV designs were proposed; and the designs and the costs of each design were presented.

3.4.1.1 Proposed 230-kV Options

Table B.1 in Appendix B lists the construction costs, magnetic fields, and electric fields for three 230-kV transmission line configurations: vertical (base case), inverted delta, and split phase.

Base-Case 230-kV Vertical Configuration. Figure 15 shows the 230-kV vertical transmission line (base case) configuration. The calculated field strengths for this configuration are listed in Table 6. The Florida study (Oppel and Stewart 1993) gives an estimate of \$120,000/mi for the base-case design, which uses conductors with a 1.427-in. diameter.

FIGURE 15 Presently Used Florida 230-kV Vertical Design

Proposed 230-kV Inverted-Delta Configuration. Figure 16 shows the proposed inverted-delta configuration. Table 6 also shows the calculated field strengths for the inverted-delta configuration.

Oppel and Stewart (1993) estimated a cost of \$175,000/mi for this design, which uses 1.762-in.-diameter conductors. The larger conductor size was used to reduce corona problems associated with the smaller conductors.

Proposed 230-kV Split-Phase Configuration. Figure 17 shows the proposed 230-kV split-phase design. Currents of 500 A per conductor were assumed to normalize the power levels of the split-phase configuration for comparison purposes. The results of the 230-kV split-phase calculations are also shown in Table 6.

TABLE 6 Calculated EMF Strengths for Florida Base-Case and Proposed 230-kV Designs^a

Configuration and Field	Distance from Centerline of Tower (ft)						
	0	20	40	60	80	100	200
Vertical (base case)							
Magnetic field (mG)	79.0	57.3	32.1	18.7	11.9	8.06	2.2
Electric field (kV/m)	1.88	0.9	0.15	0.061	0.079	0.07	0.03
Inverted delta							
Magnetic field (mG)	58.6	41.2	21.7	12.1	7.42	4.95	1.3
Electric field (kV/m)	1.37	0.77	0.42	0.25	0.16	0.11	0.03
Split phase							
Magnetic field (mG)	33.5	22.2	9.84	4.5	2.3	1.3	0.19
Electric field (kV/m)	0.99	1.03	0.33	0.06	0.02	0.02	0.01

^a Field strengths were calculated with FIELDS 1.0 program.

The estimated cost for the split-phase transmission line was \$198,000/mi. The cost includes the cost of six conductors of the same size and type used in the estimates for the vertical configuration. Because the cost of conductors is roughly proportional to their diameter, the assumption was made that the cost of the smaller conductors for the split-phase configuration could be reduced by 50% ($\$56,000 \times 0.5 = \$28,000$). Hence, the conductor cost for the split-phase design was reduced by \$28,000 to \$170,000/mi. A comparison of the calculated field strengths at three different distances from the centerline and the cost per mile for the 230-kV vertical, inverted-delta, and split-phase designs are presented in Table 7. Table 7 shows that the vertical design offers the lowest cost but the highest fields. Compared with the vertical design, the inverted-delta design reduces the magnetic fields by about 26%, 38%, and 36% at 0, 100, and 200 ft from the centerline but increases the cost by 46%.

The design with the lowest magnetic (and electric) fields is the split-phase design, which yielded 58%, 84%, and 90% decreases in magnetic field strengths compared with the base case at 0, 100, and 200 ft, respectively, but at an increased cost. The cost of the inverted-delta design increased disproportionately because of the larger conductor size that was selected to control the corona expected from this design.

Alternately, the assumption was made that the split-phase design could use smaller conductors (because of the 500-A phase current) without increasing corona effects. These two

**FIGURE 16 Proposed Florida 230-kV
Inverted-Delta Design**

considerations and the extra cost associated with the nonstandard inverted-delta design caused the split-phase design to be less costly than the inverted-delta design. The low EMFs show that the split-phase design is extremely effective in reducing magnetic fields. Although the other configurations exhibit relatively low electric field strengths at all distances, the split-phase design yielded the lowest electric field strength.

3.4.1.2 Proposed 500-kV Options

Data on one existing and two proposed 500-kV designs from the Florida study are shown in Table B.2 in Appendix B. The designs are vertical (base case), davit, and delta configurations. The FIELDS 1.0 program was run for each of these designs to provide a comparison of field strengths, as well as costs.

FIGURE 17 Proposed Florida 230-kV Split-Phase Design

Base-Case 500-kV Vertical Configuration. Figure 18 shows the existing 500-kV vertical configuration. One shield wire on the centerline at a height of 37 ft above the top conductor was assumed.

With the exception of directly under the line (0 ft), the magnetic field for the base case is lower at distances up to 60 ft from the centerline (Table 8) when compared with those of the other two alternatives but is higher at distances greater than 60 ft. The field is less than 10 mG at the 200-ft distance and decreases rapidly beyond this distance. The estimated construction cost for this design (Table 9) is \$534,000/mi.

Proposed 500-kV Davit Configuration. Figure 19 shows the proposed 500-kV davit configuration. The shield wires are 30 ft above the top conductor and 16 ft on either side of the centerline.

TABLE 7 Estimated Costs and Calculated EMF Strengths for 230-kV Designs from the Florida Study

Design	Cost per Mile ^a	Field and Location Relative to Centerline			
		Field	Maximum Field ^b	100 ft ^b	200 ft ^b
Vertical	\$120,000	Magnetic (mG)	79.0 at 0 ft	8.06	2.20
		Electric (kV/m)	1.88 at 0 ft	0.07	0.03
Inverted delta	\$175,000	Magnetic (mG)	58.6 at 0 ft	4.95	1.3
		Electric (kV/m)	1.37 at 0 ft	0.11	0.03
Split phase	\$170,000	Magnetic (mG)	33.5 at 0 ft	1.3	0.19
		Electric (kV/m)	1.17 at 10 ft	0.02	0.01

^a Source: Oppel and Stewart (1993).

^b Calculated with FIELDS 1.0 program.

TABLE 8 Calculated EMF Strengths for Florida Base-Case and Proposed 500-kV Designs^a

Configuration and Field	Distance from Centerline of Tower (ft)						
	0	20	40	60	80	100	200
Vertical							
Magnetic field (mG)	158	123	79.7	53.0	37.1	27.1	8.65
Electric field (kV/m)	6.76	4.02	1.40	0.43	0.21	0.22	0.13
Davit							
Magnetic field (mG)	141	145	95.4	57.0	36.1	24.3	6.25
Electric field (kV/m)	3.86	6.19	3.34	1.37	0.75	0.52	0.15
Delta							
Magnetic field (mG)	185	156	93.8	93.9	34.9	23.8	6.61
Electric field (kV/m)	4.23	6.15	3.63	1.57	0.76	0.44	0.12

^a Field strengths were calculated with FIELDS 1.0 program.

FIGURE 18 Existing Florida 500-kV Vertical Design

FIGURE 19 Proposed Florida 500-kV Davit Design

Table 8 also shows the EMF strengths for the davit design. The estimated construction cost (Table 9) for this design is \$606,000/mi.

Proposed 500-kV Delta Configuration. Figure 20 shows the proposed 500-kV delta configuration. The shield wires are placed 17.5 ft above the top conductor and 16 ft on either side of the centerline.

Table 8 also shows the EMF strengths for the delta design. The estimated construction cost (Table 9) for this design is \$593,000/mi.

TABLE 9 Estimated Costs and Calculated EMF Strengths for 500-kV Designs from the Florida Study

Design	Cost per Mile ^a	Field and Location Relative to Centerline			
		Field	Maximum Field ^{b,c}	100 ft ^c	200 ft ^c
Vertical	\$534,000	Magnetic (mG)	158	27.2	8.65
		Electric (kV/m)	6.76	0.22	0.13
Davit	\$606,000	Magnetic (mG)	145	24.3	6.25
		Electric (kV/m)	6.19	0.52	0.15
Delta	\$593,000	Magnetic (mG)	185	23.8	6.61
		Electric (kV/m)	6.15	0.44	0.12

^a Source: Oppel and Stewart (1993).

^b Maximum field inside of 160-ft right-of-way.

^c Data were generated with FIELDS 1.0 program.

