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Electric and Magnetic Fields (EMF)
RAPID Program Engineering
Project 8: FINAL REPORT

Evaluation of Field Reduction Technologies

Volume 1 (Report)
Volume 2 (Appendices)

Prepared for:

Oak Ridge National Laboratory
EMF Research Program
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Oak Ridge, Tennessee 37831-6070

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FOREWORD

IIT Research Institute is pleased to submit this final report to Oak Ridge National Laboratory for work performed under Subcontract No. 62X-SV820V, RAPID Program Engineering Project 8.

This draft report consists of two volumes.

Volume 1, the main body, contains an introductory section, an overview of magnetic fields section, and field reduction technology evaluation section. Magnetic field reduction methods are evaluated for transmission lines, distribution lines,substations, building wiring, appliances/ machinery, and transportation systems. The evaluation considers effectiveness, cost, and other factors.

Volume 2 contains five appendices. Appendix A presents magnetic field shielding information. Appendices B and C present design assumptions and magnetic field plots for transmission and distribution lines, respectively. Appendices D and E present cost estimate details for transmission and distribution lines, respectively.

Respectively Submitted,

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transmission line right of way. If low magnetic field levels were mandated, minimizing unbalanced current would be necessary throughout the transmission network. This would entail balancing the line loading at transmission substations, transposing transmission line conductors, and adding low-impedance shield wires to "attract" zero sequence current.

Distribution Lines

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

For balanced phase current conditions, low-field distribution line life-cycle costs were predicted to increase significantly only for presumed exposure limits of about 5 mG or less. Costs increased as much as 40% for a 2 mG limit at 7.6 kV and 13.2 kV, for which tall compact and split-phase Hendrix cable designs could be used. Life cycle costs for 34.5 kV lines were predicted to increase by 50% to 100% to meet a 2 mG limit, accomplished with a split-phase Hendrix cable design. Heavily loaded distribution lines would have to be shielded, perhaps by underground conduit, to meet a 2 mG limit.

Underground duct and direct burial designs produced the highest magnetic fields at 13.2 kV and 34.5 kV. The underground duct designs nearly triple the baseline design life cycle costs.

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

Substations

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

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

Customer-Side Power Distribution

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

1.0 INTRODUCTION

Purpose

The purpose of EMF RAPID Engineering Project 8 is to inform decision makers about existing power frequency magnetic field reduction techniques. To do this, field reduction methods have been evaluated for a variety of sources on the basis of their effectiveness, cost, safety, and environmental impact.

Background and Scope

It is possible to specify magnetic field interference thresholds for devices like pacemakers, computer video displays, and electron scanning microscopes. It is not possible, on the other hand, to specify "safe" magnetic field human exposure levels based on the current state of health effects research. No biological mechanism has yet been found by scientific consensus to explain the magnetic field-health effects associations reported in several epidemiology studies.

Until the proposed power frequency magnetic field health effects hypotheses are either proven or disproven, there will be no scientific basis for defining health-effects-related safe exposure thresholds. Hence, "low field" methods for generating, transmitting, or using electric power on the basis of health concerns cannot be determined at the present time.

Long-term planners must nonetheless ask some intriguing questions. If magnetic fields were linked to adverse health, would it be technically and economically possible to modify the existing electric power transmission and distribution network? Would it be possible to design low-field building and plant power systems? Could low-field appliances and machines be devised? Would it be possible to design transportation systems to ensure low-enough field exposure?

RAPID Project 8 provides information to assist decision makers at all levels. The project examines field reduction methods for electric power transmission, distribution, and end use devices from both an engineering and financial viewpoint. The report focuses on power frequency magnetic fields because these have been the focus of most of the recent health effects research. The effect of magnetic field reduction methods on electric fields is included.

Overview

The report is organized into three basic sections. The first is this introductory section. The second provides an overview of magnetic fields and basic reduction methods. The third provides a detailed evaluation of the application of various field reduction methods for specific sources. These are: transmission lines, distribution lines, substations, building wiring, machinery/appliances, and transportation systems.

Augmenting the basic report are several appendices.

2.0 MAGNETIC FIELD REDUCTION OVERVIEW

Fundamentals

Electromagnetic fields permeate the modern world. Man-made fields run the gamut of the frequency spectrum from DC (0 Hertz) to the extremely high frequency band (EHF 30-300 Gigahertz), as Table 2-1 illustrates. Man-made electromagnetic fields also exist at higher frequencies, in the infrared, visible light, ultraviolet, X-ray, and gamma ray bands.

Natural electromagnetic fields also exist. The earth has a 250-500 milligauss static magnetic field and a small time-varying "magneto-telluric field" that measures about 0.0002 milligauss at 60 Hz. Higher frequency electromagnetic energy from our sun and from other solar systems also reaches the earth. Even the brain and nervous system of humans and other animals creates small, but measurable, electromagnetic fields in the ELF frequency band.

Table 2-1: The Electromagnetic Frequency Spectrum

Frequency Band	Frequency Range	Primary Use
Extremely Low Frequency (ELF)	3-300 Hz	Power, ELF Communication, Seismic Exploration
Ultra Low Frequency (ULF)	300-3,000 Hz	Aircraft/Spacecraft Power
Very Low Frequency (VLF)	3 KHz-30 KHz	Navigation, Induction Heating
Low Frequency (LF)	30 KHz-300 KHz	Induction Heating
Medium Frequency (MF)	300 KHz-3 MHZ	Navigation, AM Radio
High Frequency (HF)	3 MHZ-30 MHZ	Radio
Very High Frequency (VHF)	30 MHZ-300 MHZ	Television, FM Radio
Ultra High Frequency (UHF)	300 MHZ-3 GHz	TV, Microwave Communication, Microwave Heating
Super High Frequency (SHF)	3 GHz-30 GHz	Radar, Microwave Communication
Extremely High Frequency (EHF)	30 GHz-300 GHz	Research

Fundamental power frequencies reside in the ELF band, with harmonics extending into the VLF band. At such low frequencies, the electric field (related to voltage) and magnetic field (related to current) are effectively independent of one another and can be studied separately. Power frequency magnetic fields are the primary focus of RAPID Project 8.

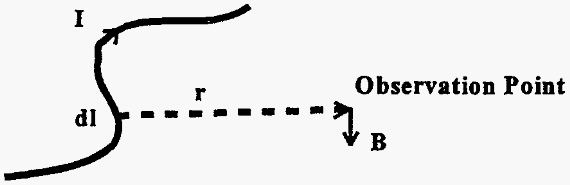
The Magnetic Field

Electric current in a conductor can deflect a nearby compass needle, can induce voltage and current in nearby conductors, and can exert forces on nearby moving charges or current elements. To describe these effects of *action at a distance*, 19th century scientists devised the theoretical *magnetic field.*

The force between two current elements is determined by the magnitude and orientation of the currents, the distance between the currents, and the properties of the medium surrounding the currents. In the absence of one of the current elements, the *possibility* of a force can still be predicted by the magnetic field of the remaining element.

Permanent magnets also "create" magnetic fields, but the forces associated with them are actually due to currents at the atomic level. Thus, it can be said that magnetic fields are created only by charge in motion.

The Biot-Savart Law, sometimes called Ampere's Law, defines the basic relationship between electric current and magnetic fields [Ramo, 1984]. It predicts the magnetic field at any fixed observation point near a line of current by describing a line integral along the current path. The differential current element **dl**, source-subject distance **r**, and magnetic field intensity **H** are all vectors. Their magnitudes *and* directions are interrelated, as shown in Figure 2-1.



$$\vec{H}=\frac{I}{4\pi}\int\frac{d\vec{l}\times\vec{r}}{r^{3}} \qquad (1)$$

Figure 2-1: Biot-Savart Law Description

Where: **H** is the magnetic field intensity in Oerstead (Oe) (cgs) or amperes per meter (A/m) (mks)
I is the current in amperes (A) flowing along a conductor
dl is a differential vector element oriented in the direction of the current
r is a vector (in meters) from the differential vector element to the observation point

The meter-kilogram-second (mks) unit, tesla, is 10^4 times the common centimeter-gram-second (cgs) unit, gauss.
1 Oersted = 79.577 amperes per meter.

The magnetic field vector is best visualized by the right hand rule. If the thumb of the right hand points along the current path, the magnetic flux density vector is oriented in the direction of the fingers. The field curves around and completely encloses the current path.

Another commonly used magnetic field descriptor is the magnetic flux density vector, **B**, given in gauss (G) (cgs) or tesla (T) (mks). **B** is related to **H** by the expression $\mathbf{B} = \mu \mathbf{H}$, where μ is the magnetic permeability of the region near the current element. $\mu = \mu_o \mu_r$, where μ_o is the magnetic permeability of free space, a constant $\mu_o = 4\pi \times 10^{-7}$ henries per meter (mks), and μ_r is the relative permeability of the medium.

Ferromagnetic permeabilities, for materials such as iron and steel, can be hundreds to thousands of times larger than free space permeability. These materials act as a sort of magnifying lens for a magnetic field, an effect used to advantage in transformers, electromagnets, and magnetic shields. Ferromagnetic material permeabilities are not constants. Instead, they vary with the strength and frequency of an applied magnetic field **H**.

At a specific point, the magnetic field vector of a steady direct current (DC) source points constantly in one direction. For a single-phase alternating current (AC) source, the magnetic field vector still points in one direction, but it's magnitude changes polarity every half cycle. Single-phase AC fields are said to be "linearly polarized".

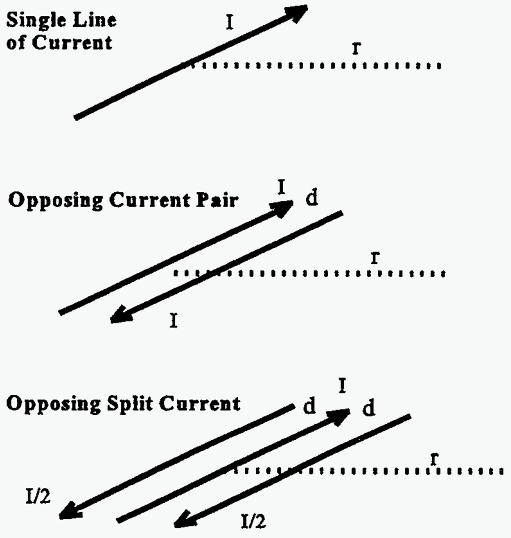
Three-phase AC magnetic fields are more complex. Standard electric power systems use three phase currents of equal magnitude but offset in phase, with Phase A at 0 degrees, Phase B at 240 degrees, and Phase C at 120 degrees. Near a three-phase source, the magnetic field vector rotates on its "tail" while at the same time varying in magnitude. The vector describes an ellipse every 1/60th of a second (1/50th of a second in Europe) and is said to be "elliptically polarized". Near a three-phase power line or cable, the field ellipse is in a plane perpendicular to the conductors.

Care must be used when measuring a three-phase magnetic field. Most field meters provide a resultant field value calculated by taking the square root of the sum of the squares from three orthogonal field coils. In the presence of an elliptially-polarized field, these meters can overestimate the actual maximum field; typically by 10-15 percent but sometimes by as much as 30 percent. The easiest way to measure an elliptially-polarized magnetic field is to rotate a single-axis coil, or one of the coils on a three-axis meter, to find a maximum reading.

Magnetic Field Reduction Methods

Closed-form solutions of the Biot-Savart line integral are possible for simple problems such as long straight lines or circular loops of current. Computer-based numerical integration can solve more complex cases.

Long straight lines of current create magnetic fields that, being constant at a fixed from the line, vary only in two dimensions. Some basic two-dimensional sources are shown in Figure 2-2. The equations are valid only when the observation distance **r** is relatively large compared to the conductor separation distance **d** [Zaffanella, 1992].



$$|B| = \frac{\mu_o I}{2\pi r} \qquad (2)$$

$$|B| = \frac{\mu_o I d}{2\pi r^2} \qquad (3)$$

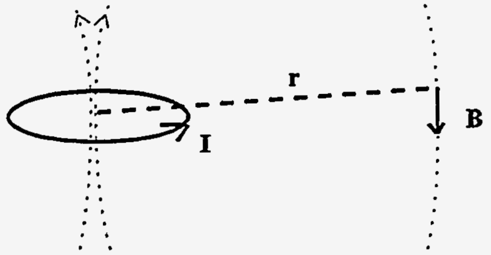
$$|B| = \frac{\mu_o I d^2}{2\pi r^3} \qquad (4)$$

Figure 2-2: Basic Two-Dimensional Sources

This simple example illustrates at least five magnetic field reduction methods. First, magnetic fields are minimized when current-carrying conductors are matched with the appropriate return conductors. Second, fields are lowest when opposing current pairs are placed as close together as possible. Third, current splitting is available as a magnetic field reduction option. Fourth, magnetic fields decrease with distance from the source. Fifth, and finally, magnetic fields are directly proportional to the current flowing on the conductors. Whenever current is reduced, magnetic fields are reduced.

Return current "splitting" can be carried further. The more times the return current is split, the faster the field will drop with distance. Carried to an infinite conclusion, current splitting leads to an ideal coaxial cable. An ideal "coax" creates no magnetic field outside it outer conductor.

Another magnetic field source type with a closed-form Biot-Savart law solution is the three-dimensional magnetic field dipole. This source, a small circular current loop, approximates magnetic field sources whose largest dimensions are small compared to the observation distance. Examples include small transformers and motors. Its magnetic field magnitude is given by the following expression.



$$|B| = \frac{\mu_o IA}{2r^3} \tag{5}$$

Figure 2-3: Basic Three-Dimensional Source

Where: A is the area enclosed by the loop and r, the observation distance from the center of the source, is much greater than the loop diameter.

Equation (5) shows that three-dimensional dipole fields are inversely proportional to the cube of distance from the source. "3D-dipole" fields can be reduced by reducing current, reducing loop diameter, and, especially, increasing source-observation distance.

One additional field reduction method can be considered for three dimensional sources. If an opposing three-dimensional dipole is placed nearby, its field will partially cancel the original dipole's magnetic field, as shown in Figure 2-4. Field reduction improves as the distance between dipoles is reduced.

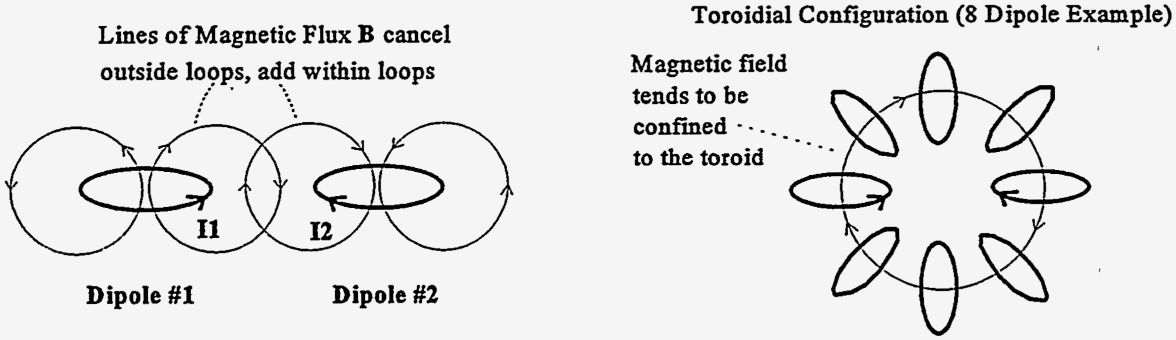


Figure 2-4: Three Dimensional Dipole Cancellation

Unless the dipoles are placed right on top of one another, the magnetic fields will tend to cancel each other outside the loops and add to each other inside the loops. More dipoles can be added to reduce magnetic fields even further. Carried to its ultimate conclusion the process leads to an ideal toroid that produces no magnetic field outside of its coils.

Cancellation

Most of the magnetic field reduction methods mentioned so far can be achieved through "self cancellation", in which the source currents are simply rearranged to reduce magnetic fields

Magnetic field reduction can also be achieved through "active cancellation", where add-on "cancellation currents" are used to minimize fields. Some type of active control system, based on a magnetic field sensor, drives cancellation current in a set of conductors or coils. The cancellation current is supplied independently of the original source current.

Active cancellation systems are used in specialized applications, such as magnetic field exposure systems, but their added complexity make them the option of last resort for most power frequency magnetic field applications.

Another type of magnetic field cancellation is passive cancellation, also called inductive cancellation or eddy current cancellation. Passive cancellation occurs when a magnetic field induces current in a closed conductive path such as a loop. The induced current creates its own opposing magnetic field that tends to cancel the original field.

A magnetic field induces a current in a passive conductive loop according to the following expression [Ramo, 1984].

$$I=\frac{j2\pi f\int(\vec{A}_n\times\vec{B})\vec{dS}}{R_l+j2\pi fL_l} \qquad (6)$$

Where: A_n is a unit vector normal to the coil surface area dS
B is the magnetic flux density vector
f is the frequency of the magnetic field in Hertz
R_l is the resistance of the coil in Ohms
L_l is the inductance of the coil in Henrys

Passive cancellation works best when the loop is large, has low impedance, is close to the field source, and is oriented so that most of the magnetic field is perpendicular to the loop face. The loop impedance can be minimized by using a thick conductor and by adding series capacitance to offset the inductance.

Passive cancellation in the form of long cancellation loops has been studied for use with transmission lines, with intriguing results [EPRI TR-105571, 1995].

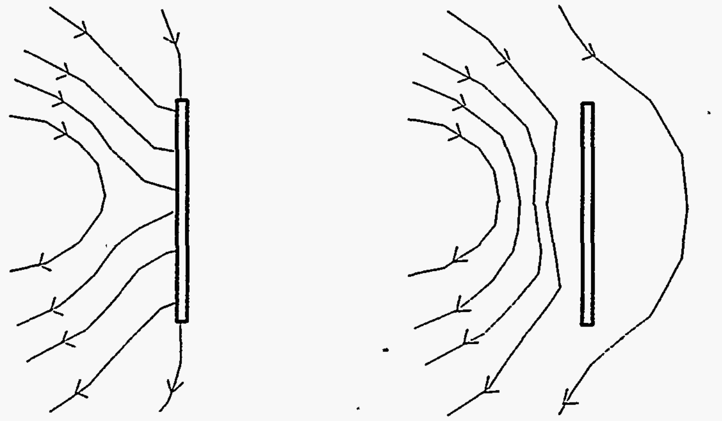
Shielding

Passive shielding can be an important tool for reducing power frequency magnetic fields. It has been used for many years to shield sensitive instruments from electromagnetic interference usually caused by higher frequency fields. In recent years, more and more power frequency and static field (DC) shielding applications have appeared.

Two passive shielding mechanisms are available. The first is magnetic flux shunting, provided by materials with high magnetic permeability. The second is inductive, or eddy current, cancellation, which is a “continuous sheet” version of passive loop cancellation.

Examples of materials with high permeability include steel, iron, and any of a variety of nickel-iron alloys. One well known high permeability alloy, called Mumetal, is composed of 77% nickel, 16% iron, 5% copper, and 2% chromium. Similar alloys are called Permalloy, Supermalloy, Hypernick, Conetic, and so on. Such alloys are usually much more expensive than steel and are more difficult to work with, but provide permeabilities that can exceed those of steel by more than 100 times.

Magnetic flux shunting occurs when a shield of sufficiently high magnetic permeability provides a shunt, or shortcut, path for a magnetic field. This is analogous to the low resistance shorting of an electrical circuit, with the shield providing a so-called “low reluctance” path for magnetic flux in the same way that a short circuit provides a path for electric current. Another way to think about flux shunting is that the shielding material “attracts” the magnetic field, drawing it away from the shielded area. Magnetic flux shunting works for both static (DC) and time-varying (AC) magnetic fields. The flux shunting mechanism improves with higher shield magnetic permeability, with increasing shield thickness, and, in many cases, with smaller source-shield distance.



Flux Shunting Shielding *Eddy Current Shielding*

Figure 2-5: Magnetic Field Shielding Mechanisms

Inductive, or eddy current, cancellation, is provided by materials with high electrical conductivity. Examples of such materials include copper, aluminum, gold, brass, and chromium. Aluminum is usually the shielding material of choice due to its lower cost. Eddy current cancellation only works for time varying (AC) fields.

Eddy current shielding occurs when a magnetic field induces current in a conductive material. The induced current creates its own opposing magnetic field that partially cancels the original field. The eddy current shield appears to "repulse" magnetic fields while a flux shunting shield seems to "attract" them.

The eddy current effect improves with shield conductivity, with shield thickness, with increasing frequency, and with the amount of surface area available for eddy current induction. Eddy current shielding improves as the source moves further from the shield, at least as long as the shield "appears" to be much larger than the source-shield distance, because more shield surface area is exposed to the field.

Some materials provide both flux shunting and inductive cancellation. Iron and steel, for example, have high permeability and are good conductors. They provide flux shunt shielding at DC and at low frequencies and eddy current shielding at higher frequencies. The geometry of source and shield interacts with these materials in a more complex way than with "pure" flux shunting eddy current shields. A change in the source-shield distance may, for example, decrease shielding at low frequencies while improving it at higher frequencies.

Another way to provide both flux shunting and eddy current cancellation is with layered shields of conductive and highly permeable materials. An aluminum/steel "sandwich" can work better than single-material shields of comparable thickness, for example. The layered shield works best if the material closest to the magnetic field source is the more conductive layer.

Appendix A provides an expanded discussion of magnetic field shielding.

3.0 MAGNETIC FIELD REDUCTION TECHNOLOGY: EVALUATION BY SOURCE

To evaluate the state of power frequency magnetic field reduction technology, it is necessary to consider in some detail how the available methods might be applied. In order to do this, RAPID Project 8 considers a variety of magnetic field sources, including transmission lines (Section 3.1), distribution lines (Section 3.2), substations (Section 3.3), building wiring (Section 3.4), appliances and machinery (Section 3.5), and transportation systems (Section 3.6). In each category, magnetic field reduction methods are evaluated on the basis of effectiveness, cost, environmental impact, and safety impact.

Some of the source categories are examined in more detail than others. This is due to the fact that field reduction techniques for some sources; transmission lines for example; have been studied in detail during the past few years, while methods for other sources, such as transportation systems, have not been considered in depth.

3.1 TRANSMISSION LINES

Case Study Description

A case study approach is used in RAPID Project 8 to compare magnetic fields, electric fields, and life cycle costs of various transmission line designs. Both "rural" and "suburban" designs are examined within each of four voltage categories. These include 69 kV, 115 kV, 230 kV, and 345 kV. In addition, rural-only designs are examined at 500 kV and 765 kV. Both overhead and underground designs are considered for the four suburban voltage categories.

Standard reference loads are assumed within each voltage class as follows.

Voltage Class	Reference Load Level	Current per Phase
69 kV	72 MVA	600 amperes
115 kV	120 MVA	600 amperes
230 kV	239 MVA	600 amperes
345 kV	717 MVA	1200 amperes
500 kV	1559 MVA	1800 amperes
765 kV	3180 MVA	2400 amperes

Higher voltage, same-load options are tested for the 69 kV and 115 kV voltage classes. Lower voltage, same-load designs are examined for all but the 69 kV voltage class.