The calculations yielded no dramatic decrease in the magnetic fields for either the delta or davit designs. When compared with the base-case vertical design, the delta design produced an increase in magnetic field strength of 18% at 40 ft and a decrease of 24% at 200 ft (Table 8), in return for a cost increase of 11% (Table 9). The davit design provided an increase in magnetic field strength of 19% at 40 ft and a decrease of 28% at 200 ft (Table 8) in return for a cost increase of 13% (Table 9).

3.4.2 Rhode Island Study

In 1992, Commonwealth Associates, Inc., published a report for the state of Rhode Island entitled *Cost Effectiveness Analysis: Mitigation of Electromagnetic Fields*. This report compared costs and EMF strengths of five different 345-kV configurations. The configurations were

- Horizontal,
- Davit arm,
- Inverted delta,
- Split phase, and
- Underground.

For purposes of calculation, all 345-kV configurations were assumed to have a minimum (sag point) phase-to-ground clearance of 30 ft and currents of 1,000 A per phase, except for the split phase, where 500 A per phase was assumed to normalize power transmission capability.

**FIGURE 20 Proposed Florida 500-kV
Delta Design**

3.4.2.1 Horizontal Configuration for 345-kV ac

The design studied had a phase-to-phase spacing of 26 ft and grounded shield wires 18 ft above the top conductor and 13 ft on either side of the transmission line centerline. New EMF strengths were calculated by using the FIELDS 1.0 computer program for various distances from the centerline and 3 ft above ground level. The estimated construction cost in 1991 dollars for the horizontal design was \$390,000/mi.

The horizontal configuration produces the highest calculated magnetic field levels of the five designs studied (Table 10) because of the minimal height of the structure. The ineffective phase-to-phase attenuation under the conductors limits the decrease in magnetic field strength until the measuring point is moved beyond the outside conductor. Because the electric fields are less than 4.5 kV/m at all points calculated, these fields are not a great concern.

TABLE 10 Calculated 345-kV EMF Strengths from the Rhode Island Study^a

Configuration and Field	Maximum Field	Distance from Centerline of Structure (ft)						
		0	20	40	60	80	100	200
Horizontal								
Magnetic field (mG)	210 at 0 ft	210	208	141	77.1	45.4	29.4	7.39
Electric field (kV/m)	4.32 at 30 ft	2.73	3.67	3.75	1.89	0.92	0.5	0.07
Davit								
Magnetic field (mG)	135 at -10 ft	132	95.7	58.7	35.6	22.8	15.6	4.23
Electric field (kV/m)	3.64 at -20 ft	2.54	1.90	1.61	0.99	0.58	0.36	0.07
Inverted delta								
Magnetic field (mG)	124 at 0 ft	124	94.7	57.0	34.6	22.3	15.3	4.16
Electric field (kV/m)	3.95 at 0 ft	3.95	2.18	0.86	0.55	0.39	0.27	0.07
Split phase								
Magnetic field (mG)	67.4 at 0 ft	67.4	52.8	29.2	15.5	8.69	5.2	0.83
Electric field (kV/m)	3.00 at 10 ft	2.45	2.99	1.36	0.7	0.46	0.3	0.05
Underground delta								
Magnetic field (mG)	86.2 at 0 ft	86.2	10.8	2.97	1.35	0.76	0.5	0.12
Electric field (kV/m)	0	0	0	0	0	0	0	0

^a Table data were generated by FIELDS 1.0 program.

3.4.2.2 Davit Arm Configuration for 345-kV ac

For the davit design, the phase-to-phase distance is 29 ft. All other conditions are the same as those assumed for the horizontal design, except the shield wires are 6 ft on either side of the centerline and 20 ft above the top conductor.

When compared with the equivalent points for the horizontal configuration, the davit design shows lower calculated EMF strengths (Table 10) at all points except one. The decreases are caused by EMF attenuation that results from the phases being closer to one another. When compared with the horizontal configuration, the davit design shows decreases in the magnetic field strength in excess of 35% occurring at all distances from 0 to 200 ft from the centerline. Near the centerline, the electric field strengths are much lower (40% to 58%) than those of the horizontal design. More than 80 ft from the centerline, the differences in the electric field strengths decrease until the values converge at 200 ft from the centerline.

The estimated construction cost in 1991 dollars for the davit arm configuration is \$454,000/mi. This cost is 16% higher than that of the horizontal design.

3.4.2.3 Inverted-Delta Configuration for 345-kV ac

The inverted-delta configuration has a phase-to-phase spacing of 28 ft. The shield wires are 24 ft above the top conductors of the inverted delta and 21 ft on either side of the centerline. At the 200-ft point, the davit and inverted delta designs have similar EMF strengths.

The construction cost in 1991 dollars for the inverted-delta configuration is \$470,000/mi. This cost is 21% higher than that of the horizontal design.

3.4.2.4 Split-Phase Configuration for 345-kV ac

For the split-phase design, the vertical phase-to-phase spacing was 26 ft. The horizontal (phase A to C) spacing is 24 ft for the upper and lower arms and 48 ft for the middle arms (phase B to B). The shield wires were 20 ft above the top conductor and 20 ft on either side of the centerline. To equalize the power transmission level, a current of 500 A, instead of 1,000 A, was assumed.

The construction cost in 1991 dollars was \$550,000/mi for the split-phase transmission line. This cost is 41% higher than that of the horizontal design.

Table 10 shows the EMF strengths for the 500-A 345-kV split-phase design. The magnetic fields are the lowest of all of the considered aboveground configurations at all measurement points. This reduction is primarily caused by the reduced conductor current levels; however, the split-phase electric fields are only slightly improved over those of the horizontal design.

3.4.2.5 Underground Delta Configuration for 345-kV ac

The conductors of the underground transmission system form a delta configuration. The phases are physically spaced 8 in. apart by the electrical insulation on the conductors and are buried inside a steel pipe approximately 5 ft below the surface. By conventional utility design, the transmission pipe contains a specially formulated fluid that is kept under high pressure. This fluid helps to dissipate the power loss heat generated by the conductors.

The construction costs in 1991 dollars for this 345-kV design type is \$1,450,000/mi. This cost, which is the highest of the five designs considered, is 3.7 times the cost of the horizontal design.

The magnetic field strengths are calculated to be very low at all points except the centerline (Table 10). This high peak followed by rapid attenuation is the result of the very close (8-in.) spacing of the conductors, which produces a peak close to the conductors but exhibits excellent phase-to-phase field cancellation effects away from the conductors. The actual fields would be significantly lower because of the attenuation effect of the steel pipe on the field. In the Rhode Island study, a 94% magnetic field reduction was calculated at the centerline when pipe shielding was taken into account. If this effect is applied to all of the magnetic field, all magnetic field strengths would be less than 1 mG. The electric field is 0 kV/m at all points because of the electric grounding effects of the earth.

3.4.3 Washington State Study

In 1990, the Washington State Legislature established and directed an Electric Transmission Research Needs Task Force to investigate research needs associated with limiting human exposure to EMFs from electric power transmission and distribution lines. The task force was also directed to recommend any additional research needed on ways to reduce EMF exposure.

The report (Waller and Geissinger 1992) includes a comparison of the costs and EMF fields of six 230-kV transmission line designs. Table 11 gives the calculated values that are based on the phase spacings noted and 30-ft minimum (sag point) ground clearances. As in the 230-kV and 500-kV Florida cases and the Rhode Island 345-kV cases, the EMF impact point was 3 ft above ground level; and the currents were 1,000 A per phase, except for the split-phase configurations, which were 500 A per phase to equalize power transmission. The six different configurations that were studied were

- Horizontal,
- Davit arm,
- Delta,
- Split phase,
- Vertical, and
- Underground delta.

**TABLE 11 Calculated 230-kV EMF Strengths
from the Washington State Study^a**

Configuration and Field	Maximum Field	Distance from Centerline of Structure (ft)						
		0	20	40	60	80	100	200
Horizontal								
Magnetic field (mG)	198 at 0 ft	198	172	99	53.3	31.8	21	5.36
Electric field (kV/m)	2.35 at 20 ft	1.21	2.35	1.76	0.82	0.4	0.2	0.03
Davit arm								
Magnetic field (mG)	90.5 at 0 ft	90.5	69.5	37.1	20.4	12.4	8.2	2.13
Electric field (kV/m)	1.80 at 10 ft	1.52	1.51	0.67	0.33	0.2	0.1	0.03
Delta								
Magnetic field (mG)	93.5 at 0 ft	93.5	64.5	32.5	17.6	10.7	7.1	1.82
Electric field (kV/m)	1.60 at 10 ft	1.47	1.43	0.67	0.3	0.16	0.1	0.02
Split phase								
Magnetic field (mG)	48.2 at 0 ft	48.2	33.9	16.1	7.7	4.06	2.3	0.35
Electric field (kV/m)	1.40 at 10 ft	1.13	1.4	0.51	0.11	0.03	0	0.01
Vertical								
Magnetic field (mG)	109 at 0 ft	109	81.9	48.7	29.8	19.4	14	3.8
Electric field (kV/m)	2.38 at 0 ft	2.38	1.26	0.29	0.03	0.08	0.1	0.04
Underground delta								
Magnetic field (mG)	86.2 at 0 ft	86.2	10.8	2.97	1.35	0.76	0.5	0.12
Electric field (kV/m)	0	0	0	0	0	0	0	0

^a Table data were generated by FIELDS 1.0 program.

FIGURE 21 Horizontal Configuration for 230-kV ac

FIGURE 22 Davit Arm Configuration for 230-kV ac

FIGURE 23 Delta Configuration for 230-kV ac

3.4.3.1 Horizontal Configuration for 230-kV ac

This design had a phase-to-phase spacing of 19 ft and grounded shield wires 15 ft above the conductor and 15 ft on either side of the tower's centerline (Figure 21). The estimated construction cost in 1991 dollars was \$230,000-\$260,000/mi for the horizontal design.

This configuration produced the highest calculated magnetic field levels (Table 11) of these 230-kV configurations. The electric field strengths are not a great concern because they are less than 2.5 kV/m at any location beneath or near the lines.

3.4.3.2 Davit Arm Configuration for 230-kV ac

For the 230-kV davit arm design, the phase-to-phase distance was 14 ft (Figure 22). The shield wire was assumed to be placed at the centerline and 20 ft above the topmost conductor.

Table 11 also lists the EMF strengths at all points for the davit arm design. Because the electric field strengths are 1.80 kV/m or less, the electric fields are low enough to be of little concern.

The estimated construction cost in 1991 dollars was \$230,000-\$250,000/mi for the davit arm design. This cost is about the same as that for the horizontal design.

3.4.3.3 Delta Configuration for 230-kV ac

The phase-to-phase spacing for the delta design (Figure 23) was 12.7 ft. Two shield wires are placed 19 ft above the top conductor and 6 ft on either side of the centerline.

Table 11 shows that the magnetic field at the centerline for the delta design is slightly higher than that of the davit arm but still much improved over that of the horizontal design. At the 200-ft point, the magnetic field of the delta design is 14% lower than that of the davit arm design and 66% lower than that of the horizontal design.

The construction cost in 1991 dollars for this configuration is \$220,000-\$250,000/mi. As with the davit arm, this cost is about the same as that of the horizontal design.

3.4.3.4 Split-Phase Configuration for 230-kV ac

Figure 24 presents a typical 230-kV split-phase design. The horizontal spacing from phase A to phase C is 18 ft 8 in. and from phase B to phase C and from phase B to phase A is about 14 ft. The design shows a vertical spacing from phase B to phase A and from phase B to phase C of 14 ft. Two grounded shield wires are 20 ft above the top conductors and 6 ft on either side of the centerline. Currents of 500 A per phase were assumed.

Table 11 shows the results of the EMF calculations. The magnetic fields for the split-phase design are the lowest of all of the considered aboveground configurations at all measurement points, primarily because of the lower currents.

The estimated construction cost in 1991 dollars was \$350,000-\$400,000/mi for the split-phase transmission line. This cost is 54% higher than that for the base-case horizontal design.

3.4.3.5 Vertical Configuration for 230-kV ac

This vertical configuration (Figure 25) had a 14-ft phase-to-phase spacing and a single shield wire 12 ft above the top conductor at the centerline. The calculated magnetic field strengths for the vertical design are 20% higher than those of the davit arm design but 45% lower than those of the base-case horizontal design. The electric field strengths are below 2.5 kV/m at all points.

The estimated construction cost in 1991 dollars was \$275,000-\$350,000/mi for this design. This cost is an increase of 35% over that of the horizontal design.

FIGURE 24 Split-Phase Configuration for 230-kV ac

FIGURE 25 Vertical Configuration for 230-kV ac

3.4.3.6 Underground Configuration for 230-kV ac

The underground transmission system naturally assumes a delta conductor configuration (Figure 26). The phases are physically spaced 8 in. apart by the electrical insulation on the conductors and are buried inside a steel pipe approximately 5 ft below ground. The transmission pipe contains a specially formulated fluid at high pressure to dissipate the power loss heat of the conductors.

This design option has the highest estimated construction cost of all of the 230-kV configurations considered. The construction cost in 1991 dollars for the underground design was estimated at \$1,500,000-\$2,000,000/mi. This cost is an 870% increase over that of the horizontal design.

Calculated magnetic field strengths for the underground delta design are very low at all points except along the centerline. This reduction is a consequence of the very close (i.e., 8-in.) spacing of the conductors. The actual magnetic fields will be significantly lower because of the attenuation effect of the steel pipe on the field. The Rhode Island study (Commonwealth Associates, Inc. 1992) estimates a 94% reduction of the calculated results because of the shielding effects of the pipe. If this factor is applied to the Washington state study values in Table 11, the centerline field would be less than 6 mG, and all points beyond 20 ft would have magnetic field strengths of less than 1 mG. No electric fields exist around the pipe because of the electrical grounding of the earth.

3.4.4 Bonneville Power Administration 500-kV Estimation Study

A 1992 Bonneville Power Administration (BPA) memorandum (A.M. Wykoff, unpublished information) provided information concerning transmission-line construction-cost estimating data for 500-kV delta and split-phase transmission lines that use different sizes of conductors. The data included a breakdown of the material and construction costs per mile of transmission lines. These data were to be used for initial planning purposes. The data included estimated costs for different conductors. The conductor costs that were provided are as follows:

- Delta configuration with 3,578-MCM conductors, \$354,000/mi;
- Delta configuration with 5,607-MCM conductors, \$410,000/mi;
- Split-phase configuration with 3,578-MCM conductors, \$790,000/mi;
- Split-phase configuration with 5,607-MCM conductors, \$881,000/mi; and
- Split-phase configuration with 6,935-MCM conductors, \$950,000/mi.

The MCM is the unit used to denote the size of conductors and stands for 1,000 circular mils (kilo circular mil). The MCM unit is derived by squaring the diameter of

FIGURE 26 Underground Configuration for 230-kV ac

the conductor in mils (thousandths of an inch) and then dividing by 1,000. Hence, to determine the diameter of a 5,607-MCM conductor, one would multiply 5,607 (MCMs) by 1,000 to determine its circular measurement in mils. Taking the square root of this measurement (5,607,000) would yield 2,367, which is the diameter of the conductor in mils. Thus, a 5,607-MCM conductor would have a diameter of 2.367 in.

High-voltage transmission lines are generally uninsulated aluminum-core steel-reinforced (ACSR) cables. For ease of production and reduced corona effects, a single large high-voltage conductor is not used. Instead, the conductors actually consist of numerous smaller ACSR conductors; for instance, a 5,607-MCM cable is actually composed of three 1,867-MCM ACSR conductors, each of which has a diameter of 1.366 in.

As can be seen from the previous data, reducing the size of the cable can significantly reduce the cost of constructing an electric power transmission line. Extrapolation of a linear model that is based on the costs of the three split-phase configurations noted previously to a conductor size of 2,804 MCM yields a cost of \$657,000/mi. As pointed out by Oppel and Stewart (1993), the split-phase design also offers minimum line impedance, which, in turn, allows improved surge impedance for maximum power transfer capability.