Rural lines are assumed to traverse cross-country with long spans, few bends, and no distribution underbuild. Suburban lines are designed for routing along streets and roadways with many turns and short, 250 foot spans. Suburban transmission line poles are sized to provide clearance and strength for distribution line underbuilds. All designs include overhead ground wires and are based on NESC Heavy Load conditions.

Tables 3.1-1 and 3..1-2 provide basic design information for the modeled transmission lines. Figure 3.1-1 shows the basic transmission line tower types considered. Additional design details are provided in Appendix B.

Figure 3.1-1: Transmission Line Tower Types

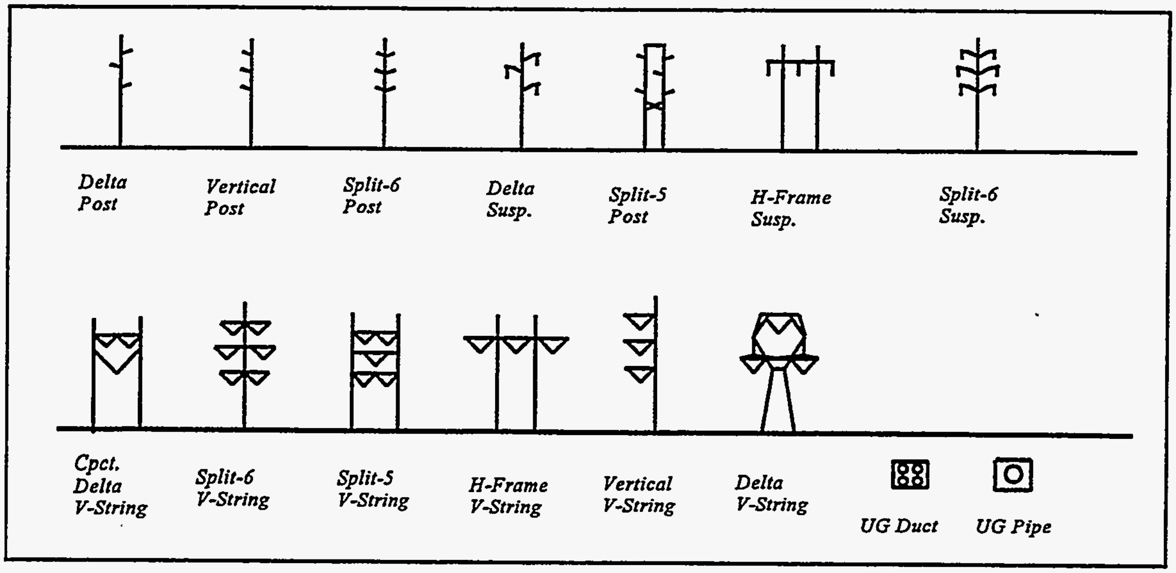


Table 3.1-1: 69 kV-115 kV Transmission Line Designs

Type	Tower Type (See Fig. 3.1-1)	Horizontal Phase Spacing (Feet)	Vertical Phase Spacing (Feet)	Rural Mid-Span Minimum Height (Feet)	Suburban Mid-Span Minimum Height (Feet)
69 kV Delta	Delta Post	4.6	6.0	23.5	40.3
69 kV Vertical	Vertical Post	0.0	8.0	24.0	40.8
69 kV Split-6	Split-6 Post	4.6	8.0	23.9	40.7
115 kV Delta (72 MVA)	Delta Susp.	12.0	6.0	24.9	41.7
69 kV Split-5	Split-5 Post	9.6/4.6	6.0	26.8	44.2
69 kV UG Duct	UG Duct	0.75	0.75	N/A	-3.5
69 kV UG HPGF Pipe	UG Pipe	~0.17	~0.17	N/A	-3.5
115 kV H-Frame	H-Frame Susp.	12.5	0.0	27.3	N/A
115 kV Delta	Delta Susp.	12.0	6.0	25.0	41.8
115 kV Delta Cpct.	Delta Post	6.0	6.0	23.5	44.8
115 kV Split-6	Split-6 Susp.	12.0/16.0	12.0	26.4	43.2
115 kV Split-6 Cpct.	Split-6 Post.	6.0	12.0	24.9	46.2
69 kV Split-6 (120 MVA)	Split-6 Post	4.6	8.0	24.0	40.8
230 kV Delta (120 MVA)	Delta Susp.	16.0	8.0	25.9	47.2
115 kV Split-5	Split-5 Post	13.0/6.0	10.0	28.3	N/A
115 kV UG Duct	UG Duct	0.75	0.75	N/A	-3.5
115 kV UG HPGF Pipe	UG Pipe	~0.17	~0.17	N/A	-3.5

Table 3.1-2: 230 kV-765 kV Transmission Line Designs

Type	Tower Type (See Fig.3.1-1)	Horizontal Phase Spacing (Feet)	Vertical Phase Spacing (Feet)	Rural Mid-Span Minimum Height (Feet)	Suburban Mid-Span Minimum Height (Feet)
230 kV H-Frame	H-Frame Susp.	20.0	0.0	31.7	N/A
230 kV Delta	Delta Susp.	16.0	8.0	29.9	46.7
230 kV Delta Cpct.	Delta Post	15.0	8.0	25.9	42.7
230 kV Split-6	Split-6 Susp.	16.0/20.0	16.0	28.0	44.8
230 kV Split-6 Cpct.	Split-6 Post	15.0	16.0	28.5	45.3
115 kV Split-6 (239 MVA)	Split-6 Susp.	12.0/16.0	12.0	26.5	43.3
115 kV Split-6 Cpct. (239 MVA)	Split-6 Post	6.0	12.0	25.0	41.8
230 kV Split-5	Split-5 Post	31.0/15.0	8.0	30.1	N/A
230 kV UG Duct	UG Duct	0.75	0.75	N/A	-3.5
230 kV UG HPFF Pipe	UG Pipe	~0.17	~0.17	N/A	-3.5
345 kV H-Frame	H-Frame Susp.	26.0	0.0	31.7	N/A
345 kV Delta	Delta Susp.	25.0	12.0	30.9	47.7
345 kV Delta Cpct.	Cpct. Delta V-String	20.0	25.0	33.6	N/A
345 kV Split-6	Split-6 V-String	20.0/28.0	24.0	29.4	42.2
230 kV Split-6 (717 MVA)	Split-6 Susp.	16.0/20.0	16.0	27.4	44.2
230 kV Split-6 Cpct. (717 MVA)	Split-6 Post	15.0	16.0	27.9	44.7
345 kV Split-5	Split-5 V-String	20.0	20.0	32.1	N/A
345 kV UG HPFF Pipe	UG Pipe	~0.17	~0.17	N/A	-3.5
500 kV H-Frame	H-Frame V-String	24.0	0.0	38.7	N/A
500 kV Delta	Delta V-String	35.0	30.0	38.7	N/A
500 kV Vertical	Vertical V-String	0.0	25.0	35.2	N/A
500 kV Split-6	Split-6 V-String	25.0/40.0	25.0	35.2	N/A
345 kV Split-6 (1559 MVA)	Split-6 V-String	20.0/28.0	24.0	29.4	N/A
765 H-Frame	H-Frame V-String	32.0	0.0	44.7	N/A
500 kV Split-6 (3180 MVA)	Split-6 V-String	25.0/40.0	25.0	35.2	N/A

Cost Estimates

The following assumptions are made for cost estimating purposes.

Case	Voltage Class	Length of Line Miles	Number of Structures Medium Angle	Dead End
Suburban	All*	10	20	10
Rural	69	25	10	5
Rural	115	25	10	5
Rural	230	25	10	5
Rural	345	50	16	8
Rural	500	75	24	12
Rural	765	100	32	16

Angle and dead end structures must be stronger, and thus are more costly, than tangent structures. To make generic cost estimates, the lines are assumed to be over relatively flat terrain with the above number of angles and dead end structures.

Three cost estimates are provided: material and labor, project, and life-cycle. The material and labor cost estimate includes all hardware and the cost of the labor needed to construct the line. Project costs include material and labor costs plus cost of land and land rights, right of way clearing and restoration, licensing and permits, engineering and surveying, inspections, and administrative costs. Rapid 8 project cost estimates are based on national averages for comparison purposes, but actual costs can vary significantly from region to region. The project cost represents the total capital required to build the line and place it in service [Cost Effectiveness Analysis ... , 1991].

Life-cycle cost is the present worth of all costs incurred over the 35-year lifetime of the project. Life-cycle cost includes fixed costs, cost of losses, and O&M costs. The annual fixed costs of owning the power line are calculated using a 16% fixed charge rate, which is representative of the utility industry. The fixed charge rate includes capital depreciation, interest or dividends paid to investors, property taxes, and insurance. Fixed costs are usually the most significant component of life-cycle costs. Cost of losses represent the power losses that occur during operation of the power line. These can represent 5 to 30% of the total life-cycle costs. O&M (operation and maintenance) costs are related to upkeep of the transmission line and its right of way. O&M costs are usually a small component of life-cycle costs. For Rapid 8, an industry average of 1% is assumed.

Cost estimates do not include transformers, switches, capacitors, arresters, and related equipment that usually comprise a transmission system. This omission is not important for side-by-side comparison of same-voltage design options.

Appendix D provides details of the transmission line cost estimating method.

Transmission Line Field Modeling Methods

The Southern California Edison "Fields" computer program was used to predict the modeled transmission line magnetic and electric fields for mid-span transverse profiles one meter above ground. It uses a Biot-Savart Law approximation [IEEE Committee Report, 1988]. Magnetic and electric fields were modeled for both balanced and unbalanced current conditions. A "worst-case" transmission line unbalanced condition of 5% current unbalance and 2 degree phase unbalance was assumed [Olsen, et al, 1993][EPRI TR-104413, 1995].

Balanced three-phase transmission line currents have equal magnitude, are each 120 degrees out of phase with the other two, and sum to zero. When unbalanced in magnitude or phase, the phase currents sum to a non-zero value. This unbalance resultant, called "zero-sequence current" by power engineers, flows in grounded overhead shield wires and through the earth beneath the line via transformer and tower grounding connections. Shield wires are typically grounded at every tower. Usually, transmission line zero-sequence current is a small percentage of the phase current magnitudes. Its division between the shield wire and earth paths is based on the shield wire impedance, on grounding connection impedances, and on the impedance of the earth in the vicinity of the line.

It is the "stray" unbalanced resultant current flowing through the earth that is responsible for most of the magnetic field increase seen near an unbalanced line. The effective "depth" of this dispersed earth current separates it from transmission line conductors by hundreds of feet depending on soil conditions, creating a large current "loop". The resulting magnetic field source looks like a single line of current with a magnitude equal to the earth current. Its field decreases slowly, in inverse proportion to distance from the line, and dominates the balanced current magnetic field in areas off the right of way. .

Transmission line current unbalance has two sources. One source; unbalanced loading; is uncommon for transmission lines because they are usually terminated in inherently-balanced, delta-configured transformer banks. The second source is long, non-transposed transmission line segments. If one phase conductor is nearer to the earth than the others for a long distance, it will induce more current in the earth and suffer more losses, creating current unbalance. Most transmission line designs limit this type of unbalance to 2% or less by occasionally transposing, or rearranging, the conductors.

For this RAPID Project 8 modeling effort, none of the 5% unbalanced resultant (zero sequence) current was assumed to return in overhead ground wires. This worst-case assumption was used because transmission line shield wires are usually not designed to carry zero sequence currents. Shield wires, used primarily for lightning protection, are sometimes actually segmented to minimize line losses.

While it seems unlikely that underground lines should experience much current unbalance, unbalance can in fact occur when multiple buried lines are next to one another over some distance. Zero sequence currents can be induced in and circulate between different circuits. The problem is worst when cables are unsymmetrically arranged and/or more than two or three circuits are adjacent [Nakanishi, et al, 1991].

This analysis only considers single-circuit transmission lines. Actual transmission lines often have two or more independent three-phase circuits. It is difficult to model double-circuit line fields to allow the type of side-by-side comparison sought here, however, because of the unpredictable nature of independent circuit loading.

Transmission Line Magnetic Field Reduction Concepts

This analysis considers several magnetic field reduction concepts for transmission lines. These include compaction, phase splitting, use of higher voltages to reduce current, shielding provided by underground pipe-type cables, and use of line-side passive cancellation loops. The five and six-wire split-phase designs are true split-phase, single-circuit designs. Phase conductors are arranged in a low reactance configuration as follows.

A/2	C/2		A/2		C/2
B/2	B/2	or		B	
C/2	A/2		C/2		A/2

This is a three-phase version of two-dimensional current splitting. If phase currents are balanced and are assumed to divide evenly, the magnetic field will drop with the cube of distance, versus the square of distance for the three-conductor line.

Underground pipe-type transmission cables use steel pipes. The pipes allow high pressure gas (HPGF: high pressure gas filled) or insulating oil (HPFF: high pressure fluid filled) to be pumped through, cooling the cables. Pipe-type cables have been used at voltages up to and including 345 kV. Higher-voltage designs have been tested, but have not been installed.

The steel pipes almost incidently provide eddy current and flux shunt magnetic field shielding. Steel pipe-type cable magnetic field shielding is predicted using techniques described in Appendix A. The model results were compared with reported measurements when possible [EPRI TR-102003, 1993].

Horizontal passive cancellation loops with compensating capacitors are examined for use with rural H-frame designs at all voltages except 69 kV. They are implemented by adding wooden poles on each side of the right of way, as shown in Figure 3.1-2 [EPRI TR-105571, 1995][R. Walling et al, 1993][U. Jonsson et al, 1994]. The cancellation loop conductor is the same size as the phase conductor in each case. Cancellation loop costs incremental to the total transmission line costs are provided on a per-mile basis. In practice, cancellation loops would probably be used only for relatively short distances along an existing line.

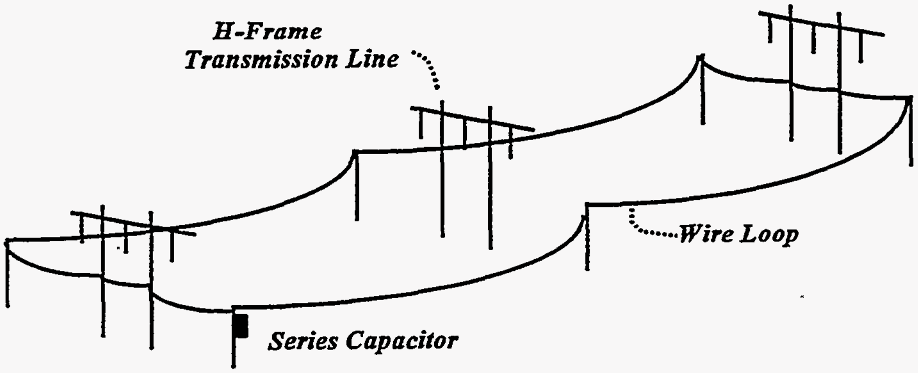


Figure 3.1-2: H-Frame Transmission Line Horizontal Cancellation Loop

Transmission Line Field Modeling Results

Tables 3.1-3, through 3.1-8 list the estimated magnetic fields, electric fields, project costs, and life cycle costs for the rural and suburban designs. The tables also list a theoretical "right of way" width needed to enclose magnetic fields exceeding five milligauss. This value, provided for comparison purposes only, is twice the largest distance predicted from tower center line to a five milligauss contour. In the tables, "Far Field" Shielding Factor (SF) refers to the predicted magnetic field reduction provided by cancellation loops off of the right of way. The Far Field SF is valid for distances several times greater than the conductor separation distance.

Appendix B provides detailed transmission line magnetic field model results.

Table 3.1-3A: 69 kV (72 MVA) Rural Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Delta	64.332	0.765	178	75.661	0.776	208	260	581
Vertical	72.612	0.838	206	83.914	0.850	234	263	586
Split-6	12.392	0.413	50	20.302	0.447	110	290	659
Split-5	15.689	0.636	64	19.876	0.667	116	311	682
115kV Delta (72 MVA)	43.328	1.095	144	46.474	1.119	174	235	515

Table 3.1-3B: 69 kV (72 MVA) Suburban Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Delta	22.764	0.303	164	29.124	0.310	202	336	702
Vertical	27.305	0.348	194	33.634	0.355	228	346	718
Split-6	2.836	0.164	N/A	8.162	0.182	86	417	861
Split-5	3.862	0.341	N/A	6.621	0.358	86	463	925
115kV Delta (72 MVA)	15.764	0.437	126	17.644	0.443	156	339	680
UG Duct	70.646	0.000	54	92.827	0.000	116	916	1,632
UG HPGF Pipe	1.028	0.000	N/A	29.034	0.000	78	901	1,551

Table 3.1-4A: 115 kV (120 MVA) Rural Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
H-Frame	116.254	1.173	260	120.885	1.201	316	280	613
Delta	72.210	1.187	190	77.565	1.211	240	283	617
Delta Cpct.	65.386	1.280	180	76.371	1.300	210	267	591
Split-6	26.279	0.725	94	30.014	0.769	140	367	781
Split-6 Cpct.	16.576	0.779	70	24.298	0.835	122	332	725
69 kV (120 MVA) Split-6	40.835	0.449	96	67.145	0.484	330	365	816
230 kV (120 MVA) Delta	40.822	2.403	152	43.477	2.447	176	282	545
Split-5	22.512	1.064	88	25.561	1.113	136	345	736
Cancellation Loop for H-Frame			Far Field SF=0.40				165 (incremental)	266 (incremental)

Table 3.1-4B: 115 kV (120 MVA) Suburban/Urban Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Delta	26.148	0.469	178	29.275	0.484	228	377	767
Delta Cpct.	18.682	0.420	160	24.301	0.431	202	363	745
Split-6	7.590	0.268	56	10.325	0.299	122	516	1,018
Split-6 Cpct.	3.525	0.260	N/A	8.060	0.287	86	476	954
69 kV (120 MVA) Split-6	9.390	0.179	64	27.106	0.197	324	485	1,007
230 kV (120 MVA) Delta	13.003	0.832	128	14.365	0.857	154	482	863
UG Duct	70.646	0.000	54	92.827	0.000	116	1,182	2,073
UG HPGF Pipe	1.028	0.000	N/A	29.034	0.000	78	994	1,705
UG Duct (Urban)	70.646	0.000	54	92.827	0.000	116	1,494	2,569 (Urban)
UG HPGF (Urban)	1.028	0.000	N/A	29.034	0.000	78	1,249	2,110 (Urban)

Table3.1-5A: 230 kV (239 MVA) Rural Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
H-Frame	112.927	2.385	332	117.371	2.430	388	334	673
Delta	62.396	2.041	220	66.828	2.081	268	350	699
Delta Cpct.	78.835	2.627	216	84.718	2.670	264	342	685
Split-6	32.092	1.757	116	34.781	1.830	160	477	839
Split-6 Cpct.	29.259	1.680	112	31.894	1.753	156	439	779
115 kV (239 MVA) Split-6	53.077	0.781	128	59.476	0.826	228	417	1,001
115kV (239 MVA) Split-6 Cpct.	32.807	0.842	104	48.226	0.900	220	382	946
Split-5	29.661	2.232	124	32.389	2.298	164	442	804
Cancellation Loop for H-Frame			Far Field SF=0.38				177 (incremental)	290 (incremental)

Table 3.1-5B: 230 kV (239 MVA) Suburban/Urban Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Delta	26.609	0.924	204	29.300	0.950	256	443	848
Delta Cpct.	30.332	1.095	204	33.783	1.122	252	430	828
Split-6	10.269	0.682	84	12.446	0.730	144	631	1,085
Split-6 Cpct.	9.416	0.693	80	11.608	0.751	140	576	998
115 kV (239 MVA) Split-6	15.089	0.291	104	20.543	0.323	220	558	1,228
115kV (239 MVA) Split-6 Cpct.	9.106	0.338	72	19.041	0.368	204	519	1,165
UG Duct	70.646	0.000	54	92.827	0.000	116	1,543	2,599
UG HPFF Pipe	1.165	0.000	N/A	29.034	0.000	78	1,537	2,555
UG Duct (Urban)	70.646	0.000	54	92.827	0.000	116	1,876	3,129 (Urban)
UP HPFF (Urban)	1.165	0.000	N/A	29.034	0.000	78	1,845	3,043 (Urban)

Table 3.1-6A: 345 kV (717 MVA) Rural Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
H-Frame	241.131	5.479	536	251.980	5.555	648	486	1,061
Delta	154.096	4.991	396	162.801	4.048	496	526	1,126
Delta Cpct.	121.865	4.695	392	135.058	4.743	444	613	1,265
Split-6	74.982	4.342	192	79.892	4.454	280	1,428	2,416
230 kV (717 MVA) Split-6	101.250	1.863	188	109.462	1.937	336	520	1,486
230 kV (717 MVA) Split-6 Cpct.	92.297	1.778	180	100.336	1.853	332	471	1,408
Split-5	59.177	4.552	180	63.469	4.687	264	839	1,525
Cancellation Loop for H-Frame			Far Field SF=0.36				182 (incremental)	337 (incremental)

Table 3.1-6B: 345 kV (717 MVA) Suburban/Urban Transmission Lines

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Delta	71.353	2.365	388	162.801	5.048	496	685	1,381
Split-6	33.322	2.153	180	37.111	2.103	272	2,356	3896
230 kV (717 MVA) Split-6	31.864	0.711	168	38.420	0.769	328	697	1,769
230 kV (717 MVA) Split-6 Cpct.	29.212	0.721	164	35.817	0.781	324	616	1,639
UG HPFF Pipe	2.467	0.000	N/A	58.068	0.000	160	2,436	4,112
UG HPFF (Urban)	2.467	0.000	N/A	58.068	0.000	160	2,804	4,696

Table 3.1-7: 500 kV (1559 MVA) Transmission Lines (Rural Only)

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
H-Frame	268.208	6.106	632	278.733	6.210	800	1,017	2,054
Delta	229.367	6.271	552	238.783	6.347	712	983	2,001
Vertical	201.775	7.720	656	223.184	7.777	720	1,116	2,213
Split-6	90.184	5.478	248	96.295	5.620	376	1,624	2,799
345 kV (1559 MVA) Split-6	163.023	4.326	264	173.699	4.450	496	1,453	3,005
Cancellation Loop for H-Frame			Far Field SF=0.38				166 (incremental)	330 (incremental)

Table 3.1-8: 765 kV (3180 MVA) Transmission Lines (Rural Only)

	Balanced Current Cases			5% Unbalanced Cases			Project Costs Sx1000 per Mile	Life Cycle Costs Sx1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
H-Frame	309.399	8.344	800	321.532	8.491	1024	1,368	2,761
500 kV (3180 MVA) Split-6	183.975	5.478	328	196.441	5.433	664	1,643	3,531
Cancellation Loop for H-frame			Far Field SF=0.38				184 (incremental)	440 (incremental)

Transmission Line Discussion

In this analysis, underground pipe-type cables, either high-pressure gas-filled (HPGF) or high-pressure fluid-filled (HPFF), provided the lowest transmission line magnetic fields. This is primarily the result of ferromagnetic and eddy current shielding provided by the steel pipes. Underground pipe-type transmission line life cycle costs were 2.21 to 3.01 times greater than for the baseline suburban overhead designs. The cost differential increases with voltage.