**TABLE 12 Comparative Construction Costs and EMF Strengths
for Two 500-kV Low-EMF Transmission Line Designs**

Design	Cost per Mile	Field and Location Relative to Centerline			
		Field	Maximum Field ^a	120 ft	200 ft
Delta	\$410,000 ^b (5,607 MCM)	Magnetic (mG)	181 at 0 ft	13.3	4.86
		Electric (kV/m)	5.80 at 20 ft	0.27	0.09
Split phase	\$657,000 ^c (2,804 MCM)	Magnetic (mG)	158 at 0 ft	8.60	2.28
		Electric (kV/m)	5.12 at 20 ft	0.27	0.08

^a Maximum field inside a 160-ft right-of-way at 3 ft above ground level.

^b Source: Lee et al. (1993).

^c Extrapolation of data from Lee et al. (1993).

The EMF strengths for the 500-kV delta and split-phase configurations calculated in Section 3.3.1.2 of this report, the construction costs for the 5,607-MCM 500-kV delta configuration provided by the BPA, and extrapolation of the BPA-provided construction costs for 500-kV split-phase configurations to a 2,804-MCM size were combined to produce Table 12. Although both the delta and split-phase configurations produce low EMF strengths, the magnetic field of the split-phase configuration is 12.7% lower than that of the delta configuration at the centerline and is 53% lower at 200 ft from the centerline; however, these reduced magnetic fields would require a 60% increase in the per-mile construction costs.

4 CONCLUSIONS

4.1 SENSITIVITY STUDY

Calculations were made to quantify the change in magnetic or electric field strengths near high-voltage electric transmission lines when the conductors are either moved closer together or the line height is increased. Coefficients (called the compacting sensitivity or the height sensitivity) were developed to report the calculated changes in EMF strengths per foot of conductor movement for several different designs for transmission lines and at several different voltages. The values for sensitivity are the percent per foot that the magnetic or electric field decreases (positive value) when the phase-to-phase distance is compacted (decreased) by 5 ft or the phase-to-ground height is increased by 5 ft.

The results in Table 13 are representative of the values for the compacting and height sensitivity at 100 and 200 ft from the transmission line's centerline that were calculated for four 345-kV power line configurations (horizontal, delta, davit, and split phase). Table 13 shows that the phase-to-phase magnetic field compacting sensitivity ranges from less than 4%/ft to more than 5%/ft if the conductors are assumed to be 5 ft closer to each other. One conclusion that can be drawn from Table 13 is that all of the configurations will yield similar field reductions when the phases are compacted.

The compacting strategy might be useful when a localized area (such as a school or residential area) requires a low magnetic field. The phases could be compacted for a limited portion of the line to meet the local need and should not affect the overall performance of the line in a substantial way. The compacted portion would incur additional corona losses and have increased phase-to-phase capacitance; however, calculations or tests should be made to ensure that the compaction has no significant impact on the reliability of the transmission line (that the compacted phase-to-phase distance offers reasonably low probabilities of arc-over between lines)

Small increases of the phase-to-ground height of a power line are much less effective for reducing magnetic field strength than compacting the phase-to-phase distances. Large

TABLE 13 Sensitivity Analysis for Four 345-kV Configurations

345-kV Configuration	Compacting Sensitivity (%/ft)		Height Sensitivity (%/ft)	
	At 100 ft ^a	At 200 ft ^a	At 100 ft ^a	At 200 ft ^a
Horizontal	4.71	4.49	0.62	0.15
Delta	4.03	3.88	0.63	0.16
Davit	4.61	4.57	0.77	0.21
Split phase	5.58	5.17	1.05	0.30

^a Distance from centerline.

increases in the height of a transmission line would necessitate stronger towers because of wind loading. Stronger towers, in turn, increase the construction costs. These latter considerations, plus the relatively small reduction in magnetic field strengths, discourage the use of small increases in the height of the tower as a means of reducing magnetic fields, except where the requirements for such reduction are severe and where no compaction or configurational changes are possible.

4.2 STUDY OF COST VERSUS FIELDS

Table 14 presents the overall comparisons of construction cost versus EMF strengths for the 345-kV ac designs from the Rhode Island study (Commonwealth Associates, Inc. 1992). Table 14 clearly shows the trade-off between cost and reduction in magnetic field strength, where the least costly (to construct) horizontal configuration has the highest magnetic fields. By changing configurations, the 16%, 21%, and 41% increases in the construction costs for overhead davit, inverted-delta, or split-phase lines obtain, respectively, magnetic field reductions of 36%, 41%, and 68% at the maximum field points and reductions of 43%, 44%, and 89% at 200 ft from the centerline. Changing an overhead horizontal system to an underground system yielded even more impressive results, but at an equally impressive increase in construction costs. In this case, a 3.7-fold (370%) increase in construction costs provided a calculated 59% and 98% reduction in magnetic fields at the maximum field point

TABLE 14 Estimated Costs and Calculated EMF Strengths for Five 345-kV Power Line Configurations from the Rhode Island Study

Design	Cost per Mile ^a	EMF Strengths and Location Relative to Centerline		
		Field	Maximum Field and Location	Field at 200 ft
Horizontal	\$390,000	Magnetic (mG) Electric (kV/m)	210 at 0 ft 4.32 at 30 ft	7.39 0.07
Davit	\$454,000	Magnetic (mG) Electric (kV/m)	135 at 10 ft 3.64 at 20 ft	4.23 0.07
Inverted delta	\$470,000	Magnetic (mG) Electric (kV/m)	124 at 0 ft 3.95 at 0 ft	4.16 0.07
Split phase (I = 500 A)	\$550,000	Magnetic (mG) Electric (kV/m)	67.4 at 0 ft 3.00 at 10 ft	0.83 0.05
Underground	\$1,450,000	Magnetic (mG) Electric (kV/m)	86.2 at 0 ft (unshielded); 5.2 at 0 ft (pipe shield) 0	0.12 0

^a Source: Commonwealth Associates, Inc. (1992).

for the unshielded and pipe-shielded conditions, respectively. At 500 kV, a similar trade-off of an increase in construction cost for magnetic field reduction is noted when the calculations of magnetic field strength and the data on construction costs for several overhead power line configurations are reviewed.

Previous studies and the calculations made for this report show that small changes in magnetic fields are obtainable at reasonable cost by compacting the phase-to-phase spacing of power lines but at a possible decrease in the reliability of the power line. Even smaller reductions in the magnetic field can be obtained by increasing the phase-to-ground height of power lines, but the costs to do so may be prohibitively high for the small amount of magnetic field reduction that can be achieved; however, significant reductions in magnetic field strength can be obtained by changing the power line configuration to a configuration that is more costly to construct. The most expensive (to construct) power line design, the underground system, is also the design that produced the lowest magnetic fields; however, the very high cost of the underground system would restrict its application for magnetic field reduction to only those locations where severe restrictions on magnetic fields apply.

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APPENDIX A:

SENSITIVITY CALCULATIONS

This appendix contains the calculated EMF strengths of electric power transmission lines for various spacing configurations at 765-kV, 500-kV, and 345-kV ac and for one configuration at ± 450 -kV dc as a function of distance from the centerline of the power line. The calculations were made by using the FIELDS 1.0 personal-computer program from Southern California Edison Co. This program uses the basic algorithms from the EPRI *Transmission Line Reference Book* (General Electric Co. 1982). The electric field calculation assumes that the earth is a perfect conductor and sums the vector components of the electric fields created by the charge on each conductor of each phase. Likewise, the magnetic field calculation sums the vector components of the magnetic fields from an assumed current in each of the conductors of each phase.

All calculations were repeated for a compact design where the phases are 5 ft closer to each other than in the original calculation. The comparative EMF strengths were then used to calculate the compacting sensitivity (in percent per foot) caused by compacting the phase-to-phase clearance. The calculation was repeated a third time with the original phase-to-phase clearance but with the phase-to-ground distance increased by 5 ft. This change produced new values of EMF strengths that were used to calculate height sensitivity caused by changes in the height of the conductor above ground.

As an example of how to use the sensitivity values, suppose that the magnetic field strength for a particular power-line configuration at a particular voltage is 15 mG at 200 ft from the centerline of the power line. Also assume that the applicable compacting sensitivity is 2.5%/ft and the applicable height sensitivity is 0.5%/ft. If one wants to consider the options available to manipulate line spacing or increase line height to reduce the field to 12.5 mG, a calculation can be made to determine how much to reduce the phase-to-phase (or phase-to-ground) spacing to achieve the 12.5-mG objective.

For example, to calculate the desired percentage of field reduction, $12.5 \text{ mG} / 15 \text{ mG} = 0.8333$. This percentage requires a 17% field reduction; then $17\% / (2.5\%/\text{ft}) = 6.8 \text{ ft}$ of phase-to-phase distance reduction will result in a 12.5-mG field at 200 ft.

The tables in this appendix contain the results of the FIELDS 1.0 personal-computer program's calculations of EMF strengths for one 765-kV ac transmission-line configuration, five 500-kV ac configurations, four 345-kV ac configurations, and one ± 450 -kV dc configuration. The tables also include the data on EMF strengths for each of these configurations at several distances from 0 to 200 ft under both the compacted-phase condition and the raised-height condition. Finally, the tables include the results of calculations of both the compacting sensitivity and the height sensitivity for each of the configurations and at several distances from 0 to 200 ft from the transmission line centerline.

A.1 HORIZONTAL CONFIGURATION FOR 765-kV ac

For the 765-kV ac horizontal configuration (Figure 3), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -40$ ft and $y = 45$ ft (at sag point for the line considered),
 - Phase B, $x = 0$ ft and $y = 45$ ft,
 - Phase C, $x = 40$ ft and $y = 45$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wires at tower,
 - Wire 1, $x = -30$ ft and $y = 65$ ft,
 - Wire 2, $x = 30$ ft and $y = 65$ ft; and
- Height of points of calculated EMFs (Table A.1) equals 3 ft above ground level.

A.2 CONFIGURATIONS FOR 500-kV ac

A.2.1 Horizontal Configuration for 500-kV ac

For the 500-kV ac horizontal configuration (Figure 4), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -35$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = 0$ ft and $y = 30$ ft,
 - Phase C, $x = 35$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);

TABLE A.1 Calculated EMF Strengths and Sensitivities for 765-kV ac Horizontal Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	135.1	133.1	119.4	0.30	2.32
20	137.1	131.5	119	0.82	2.64
40	124.6	112.7	107.5	1.91	2.74
60	93.15	80.38	82.89	2.74	2.20
80	63.23	53.82	58.48	2.98	1.50
100	43.28	36.89	41.11	2.95	1.00
120	30.86	26.42	29.79	2.88	0.69
160	17.66	15.23	17.32	2.75	0.39
200	11.35	9.832	11.21	2.67	0.25
Electric field					
0	3.985	3.339	3.099	3.24	4.45
20	3.989	3.997	3.384	-0.04	3.03
40	5.671	5.526	4.759	0.51	3.22
60	5.132	4.53	4.51	2.35	2.42
80	3.329	2.841	3.142	2.93	1.12
100	2.001	1.708	1.991	2.93	0.10
120	1.233	1.062	1.269	2.77	-0.58
160	0.54	0.474	0.575	2.44	-1.30
200	0.279	0.247	0.301	2.29	-1.58

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

- Coordinates of grounded shield wires,
 - Wire 1, $x = -26$ ft and $y = 57$ ft,
 - Wire 2, $x = 26$ ft and $y = 57$ ft; and
- Height of points of calculated EMFs (Table A.2) equals 3 ft above ground level.

A.2.2 Delta Configuration for 500-kV ac

For the 500-kV ac delta configuration (Figure 5), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates

TABLE A.2 Calculated EMF Strengths and Sensitivities for 500-kV ac Horizontal Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	203.6	209.3	176.9	-0.56	2.62
20	226.4	219.7	185.4	0.59	3.62
40	192.9	164.9	158.0	2.90	3.62
60	113.7	92.49	101.1	3.73	2.22
80	65.81	53.97	61.77	3.60	1.23
100	41.77	34.67	40.24	3.40	0.73
120	28.71	24.03	28.01	3.26	0.49
160	15.92	13.46	15.72	3.09	0.25
200	10.11	8.584	10.03	3.02	0.16
Electric field					
0	5.443	4.754	3.943	2.53	5.51
20	4.608	5.043	3.836	-1.89	3.35
40	6.831	6.130	5.439	2.05	4.08
60	4.080	3.250	3.721	4.07	1.76
80	1.938	1.544	1.963	4.07	-0.26
100	0.995	0.806	1.064	3.80	-1.39
120	0.567	0.466	0.623	3.56	-1.98
160	0.232	0.195	0.262	3.19	-2.59
200	0.117	0.099	0.133	3.08	-2.74

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -15.33$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = 0$ ft and $y = 59.4$ ft,
 - Phase C, $x = 15.33$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);

TABLE A.3 Calculated EMF Strengths and Sensitivities for 500-kV ac Delta Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	180.7	163.2	138.4	1.94	4.68
20	147.7	127.1	115.9	2.79	4.31
40	83.97	69.83	72.23	3.37	2.80
60	46.65	38.69	42.74	3.41	1.68
80	28.44	23.64	26.91	3.38	1.08
100	18.85	15.70	18.15	3.34	0.74
120	13.31	11.11	12.94	3.31	0.56
160	7.577	6.348	7.455	3.24	0.32
200	4.863	4.086	4.811	3.20	0.21
Electric field					
0	3.732	3.866	3.234	-0.72	2.67
20	5.798	5.254	4.510	1.88	4.44
40	3.392	2.836	3.058	3.28	1.97
60	1.486	1.235	1.505	3.38	-0.26
80	0.724	0.612	0.768	3.09	-1.22
100	0.412	0.355	0.440	2.77	-1.36
120	0.266	0.232	0.281	2.56	-1.13
160	0.141	0.123	0.144	2.55	-0.43
200	0.088	0.077	0.089	2.50	-0.23

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

- Coordinates of grounded shield wires,
 - Wire 1, $x = -12$ ft and $y = 76$ ft,
 - Wire 2, $x = 12$ ft and $y = 76$ ft; and
- Height of points of calculated EMFs (Table A.3) equals 3 ft above ground level.

A.2.3 Vertical Configuration for 500-kV ac

For the 500-kV ac vertical configuration (Figure 6), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = 18$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = 22$ ft and $y = 60$ ft,
 - Phase C, $x = 18$ ft and $y = 90$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wire,
 - Wire 1, $x = 9$ ft and $y = 123$ ft; and
- Height of points of calculated EMFs (Table A.4) equals 3 ft above ground level.

TABLE A.4 Calculated EMF Strengths and Sensitivities for 500-kV ac Vertical Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	151.7	141.8	120.2	1.31	4.15
20	117.8	109.4	99.01	1.43	3.19
40	75.33	68.89	67.65	1.71	2.04
60	49.55	44.56	46.13	2.01	1.38
80	34.35	30.41	32.64	2.29	1.00
100	24.90	21.77	23.97	2.51	0.75
120	18.73	16.22	18.19	2.68	0.58
160	11.54	9.865	11.33	2.90	0.36
200	7.748	6.570	7.649	3.04	0.26
Electric field					
0	6.531	6.224	5.239	0.94	3.96
20	3.800	3.532	3.427	1.41	1.96
40	1.212	1.031	1.316	2.99	-1.72
60	0.292	0.189	0.372	7.05	-5.48
80	0.217	0.220	0.139	-0.28	7.19
100	0.262	0.261	0.197	0.08	4.96
120	0.258	0.248	0.215	0.78	3.33
160	0.207	0.190	0.187	1.64	1.93
200	0.156	0.140	0.146	2.05	1.28

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

A.2.4 Davit Configuration for 500-kV ac

For the 500-kV ac davit configuration (Figure 7), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -17$ ft and $y = 42$ ft (at sag point for the line considered),
 - Phase B, $x = 17$ ft and $y = 55$ ft,
 - Phase C, $x = 18$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wires,
 - Wire 1, $x = -10$ ft and $y = 74$ ft,
 - Wire 2, $x = 10$ ft and $y = 74$ ft; and
- Height of points of calculated EMFs (Table A.5) equals 3 ft above ground level.