Underground duct-type cables created higher peak magnetic fields than all other options. Underground ducts are made from materials that provide no magnetic field shielding. Although their conductors are relatively close together, reducing magnetic fields off the right of way, their conductors are typically only a few feet below the surface.

Six-wire and five-wire split-phase designs produced the lowest magnetic fields for the rural balanced current cases at all voltages, and were the lowest-field overhead designs. The split phase designs were 1.13 to 1.44 times more expensive than baseline designs in terms of life cycle costs. An exception was the 345 kV six-wire split phase V-string insulator design that was 2.28 times more expensive in rural applications and 2.82 times more expensive in suburban settings. This result was due to the fact that steel poles were required for increased strength for the split-phase design while wood poles were used for the 345 kV baseline design.

The so-called "compact" designs, most of which use post insulators to reduce conductor spacing, did not usually reduce magnetic fields by significant amounts. Often, however, these designs had lower life-cycle costs than comparable suspension insulator designs. This was especially true at the lower transmission voltages.

Series capacitor compensated cancellation loops for H-frame transmission lines offer about the same magnetic field reduction as split-phase designs off the right of way. At 115 kV and 230 kV, the split phase designs have much lower life-cycle cost than an H-frame with a cancellation loop. At 345 kV and 500 kV the opposite is true; cancellation loops are less expensive. This is because larger phase conductors are required on split-phase designs at 345 kV and above to reduce corona.

At 765 kV, the cancellation loop option is the only field reduction method available without resorting to a more expensive 500 kV split-phase design.

The suburban overhead transmission lines considered at 345 kV and below offered much lower peak magnetic and electric fields than their rural counterparts. The effect was less significant off the right of way. The difference is due to the taller towers and shorter spans of the suburban designs. Suburban transmission line tower designs are often taller to allow for the possibility of distribution line underbuilds.

Split-phase designs produce lower peak magnetic fields than underground pipe-type cables when worst-case unbalanced conditions are assumed. Unbalanced current pipe-type cable magnetic fields fall off more rapidly with distance than split-phase fields, however, so their magnetic fields affect a smaller area.

With one exception, magnetic field reduction comes at increased cost. The exception is use of a higher voltage, lower current option for 69 kV and 115 kV designs. In these cases, the higher voltage designs are less expensive than, and produce lower magnetic fields than, the baseline design. These higher voltage designs also produce lower unbalanced current fields because less current is used. The reader should keep in mind that these example designs used same-load (lower current), higher voltage designs. Higher voltage transmission lines usually carry *more* current and produce *larger* magnetic fields than lower-voltage lines.

The comparisons show that transmission line magnetic field reduction is possible with some attention to design detail. Lower fields usually, but not always necessarily, come at higher cost.

An important observation is that unbalanced resultant (zero sequence) current can be the most significant magnetic field source for most areas near a transmission line. If low magnetic field levels were mandated, minimization of unbalanced current would be necessary throughout the transmission network. This would entail balancing the line loading at transmission substations and transposing transmission line conductors where necessary.

Unbalanced current magnetic fields could also be reduced in new designs by including low-impedance shield wires to "attract" zero sequence current. The portion of zero sequence current that flows in the earth is responsible for most of the unbalanced current magnetic field, especially off the right of way. More of this current would flow in the shield wires if they were larger in diameter.

If very low magnetic field levels, roughly five milligauss for example, were ever mandated, the models show that providing such results on transmission line rights of way would be extremely difficult. Most overhead transmission lines designs could not meet such a standard. Split-phase and pipe-type underground designs could meet the standard at 69 kV and 115 kV if phase current balance prevailed. Only underground pipe-type cables appear to meet such standards at 230 kV and 345 kV. No practical design option appears able to meet such a low field level at 500 kV and 765 kV. Utility companies could conceivably purchase and fence off transmission line rights of way. However, designers would still have to devise cost-effective methods to get transmission lines across roads, sidewalks, and paths. For example, the 500 kV six-conductor split-phase design examined here would have to be supported by towers more than 250 feet tall to meet the five milligauss level at road crossings.

Other Transmission Line Considerations

Utility workers have voiced safety concerns about reduced field transmission line designs. These are mostly related to the live-line work necessary to maintain some transmission lines. A common live-line task, for example, is replacing insulator strings at towers [Lineman's Handbook, 1976]. Live-line workers must maintain safe distances from grounded towers and conductors when working on energized conductors to prevent flash overs between themselves and ground. In fact, extremely high voltage transmission line (345 kV and above) conductor spacing is often determined by safe live-line working distance requirements. Compact transmission line conductors are closer to each other and to towers, making live-line work more difficult and dangerous.

One potential live-line work safety aid is the temporary installation of portable protective gaps (PPGs) on towers next to the live-line work area while the work is in progress. One principal concern with live-line work is the rare "transient over voltage" event, which has led to the establishment of minimum safe working distance requirements. PPGs are supposed to spark-over at a lower voltage than that needed to create a flash over between the live-line worker and grounded conductors. When PPGs are temporarily installed, the minimum safe working distance can be reduced, allowing work to be done on compact transmission lines. Workers, however, must trust their safety to the proper functioning of the PPGs.

Other solutions for live-line worker safety might involve the use of larger bucket trucks to reach the line, use of helicopter maintenance procedures, or deenergizing the line while work is underway.

Low field transmission line designs must also be evaluated for their environmental impact. The most significant environmental impacts are usually associated with the line construction process, which involves right of way clearing and temporary road construction. Most of the low-field designs considered here would cause no more environmental disruption than a standard line. One exception might be the use of a passive cancellation loop along an H-Frame right of way. Such a design would require four times as many line poles as a standard design and would probably require a wider right of way. Another exception would be the use of taller towers with shorter spans, which would require more foundations and structures.

Underground line construction requires much less right of way clearing than overhead line construction. Underground lines have less visual impact than overhead lines. Underground lines are less susceptible to damage from wind, ice, and lightning. On the other hand, the excavation required for underground lines is much more substantial than for overhead lines. Underground line excavation must often disturb roads, streams, wetlands, and steep terrain; obstacles that overhead lines easily span. Pipe-type cables also add the possibility of underground fluid or gas leaks. The experience provided by tens of thousands of miles of underground transcontinental oil and gas pipelines should offer significant data on this risk, however.

Transmission Line Summary

Table 3.1-9 provides a transmission line feasibility/cost summary for five possible maximum magnetic field exposure limits: 100 mG, 50 mG, 20 mG, 5 mG, and 2 mG. The lowest life cycle-cost design for each exposure criterion is selected from those presented in this report, assuming balanced current loading. The life cycle cost is listed as a multiplier of the baseline cost for each voltage category. Limits that cannot be reached by designs considered in this report have question mark ("?") entries.

Table 3.1-9: Transmission Line Magnetic Field Reduction Summary

Voltage	<100 mG		<50 mG		<20 mG		<5 mG		<2 mG	
	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier
69 kV (72 MVA) Rural	Delta (Baseline)	1..00	Split-6	1.13	Split-6	1.13	Split-6 Suburban	1.48	UG HPGF PIpe	2.67
69 kV (72 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Split-6	1.23	Split-6	1.23	UG HPGF Pipe	2.21
115 kV (120 MVA) Rural	Delta	1.01	Delta Cpct.	0.96	Split-6 Cpct.	1.18	Split-6 Cpct. Suburban	1.56	UG HPGF Pipe	2.78
115 kV (120 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Delta Cpct.	0.97	Split-6 Cpct.	1.24	UG HPGF Pipe	2.22
230 kV (239 MVA) Rural	Delta Cpct.	1.02	Split-6 Cpct.	1.16	Split-6 Cpct. Suburban	1.48	UG HPFF Pipe	3.80	UG HPFF Pipe	3.80
230 kV (239 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Split-6 Cpct.	1.18	UG HPFF Pipe	3.01	UG HPFF Pipe	3.01
345 kV (717 MVA) Rural	Split-5	1.44	230 kV Split-6 Cpct. Suburban	1.54	UG HPFF Pipe	3.88	UG HPFF Pipe	3.88	UG HPFF Pipe+?	3.88+?
345 kV (717 MVA) Suburban	Delta (Baseline)	1.00	230 kV Split-6 Cpct.	1.19	UG HPFF Pipe	2.98	UP HPFF Pipe	2.98	UG HPFF Pipe+?	2.98+?
500 kV (1559 MVA) Rural	Split-6	1.36	?	?	?	?	?	?	?	?
765 kV (3180 MVA) Rural	?	?	?	?	?	?	?	?	?	?

The summary shows that low-field rural transmission line costs increase more than low-field suburban costs. The summary also clearly shows that transmission line life-cycle costs increase sharply at 5 mG and 2 mG for 69 kV, 115 kV, and 230 kV designs. 345 kV line costs increase significantly below 20 mG for suburban designs and below 100 mG for rural designs. No 500 kV options are available for 50 mG or less and no 765 kV options are available for 100 mG or less.

3.2 DISTRIBUTION LINES

A case study approach is also used in RAPID Project 8 to compare magnetic fields, electric fields, and life cycle costs of various distribution line designs. Both "rural" and "suburban" designs are examined within each of three voltage categories. These include 7.6 kV single-phase, 13.2 kV three-phase, and 34.5 kV three phase categories.

Standard reference loads are assumed within each voltage class as follows.

Voltage Class	Reference Load Level	Current Per Phase
7.6 kV single-phase	0.76 MVA Rural/1.52 MVA Suburban	100 amps Rural/200 amps Suburban
13.2 kV three-phase	6.86 MVA Rural/13.7 MVA Suburban	300 amps Rural/600 amps Suburban
34.5 kV three-phase	17.9 MVA Rural/35.9 MVA Suburban	300 amps Rural/600 amps Suburban

Higher voltage, same-load options are tested for the 13.2 kV rural and suburban categories.

Rural lines are assumed to be 10 miles long with 400 foot average spans, one dead-end or 90 degree angle every two miles, and two angle structures every two miles. Suburban lines are assumed to be five miles long with 250 foot average spans, one dead-end or 90 degree angle every mile, and two angle structures every mile. All designs are based on NESC Heavy Load conditions. None of the designs have overhead ground wires. All of the designs were wye-configured at the substation transformer bank and used multi-grounded neutral wires.

Figure 3.2-1 shows the basic distribution line types considered. Table 3.2-1 lists basic design information for the distribution line options. Additional design details are provided in Appendix C of this report.

Figure 3.2-1: Distribution Line Types

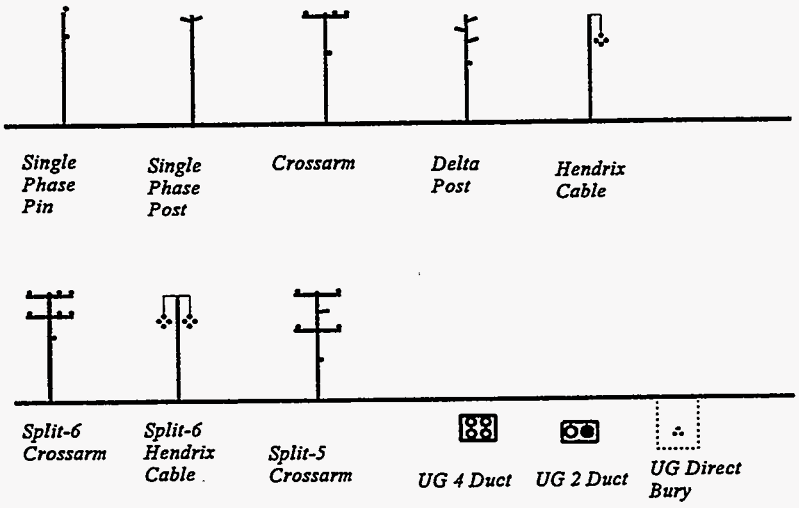


Table 3.2-1: Distribution Line Design Details

Type	Line Type (See Fig. 3.2-1)	Horizontal Phase Spacing (Feet)	Vertical Phase Spacing (Feet)	Rural Mid-Span Minimum Height (Feet)	Suburban Mid-Span Minimum Height (Feet)
7.6 kV Single Phase	Single Phase Pin	0.0	6.00	25.7	24.4
7.6 kV Single Phase Cpct.	Single Ph. Post	2.0	0.0	39.7	38.4
7.6 kV Single Phase UG	UG Direct Bury	~0.17	~0.17	N/A	-3.0
13.2 kV Crossarm	Crossarm	1.08/5.17	0.0 (7.0 to N)	24.7 (N)	23.4 (N)
13.2 kV Delta	Delta Post	2.0	2.0 (6.0 to N)	25.2 (N)	23.9 (N)
13.2 kV Hendrix	Hendrix Cable	0.67/0.33	1.04/0.52	24.3	24.3
13.2 kV Split-6	Split-6 Crossarm	1.08/5.17	4.0 (7.0 to N)	25.2 (N)	23.9 (N)
13.2 kV Split-6 Hendrix	Split-6 Hendrix	0.67/0.33 + 3.4	1.04/0.52	24.8	24.8
34.5 kV Crossarm (13.74 MVA)	Crossarm	1.33/6.67	0.0 (7.0 to N)	24.7 (N)	23.4 (N)
13.2 kV Split-5	Split-5 Crossarm	7.33/2.67/4.67	4.0 (7.0 to N)	25.7 (N)	24.4 (N)
13.2 kV UG 4-Duct	UG 4-Duct	0.75	0.75	N/A	-3.5
13.2 kV UG 2-Duct	UG 2-Duct	~0.17	~0.17	N/A	-3.5
13.2 kV UG Direct Bury	UG Direct Bury	~0.17	~0.17	N/A	-3.0
34.5 kV Crossarm	Crossarm	1.33/6.67	0.0 (7.0 to N)	24.7 (N)	23.4
34.5 kV Delta	Delta Post	2.0	2.0 (6.0 to N)	25.2 (N)	23.9 (N)
34.5 kV Hendrix	Hendrix Cable	0.625/1.25	0.67/1.33	23.8	23.8
34.5 kV Split-6	Split-6 Crossarm	1.33/6.67	5.0 (7.0 to N)	24.2 (N)	22.9 (N)
34.5 kV Split-6 Hendrix	Split-6 Hendrix	0.625/1.25 + 3.4	0.67/1.33	24.3	24.3
34.5 kV Split-5	Split-5 Crossarm	9.33/3.67/5.67	5.0 (7.0 to N)	23.7 (N)	22.4 (N)
34.5 kV UG 4-Duct	UG 4-Duct	0.75	0.75	N/A	-3.5
34.5 kV UG 2-Duct	UG 2-Duct	~0.17	~0.17	N/A	-3.5
34.5 kV UG Direct Bury	UG Direct Bury	~0.17	~0.17	N/A	-3.0

Distribution Line Magnetic Field Modeling Methods

Distribution line magnetic and electric fields were modeled for both balanced and unbalanced current conditions. Fields were calculated for a mid-span transverse profile one meter above ground beneath the first span out of a substation, where currents and magnetic fields are highest.

Distribution line loads are connected all along the length of a line, as shown in Figure 3.3-2. Distribution line currents and magnetic fields are generally highest on the first few spans out of the substation.

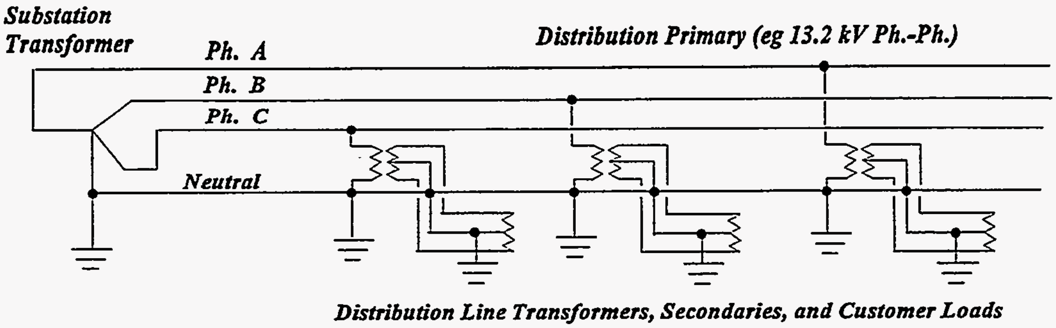


Figure 3.2-2: Typical Distribution Line Schematic

A "worst-case" distribution line unbalanced condition of 20% current unbalance and 5 degree phase unbalance is assumed. Half of the unbalanced resultant, or zero sequence, current is assumed to return in the neutral conductor. The other half is assumed to flow through the earth. It is the portion of unbalance current that strays from the neutral wire and flows through the earth that causes most of the magnetic field increase seen on unbalanced lines.

As Figure 3.2-2 makes apparent, multi-grounded distribution neutral wires present a complex modeling problem. A network-scale modeling approach, not performed here, is needed to provide accurate predictions of actual neutral conductor currents. The "worst-case" assumption would probably be rare on an actual system, because distribution line current unbalance is lowest near the substation. In addition, more of the unbalance resultant current tends to flow on the neutral wire near the substation [Mader and Zafanella, 1993][Ground Current Study, 1993].

This analysis models one distribution line circuit at a time. In practice, distribution lines often carry more than one circuit. Distribution line primary and secondary circuits are also usually strung together for much of the line length. The single-circuit model is used to allow side-by-side comparison of various line designs.

Distribution Line Magnetic Field Reduction Concepts

Several magnetic field reduction concepts are evaluated for distribution lines, including compaction, phase splitting, and use of higher voltage (same load) to reduce current. The five and six-wire split-phase designs are true split-phase, single-circuit designs. Phase conductors are arranged in a low reactance configuration as follows.

A/2	C/2		A/2	C/2
B/2	B/2	or	B	
C/2	A/2		C/2	A/2

This is a three-phase version of two-dimensional current splitting. If phase currents are balanced and are assumed to divide evenly, the magnetic field will drop with the cube of distance, versus the square of distance for the three-conductor line.

The split-phase Hendrix Cable design requires a slight variation on the above for best results, as follows.

N	N
A C	C B
B	A

Distribution Line Cost Estimates

Three cost estimates are provided: material and labor, project, and life-cycle. These costs are described in the transmission line section of this report, and are detailed in Appendix E. Distribution line cost estimates do not include transformers, switches, capacitors, arresters, secondary wiring, service drops, meters, and related equipment that usually comprise a distribution system.

Distribution Line Model Results

The Southern California Edison "Fields" computer program was used to predict distribution line magnetic and electric fields for mid-span transverse profiles one meter above ground. Magnetic field, electric field and cost results are provided in Tables 3.2-2 to 3.2-4. The tables also list a theoretical "right of way" width needed to enclose magnetic fields exceeding five milligauss. This value, provided for comparison purposes only, is twice the largest distance predicted from the center of the line to a five milligauss contour.

The six-wire and five-wire split-phase designs produced the lowest magnetic fields for the balanced current three-phase cases. The six-wire split-phase Hendrix cable design was especially effective, but was the most expensive overhead design option.

When 20% current magnitude unbalanced was assumed, stray unbalanced resultant (zero sequence) current was the dominant magnetic field source for all of the line designs. For the 13.2 kV category, the 34.5 kV same-load option produced lower unbalanced magnetic fields because it carried less current. It was also the lowest cost design design in the 13.2 kV category because its used smaller conductors and because its lower line losses reduced life cycle costs.

Usually, a 34.5 kV line would be designed to carry *more* current, and would produce *higher* magnetic fields, than a 13.2 kV line. The cost estimate process mentioned earlier does not include the slightly higher purchase cost of 34.5 kV versus 13.2 kV transformers, switches, capacitors, arresters, and related equipment. However, the increased cost of higher-voltage equipment would likely be offset by lower conductor costs and operating costs.

Underground duct and direct burial designs produced the highest magnetic fields at 13.2 kV and 34.5 kV and, except for the direct burial design, cost 2.63 to 2.91 times more than the baseline cases during the lifetime of the lines. The relative cost to construct underground lines is even higher, but lower operating costs narrow the difference over the life of the line.

Table 3.2-2A: 7.6 kV (0.76 MVA) Rural Single Phase Distribution Lines

	Balanced Current Cases			20% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Standard 1-Phase	6.179	0.140	26	4.488	0.140	N/A	107	172
Tall Compact	0.989	0.108	N/A	2.259	0.108	N/A	119	192

Table 3.2-2B: 7.6 kV (1.52 MVA) Suburban Single Phase Distribution Lines

	Balanced Current Cases			20% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Standard 1-Phase	14.277	0.145	66	10.918	0.145	60	115	199
Tall Compact	2.126	0.112	N/A	4.741	0.112	N/A	130	223
UG Direct Bury	3.275	0.000	N/A	24.500	0.000	52	123	214

Table 3.2-3A: 13.2 kV (6.86 MVA) Rural Distribution Lines

	Balanced Current Cases			20% Unbalanced Cases			Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)		
Cross-Arm	16.171	0.059	86	20.679	0.064	162	189	312
Delta	7.532	0.024	46	15.081	0.030	118	199	328
Hendrix Cable	2.597	0.030	N/A	15.599	0.038	112	224	368
Split-6 Cross-Arm	3.832	0.039	N/A	9.544	0.048	108	217	359
Split-6 Hendrix	0.883	0.046	N/A	13.800	0.058	104	262	431
34.5 kV (6.87 MVA) Cross-Arm	8.025	0.167	46	9.778	0.181	78	166	266
Split-5	3.740	0.087	N/A	9.009	0.098	104	220	364

Table 3.2-3B: 13.2 kV (13.7 MVA) Suburban Distribution Lines

	Balanced Current Cases			20% Unbalanced Cases				
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
Cross-Arm	35.284	0.063	134	44.622	0.069	286	194	363
Delta	16.347	0.026	90	31.809	0.027	230	214	396
Hendrix Cable	5.194	0.030	N/A	31.197	0.038	222	224	411
Split-6 Cross-Arm	8.403	0.043	48	20.561	0.052	226	229	429
Split-6 Hendrix	1.765	0.046	N/A	27.599	0.058	214	261	480
34.5 kV (13.74 MVA) Cross-Arm	17.499	0.180	88	21.162	0.194	144	173	293
Split-5	7.610	0.087	38	17.937	0.097	218	232	431
UG 4-Duct	71.216	0.000	54	127.945	0.000	226	630	1,059
UG 1-Duct	18.559	0.000	24	88.464	0.000	218	576	956
UG Direct Bury	22.468	0.000	24	98.835	0.000	218	203	380

Table 3.2-4A: 34.5 kV (17.93 MVA) Rural Distribution Line Magnetic Fields and Costs

	Balanced Current Cases			20% Unbalanced Cases				
	Bmax (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	B max (mG)	Emax (kV/m)	ROW for 5 mG (Ft.)	Project Costs $x1000 per Mile	Life Cycle Costs $x1000 per Mile
Crossarm	20.788	0.181	102	25.336	0.194	176	189	313
Delta	7.532	0.062	46	15.081	0.078	118	200	329
Hendrix Cable	4.999	0.068	N/A	17.048	0.094	116	251	411
Split-6 Crossarm	5.583	0.121	22	11.068	0.146	114	219	362
Split-6 Hendrix	1.807	0.150	N/A	13.618	0.183	106	296	485
Split-5 Crossarm	5.427	0.242	16	10.014	0.271	106	211	365

Table 3.2-4B: 34.5 kV (35.85 MVA) Suburban/Urban Distribution Lines

	Balanced Current Cases			**5% Unbalanced Cases**			**Project Costs $x1000 per Mile**	**Life Cycle Costs $x1000 per Mile**
	Bmax (mG)	**Emax (kV/m)**	**ROW for 5 mG (Ft.)**	**B max (mG)**	**Emax (kV/m)**	**ROW for 5 mG (Ft.)**		
Crossarm	45.315	0.194	154	54.818	0.208	304	198	369
Delta	16.347	0.068	90	31.809	0.084	230	215	397
Hendrix Cable	10.000	0.068	42	34.096	0.094	228	250	453
Split-6 Crossarm	12.292	0.129	66	23.503	0.155	234	231	433
Split-6 Hendrix	3.615	0.150	N/A	27.236	0.183	218	296	536
Split-5 Crossarm	12.131	0.259	56	21.723	0.289	220	234	433
UG 4-Duct	70.646	0.000	54	128.151	0.000	224	672	1,126
UG 1-Duct	15.061	0.000	20	92.978	0.000	216	646	1,066
UG Direct Bury	17.286	0.000	20	93.394	0.000	216	241	442
UG 4-Duct (Urban)	70.646	0.000	54	128.151	0.000	224	966	1,594
UG 1-Duct (Urban)	15.061	0.000	20	92.978	0.000	216	941	1,536

Distribution Line Discussion

The comparisons show that distribution magnetic field reduction is possible with some attention to design detail. Lower fields usually, but not always necessarily, come at higher cost. Most important, zero sequence current can be, and probably is usually, the most significant magnetic field source for distribution lines.