A.2.5 Split-Phase Configuration for 500-kV ac

For the 500-kV ac split-phase configuration (Figure 2), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -15$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = -25$ ft and $y = 61$ ft,
 - Phase C, $x = -15$ ft and $y = 92$ ft,
 - Phase D, $x = 15$ ft and $y = 92$ ft,
 - Phase E, $x = 25$ ft and $y = 61$ ft,
 - Phase F, $x = 15$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);

TABLE A.5 Calculated EMF Strengths and Sensitivities for 500-kV ac Davit Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	152.4	146.9	121.6	0.72	4.04
20	145.9	131.1	114.6	2.03	4.29
40	89.44	75.79	76.25	3.05	2.95
60	49.54	41.83	45.34	3.11	1.70
80	29.83	25.64	28.34	2.81	1.00
100	19.76	17.25	19.12	2.54	0.65
120	14.08	12.38	13.75	2.41	0.47
160	8.209	7.230	8.094	2.39	0.28
200	5.366	4.719	5.316	2.41	0.19
Electric field					
0	2.805	2.844	2.483	-0.28	2.30
20	5.749	5.263	4.467	1.69	4.46
40	3.492	2.951	3.112	3.10	2.18
60	1.579	1.376	1.559	2.57	0.25
80	0.865	0.765	0.866	2.31	-0.02
100	0.547	0.476	0.547	2.60	0.00
120	0.371	0.318	0.372	2.86	-0.05
160	0.196	0.163	0.197	3.37	-0.10
200	0.117	0.096	0.118	3.59	-0.17

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

- Coordinates of grounded shield wire,
 - Wire 1, $x = 0$ ft and $y = 127$ ft; and
- Height of points of calculated EMFs (Table A.6) equals 3 ft above ground level.

A.3 CONFIGURATIONS FOR 345-kV ac

Many different 345-kV ac configurations exist. For discussion purposes, the following were chosen to be representative of the group:

- Horizontal,

TABLE A.6 Calculated EMF Strengths and Sensitivities for 500-kV ac Split-Phase Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	157.8	138.3	117.7	2.47	5.08
20	129.1	107.3	98.46	3.38	4.75
40	73.04	57.58	60.70	4.23	3.38
60	38.91	29.79	34.48	4.69	2.28
80	21.99	16.52	20.24	4.97	1.59
100	13.33	9.890	12.56	5.16	1.16
120	8.604	6.328	8.228	5.29	0.87
160	4.138	3.001	4.023	5.50	0.56
200	2.277	1.634	2.233	5.65	0.39
Electric field					
0	3.337	3.354	2.785	-0.10	3.31
20	5.121	4.439	3.878	2.66	4.85
40	2.591	2.023	2.315	4.38	2.13
60	1.071	0.853	1.023	4.07	0.90
80	0.617	0.483	0.566	4.34	1.65
100	0.399	0.302	0.365	4.86	1.70
120	0.268	0.200	0.248	5.07	1.49
160	0.136	0.100	0.128	5.29	1.18
200	0.078	0.057	0.074	5.38	1.03

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

- Delta,
- Davit, and
- Split phase.

A.3.1 Horizontal Configuration for 345-kV ac

For the 345-kV ac horizontal configuration (Figure 8), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the

coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -22.7$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = 0$ ft and $y = 30$ ft,
 - Phase C, $x = 22.7$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wires,
 - Wire 1, $x = -18.6$ ft and $y = 48$ ft,
 - Wire 2, $x = 18.6$ ft and $y = 48$ ft; and
- Height of points of calculated EMFs (Table A.7) equals 3 ft above ground level.

A.3.2 Delta Configuration for 345-kV ac

For the 345-kV ac delta configuration (Figure 9), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -13.5$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = 0$ ft and $y = 50.3$ ft,
 - Phase C, $x = 13.5$ ft and $y = 30$ ft;
- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wires,
 - Wire 1, $x = -8$ ft and $y = 59$ ft,
 - Wire 2, $x = 8$ ft and $y = 59$ ft; and
- Height of points of calculated EMFs (Table A.8) equals 3 ft above ground level.

TABLE A.7 Calculated EMF Strengths and Sensitivities for 345-kV ac Horizontal Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	207.3	193.0	167.6	1.38	3.83
20	193.7	162.9	153.3	3.18	4.17
40	120.9	91.57	102.8	4.85	2.99
60	65.46	49.22	60.06	4.96	1.65
80	38.77	29.42	36.91	4.82	0.96
100	25.27	19.32	24.49	4.71	0.62
120	17.69	13.59	17.31	4.64	0.43
160	10.02	7.742	9.897	4.55	0.25
200	6.426	4.982	6.378	4.49	0.15
Electric field					
0	2.380	1.630	1.573	6.30	6.78
20	3.653	3.464	2.768	1.03	4.85
40	3.184	2.467	2.685	4.50	3.13
60	1.523	1.142	1.479	5.00	0.58
80	0.732	0.556	0.767	4.81	-0.96
100	0.392	0.302	0.427	4.59	-1.79
120	0.231	0.180	0.257	4.42	-2.25
160	0.099	0.078	0.113	4.24	-2.83
200	0.051	0.041	0.059	3.92	-3.14

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

A.3.3 Davit Configuration for 345-kV ac

For the 345-kV ac davit configuration (Figure 10), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -9$ ft and $y = 41.5$ ft (at sag point for the line considered),
 - Phase B, $x = 9$ ft and $y = 53$ ft,
 - Phase C, $x = 9$ ft and $y = 30$ ft;
- Phase current of 1,000 A;

TABLE A.8 Calculated EMF Strengths and Sensitivities for 345-kV ac Delta Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	168.4	147.1	127.2	2.53	4.89
20	131.2	108.9	103.1	3.40	4.28
40	70.91	56.77	61.50	3.99	2.65
60	38.45	30.62	35.50	4.07	1.53
80	23.11	18.43	22.02	4.05	0.94
100	15.19	12.13	14.71	4.03	0.63
120	10.66	8.537	10.43	3.98	0.43
160	6.040	4.854	5.964	3.93	0.25
200	3.868	3.118	3.837	3.88	0.16
Electric field					
0	2.442	2.432	2.090	0.08	2.88
20	3.677	3.224	2.857	2.46	4.46
40	2.062	1.695	1.875	3.56	1.81
60	0.906	0.744	0.923	3.58	-0.38
80	0.441	0.365	0.472	3.45	-1.41
100	0.244	0.203	0.266	3.36	-1.80
120	0.151	0.126	0.165	3.31	-1.85
160	0.073	0.059	0.078	3.84	-1.37
200	0.042	0.034	0.044	3.81	-0.95

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wire,
 - Wire 1, $x = 0$ ft and $y = 86.5$ ft; and
- Height of points of calculated EMFs (Table A.9) equals 3 ft above ground level.

TABLE A.9 Calculated EMF Strengths and Sensitivities for 345-kV ac Davit Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	111.5	95.86	85.09	2.81	4.74
20	96.34	78.49	75.69	3.71	4.29
40	56.15	44.19	48.44	4.26	2.75
60	32.24	25.02	29.50	4.48	1.70
80	19.98	15.41	18.87	4.57	1.11
100	13.32	10.25	12.81	4.61	0.77
120	9.422	7.250	9.162	4.61	0.55
160	5.362	4.131	5.276	4.59	0.32
200	3.434	2.649	3.398	4.57	0.21
Electric field					
0	2.702	2.542	2.177	1.18	3.89
20	2.972	2.467	2.398	3.40	3.86
40	1.272	1.028	1.212	3.84	0.94
60	0.605	0.516	0.593	2.94	0.40
80	0.385	0.328	0.369	2.96	0.83
100	0.270	0.225	0.259	3.33	0.81
120	0.196	0.162	0.190	3.47	0.61
160	0.114	0.092	0.112	3.86	0.35
200	0.073	0.059	0.072	3.84	0.27

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

A.3.4 Split-Phase Configuration for 345-kV ac

For the 345-kV ac split-phase configuration (Figure 11), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the three phases are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of phase conductors,
 - Phase A, $x = -16.5$ ft and $y = 30$ ft (at sag point for the line considered),
 - Phase B, $x = -25$ ft and $y = 46$ ft,
 - Phase C, $x = -15$ ft and $y = 66$ ft,
 - Phase D, $x = 15$ ft and $y = 66$ ft,
 - Phase E, $x = 25$ ft and $y = 46$ ft,
 - Phase F, $x = 16.5$ ft and $y = 30$ ft;

- Phase current of 1,000 A;
- Minimum phase-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wires,
 - Wire 1, $x = -20$ ft and $y = 78$ ft,
 - Wire 2, $x = 20$ ft and $y = 78$ ft; and
- Height of points of calculated EMFs (Table A.10) equals 3 ft above ground level.

A.4 HORIZONTAL CONFIGURATION FOR ± 450 -kV dc

For the ± 450 -kV dc configuration (Figure 12), the following conditions and spacing were assumed for each of the calculations for baseline or nominal conditions; the coordinates of the two conductors are specified in relation to the tower's centerline ($x = 0$ ft) and to ground level ($y = 0$ ft):

- Coordinates of two conductors,
 - Conductor A, $x = -20$ ft and $y = 30$ ft (at sag point for the line considered),
 - Conductor B, $x = 20$ ft and $y = 30$ ft;
- Conductor current of 1,000 A;
- Minimum conductor-to-ground distance (per NESC [IEEE 1990]) of 30 ft (at conductor sag point);
- Coordinates of grounded shield wire,
 - Wire 1, $x = 0$ ft and $y = 60$ ft; and
- Height of points of calculated EMFs (Table A.11) equals 3 ft above ground level.

A.5 REFERENCES FOR APPENDIX A

General Electric Co., 1982, *Transmission Line Reference Book: 345 kV and Above*, 2nd ed., Electric Power Research Institute, Palo Alto, Calif.

IEEE: See Institute of Electrical and Electronics Engineers, Inc.

Institute of Electrical and Electronics Engineers, Inc., 1990, *National Electrical Safety Code*, New York, N.Y., Feb.

TABLE A.10 Calculated EMF Strengths and Sensitivities for 345-kV ac Split-Phase Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	146.6	124.1	109.5	3.07	5.06
20	120.7	95.66	91.36	4.15	4.86
40	65.16	47.97	54.09	5.28	3.40
60	32.69	23.82	29.20	5.43	2.14
80	18.01	13.05	16.70	5.51	1.45
100	10.81	7.796	10.24	5.58	1.05
120	6.938	5.006	6.670	5.57	0.77
160	3.338	2.434	3.261	5.42	0.46
200	1.865	1.383	1.837	5.17	0.30
Electric field					
0	1.683	1.676	1.371	0.03	3.71
20	3.166	2.562	2.336	3.82	5.24
40	1.636	1.376	1.434	4.40	2.47
60	0.713	0.627	0.666	2.41	1.32
80	0.370	0.324	0.350	2.49	1.08
100	0.209	0.180	0.201	2.78	0.77
120	0.128	0.108	0.124	3.13	0.63
160	0.058	0.047	0.057	3.79	0 ^c
200	0.031	0.025	0.030	3.84	0 ^c

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

^c Field differences were too small for meaningful results.

TABLE A.11 Calculated EMF Strengths and Sensitivities for ± 450 -kV dc Horizontal Configuration at 1,000 A per Phase

Distance from Centerline (ft) ^a	Field Strength ^b			Compacting Sensitivity (%/ft)	Height Sensitivity (%/ft)
	Normal Design	Compacted Condition	Raised Condition		
Magnetic field					
0	232.5	221.8	184.3	0.92	4.15
20	201.4	183.3	160.1	1.80	4.10
40	118.7	102.9	102.3	2.66	2.76
60	64.41	55.58	59.47	2.74	1.53
80	38.51	33.34	36.76	2.69	0.91
100	25.27	21.94	24.53	2.64	0.59
120	17.77	15.46	17.41	2.60	0.41
160	10.11	8.819	9.997	2.55	0.22
200	6.506	5.680	6.458	2.54	0.15
Electric field					
0	2.185	2.258	1.622	-0.67	5.15
20	11.11	10.61	8.353	0.90	4.96
40	8.408	7.375	7.276	2.46	2.69
60	4.023	3.487	3.954	2.66	0.34
80	1.995	1.737	2.095	2.59	-1.00
100	1.095	0.958	1.190	2.50	-1.74
120	0.657	0.577	0.728	2.44	-2.16
160	0.287	0.253	0.324	2.37	-2.58
200	0.149	0.132	0.170	2.28	-2.82

^a Calculated for a position 3 ft above ground level at the point of maximum line sag between towers.

^b Field strength data are in milligauss for the magnetic field and in kilovolts per meter for the electric field.

APPENDIX B:

DESIGN AND CONSTRUCTION COST DATA

Many state governments and utilities have taken a proactive position toward the mitigation of EMFs by developing public outreach programs and improving communication within their states and service areas. Only a few studies of mitigation have thus far been published. The cost data in the tables in Appendix B were developed by Commonwealth Associates, Inc. (1992), of Jackson, Michigan, for the state of Rhode Island; by Oppel and Stewart (1993) of Power Technologies, Inc., of Schenectady, New York, for the state of Florida; and by Waller and Geissinger (1992) of the Electric Transmission Research Needs Task Force for the state of Washington's Department of Health. These three studies are believed to contain the most current and comprehensive data on design and construction costs. Costs for right-of-way acquisition are significant and are not included in the cost data. While costs for right-of-way acquisition vary from location to location, Baltimore Gas and Electric (E.H. Bauman, personal communication, Baltimore, Md., 1993) estimated that right-of-way acquisition in its densely populated service area adds an additional 100-200% to construction costs.

Note that mitigative configurations and associated costs are necessarily specific to a site. The Rhode Island study (Commonwealth Associates, Inc. 1992) did not address designs and costs for 500-kV transmission lines because none of these lines are planned for that state. Moreover, Rhode Island utilities tend to build multiple circuits on the same right-of-way and have many rights-of-way that are 200-300 ft wide, with typical magnetic fields of between 1 and 28 mG at the edge of the right-of-way. In developing designs and costs, the Florida study (Oppel and Stewart 1993) addressed three concerns considered specific to Florida: (1) the need to protect insulators from sea salt contamination; (2) the high incidence of lightning; and (3) high winds, especially from hurricanes.

B.1 FLORIDA STATE STUDY

The stated purpose for the study undertaken by Power Technologies, Inc., for the state of Florida was "to analyze options and propose designs to further reduce the magnetic fields beyond the present Florida designs" (Oppel and Stewart 1993, p. i). The study evaluated presently preferred 230-kV and 500-kV Florida transmission-line conductor configurations and towers to determine their electrical performance characteristics and identified the design with the lowest resulting magnetic fields. The study proposed two new 230-kV and two new 500-kV designs and presented their design characteristics and costs.

B.1.1 Designs for 230-kV ac

Table B.1 provides construction costs and calculated EMF strengths for the proposed inverted-delta and split-phase 230-kV designs (Figures 16 and 17). These designs were compared to the currently used vertical design (Figure 15), which served as the base case. The study (Oppel and Stewart 1993) identified the following benefits and disadvantages of the proposed designs:

- Benefits of the proposed 230-kV inverted-delta design,
 - Magnetic field at 50 ft from the tower's center that is one-half of the magnetic field level of the presently used 230-kV design,
 - Electric field strengths, audible noise, and radio noise within the same range as present 230-kV vertical designs,
 - Low impedance resulting in small voltage drop,
 - Small phase impedance imbalance,
 - Good lightning performance and reduced probability of flashovers caused by lightning strokes,
 - Compact configuration with single-pole tower viable for city application,
 - Less visual impact than a two-pole H-frame support;

TABLE B.1 Calculated EMF Strengths versus Construction Cost Data from the Florida Study for 230-kV Transmission Lines

Proposed Design	Construction Cost per Mile (10^3 \$) ^a	Magnetic Field (mG)			Electric Field (kV/m)		
		Maximum in Right-of-Way	>50 ft from Centerline	<50 ft from Centerline	Maximum in Right-of-Way	>50 ft from Centerline	<50 ft from Centerline
Vertical (base case)	120	111.7	34.1	21.2	2.80	0.06	0.10
Inverted delta	175	85.86	17.6	17.6	2.36	0.38	0.38
Split phase	198	51.13	7.02	7.02	1.92	0.11	0.11

^a Source: Oppel and Stewart (1993).