If very low magnetic fields, roughly five milligauss for example, were mandated, control of zero sequence current would be necessary at every point in the distribution network. This significant challenge would require rethinking not only line design methods as illustrated here, but broader network-scale issues such as grounding methods, distribution voltage selection, and transformer sizing.

Other Distribution Line Considerations

The magnetic field reduction methods considered here would not differ significantly in safety or environmental effects from standard line designs. An exception might be the Hendrix Cable design, which requires shorter 250 foot rural spans than the standard 400 foot spans for other rural designs. Hendrix Cable lines might also present a "denser" appearance than standard lines.

Distribution Line Summary

Table 3.2-5 provides a distribution line feasibility/cost summary for five possible maximum magnetic field exposure limits: 100 mG, 50 mG, 20 mG, 5 mG, and 2 mG. The lowest life cycle-cost design for each exposure criterion is selected from those presented in this report. Balanced phase current loading is assumed for comparison, though distribution lines rarely carry balanced current. Distribution line life cycle cost is listed as a multiplier of the baseline cost for each voltage category. Limits that cannot be reached by designs considered in this report have question mark ("?") entries.

Table 3.2-5: Distribution Line Magnetic Field Reduction Summary

Voltage	<100 mG		<50 mG		<20 mG		<5 mG		<2 mG	
	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier	Type	Life-Cycle Cost Multiplier
7.6 kV (0.76 MVA) Rural	Standard (Baseline)	1.00	Standard	1.00	Standard	1.00	Tall Cpct.	1.12	Tall Cpct.	1.12
7.6 kV (1.52 MVA) Suburban	Standard (Baseline)	1.00	Standard	1.00	Standard	1.00	UG Direct Bury	1.08	Tall Cpct.+?	1.12+?
13.2 kV (6.86 MVA) Rural	Cross Arm (Baseline)	1.00	Cross Arm	1.00	Cross Arm	1.00	Split-6 Cross Arm	1.15	Split-6 Hendrix	1.38
13.2 kV (13.7 MVA) Suburban	Cross Arm (Baseline)	1.00	Cross Arm	1.00	UG Direct Bury	1.05	Split-6 Hendrix	1.32	Split-6 Hendrix	1.32
34.5 kV (17.93 MVA) Rural	Cross Arm (Baseline)	1.00	Cross Arm	1.00	Delta	1.05	Hendrix Cable	1.31	Split-6 Hendrix	1.55
34.5 kV (35.85 MVA) Suburban	Cross Arm (Baseline)	1.00	Cross Arm	1.00	Delta	1.08	Split-6 Hendrix	1.45	?	?

The summary shows that low-field distribution line life-cycle costs increase significantly only for field limits of about 5 mG or less. The summary also shows that distribution line cost multipliers increase with voltage. No 34.5 kV suburban design option was available for the 2 mG threshold.

3.3 SUBSTATIONS

Substations convert electric power from one voltage level to another. Substations also interconnect same-voltage power lines and provide means for controlling the utility network.

Electric utilities use two basic substation types: transmission and distribution. Transmission substations interconnect transmission lines with each other and with lower-voltage "subtransmission" lines. In modern networks, transmission line voltages are in the 230 kV or higher range and subtransmission voltages are in the 69 kV to 115 kV range. Lower subtransmission voltages are used, however.

Distribution substations interconnect subtransmission lines with each other and with lower voltage distribution lines. Distribution substation primary, or subtransmission, voltages are usually in the 69 kV to 115 kV range, but lower voltages are common. Secondary, or distribution, voltages are usually in the 4 kV to 33 kV range.

Radial distribution circuits emanate from distribution substations to deliver power to customers. Lower voltage distribution lines must be relatively short to prevent excessive power loss. As the result, distribution substations are found relatively close to utility customers, often in highly populated areas. Transmission substations require much more space than distribution substations and are usually in rural areas. Electric utility companies will co-locate distribution and transmission substations whenever possible.

Transformers are the heart of a substation. They convert voltages up or down from a "primary" to a "secondary" level. Three-phase transformers are frequently used, but single-phase transformers are also common. Single-phase transformers are arranged in a transformer "bank" to provide three-phase service. Both transformer types can be "banked" in parallel to provide more power capacity. Transformers with one to 25 MVA capacity are common in distribution substations. The largest transformers can be as big as a small building.

On each "side" of the transformer banks are open-air buses and "switchracks" or, for some distribution secondaries, metal-clad "switchgear." These contain circuit breakers, to protect power equipment from short circuits, and air or oil-immersed disconnect switches, to control the flow of power between power lines and the substation. Other equipment, such as large capacitor banks, may also appear. At transmission and subtransmission voltages, this equipment can rival transformers in size.

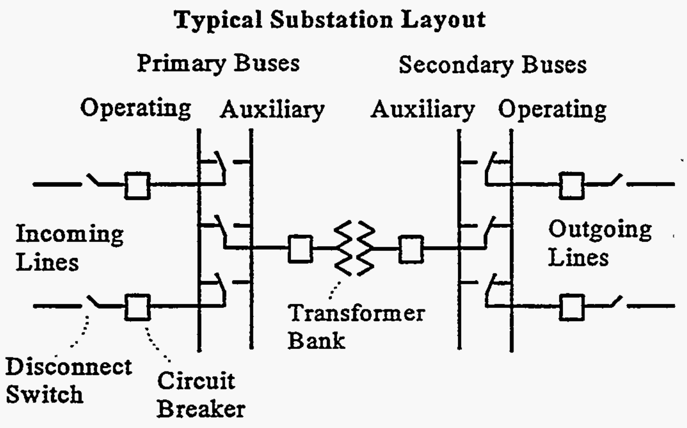


Figure 3.3-1: Typical Substation Layout

Primary and secondary switchrack equipment is fed by three-phase open-air buses. Metal-clad switchgear uses compact, enclosed buses. A common substation design uses both an "operating" bus and an "auxiliary" or "transfer" bus. The auxiliary bus is only used when needed for maintenance purposes or to isolate a fault on the main bus.

Substation Magnetic Field Management

Nearly all substations are surrounded by a fence or wall that clearly defines the limit of public accessibility. The magnetic fields measured at the perimeter fence are most often created by the overhead and underground lines entering and leaving the station. Transformers and open-air switchrack buses are usually the other most significant substation magnetic field sources.

Transformers exhibit three-dimensional dipole behavior. They produce large peak magnetic fields within a few feet, but the fields drop off quickly with distance. Transformers are not usually important field sources when viewed from the fence line.

A substation's open-air buses are usually the most significant substation magnetic field source in the area encompassed by a given field level. Like the overhead power lines connected to them, open-air-bus magnetic fields are determined by the phase conductor spacing and height, by the current magnitude, and by current unbalance. Substation buses are usually nearer to the ground than power lines. They can carry higher currents than power lines if more than one line is connected to them.

The highest currents and magnetic fields in a substation are usually found at the secondary bus. Several thousand amperes can flow on a distribution substation secondary bus, for example.

Several substation magnetic field reduction methods can be considered, include the following.

1. Increase source-subject distance by enlarging the fence perimeter.
2. Rearrange substation layouts, especially of secondary switchrack bus and feeders.
3. Decrease switchrack bus phase spacing.
4. Increase height of overhead conductors entering and leaving the station.
5. Shield underground distribution lines exiting station.
6. Replace open-air distribution switchracks with metal-clad switchgear.
7. Replace open-air transmission buses with compact gas-insulated buses.

Of these options, a utility company would most likely first choose to enlarge the fence perimeter. This can be a low cost option, especially if the land is already owned by the company. It may not be an option in urban settings with high land costs, however.

Electric utility companies would be least inclined to decrease the bus spacing, especially on the high voltage side. Bus spacing is determined by insulation requirements, by electromagnetic forces acting on the bus insulators under short circuit conditions, and by clearance requirements for maintenance activity. [EMF Design Guidelines . . . , 1994]

Substation Example

A simple, hypothetical distribution substation example is shown in Figure 3.3-2. It consists of a 115 kV primary open-air bus and switchrack, a transformer bank, and a 13.2 kV secondary open-air bus and switchrack. The substation feeds three distribution lines. Two are standard overhead cross arm designs. The third is in an underground duct.

The substation was modeled using a three-dimensional Biot-Savart approximation. Its load was assumed to be 41.15 MVA, with equal loading on the distribution lines and 1800 amperes per phase on the secondary bus. Its phase currents were assumed to be balanced. Only buses and power lines were modeled. Transformers, circuit breakers, and disconnect switches were disregarded.

Figure 3.3-2 shows a contour plot of the predicted substation magnetic fields one meter above the ground. The largest magnetic fields were found directly beneath the secondary bus and in areas near the underground duct distribution line. The underground duct produced the largest peak fields, both in the substation and at a standard perimeter fence at least 20 feet from substation equipment. The primary switchgear bus was the most significant field source overall, in terms of the area encompassed by a given field level.

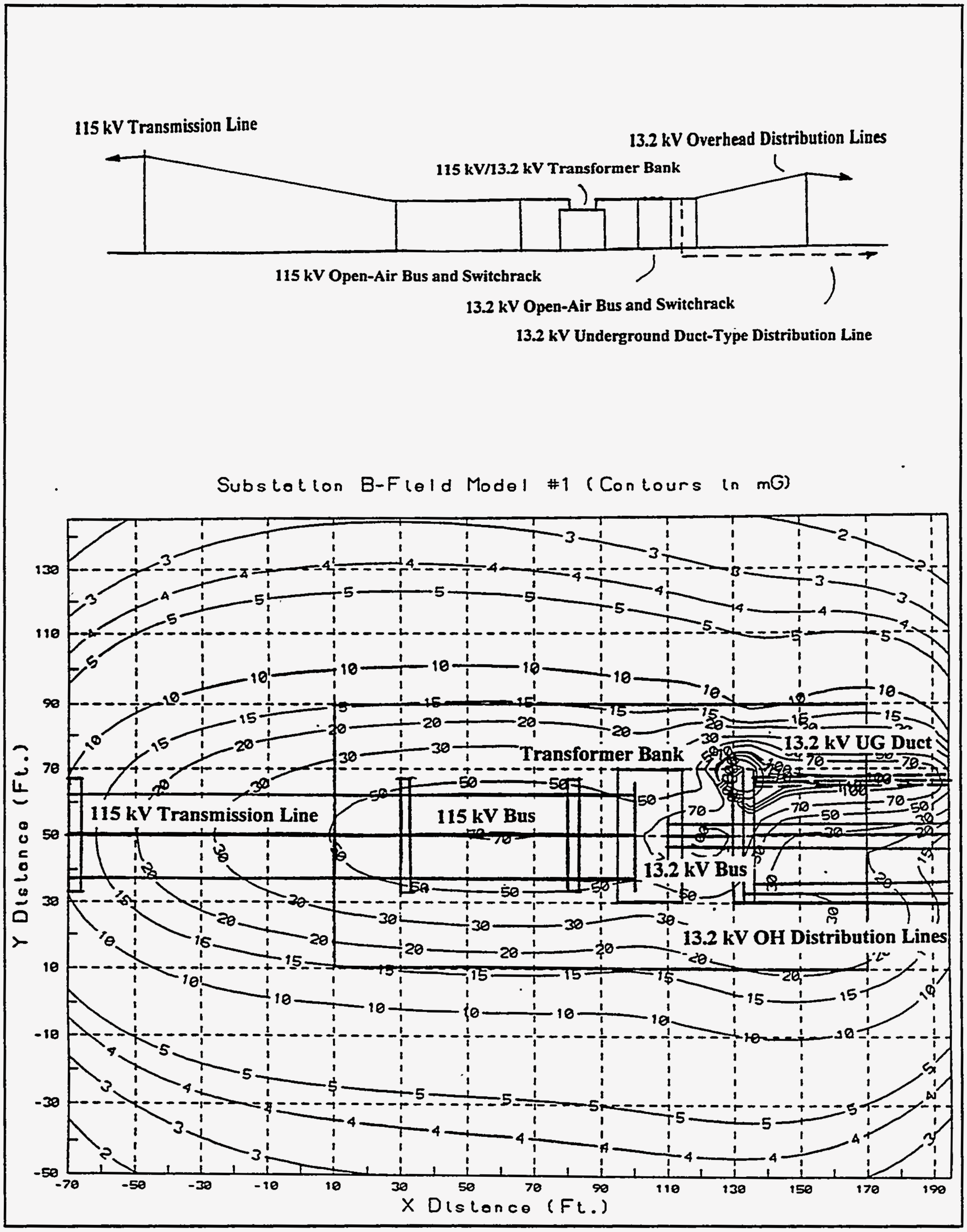


Figure 3.3-2: Distribution Substation Example No. 1

An alternative design for the same substation is shown in Figure 3.3-3. It uses a compact 115 kV switchrack arrangement, metal-clad 13.2 kV switchgear, and is fed by a 115 kV transmission line tower that keeps line conductors elevated as they pass the substation perimeter. The substation still feeds three distribution lines, but they are all routed in underground metal pipes designed to provide about an order of magnitude of magnetic field shielding.

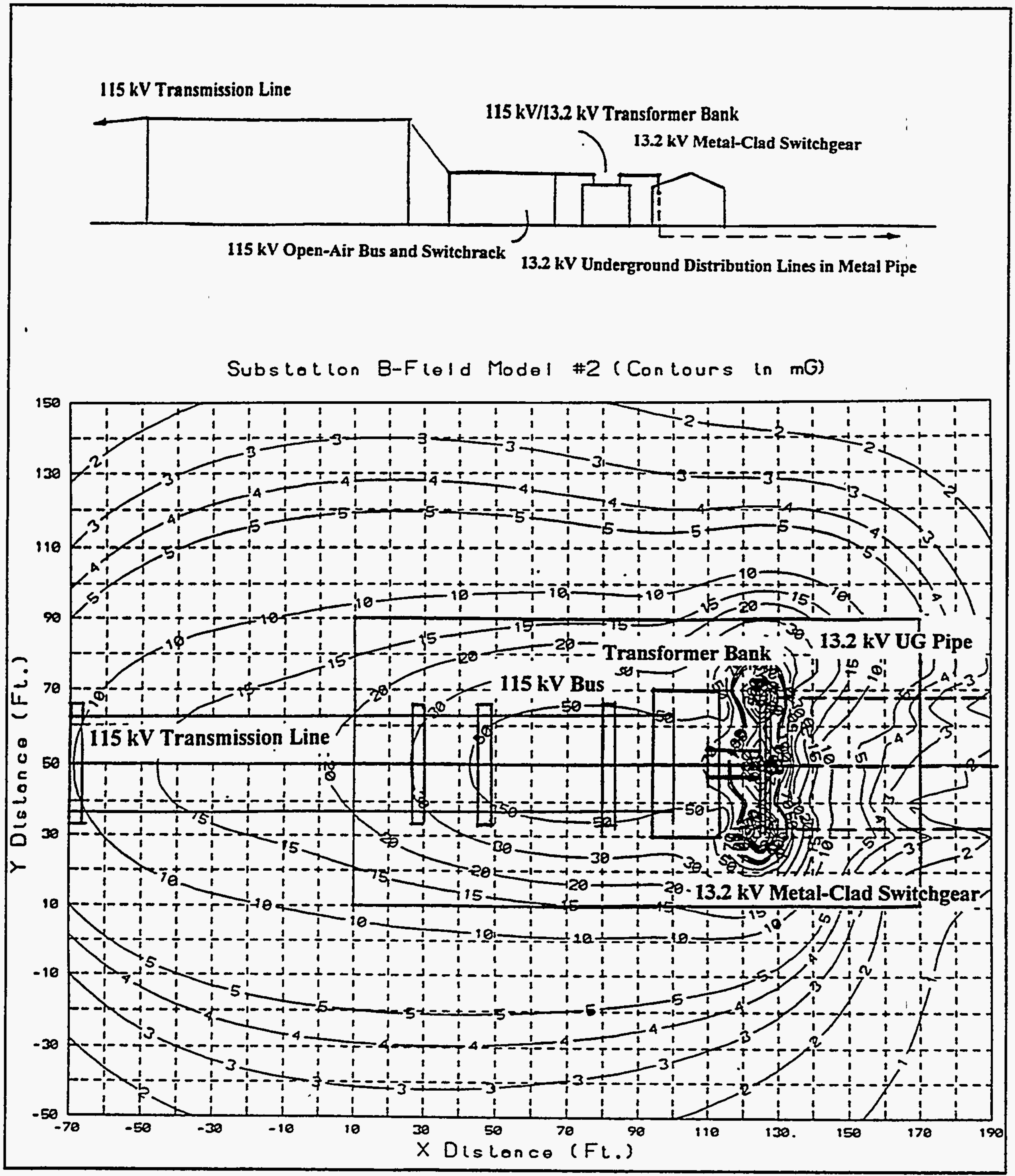


Figure 3.3-3: Distribution Substation Example No. 2

Figure 3.3-3 also shows magnetic field contours for the more compact design. Its peak magnetic fields are still found near the secondary bus, but the distribution line fields have been reduced. The overhead transmission line and primary switchgear bus are now the most significant magnetic field source at the fence line.

In both examples, the magnetic field at the fence line could be reduced to some extent by expanding the fence perimeter. This approach has no impact on magnetic fields from lines going into or out of the station, however.

Magnetic field reduction beyond that shown in the second example is technically possible. The 115 kV transmission line feeding the substation could conceivably be run in an underground pipe-type cable to reduce magnetic fields. The open-air 115 kV bus could be compacted slightly, but substantial phase compaction could only come by using a gas-insulated bus structure. Gas-insulated buses are insulated by inert gas-filled sheaths that allow the conductors to be much closer together than in air, resulting in a compact bus structure. These buses are found in gas-insulated substations (GIS) typically used only in dense urban settings.

Measurements conducted at a London, England 230 kV/28 kV gas-insulated substation operating at 120 MVA found that fields outside the substation were predominantly caused by underground distribution lines leaving the station [Wong et al, 1994]. An underground 230 kV pipe-type cable feeding the station and the 230 kV gas-insulated buses within the station were virtually "invisible" to a magnetic field meter just outside the substation building walls.

Cost Discussion

The cost of a substation depends heavily on the cost of the land on which it is found. Higher land cost drives substations toward more compact designs. Compact substation design can entail use of more compact bus spacing, which would help reduce magnetic fields. Compact open-air buses are more expensive, however, because they require stronger supporting structures and insulators to withstand short-circuit mechanical forces. [Anders et al, 1994]

Metal-clad distribution voltage switchgear is more expensive than open-air switchrack equipment. It can be cost-effective in urban settings, however, since it uses less land. At least one electric utility company, Southern California Edison, installs metal-clad distribution switchgear when the cost of land exceeds $15 per square foot ($653,400 per acre).

Although specific cost information is not available, gas-insulated substation bus designs are more expensive than open-air buses. They are used only in the most densely populated areas, where land costs probably approach or exceed $1,000,000 per acre.

Underground pipe-type cables for lines entering and leaving a substation are also more expensive than their overhead or underground duct-type counterparts. A description of these costs is provided in the transmission and distribution line sections of this report.

Other Substation Considerations

Substation magnetic field reduction methods must be carefully evaluated for their impact on public and worker safety. Expanding a substation fence perimeter may slightly enhance public safety, but probably has few worker safety implications. On the other hand, compacting an open air bus switchrack design might affect worker safety by making maintenance activities more difficult. Electric utility companies can probably examine this issue in detail, because compact buses have long been used in urban substations. Presumably, safe operating practices have been devised for these facilities.

Metal-clad switchgear appears, at first glance, to be safer than open air switchrack equipment. Workers are, however, more likely to work nearer its components than those of open-air equipment. Again, safety data should be available because metal-clad switchgear has been used for many years.

Underground lines unquestionably improve public safety, but this may come at the expense of worker safety. Few electric utility maintenance tasks are more dangerous than working in an underground vault where live cables are present.

Most substation magnetic field reduction methods would have little environmental impact. Enlarging a substation fence perimeter would have an environmental impact in the sense that additional land would be used. Usually, however, the fence perimeter might only need to be extended 10 to 20 feet. Less land would be needed, and presumably less environmental impact would result, if the utility employed a compact substation design to reduce fields.

Urban gas insulated substation designs are currently under environmental scrutiny because their insulating gases contain chloroflorocarbons (CFCs), which are believed to affect the earth's ozone layer. At least some gas leakage is almost unavoidable.

Substation Summary

Most of the magnetic field at a substation perimeter fence is from transmission and distribution lines entering the facility. The feasibility and cost of limiting public exposure to substation magnetic fields would be heavily influenced by the need to build low-field transmission and distribution lines segments at the station entrance. Table 3.3-1 summarizes the cost and feasibility of low-field distribution and transmission lines for five theoretical exposure limits: 100 mG, 50 mG, 20 mG, 5 mG, and 2 mG.

The Table 3.3-1 data is based on the lowest life cycle-cost design for each exposure criterion presented in sections 3.1 and 3.2 of this report. Suburban design data are shown, except the 500 kV and 765 kV cases. Balanced phase current loading is assumed for comparison, though power lines rarely carry balanced current. The power line life cycle cost is listed as a multiplier of the baseline cost for each voltage category. Limits that cannot be reached by designs considered in this report have question mark ("?") entries.

The cost of a "low-field" substation design would also include the cost expanding the perimeter fence or wall, if needed.

More difficult to predict would be the cost of reducing substation worker exposures. Potential methods for reducing worker exposures include shielding, especially with metal-clad switchgear or gas insulated substation buses, and remote operation and maintenance. Substations could also be designed so that low-field work areas existed when buses were not energized.