- Disadvantages of the proposed 230-kV inverted-delta design,
 - Large-diameter conductors required to reduce corona-related effects, requiring larger, stronger, and more costly towers,
 - Towers costly to manufacture because of the Y-shape and also possibly more difficult to erect than a single-pole support,
 - Live-line maintenance more difficult and costly because of less phase-to-phase space,
 - Higher visual impact,
 - More right-of-way required;
- Benefits of the proposed 230-kV split-phase design,
 - Better EMF performance (or lower EMFs),
 - Audible and radio noise levels within the same range as present 230-kV vertical designs,
 - Easy to maintain with present tools and techniques,
 - Minimum impedance for improved surge loading and improved power transfer,
 - Minimal phase impedance imbalance helpful for longer rural lines,
 - Good lightning performance and reduced probability of flashovers caused by lightning strokes,
 - Compact configuration with single-pole tower allowing city installation on narrow rights-of-way,
 - Lowest magnetic fields with the least departure from present utility practices,
 - Magnetic fields that decay faster than magnetic fields from the other designs;
- Disadvantages of the proposed 230-kV split-phase design,
 - Six phase conductors, plus two ground wires, with associated hardware and insulators increasing cost,
 - Stronger, more costly towers required; and
 - Higher visual impact.

B.1.2 Designs for 500-kV ac

Table B.2 lists the construction costs and calculated EMF strengths for two proposed 500-kV designs. These data were compared with the same data for the currently used vertical design. The Florida study (Oppel and Stewart 1993) characterized the benefits and disadvantages of the proposed 500-kV designs as follows:

- Benefits of the proposed inverted-delta and split-phase designs,
 - Magnetic fields at 100 ft from the tower's center that are less than those of the present vertical configuration,
 - Electric field, audible noise, and radio noise within the range of present 500-kV vertical design,
 - Favorable impedance balance,
 - Lower visual impact for tubular steel towers compared with steel lattice towers of the present 500-kV horizontal configurations,
 - Improved aesthetics because of shorter towers;
- Disadvantages of the proposed design,
 - Tower foundations more costly than those for the present Florida vertical configuration,
 - Increased difficulty of live-line maintenance, and
 - Wider rights-of-way required.

TABLE B.2 Calculated EMF Strengths versus Construction Cost Data from the Florida Study for 500-kV Transmission Lines

Proposed Design	Construction Cost per Mile (10^3 \$) ^a	Magnetic Field (mG)			Electric Field (kV/m)		
		Maximum in Right-of-Way	>50 ft from Centerline	<50 ft from Centerline	Maximum in Right-of-Way	>50 ft from Centerline	<50 ft from Centerline
Vertical (base case)	534	127.5	26.16	26.16	9.02	0.21	0.21
Delta	593	144.0	22.71	22.71	8.14	0.81	0.81
Davit	606	121.0	23.23	18.31	8.46	0.88	1.08

^a Source: Oppel and Stewart (1993).

B.2 RHODE ISLAND STATE STUDY

The purpose of this study undertaken by Commonwealth Associates, Inc. (1992) for the state of Rhode Island was to determine the relative cost-effectiveness of various design options to reduce human exposure to EMFs from high-voltage transmission lines. The scope of the study was limited to electric power transmission at 345 and 115 kV.

The following features were assumed for the 345-kV designs:

- 150-ft rights-of-way for overhead lines,
- 50-ft rights-of-way for underground cables,
- 500-A current,
- H-frame design span length of 800 ft,
- Davit-arm design span length of 600 ft,
- Compact delta design span length of 700 ft,
- Minimum ground clearance of 30 ft, and
- Phase spacing of 26 ft.

Table B.3 presents the cost and calculated magnetic field strength data for the 345-kV level.

The Rhode Island study (Commonwealth Associates, Inc. 1992) concluded the following for 345-kV transmission:

- Additional reduction of the magnetic fields can be achieved by using a six-wire design but at a 36% increase in construction cost;
- For overhead transmission, magnetic fields at the edge of a right-of-way can be reduced by 45% (compared with those of the existing H-frame design) by using the compact delta configuration but at a 20% increase in construction cost;
- For overhead transmission, magnetic fields at the edge of the 150-ft right-of-way can be reduced by 75% compared with existing H-frame designs by using a six-wire configuration but at a 40% increase in cost; and
- Underground transmission provides an even greater reduction in magnetic fields but at a 3.7-fold increase in cost.

TABLE B.3 Calculated Magnetic Field versus Construction Cost Data from the Rhode Island Study for 345-kV Transmission Lines

Description	Construction Cost per Mile (10 ³ \$) ^a	Magnetic Field at Edge of Right-of-Way (mG)	
		25 ft from Centerline	75 ft from Centerline
Overhead			
H-frame (base case) ^b	390	- ^c	31
Davit arm	454	-	21
Compact delta ^d	470	-	18
Six-wire split phase	550	-	8
Underground			
HPFF ^e	1,450	0.12	-

^a Source: Commonwealth Associates, Inc. (1993).

^b Horizontal configuration.

^c Not applicable.

^d Inverted-delta configuration.

^e HPFF, High-pressure fluid-filled conductors.

B.3 WASHINGTON STATE STUDY

The instructions to the Electric Transmission Research Needs Task Force of the State of Washington were as follows:

1. Recommend research needs for limiting human exposure to EMFs resulting from the transmission and distribution of electric power, focusing on engineering techniques and other ways to limit exposure;
2. Recommend options for funding needed research that is identified; and
3. Recommend options for legislative action.

The report *Electric and Magnetic Field Reduction: Research Needs* by Waller and Geissinger (1992) represents the task force's report. The conclusions of the task force were as follows:

- Known engineering techniques exist for lowering EMFs;

- Given the same amount of energy delivered, the EMF reductions depend on the transmission-line design selected;
- Ways other than engineering techniques can be used to reduce the amount or duration of time that people are exposed to EMFs;
- Electric and magnetic fields from distribution systems and grounding of homes and buildings are important sources of EMF exposure;
- Electric and magnetic fields from distribution systems are much more difficult to manage than EMFs from transmission systems;
- Field strength is only one parameter of EMF exposure that should be considered when researching techniques of field management; and
- Ultimately, the choice of field reduction will depend on the benefit of reducing field exposure versus the costs of achieving that reduction.

Table B.4 presents construction costs from the Washington state report (Waller and Geissinger 1992) and the corresponding calculated EMF strengths.

B.4 REFERENCES FOR APPENDIX B

Commonwealth Associates, Inc., 1992, *Cost Effectiveness Analysis: Mitigation of Electromagnetic Fields*, Jackson, Mich., May.

Oppel, L.J., and J.R. Stewart, 1993, *Attenuation of Electromagnetic Fields from Electrical Transmission Lines*, PTI 25-93, Power Technologies, Inc., Schenectady, N.Y.

Waller, P., and L. Geissinger, 1992, *Electric and Magnetic Field Reduction: Research Needs*, Washington State Transmission Research Needs Task Force, Olympia, Wash., Jan.

TABLE B.4 Calculated EMF Strengths versus Construction Cost Data from the Washington State Study

Description	Construction Cost per Mile (10 ³ \$) ^a	Magnetic Field (mG)			Electric Field (kV/m)		
		Under ^b	40 ft ^c	200 ft ^c	Under ^b	40 ft ^c	200 ft ^c
Wooden H-frame (base case) ^d 230 kV 300 A 125 MW 19-ft spacing	230-260	59.6	29.7	1.6	2.6	1.9	0.04
Vertical delta	220-250	27.0	11.0	0.6	1.9	0.7	0.04
Horizontal delta	220-250	28.9	9.8	0.5	1.6	0.7	0.03
Increased voltage 500 kV 138 A 30-ft spacing Steel lattice tower	400-500	24.4	18.9	1.2	5.5	5.3	0.1
Underground line: fluid-filled steel pipe ^e	1,500-2,000	4.9	0.2	0.01	0	0	0
Underground line: dry type cable, nonmagnetic pipe ^e	1,500-2,000	14.7	0.6	0.03	0	0	0

^a Source: Waller and Geissinger (1992).

^b Under the line.

^c Distances are distances from the centerline.

^d Horizontal configuration.

^e Buried 5 ft below the earth's surface.