Table 3.3-1: Substation Magnetic Field Reduction Summary

	<100 mG		<50 mG		<20 mG		<5 mG		<2 mG	
Primary and Secondary Voltage Lines	**Type**	**Life-Cycle Cost Multiplier**	**Type**	**Life-Cycle Cost Multiplier**	**Type**	**Life-Cycle Cost Multiplier**	**Type**	**Life-Cycle Cost Multiplier**	**Type**	**Life-Cycle Cost Multiplier**
7.6 kV (1.52 MVA) Suburban	Standard (Baseline)	1.00	Standard	1.00	Standard	1.00	UG Direct Bury	1.08	Tall Cpct.+?	1.12+?
13.2 kV (13.7 MVA) Suburban	Cross Arm (Baseline)	1.00	Cross Arm	1.00	UG Direct Bury	1.05	Split-6 Hendrix	1.32	Split-6 Hendrix	1.32
34.5 kV (35.85 MVA) Suburban	Cross Arm (Baseline)	1.00	Cross Arm	1.00	Delta	1.08	Split-6 Hendrix	1.45	?	?
69 kV (72 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Split-6	1.23	Split-6	1.23	UG HPGF Pipe	2.21
115 kV (120 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Delta Cpct.	0.97	Split-6 Cpct.	1.24	UG HPGF Pipe	2.22
230 kV (239 MVA) Suburban	Delta (Baseline)	1.00	Delta	1.00	Split-6 Cpct.	1.18	UG HPFF Pipe	3.01	UG HPFF Pipe	3.01
345 kV (717 MVA) Suburban	Delta (Baseline)	1.00	230 kV Split-6 Cpct.	1.19	UG HPFF Pipe	2.98	UP HPFF Pipe	2.98	UG HPFF Pipe+?	2.98+?
500 kV (1559 MVA) Rural	Split-6	1.36	?	?	?	?	?	?	?	?
765 kV (3180 MVA) Rural	?	?	?	?	?	?	?	?	?	?

3.4 CUSTOMER-SIDE POWER DISTRIBUTION

Many magnetic field sources are found on the customer side of the electric utility service connection. These include customer-owned power distribution equipment such as transformers, switchgear, busways, feeders, service panels, and general wiring. Grounding methods at and beyond the service connection can also affect magnetic fields if stray return current paths are created.

In addition, magnetic fields are produced on the customer-side by end use devices such as appliances, lighting, or machinery. These are discussed in Section 3.5.

This report considers two categories of customer-owned power distribution sources. The first encompasses mostly single-phase sources found in residential and small commercial environments. The second includes larger commercial and industrial, mostly three-phase, sources.

Residential/Small Commercial Distribution

A typical single-phase service connection is illustrated in Figure 3.4-1. The standard single-phase, three-wire system consists of two 120 volt "legs" and one grounded neutral fed from the secondary of a utility-owned distribution transformer. The service connection can be an overhead service "drop", an underground service "lateral" fed from an overhead distribution line, or an underground service lateral fed from an underground residential distribution system. A Watthour meter is usually included with the service entrance equipment.

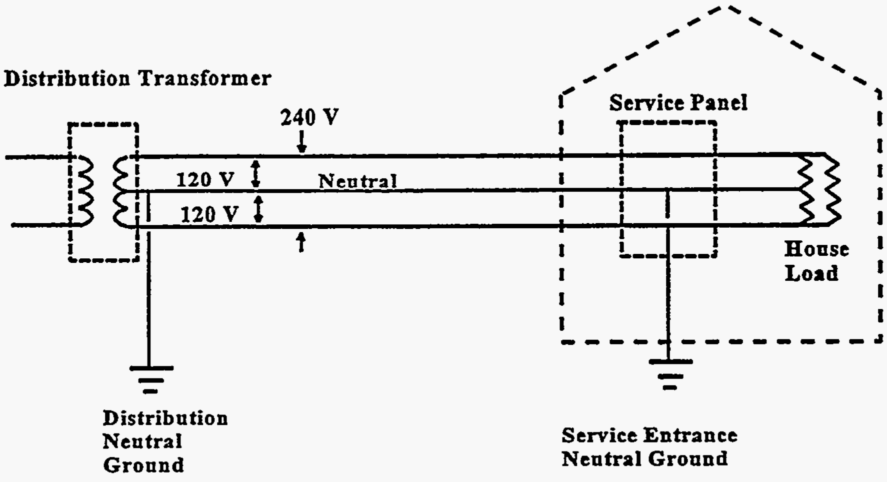


Figure 3.4-1: Typical Residential Service Entrance

Customer power distribution begins at a service panel containing a main service disconnect (a fused switch or circuit breaker) and protective devices, fuses or circuit breakers, for branch circuits. "Hot" to neutral 120 volt branch circuit loads are divided as equally as possible between the two "legs". Any 240 volt branch circuits, used for larger loads like electric ovens, washers, and dryers, are wired from "leg" to "leg".

The "service ground" is found at the service entrance. Here the neutral conductor is grounded to limit the system-to-ground voltage. More important, grounding allows automatic circuit opening in case an energized conductor is inadvertently grounded.

An "equipment ground" extends throughout the customers' distribution system. All metal equipment enclosures, including panels, cable trays, and metal conduit, are bonded to the equipment ground to prevent being charged to dangerous voltage levels. The equipment ground is supposed to be connected to the service ground only at the service entrance grounding point, according to the National Electric Code [National Electric Code, 1996].

Most residential installations have one Watthour meter and one service panel, but many variations on this basic form exist. In some residential or small commercial installations, for example, feeders are used to distribute power from the main service panel to subpanels. The subpanels, in turn, feed and house protective devices for the branch circuits. In other small commercial installations, the incoming service connection delivers power to multiple Watthour meter/service panel groups. This is usually found in apartment or multiple tenant commercial buildings, for example.

Three residential/small commercial magnetic field source types are of interest as magnetic field sources. These include service panels, branch circuit wiring, and grounding methods.

Service Panels

Service panels, through which all customer current must pass, can produce larger magnetic fields than most other residential or small commercial sources. Their fields usually drop quickly with distance, however, and so they are not usually considered a significant field source in the broader context of human exposure. They do, however, represent a type of magnetic field source that would have to be considered if field mitigation were contemplated.

This discussion also applies to subpanels and lighting distribution panels usually found in commercial and industrial locations.

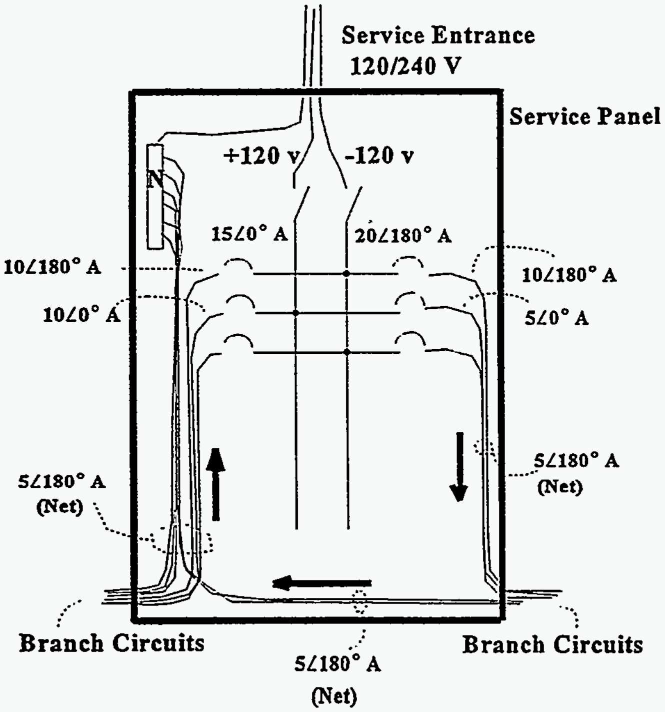


Figure 3.4-2: Example of a Service Panel Net Current Loop.

Two mechanisms create large magnetic fields near service panels. The first is simply the fact that all of the load current for a building, sometimes up to several hundred amperes, must pass through the panel. The second is the fact that unavoidable current loops are created by most service panel designs.

Service panel current loops are created when branch circuit conductors are separated within the panel for bus terminal connections, as illustrated in Figure 3.4-2 Residential service panels are usually 120/240 volt single-phase models, with two hot buses (+120 volt and -120 volt) and one neutral bus. Circuit breakers or fuses plug into the buses, usually in an alternating pattern for even load distribution.

Each branch circuit conductor pair must be separated within the panel. The hot conductor goes to a circuit breaker or fuse. The neutral conductor goes to the neutral bus. The neutral bus is normally found at one side, above, or below the circuit breaker/fuse buses. To reach it, hot and neutral conductors can be separated by 12 inches or more over a length of more than 20 inches, depending on the height of the panel. The cumulative effect of many separated branch circuit conductors can create a 12 by 20-inch or larger current loop of several amperes that behaves much like a three-dimensional magnetic dipole. A 12 inch by 20 inch current loop carrying only five amperes would create a field exceeding 100 milligauss a few inches away and 10 milligauss 20 inches away from a panel, neglecting any shielding provided by the panel enclosure.

The conductor separation effect is mitigated somewhat by the fact that hot conductors are wired alternatingly first to the +120 volt leg and then to the -120 volt leg on each side of the panel. If branch circuit loads are roughly equal, the currents are in opposition and a large current loop is not created. Usually, however, more total current is drawn from one leg. This difference creates a current loop.

Service panel field reduction options include reconfiguring the panel, moving the panel, or shielding the panel.

The goal of panel reconfiguration would be to reduce the net current loop area. One method is to replace the single neutral bus with two neutral buses, one on each side of the panel. Another method is to place the neutral bus at the bottom of the panel and feed it with a neutral conductor routed down the center of the panel. Areas further than a few inches from the panel would see magnetic fields reduced in direct proportion to the loop area reduction.

Another field reduction option is to place panels more than three feet from occupied areas. Since the panel behaves like a three-dimensional magnetic dipole, panel fields will decrease rapidly with distance, usually in proportion to the cube of distance. This may be a nontrivial task for an existing installation, however.

Conductive and/or ferromagnetic shielding could be used to reduce magnetic fields from new or existing panels. Panel shields would have to be custom made, however, since such standard panel shielding is not commercially available now.

Standard service panel steel or aluminum enclosures do not effectively shield net current loop sources. They usually consist of a flat front plate with a hinged door opening joined by screws to a five-sided steel box. Conduit usually enters the box piece through holes punched or drilled through the four sides. Various fittings are used to terminate the conduit. Usually, none of these parts or the methods used to assemble them are optimized for magnetic field shielding. No known effort has been expended to address improving electric panel and junction box shielding. Improvements would be needed in this area if it became necessary to reduce magnetic fields from building wiring.

Active field cancellation is another option, though it is less likely to be implemented. A cancellation coil could be wrapped around the exterior perimeter of the service panel. A sensor and feedback circuit would drive current through the coil to cancel some of the existing field. Active cancellation presents several uncertainties, however, such as maintenance and cost.

Unusual Wiring

Branch circuit wiring is the second residential/small commercial magnetic field source of interest. Two magnetic field source types are associated with branch circuit wiring. The first is from balanced currents flowing on the hot and neutral wires of standard branch circuits. Magnetic fields of this type drop quickly, with at least the square of distance, and are not large near the wiring because the conductors are close together. Properly wired branch circuits feeding properly configured loads will carry only balanced currents.

The second branch circuit source type is due to unusual wiring methods associated with three and four-way switches and older knob and tube wiring.

Although the National Electric Code requires hot and neutral wires to follow each other, three-way switches are often wired so that neutral current is not beside the supply current. A room-sized current loop can result. For example, a 12 foot by 12 foot loop of only one ampere will produce a minimum 3.1 milligauss field at its center, with higher fields throughout the rest of the room.

Knob and tube wiring is common in older homes. This type of wiring used separate hot and neutral conductors supported by porcelain knobs. Porcelain tubes acted as conduit for the wires through building structure bore holes. The wires were separated by several inches. One ampere flowing on wires separated by nine inches, a common spacing, produces 4.92 milligauss one foot away.

To correct unusual wiring sources, rewiring is required. This ranges from the small job of correcting a three-way wiring error to the large, expensive task of rewiring an entire building, recommended for replacing knob and tube wiring.

Standard Branch Circuit Wiring

Although modern branch circuit cables are not considered a significant magnetic field source overall, they can be important in some situations. For example, wiring in a wall next to a couch or a bed can produce above-average magnetic fields in areas frequently occupied by people.

Branch circuit cables use two or three #12 or #14 AWG insulated conductors to deliver current to 120 volt or 240 volt loads. Branch circuits are usually protected by 15 or 20 ampere fuses or circuit breakers. A bare ground conductor is usually bundled with the hot and neutral conductors.

Two or three-conductor nonmetallic sheathed cable, called type NM but often known by the Romex trade name, is one of the most common branch circuit cables. Type NM cable has two or three insulated conductors, sometimes with a bare equipment ground conductor, covered by heavy paper and wrapped in a braided or plastic shell. Type NM cable often uses a flat nontwisted arrangement for two-conductor versions and a twisted arrangement for three or more conductors. Type "NM" cable can only be used for interior wiring in buildings that are less than three floors tall.

Type AC armored cable, commonly known as BX cable, is also common. This cable's flexible armor is made from soft steel or aluminum. Type AC cables used for branch wiring normally have two or three insulated conductors twisted together and one bare conductor, called an "internal bonding strip". The bare conductor is used to short the turns of the steel jacket. This ensures that the cable jacket is an effective equipment grounding conductor.

Branch circuit conductors can be pulled through various types of conduit. Electrical metal tubing, or EMT, is popular due to its low cost, ease of installation, and use of threadless compression fittings. EMT is a thin walled steel or galvanized steel conduit that can be easily bent. EMT cannot be used where it might be subject to physical damage or severe corrosion.

Intermediate metal conduit, or IMC, is thicker than EMT, but thinner than traditional rigid metal conduit. IMC is a lightweight rigid steel conduit. The 3/4 inch IMC trade size is 0.071 inches thick. IMC uses the same standard threaded fittings as rigid metal conduit and can be used in hazardous locations.

Rigid metal conduit can be made of galvanized steel or aluminum. Rigid galvanized steel conduit is 0.113 inches thick in the 3/4 inch trade size. Rigid metal conduit uses threaded fittings for coupling, termination, and bends. Field bends can be made with rigid metal conduit. Bends are more difficult to make than with EMT or IMC. Rigid metal conduit can be directly buried in soil. It is the conduit of choice in large buildings and in outdoor locations where it could be subject to physical damage.

Finally, several types of nonmetallic conduit systems are available for branch circuit wiring. These include rigid nonmetallic conduit (NMC) and flexible electrical nonmetallic tubing (ENT). None provide magnetic shielding.

Figure 3.4-3 shows magnetic fields, on a normalized per-ampere scale, from several branch circuit wiring types. The Figure is based on measurements taken at IITRI on ten-foot cable and conduit segments carrying 1-10 amperes of balanced current. Only two conductors were used for each cable measurement case. 70 Hz current and narrowband field measurement probes were used to reduce background magnetic field interference.

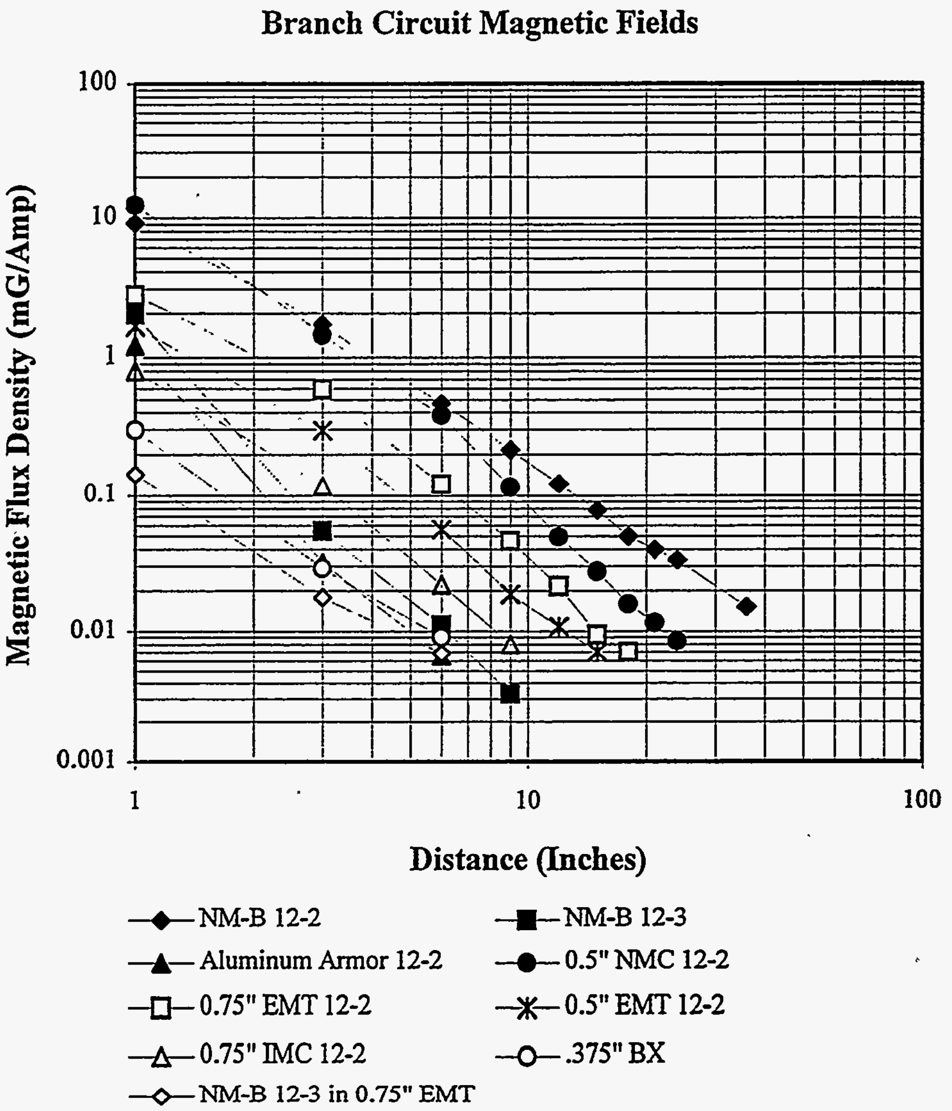


Figure 3.4-3: Residential/Light Commercial Branch Circuit Magnetic Fields

Magnetic fields from the nontwisted pair cables dropped off roughly in proportion to $1/r^2$. These included two conductor Romex (Type NM-B 12-2) and the various combinations of #12 AWG THHN wire pulled through conduit. Twisted pair cables, which included three-conductor Romex (Type NM-B 12-3) and Type AC (Aluminum Armor "BX") cables, exhibited a $1/r^3$ drop off.

Two magnetic field reduction effects, self cancellation and shielding, are apparent. Self-canceling magnetic dipoles are created by twisted conductor pairs. Type NM-B 12-3 and Type AC (BX) cables have one twist about every three inches. Their fields fall to the same levels provided by EMT and IMC conduit a few inches from the cable. A slight conductor pair "twist" provided by pulling wires through conduit also provides some self-cancellation. Magnetic fields from these circuits drop off faster with distance than from Type NM-B 12-2, which has fixed, flat conductor positioning.

Metallic EMT and IMC conduits provide magnetic field shielding. The 0.5 inch conduits shielded better than their 0.75

inch counterparts. Better shielding is provided when the shield, here the conduit wall, is nearer to the current carrying conductors. The flexible steel armor of 0.375 inch BX appears to provide some shielding, although conductor twisting contributes. Type AC (Aluminum Armor) does not seem to provide much shielding by comparison. Most of its field reduction is from conductor twisting.

Table 3.4-1 shows the measured field reduction factor, defined as the reduced field divided by the original field, for each cable compared with the baseline case of two conductors pulled through 0.5 inch nonmetallic conduit. The Table also shows Bare material and labor costs, which exclude contractor overhead and profit, for installing each cable type. The cost data was taken from the 1996 Means Electrical Cost Data Estimating Manual [Means, 1996]. For comparison purposes, the final column of the table shows a cost-field reduction factor multiplier. A lower number in this column corresponds to more field reduction per dollar spent.

Table 3.4-1: Residential/Light Commercial Branch Circuit Wiring: Field vs. Cost

Branch Circuit Cable Type	Field Reduction Factor vs. Type NM-B 12-2 at 6 inch Distance	1996 Bare Material Cost Dollars per Foot	1996 Bare Labor Cost Dollars per Foot	1996 Bare Cost Total per Foot	Total 1996 Bare Cost x Field Reduction Factor
Type NM-B (Romex) 12-2	1.0	0.25	0.94	1.19	1.19
0.5 in. NMC (PVC) 12-2	0.81	0.65	1.66	2.31	1.87
0.75 inch EMT 12-2	0.25	0.68	2.23	2.91	0.73
0.5 inch EMT 12-2	0.12	0.52	1.81	2.33	0.28
0.75 inch IMC 12-2	0.044	1.36	3.03	4.39	0.19
Type NM-B 12-3 Twisted	0.023	0.41	1.07	1.48	0.034
Type AC (BX) 12-3 Twisted (Steel Jacket)	0.019	0.47	1.17	1.64	0.031
Type AC (BX)12-2 Twisted (Alum. Armor)	0.015	0.34	1.02	1.36	0.020
NM-B 12-3 Twisted in 0.75 inch EMT	0.015	0.97	2.87	3.84	0.058

Two-conductor Type NM-B cable (Romex), the least expensive branch circuit wiring method, produced the highest fields. The field reduction provided by other wiring methods was not necessarily proportional to the cost versus Romex. In fact, the second least expensive method, Type AC (Aluminum Armor), provided substantial field reduction compared with the more expensive metal conduit options.

EMT conduit reduced magnetic fields by a factor of at least four. Both 0.5 inch and 0.75 inch diameter EMT were tested. The smaller diameter conduit provided twice the field reduction of the larger version. According to Means, EMT is more than 2.4 times as expensive as two-conductor Romex.

IMC conduit, tested only in the 0.75 inch diameter trade size, reduced fields by more than 20 times compared with two-conductor Romex. Smaller diameter IMC would likely reduce fields even more. IMC is about four times as expensive as two-conductor Romex.

In a final test, NM-B 12-3 twisted conductor cable was pulled through 0.75 inch EMT conduit. This produced the best field reduction, by a factor of more than 65, of the cables tested. This nonstandard wiring method would be more than three times as expensive as the two-conductor Romex baseline example.

Table 3.4-2 lists predicted 60 Hz shielding effectiveness for the three conduit types in the 0.5 inch to 4 inch diameter range. The predictions were developed using methods described in Appendix A. The table also lists 1996 Bare Costs for each conduit on a per linear foot basis [Means, 1996]. The Bare Cost data do not include cable installation or contractor overhead and profit. For comparison purposes, the table's final column shows a cost-field reduction factor multiplier. A lower number in this column corresponds to more field reduction per dollar spent.

Table 3.4-2: Predicted Electrical Conduit 60 Hz Magnetic Field Shielding Effectiveness

Trade Size (Inches)	Conduit Type	Inner Radius (IN.)	Wall Thickness (IN.)	Predicted 60 Hz Shielding Effectiveness	Estimated Bare Cost per Linear Foot (1996 Dollars)	Total 1996 Bare Cost x Field Reduction Factor
½	EMT	0.313	0.040	0.160	1.78	0.28
½	IMC	0.354	0.068	0.110	3.38	0.37
½	Rigid	0.313	0.109	0.070	3.89	0.27
½	Aluminum	0.313	0.109	0.854	3.36	2.87
3/4	EMT	0.415	0.046	0.167	2.36	0.39
3/4	IMC	0.457	0.071	0.128	3.84	0.49
3/4	Rigid	0.415	0.113	0.082	4.50	0.37
3/4	Aluminum	0.415	0.113	0.851	3.97	3.38
1	EMT	0.5275	0.054	0.177	2.87	0.51
1	IMC	0.5495	0.091	0.121	5.02	0.61
1	Rigid	0.5275	0.133	0.082	5.75	0.47
1	Aluminum	0.5275	0.133	0.808	4.80	3.88
2	EMT	1.0375	0.061	0.263	4.86	1.28
2	IMC	1.0945	0.097	0.190	7.99	1.52
2	Rigid	1.0375	0.154	0.115	9.50	1.09
2	Aluminum	1.0375	0.154	0.638	7.91	5.05
3	EMT	1.678	0.072	0.321	10.44	3.35
3	IMC	1.614	0.136	0.180	15.55	2.80
3	Rigid	1.534	0.216	0.088	18.95	1.67
3	Aluminum	1.534	0.216	0.386	13.75	5.31
4	EMT	2.167	0.083	0.338	14.55	4.92
4	IMC	2.101	0.149	0.190	21.75	4.13
4	Rigid	2.013	0.237	0.085	25.95	2.21
4	Aluminum	2.013	0.237	0.289	19.45	5.62

Rigid metal conduit shields better than EMT, IMC, and aluminum conduit at each diameter. EMT and IMC and rigid metal conduit shields better with decreasing conduit diameter. Aluminum works better with increasing diameter.

Electrical conduit provides the best approximation of the ideal infinite cylinder shield, but it usually consists of 10-foot long pieces that must be joined by either compression or threaded fittings. Some magnetic field "leakage" can be expected near conduit fittings, especially with aluminum conduit, because the fittings cut through the path of eddy currents. The effect is lessened by reducing the fitting impedance as much as possible. For example, threaded IMC and rigid conduit fittings most likely provide a lower impedance connection than EMT compression fittings. Fittings do not cause as much leakage with steel conduit because they do not cut through the field ducting path.

Residential/Light Commercial Stray Current

Two types of stray current on grounding systems can create magnetic fields in homes and small commercial buildings. The first type originates on premises. The second type originates off premises.

On-Premises Sources

Regrounded neutrals are largely responsible for on-premises stray currents. Article 250-23 of the National Electrical Code allows grounding of the neutral conductor only at the service entrance grounding electrode. This requirement is frequently, though perhaps inadvertently, violated.

Improper neutral to equipment grounding conductor connections are sometimes made in subpanels. When this occurs, equipment grounding conductors, such as electrical conduit, can provide more than one path back to the service entrance panel. The return current does not then necessarily follow the path of the supply current. A room to building-size net current loop of a few amperes can result.

If a regrounded neutral feeds an appliance connected to a metal water pipe, stray neutral current can flow back to the service entrance panel on the water pipe. This is because the National Electrical Code requires metal water pipe to be grounded at the service entrance. Again, a room to building-size net current loop of a few amperes can result.

If an electrical conduit carrying stray neutral current comes in physical contact with a metal water pipe, yet another current path is created. This can occur when Type AC cable is draped over a pipe in a ceiling or wall, for example [Zipse, 1972].

Off-Premises Sources

Damaged or broken neutral conductors on electric utility service drops combined with metal water pipes and water mains are the most common source of off-premises stray currents. Overhead service drop neutral conductors usually serve as the uninsulated messenger wire for supporting triplex cable. The strain of this service, combined with exposure to corrosion, can cause the conductor to degrade or even break. When this happens, neutral current returning from the service connection will seek an alternate path back to the distribution grounding system.

Stray neutral current can follow metal water pipes and water mains to a nearby service connection with a good neutral conductor. If the electrical and water service entrances of the nearby building are not adjacent, the stray current can pass through other buildings on metal water pipes. Net current loops caused by this problem can be hundreds of feet long and wide.

Stray Current Mitigation

The solution to most on-premises stray current problems is to find and correct regrounded neutrals. The solution for off-premises stray currents is more challenging. Broken or degraded neutrals can exist for years without causing obvious problems. To find them, utility companies would have to conduct regular inspections.

Another approach would be to insert an insulating coupling in metallic water laterals at the property line. This would preserve the ten-foot electrode requirement of the National Electric Code. A different approach would install the insulating coupling just inside the building wall. This does not violate the Code if it is done right at the building entrance. A supplementary grounding electrode, such as a grounding rod, must be provided.

Net current control (NCC) devices offer another potential solution to off-premises stray currents. These devices, several varieties of which are now available or under study, are designed to block common-mode, or net, currents at the service entrance. A potential NCC design, shown in Figure 3.4-4, uses a 1:1 current transformer to force most of the return current into the neutral wire between two grounding points, minimizing stray return current [Hofmann and Preston, 1995].

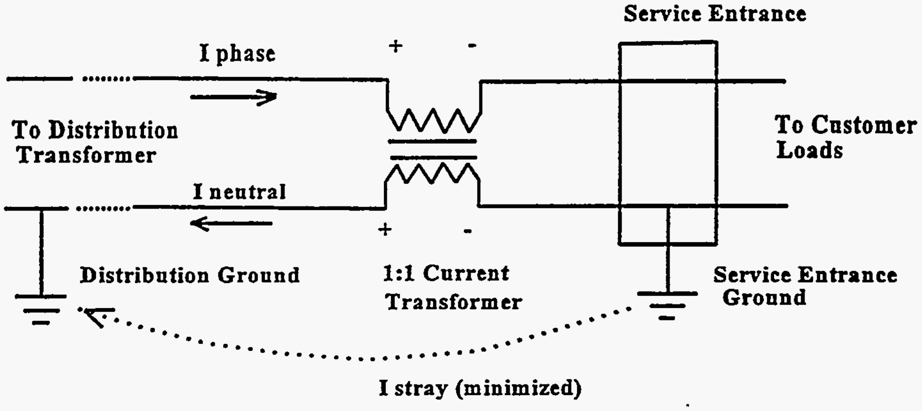


Figure 3.4-4: Net Current Control with Common Mode Rejection Transformer

The design shown in Figure 3.4-4 is positioned to reduce stray currents from off-premises sources at the service entrance. A 1:1 current transformer could also be used to reduce stray current from on-premises sources by placing it on the customer side of the service entrance ground.

Industrial/Large Commercial Power Distribution

Industrial and large commercial power distribution is a higher-current, three-phase version of residential/small commercial power distribution. An important difference is the location of distribution transformers. In residential settings, utility-owned distribution transformers serve multiple customers and are usually located on public property. In industrial/large commercial setting, distribution transformers are often dedicated to a single customer and are frequently located on the customer's property. The transformer and its associated switchgear might even be owned by the utility customer.

Several magnetic field sources are of interest in the industrial and large commercial setting. These include transformer and switchgear vaults, high-current buses and feeders, branch circuit wiring, and stray currents.

Industrial/Large Commercial Vaults

Transformer and switchgear vaults can be significant magnetic field sources in industrial and large commercial buildings. They can house one or more transformer banks, each of which might be rated from less than 100 kVA to as much as 3000 kVA. Low voltage buses connected to these transformer banks can carry up to 4,000 amperes per phase, currents in excess of those carried by transmission lines. These buses carry large currents to switchgear cabinets, from which more high-current, low-voltage feeder buses emanate.

Perhaps the most significant problem with these vaults is that they are often near occupied areas. In commercial buildings, for example, work areas are sometimes found directly above or below a vault. Work areas can literally be within two or three feet of a several thousand ampere low-voltage bus. Magnetic fields in these areas can reach the 100 to 1000+ milligauss range. The fields often become apparent when computer video display interference appears. Computer video displays are susceptible to magnetic field interference from magnetic fields as low as 10 milligauss. Other instruments found in some industrial settings, such as electron microscopes or some types of spectrometers, are even more susceptible, some to fields as small as one milligauss.

In recent years, commercial and public building owners have begun to spend money, sometimes substantial sums of money, to mitigate transformer vault fields. The principal reason has been to eliminate instrument interference. A usually unspoken reason for field mitigation is to address occupant concerns with uncertain magnetic field health effects. As the following discussion will illustrate, transformer vault magnetic field mitigation usually requires shielding.

Transformer banks usually consist of sets of dry type single-phase or three-phase transformers. They step utility distribution voltages down to low voltages for customer use. Common designs step 35 kV, 12.5 kV, or 4.16 kV three-phase distribution voltages down to 277/480 volt and/or 120/208 volt three phase secondary voltages.

Strong magnetic fields exist inside distribution-type transformer cores, but the fields are substantially contained within the cores. Low voltage bus currents are generally the dominant magnetic field source in and around a transformer vault. Many low voltage bus arrangements exist. Some produce higher fields than others. The worst "offenders" are the open bus-bar type, which use one large copper bus bar for each phase conductor. The bus bars are suspended over the transformers with each phase conductor separated from the others by anywhere from 6 inches to more than 12 inches. Low voltage bus current can also be carried by cables laid in cable trays or by enclosed manufactured compact busways called bus ducts.

To illustrate how low voltage buses affect magnetic fields from a transformer vault, several bus layouts for transformer banks with both single phase and three phase transformers were modeled using the Biot-Savart law. The model geometry for a transformer bank composed of three single-phase transformers is shown in Figure 3.4-5. The model geometry for a transformer bank composed of three or fewer three-phase transformers is shown in Figure 3.4-6.

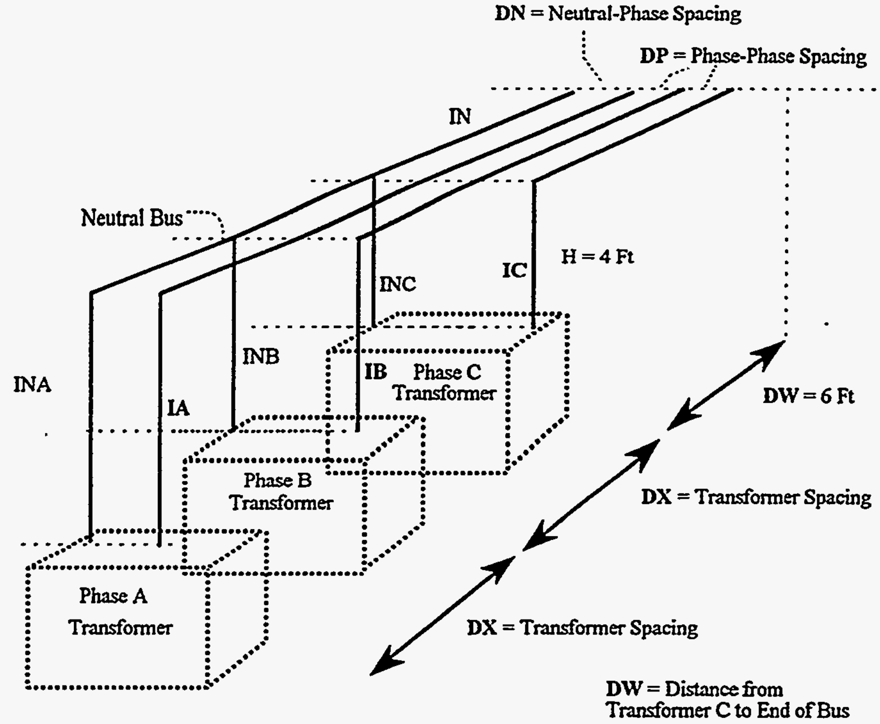


Figure 3.4-5: Single Phase Transformer Bank Low Voltage Bus

Eight cases with varying phase and transformer spacing were modeled. These, named "Case A" through "Case H", are described in Table 3.4-3. In each case, the transformer bank was assumed to provide 1000 amperes per phase to the bus.

Table 3.4-3: Transformer Bank Model Cases

Case	DP(in.)	DN(in.)	DX(ft.)	Comments
A	12	24	6	3 single-phase transformers
B	2	2	6	3 single-phase transformers
C	12	24	3	3 single-phase transformers
D	2	2	3	3 single-phase transformers
E	12	24	6	3 three-phase transformers
F	2	2	6	3 three-phase transformers
G	12	24	6	1 three-phase transformer at position #3
H	2	2	6	1 three-phase transformer at position #3

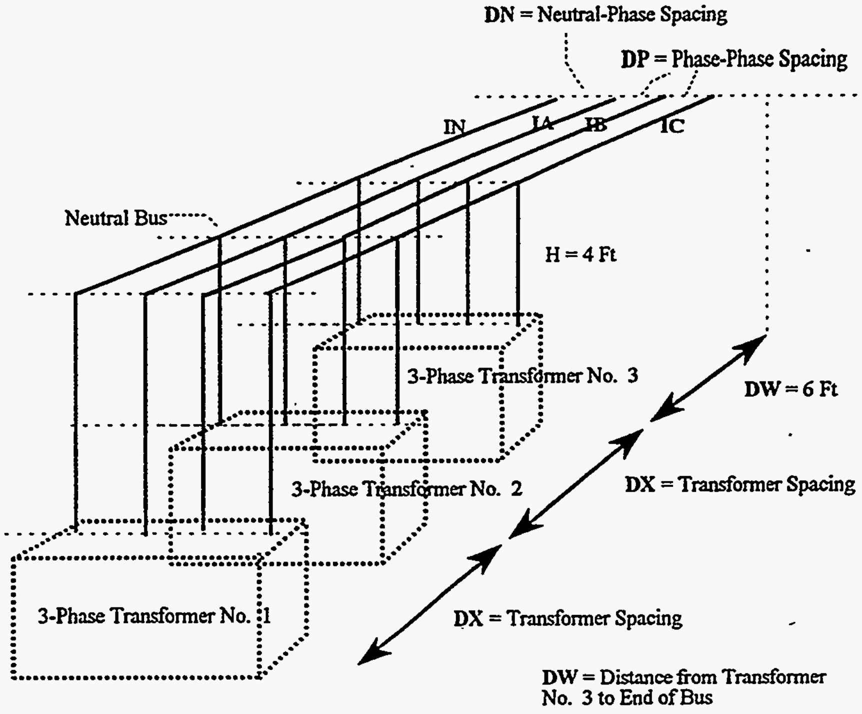


Figure 3.4-6: Three-Phase Transformer Bank Low Voltage Bus

The resulting magnetic fields are shown versus vertical distance from the highest field region of each bus in Figure 3.4-7. Figure 3.4-8 shows magnetic fields one meter above and in line with the modeled buses.

The plots show that low voltage bus conductor spacing is the most important factor for determining the maximum magnetic field at any given distance from the vault. Transformer spacing and the use of single-phase versus three-phase transformers are less important factors. These factors do, however, determine how much area a given field level will encompass because they help decide the bus length.

The plots also show that even compact buses produce large magnetic fields. In this example, the more compact bus phase conductors are only two inches apart, a distance difficult to improve upon because the conductors themselves must have effective diameters of nearly two inches to be able to carry such high currents. This basic limitation is the reason that shielding must usually be considered whenever transformer vault magnetic field mitigation is contemplated.

Flat Plate Shielding

Power frequency magnetic field shielding has become the preferred method for reducing magnetic fields caused by transformer and switchgear vaults in existing buildings. The usual impetus for such installations is a desire to prevent interference with the ubiquitous computer video display terminal. Magnetic field interference is usually caused by distortion of the vertical scan pattern, which causes "wiggles" on the display. To prevent VDT interference, shields must reduce magnetic fields to ten milligauss or less. Some shield designers specify five milligauss as the preferred minimum [Hiles et al, 1995].

Shields are rarely installed within existing electrical vaults. Such installations require power to be turned off for lengthy periods. More often, shields are installed on floors, walls, and/or ceilings in affected areas next to the vaults.

Complete shielding enclosures are also rare. Instead, shields are designed to be as simple and inexpensive as needed to get the job done. If, for example, shielding were needed in a room above a vault, the usual practice would be to first try a flat shield on the floor of the room. If the floor shield was inadequate, the designer might consider extending it to adjacent rooms or up one or more of the room's walls. The wall shields might or might not have to extend all the way to the ceiling. If further shielding was needed, the designer would probably install shielding in the vault before considering shielding the ceiling of the room above the vault.

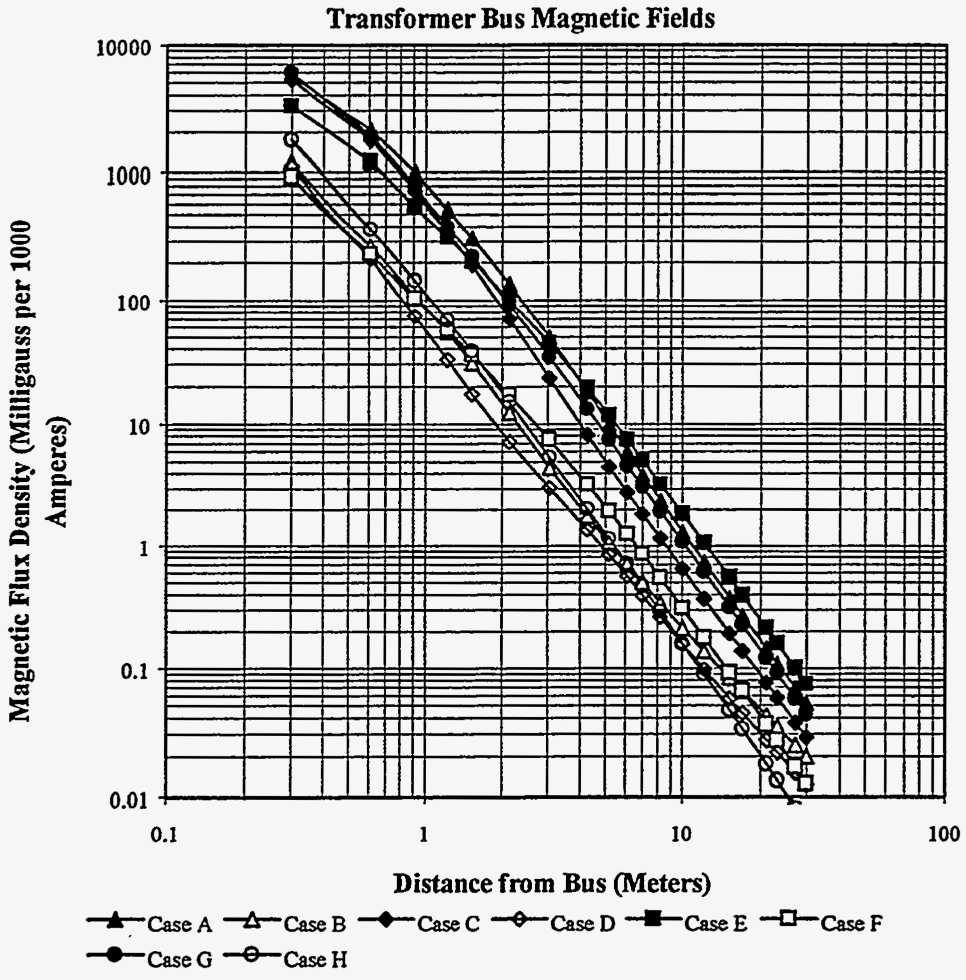


Figure 3.4-7: Transformer Vault Magnetic Fields (Modeled)

Separate parts must usually be joined to create a shield. These joints, or seams, degrade shielding performance. The best seam is "tank tight" welded continuously along its entire length. Metal inert gas (MIG) or shielded metal arc welds are the preferred methods. These produce welds with the best electromagnetic properties because the shield material is used for the welds.

On-site welding of steel or aluminum is necessary for most room-sized installations and can be a significant portion of a shield's total cost. Standard structural welding can cost $40 to $65 per hour depending on union requirements, crew size, and inspection requirements. Specialized continuous welding probably costs more. These costs are offset by the fact that fastening hardware, such as bolts or rivets, are not required. A welded plate shield can also be 10% to 20% lighter than a bolted or riveted version.

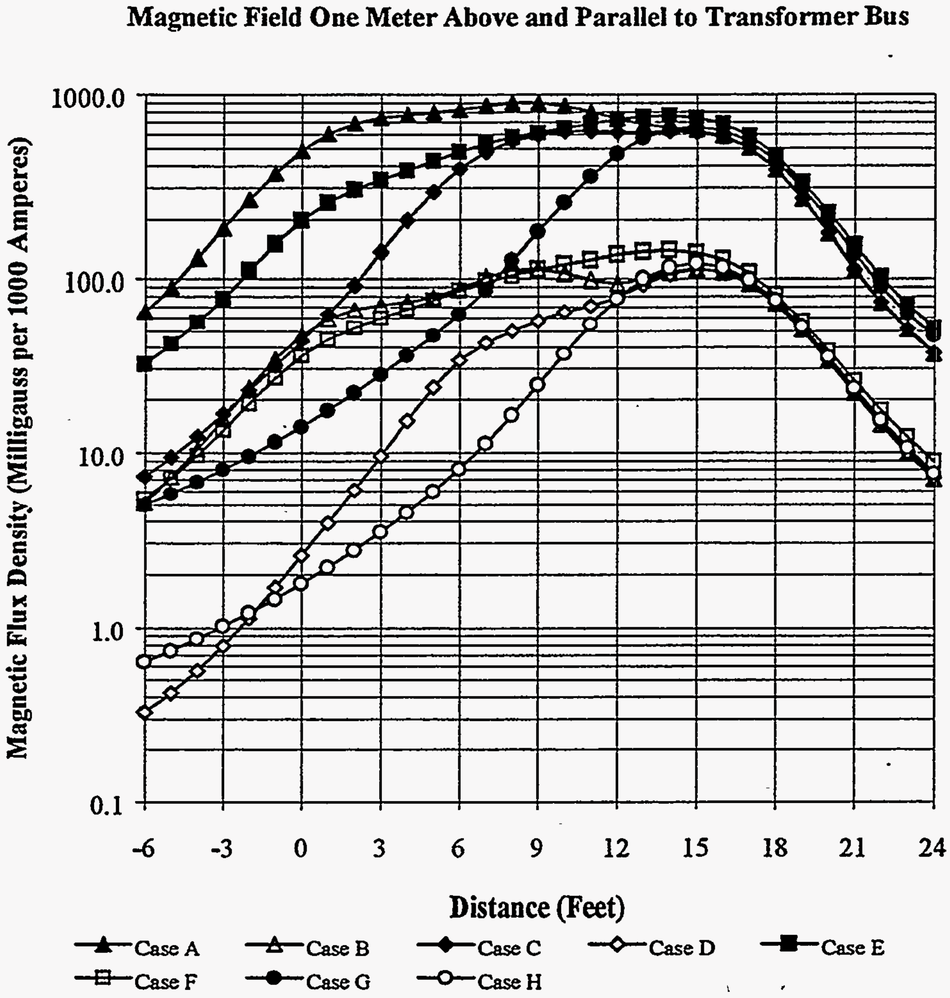


Figure 3.4-8: Transformer Vault Fields One Meter Above and Parallel to Bus (Modeled)

Flat sheets can be continuously butt-welded or, if thin enough, overlapped with continuous lap-welds. Pan-welding of thinner materials can be used to prevent buckling. In the pan-welding method, flat sheets are cut and bent at the edges to create a shallow "pan". The bent edges of adjacent sheets are then joined with square flange welds. The seams provide an expansion joint to reduce buckling. The method costs more than other methods.

At wall/floor or wall/ceiling joints, angle corner pieces that overlap the flat shield areas are recommended. These should be joined with continuous fillet welds.

Shield penetrations are almost unavoidable. In vault shields, for example, openings must be provided for cable access, ventilation, and doorways. Like seams, penetrations degrade shielding performance. The designer of practical power frequency shields must reduce the number and size of shield penetrations. If cable or wiring must penetrate a shield, it should be routed through a conduit bonded to the shield.

Heavy steel plates can also be difficult to use. A 4 x 8 foot piece of ½ inch thick steel can weigh more than 650 pounds. Smaller plates might be needed to ease handling, but this increases seam welding costs. Floor loading limits alone can force a shield designer to consider aluminum, about 1/3rd the weight of steel, or thinner, more expensive high-permeability alloys such as mumetal.

In steel frame buildings, steel decking is often used as a structural element to create composite floors and ceilings. The most common types are corrugated sheets of 20 to 16 Gauge (3/80 inch to 1/16 inch) steel. These provide little magnetic field shielding at power frequencies. Floor decks could, however, be designed to provide shielding if thicker or multi-layered plates were used.

Flat plate magnetic field shielding depends not only on shield dimensions and material properties, but also on the shape and relative size of the magnetic field source. Additionally, flat plate shielding effectiveness for any realistic source varies with both source-shield distance and source-measurement point distance.

Table 3.4-4 compares estimated steel, aluminum, and mumetal material costs with estimated infinite flat plate shielding effectiveness and with material weights. The shield predictions are based on a modified Schelkunoff approximation method described in Appendix A. The prices are based on commercial quotations obtained in late 1996 for 2024 aluminum and commercial quality cold rolled steel. Mumetal prices depend heavily on the nickel market and can vary considerably month to month. The table's final column shows a cost-shielding effectiveness multiplier for comparison purposes. Smaller numbers in this column correspond to more field reduction per dollar.

Table 3.4-4: Flat Plate Shield Material Costs

Material	**Thicknes s (Inches)**	**Shelkunoff 60 Hz Shielding Effectiveness**	**Est. Weight per Sq. Foot (lbs)**	**Est. Cost per 100 Pound Weight (1996$)**	**Est. Cost per Sq. Foot (1996 $)**	**Cost x Shielding Effectiveness**
Steel Sheet	1/16	0.55	2.5	$151	$3.80	2.09
Steel Sheet	1/8	0.30	5.0	$87	$4.42	1.33
Steel Plate	3/16	0.19	7.66	$58	$4.49	0.85
Steel Plate	1/4	0.10	10.21	$58	$5.99	0.60
Steel Plate	5/16	0.055	12.76	$58	$7.48	0.41
Steel Plate	3/8	0.03	15.32	$58	$8.98	0.27
Steel Plate	½	0.01	20.42	$58	$11.97	0.12
Aluminum Sheet	1/16	0.28	0.9163	$522	$4.79	1.34
Aluminum Sheet	1/8	0.15	1.818	$502	$9.10	1.37
Aluminum Sheet	3/16	0.09	2.763	$473	$13.10	1.18
Aluminum Plate	1/4	0.075	3.636	$357	$12.97	0.97
Aluminum Plate	5/16	0.06	4.545	$382	$17.33	1.04
Aluminum Plate	3/8	0.05	5.454	$349	$18.98	0.95
Aluminum Plate	½	0.039	7.272	$349	$25.35	0.99
Mumetal Sheet	1/50	0.07	0.91	$2,374	$21.60	1.51
Mumetal Sheet	1/40	0.055	1.13	$2,134	$24	1.32
Mumetal Sheet	1/25	0.028	1.81	$2,044	$37	1.04
Mumetal Sheet	1/16	0.008	2.83	$2,049	$58	0.46

The table shows that steel provides the lowest (best) shielding factor per dollar spent, an effect that improves with thickness. Mumetal provides the highest cost option for a given shielding factor, but the thickest aluminum plates are nearly as expensive. In fact, little performance/cost advantage is gained when aluminum is thicker than about 3/16 inch.

Mumetal is the lightest material for a given shielding factor. Steel is by far the heaviest. Thin aluminum plates, less than about 3/16 inch thick, appear to offer a potentially useful combination of shielding effectiveness, weight, and cost.

Only material costs are shown in the table. Engineering and installation costs should be expected to add significantly to these costs.

Industrial/Large Commercial Buses and Feeders

Low voltage (120/208 or 277/480 volt), three phase buses and feeders distribute power from the service entrance to circuit breaker panels. To illustrate how their magnetic fields might be mitigated, two design cases are presented. The first is a 400 ampere per phase bus. The second design carries 2,000 amperes per phase. The 400 ampere bus represents small to medium sized feeders (83 kVA to 192 kVA) used to distribute power from service entrance panels or from switchgear to branch circuit breaker panels. The 2000 ampere bus typifies medium to large sized buses (415 kVA to 1 MVA) used to carry power from a transformer vault to a switchgear panel.

The 400 ampere per phase feeder bus cases, illustrated in Figure 3.4-9, include the standard use of four 500 kcmil conductors, one for each phase and one for the neutral, routed in three inch diameter conduit or in six inch or wider cable tray. EMT, IMC, rigid galvanized steel and nonmetallic conduit (NMC) are considered. Conduit shielding is modeled using the approach described in the Residential/Small Commercial Distribution section of this report.

Also considered is the use of eight 250 kcmil conductors to create a "split-phase" 400 ampere bus. Close attention must be paid to NEC specifications for cable layering in cable trays, but this arrangement can provide substantial field reduction if the phase conductors are arranged properly. Consistent phase arrangement can be difficult to achieve with cables in cable trays, however. "Cablebus", a fixed cable tray design using spacers to keep cables in a fixed pattern, offers one possible solution. A split-phase 400 ampere cablebus design, with 1.5 inch cable spacing for the 0.72 inch diameter 250 kcmil cables per NEC requirements, is modeled.

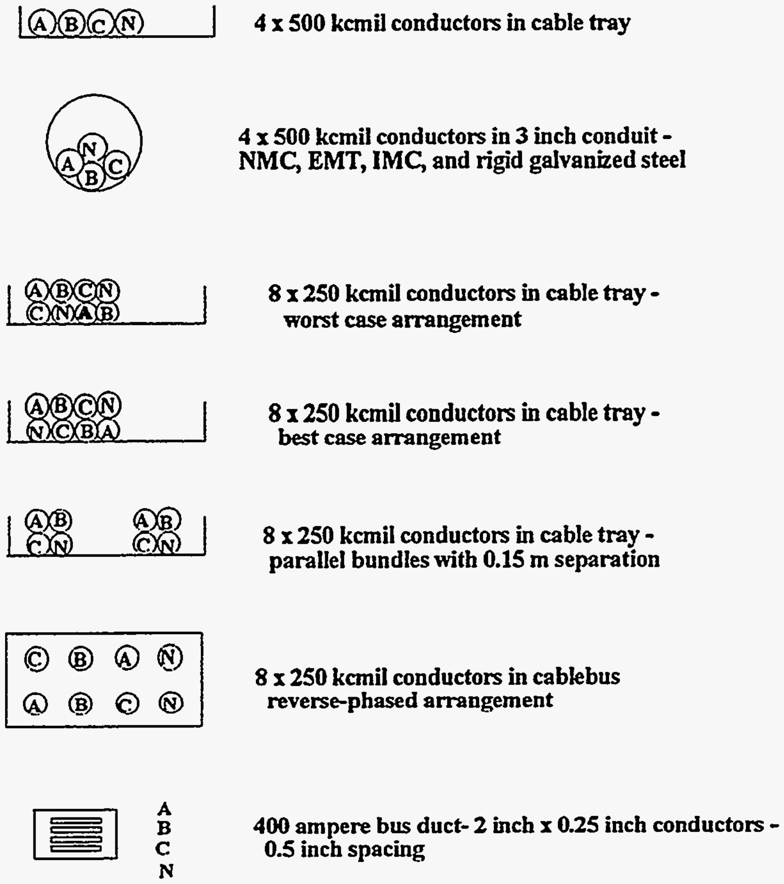


Figure 3.4-9: 400 Ampere/Phase Feeder Arrangements

The final 400 ampere feeder design considered is bus duct, also called busway. Bus ducts are premanufactured sets of enclosed bus bars, delivered in set lengths and bolted together on site. Bus duct is usually used to carry secondary bus currents from transformers to switchgear in building vaults and for high-current feeders in large buildings. The design considered is based on a commercially available product.

Three 2000 ampere bus designs, shown in Figure 3.4-10 are considered. The first two are standard 1000 kcmil cable designs. One uses 16 cables laid flat in a cable tray. The second consists of four groups of four conductors run in four conduits. This type of parallel conductor phase splitting is standard practice for high-current buses, for reasons of cost, ease of installation, and thermal limitations. The third 2000 ampere bus design considered is an eight-conductor bus duct. This design is based on a commercially available product.

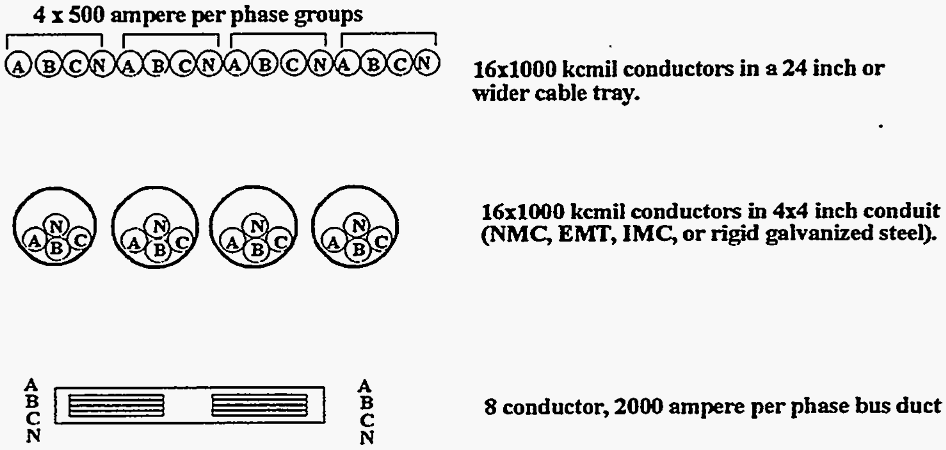


Figure 3.4-10: 2000 Ampere per Phase Feeder Bus Designs.

Magnetic field estimates for 400 and 2000 ampere feeders are shown in Figures 3.4-11 and 3.4-12, respectively. Cost and field estimates for the designs are presented in Tables 3.4-5 and 3.4-6, respectively. The conduit shielding factor predictions are based on methods described in Appendix A. Cost data is based on the 1996 Means Electrical Cost Data estimating manual [Means, 1996]. For comparison, purposes, the final column of each table shows a cost-shielding effectiveness multiplier. Smaller numbers in this column correspond to greater field reduction per dollar.

The results highlight at least three magnetic field reduction options for feeders: shielding, phase-splitting, and, to a lesser extent, use of distance. Both rigid metal conduit and phase splitting can reduce unshielded bus magnetic fields by more than an order of magnitude at typical exposure distances. Intermediate metal conduit, or IMC, reduces fields by more than a factor of six. Electrical metal tubing, or EMT, reduces fields by a factor of about five.

Although the conductors are usually very close together, large magnetic fields can still exist within several feet of a high-current feeder or bus. For example, 2000 ampere bus magnetic fields exceed five milligauss five feet away from even the rigid steel conduit design. If nonmetallic conduits were used, magnetic fields would exceed five milligauss out to about 20 feet. This represents valuable floor space in a commercial or industrial building.

According to the Means bare cost data, a rigid conduit bus is 28-37% more expensive than laying cables in a cable tray for the 400 and 2000 ampere examples. IMC is 18-30%more expensive. EMT is 2-17% more expensive. Rigid conduit offers the most field reduction per dollar spent at both 400 and 2000 amperes. IMC does not seem to.offer a substantial cost versus field reduction advantage over either EMT or rigid metal conduit in either case. Phase-splitting appears cost-competitive for the 400 ampere cablebus example. The example bus duct does not appear cost competitive at 400 amperes, but is less expensive than the rigid metal conduit and IMC designs at 2000 amperes.

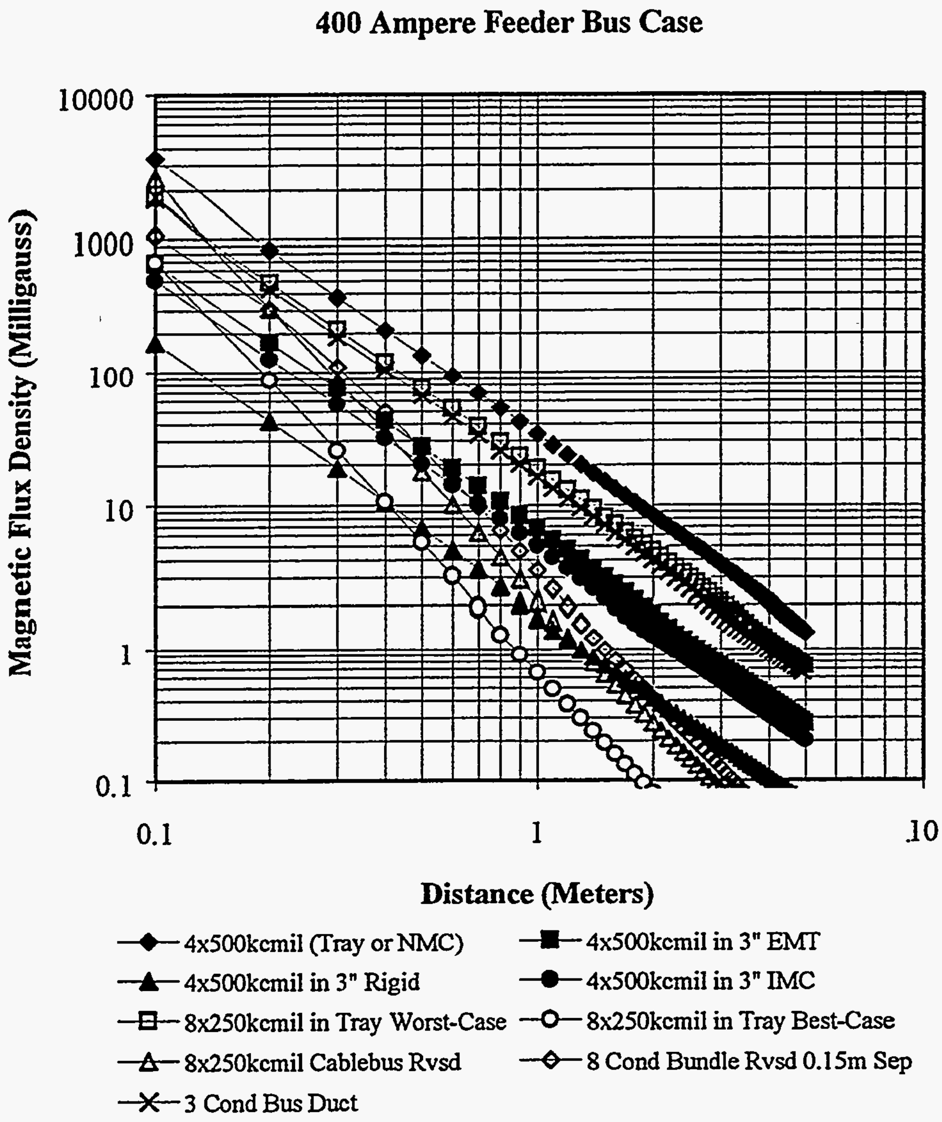


Figure 3.4-11: 400 Ampere Three-Phase Bus Magnetic Fields

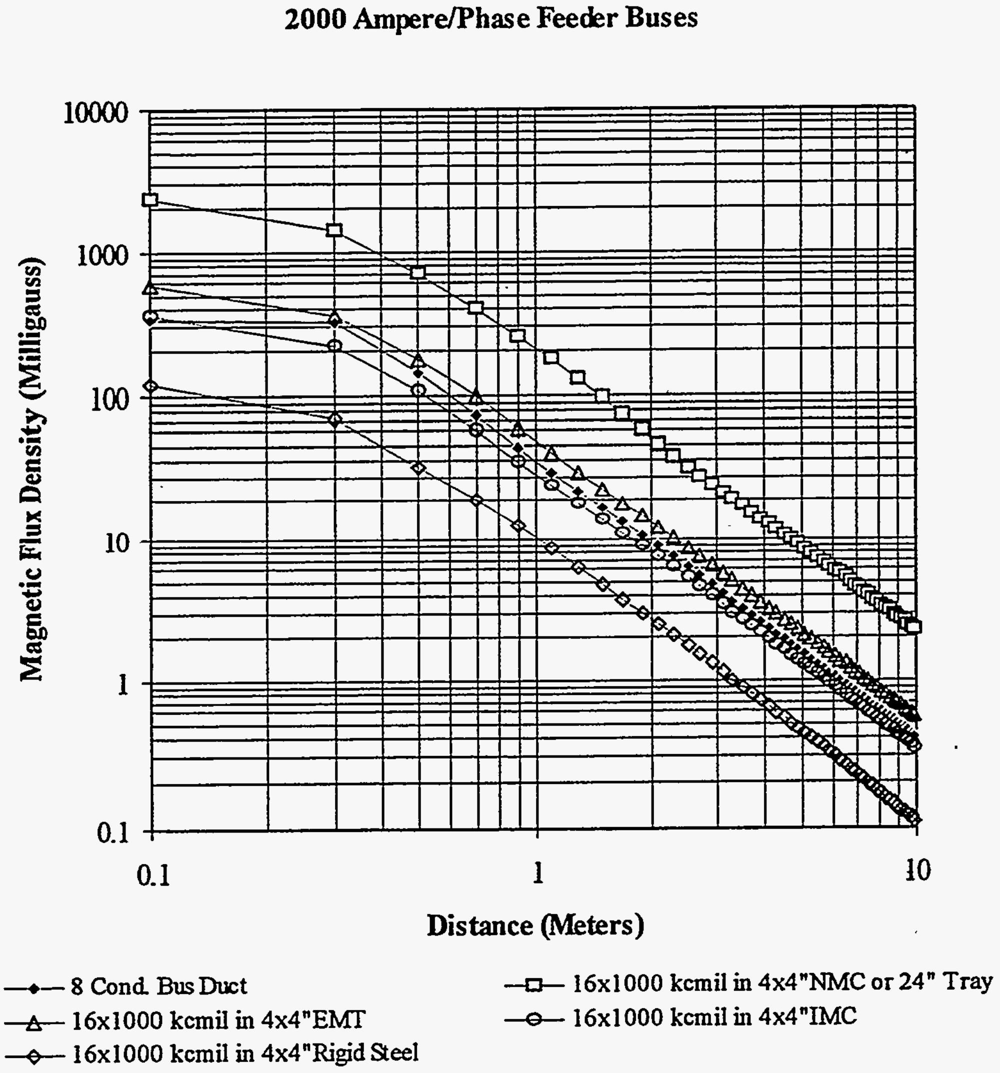


Figure 3.4-12: 2000 Ampere Three-Phase Bus Magnetic Fields

Table 3.4-5: Industrial/Heavy Commercial 400 Amp Feeder Cables: Field vs. Cost

400 Amp/Phase Feeder Cable Type	Field Reduction Factor vs. 4x500 kcmil in 3" NMC at 1 Meter Distance	1996 Bare Material Cost Dollars per Foot	1996 Bare Labor Cost Dollars per Foot	1996 Bare Cost Total per Foot	Bare Cost x Field Reduction Factor
4x500 kcmil in 6" Cable Tray	1.0	22.85	9.79	32.64	32.64
4x500 kcmil in 3" NMC	1.0	20.50	10.14	30.64	30.64
4x500 kcmil in 3" EMT	0.20	22.75	10.57	33.32	6.66
4x500 kcmil in 3" IMC	0.15	24.75	13.68	38.43	5.76
4x500 kcmil in 3" Rigid	0.05	26.55	15.28	41.83	2.09
8x250 kcmil in 6" Cable Tray	0.02-0.55	23.45	13.27	36.72	0.73-20.20
8x250 kcmil in Cable Bus	0.06	24.00	15.00	39.00	2.34
8x250 kcmil in 2x2.5" NMC	0.10-0.60+	23.60	16.58	40.18	4.02-24.11+
400 Amp 4 Cond Bus Duct	0.48	66.00	11.70	77.70	37.30

Table 3.4-6: Industrial/Heavy Commercial 2000 Amp Feeder Cables: Field vs. Cost

2000 Amp/Phase Feeder Cable Type	Field Reduction Factor vs. 16x1000 kcmil in 4x4" NMC at 1 Meter Distance	1996 Bare Material Cost Dollars per Foot	1996 Bare Labor Cost Dollars per Foot	1996 Bare Cost Total per Foot	Bare Cost x Field Reduction Factor
16x1000 kcmil in 24" Cable Tray	1.0	178.70	49.40	228.10	228.10
16x1000 kcmil in 4x4" NMC	1.0	188.20	62.40	250.60	250.60
16x1000 kcmil in 4x4" EMT	0.20	202.80	65.00	267.80	53.56
16x1000 kcmil in 4x4" IMC	0.15	217.40	79.20	296.60	44.49
16x1000 kcmil in 4x4" Rigid	0.05	225.00	88.40	313.40	15.67
2000 Amp 8 Cond Bus Duct	0.17	260.00	29.50	289.50	49.22

Customer-Side Power Distribution Summary

What would happen to building wiring if power frequency magnetic field exposure limits were required? The answer would depend on what the exposure limit values were and on how the exposure limits were defined. Exposure limits that were defined for values at a set distance from a source might be easy to achieve, because most building wiring magnetic fields drop off quickly with distance. On the other hand, exposure limits that were defined for all points in space could be extraordinarily difficult to achieve. In either case, meeting a standard with new construction would be easier than retrofitting an existing installation.

Table 3.4-7 provides a summary of the feasibility and estimated cost of new customer-side power distribution systems designed to meet one of five theoretical exposure limits: 100 mG, 50 mG, 20 mG, 5 mG, and 2 mG. The limits are assumed to be defined at a set distance, perhaps three to six inches, away from walls, floors, and ceilings. The bare cost impact is shown as a multiplier of the baseline cost for each source type. Limits that cannot be reached by designs considered in this report have question mark ("?") entries. Question marks are also added when some uncertainty exists with a field reduction method or cost estimate.

Table 3.4-7 is based as much as possible on cost and design data presented in this section of the report. For standard branch circuit wiring and large buses and feeders, the lowest bare cost design was selected that met each exposure criterion. For other source types, costs were estimated based on the cost of shielding materials and/or the cost of labor.

Table 3.4-7: Customer-Side Power Distribution Magnetic Field Reduction Summary

Source Type	<100 mG		<50 mG		<20 mG		<5 mG		<2 mG	
	Type	Bare Cost Multiplier	Type	Bare Cost Multiplier	Type	Bare Cost Multiplier	Type	Bare Cost Multiplier	Type	Bare Cost Multiplier
Service/Lighting Panels	No Change	1.00	Shield + Distance	1.10-1.50	Shield + Distance	1.10-1.50	Shield+ Distance	1.10-1.50	Shield+ Distance	1.10-1..50
Unusual Wiring	No Change	1.00	No Change	1.00	No Change	1.00	Rewire	1.10-1.50	Rewire	1.10-1.50
Standard Branch Circuit Wiring	Type NM-B (Baseline)	1.00	Type NM-B (Baseline)	1.00	Type NM-B (Baseline)	1.00	Type AC (Alum)	1.14	Type AC (Alum)	1.14
On-Premises Stray Return Current	No Change	1.00	No Change	1.00	No Change	1.00	Rewire	1.00-1.10	Rewire	1.00-1.10
Off-Premises Stray Return Current	No Change	1.00	No Change	1.00	No Change	1.00	NCC Device?	1.10-1.50?	NCC Device?	1.10-1.50?
Industrial/Large Commercial Vaults	Shield + Distance	1.10-1.50	Shield + Distance	1.10-1.50	Sheild + Distance	1.10-1.50	Shield + Distance	1.50-2.00+	Shield + Distance	1.50-2.00+
Industrial/Large Commercial Buses and Feeders (400 Amp Example)	EMT	1.02	Rigid Conduit	1.28	Rigid Conduit	1.258	Rigid Conduit + Shield	1.50-2.00	Rigid Conduit + Shield	1.50-2.00
Industrial/Large Commercial Buses and Feeders (2000 Amp Example)	Rigid Conduit	1.37	Rigid Condiut + Shield	1.50-2.00	Rigid Conduit + Shield	1.50-2.00	Rigid Conduit + Shield	1.50-2.00	Rigid Conduit + Shield	1.50-2.00

As the table illustrates, only a few sources, such as transformer vaults and heavily loaded buses and feeders, would require attention if a 100 mG exposure limit were specified. At 5 mG or less, all sources would require attention. The greatest cost impacts would occur if vaults, buses, and feeders had to meet a 5 mG or 2 mG exposure criterion.

3.5 APPLIANCES AND MACHINERY

Appliances produce electromagnetic (EM) fields at the fundamental power frequency and its harmonic frequencies, at device-generated frequencies, and at transient related frequencies. Resistive heating elements by themselves produce fields almost exclusively at the fundamental power frequency, while appliances with transformers, motors, and/or solid-state speed controllers or dimmers can have fields with significant harmonic content. Appliances with small direct-current motors (some shavers, hobby tools) full-wave rectify the line current and generate EM fields primarily at the power frequency second harmonic. Very low frequency (VLF) (3 kHz to 30 kHz) EM fields are generated by the horizontal deflection circuits in televisions and computer monitors, and by the rotating armatures and commutators in motors. Computer power supplies and electronic ballasts operate at upwards of 100 kHz. High frequency transient EM fields can be created by arcing on motor commutators and by mechanical switch contacts.

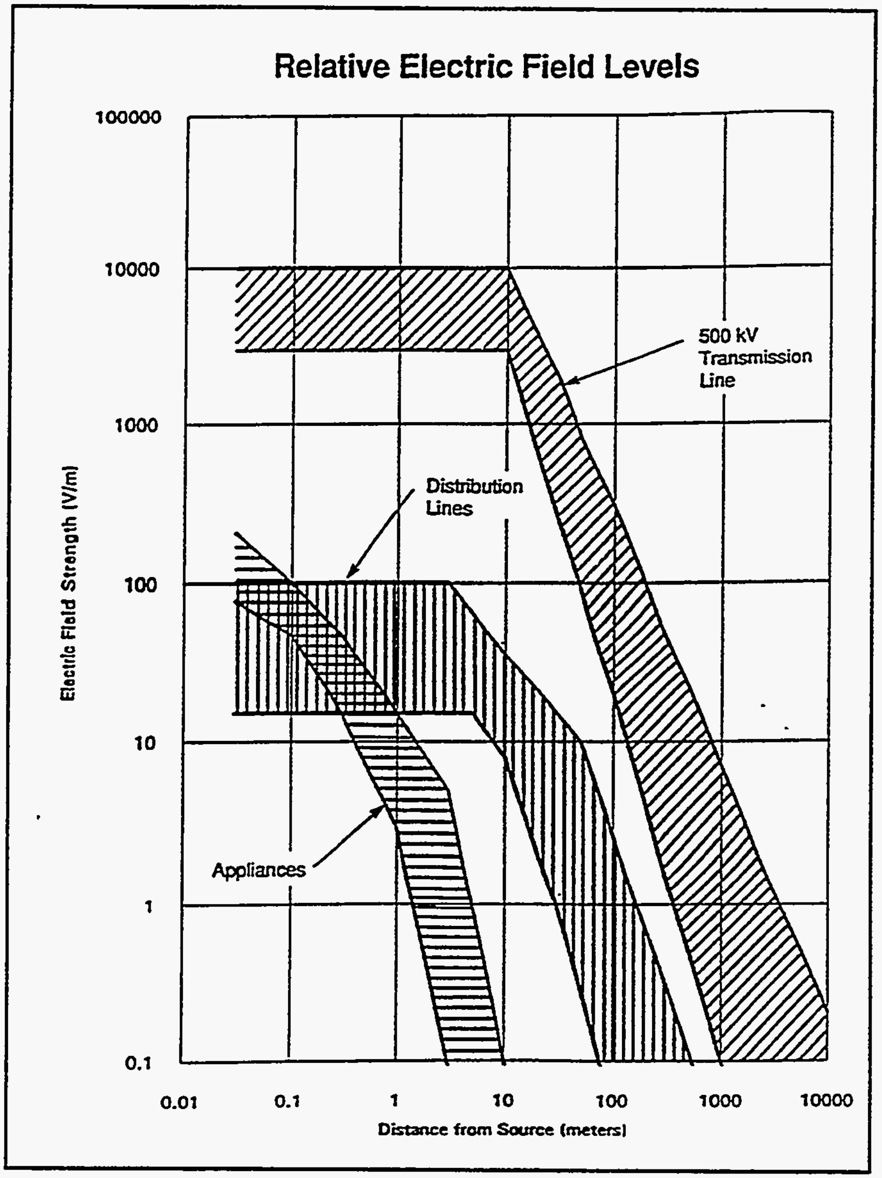


Figure 3.5-1: Relative electric field intensities [Health Effects..., 1993].

Electric fields near the surfaces of appliances are typically in the same range of intensity as those found beneath distribution lines, as shown in Figure 3.5-1, but decrease much more rapidly with distance [Health Effects..., 1993]. Localized electric field intensities at the surface of nonmetallic cased appliances may be as high as 1 kV/m. Electric fields around appliances depend greatly on the relative location and nature of surrounding objects, especially metallic grounds and other conductors. The orientation of the appliance, and the position of its user, are also important factors.

Magnetic fields at the fundamental power frequency can be quite localized near the surface of appliances and may be orders of magnitude more intense than those directly beneath large transmission lines [Gauger, 1985]. However, as shown in Figure 3.5-2, these fields diminish rapidly and become more homogeneous with distance. Typically, magnetic field magnitudes vary by less than 20 percent in any direction from a portable appliance at distances in excess of about 1 meter. This field behavior is characteristic of a three-dimensional magnetic dipole, and it has been shown analytically that most appliances can be modeled as such for low frequencies [Armanini, et al, 1990].

The primary sources of magnetic fields from end-user appliances are currents on the electrical components listed below:

- resistive heating elements
- single phase motors
- transformers and coils
- power cords and wiring

Because magnetic fields are generated by electric currents rather than differences in potential (voltages), they are present only when an appliance is operating. However, some appliances such as clothes dryers, dishwashers, and conventional and microwave ovens have multiple magnetic field sources that can cycle on and off during operation, changing the level of magnetic field produced over time.

Resistive heating elements found in appliances vary from the simple rod forms used in baseboard heaters, stoves, ovens, and water heaters, to the more complex spiral and serpentine-wound wires or filaments used in portable heaters, toasters, and hair dryers. Single-phase motors in appliances range from the milliwatt-sized pancake motors in analog clocks and timers, to the lightweight universal motors whose frame is integral with the housings of small and hand-held appliances, up to the high fractional horsepower motors used in large stationary appliances and power tools.

Transformers of various sizes are commonly found in the power supplies of all types of consumer and office electronic products. Some larger transformers are those found in the power supplies for the magnetrons in microwave ovens. Ballasts, or current-limiting transformers, are found in all non electronic fluorescent lamps and light fixtures. Most televisions, video display terminals, and computer monitors employ vertical deflection coils that operate at ELF frequencies, and a high-voltage transformer and horizontal deflection coils which operate at VLF frequencies. The interconnection wiring within appliances can be a major magnetic field source because large current loops are possible if the source and return leads to the controls and loads are not routed together. Other wiring related magnetic field sources include line cords, printed circuit board conductors (loops), and the ion currents in fluorescent lamp tubes.

Appliance/Machinery Field Reduction Options

Since most appliance magnetic field sources act like three-dimensional dipoles, their fields decline rapidly with distance. Sometimes, designing an appliance to maximize the source-user distance may be possible. For example, the motors and power supplies of large appliances like clothes washers, refrigerators, and microwave ovens could be moved to the rear of the units.

This option is not available for most end-user appliances, however. Small and/or portable devices such as radios, clocks, toasters and toaster ovens, blenders, coffee grinders, can openers, lamps and lighting fixtures, fans, portable electric heaters, and vacuum cleaners are simply too small and users must often be close to them. Distance is definitely not an exposure reduction option for hand-held devices like hair dryers, shavers, and power tools, or for electrically heated blankets. It is also difficult to "design-in" user-source distance for some larger appliances like electric stoves and cooktops, televisions, and desktop personal computers.

For most appliances, the use of distance is not a viable field exposure reduction method. If low-magnitude power frequency magnetic fields were ultimately linked to adverse health effects, appliance EMF guidelines or mandates would likely be required. The lowest existing magnetic field emission guideline was established for computer video display terminals (VDTs) by the Swedish government in 1991 [Power Frequency Magnetic Fields..., 1995]. That standard, called MPR2, requires VDT magnetic fields to be less than 250 nT (2.5 mG) 50 cm (20 in) from the monitor in the 5 Hz-2 kHz frequency range and less than 25 nT (0.25 mG) in the 2 kHz-400 kHz frequency range. Most new computer monitors are designed to meet the MPR2 standard. Manufacturers have found it possible to meet the standard with little added cost.

No magnetic field guidelines apply to electric blankets, but some manufacturers have altered their designs to reduce magnetic fields. A typical low-field electric blanket uses a bifiliar design, discussed later in this section of the report.

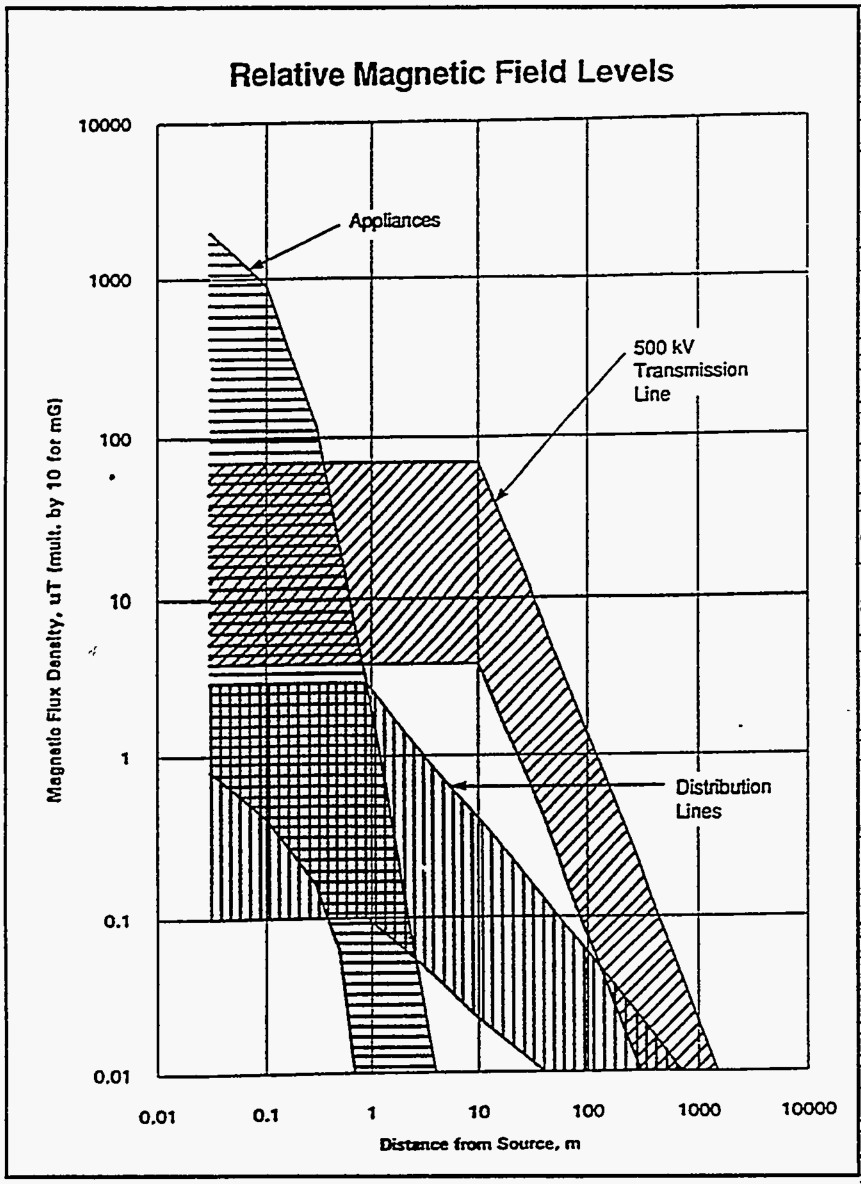


Figure 3.5-2: Relative magnetic flux densities [Health Effects..., 1993].

Usually, the maximum magnetic fields from large, fixed appliances are less than those from portable and hand-held devices. The cause of this apparent contradiction may be that the larger, heavier-cased motors employed in stationary appliances do a better job of containing the magnetic flux and thus have lower stray fields. In addition, these motors are usually placed toward the bottom and rear of the cabinets where they are already remote from the normally accessible surfaces. Tested appliances that have been found to project fields of the highest levels and/or the furthest distances are vacuum cleaners, microwave ovens, small hand-held kitchen and personal appliances, and hand power tools. These device types use lightweight, high-torque motors with little shielding material, or as with microwave ovens, large power transformers.

A quantitative summary of Gauger's [Gauger, 1985] appliance magnetic field measurements (100 appliances, 25 types) is as follows. Maximum field levels at a distance of 30 cm (1 ft) ranged from 30 nT to 27 uT (0.3 mG to 270 mG). At a distance of 1.5 m (5 ft), 95 percent of the maximum field levels were less than 0.1 uT (1 mG), with a high value of 0.47 uT (4.7 mG). The furthest distance at which a 0.1 uT (1 mG) field was projected was 2.6 m (8.5 ft). EPRI [Survey of Residential ..., 1993] reported similar appliance magnetic field data from the EPRI 1000 home survey.

Field Sources in Appliances and Machinery

End-user appliances produce ELF electric fields because of the presence of line voltage, usually at 120 or 240 V, on their electrical wiring and components. Metal-cased appliances with proper grounding are well shielded and generate little electric field even when operating. However, this is not true for devices with nonmetallic housings. Depending on its design, an appliance can generate electric fields even when it is turned off. As an example, an older appliance with a non polarized, two-wire line cord has an even chance of being plugged in so that the power switch is on the neutral side of the line. This places all electrical components within the device at full line potential when the switch is off, as opposed to an average of half the line potential when the switch is on. In this situation the electric field intensities will be higher when the appliance is not operating.

Add-on shielding for consumers is now only an option to the end-users of computer monitors. Five-sided box-like shields are commercially available for preventing interference to monitors from outside magnetic field sources [Magnetic Shield Design Handbook, 1992][Complete Guide to Magnetic Field Shielding, 1990]. These shields, however, should also be effective in reducing the magnetic fields emitted by a monitor to its rear and sides (the front of a monitor is not shielded). Monitor shielding might prove desirable in office settings where many personal computers or terminals are spaced closely together. In this situation a user could be exposed to the magnetic fields from several computers, and might be closer to the monitor of the user behind him than to his own.

End-users can also select from a growing number of so-called "green" appliances designed for reduced electrical energy consumption. Such devices generally reduce EMF exposures either through lower magnetic field levels or shorter operating times. Examples of low field devices are the reduced-wattage fluorescent tubes for retrofit into existing, conventional-ballast fixtures, and the newer electronic high-efficiency ballasts, which use even lower wattage fluorescent tubes. Personal computers with built-in automatic standby or power-down features, and high efficiency refrigerators are examples of appliances with shortened operating times.

Source Design and Manufacturing Methods

Source design methods refer to modifications of the electrical systems of an appliance at the design or manufacturing level to reduce the intensity of EMF's. Principal strategies for design-based EMF management are as follows:

- reduce appliance load currents,
- reduce effective magnetic dipole size,
- reconfigure current carrying elements so as to generate opposing, canceling fields,
- use alternative low-field technologies, and
- employ shielding materials.

These strategies have been applied to the four primary appliance magnetic field sources previously listed to develop specific management techniques for each source type.

Resistive Heating Elements

One of the simplest magnetic field reduction techniques for resistive heating elements is to double the operating voltage from 120 V to 240 V. For a given wattage element this will halve both the current and its associated magnetic field. In North America, 240 V appliances require a special power outlet or hard wiring. Thus, this method would apply primarily to stationary appliances with high wattage elements that have not already been designed for 240 V operation. Candidate devices would include baseboard and built-in heaters, dishwashers, and cooking elements on stoves and cooktops. Other magnetic field management methods for heating elements involve a redesign either of the element itself or of the layout of its feed wiring. Techniques include the use of split-return currents, bifilar or coaxial elements, and reduced loop area element geometries.

The split-return current method can be applied to a typical serpentine radiant heating grid such as the one illustrated at the top of Figure 3.5-3. From a magnetic field standpoint, this grid is roughly equivalent to the single current loop of the same dimensions but carrying half the grid current, shown in the middle of the figure. The grid at the bottom of the figure has a split return current. This cancels the effect of the grid's net current loop.

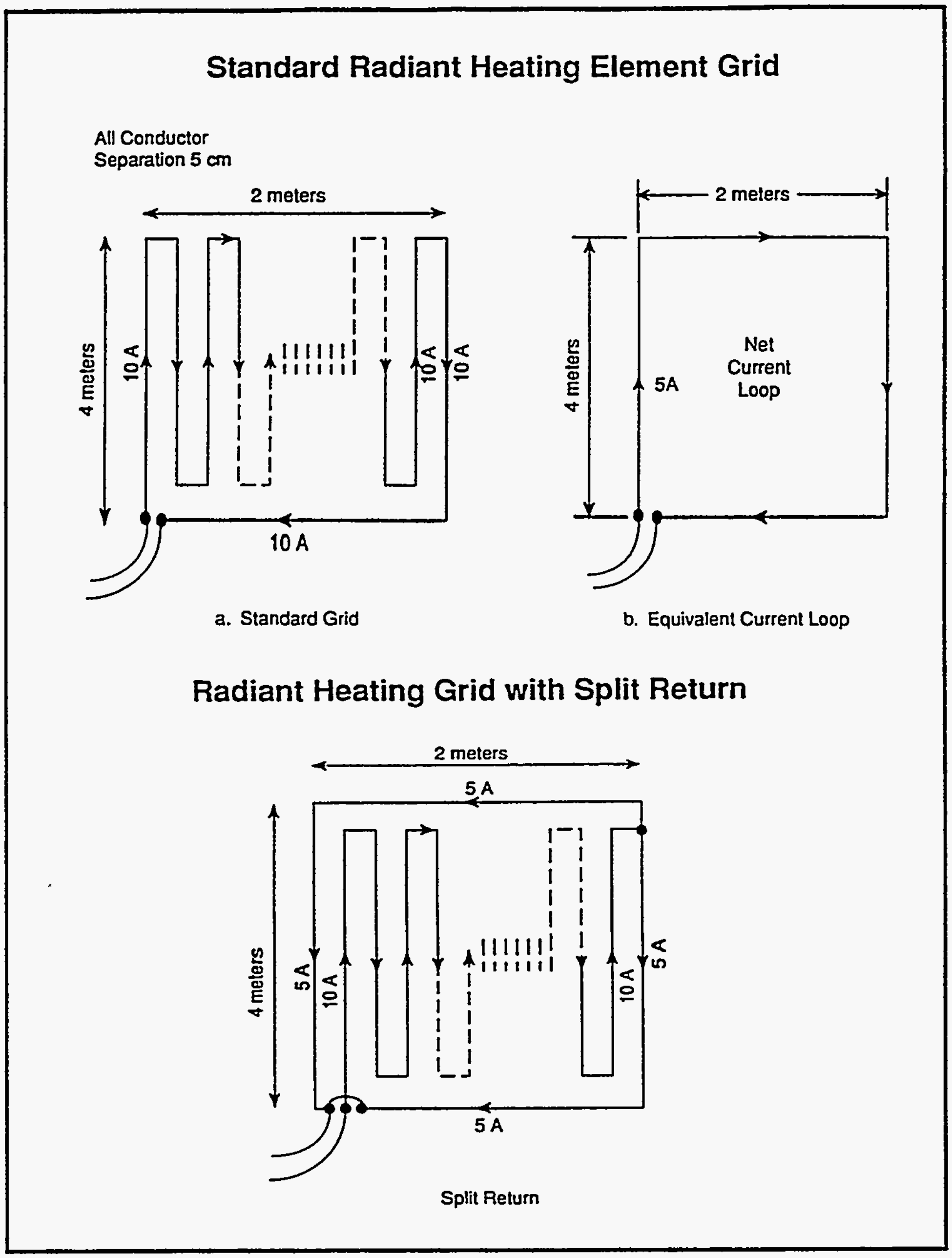


Figure 3.5-3: Radiant heating element topologies.

The magnetic fields produced by the standard and the split-return radiant heating grids were compared by computer analysis. The program uses an approximation to the Biot-Savart law to model the sum fields from multiple line current elements in three dimensions. Calculated vertical-plane magnetic field contours through the centers of standard and split-return electric room heating grids are shown in Figure 3.5-4. In this figure the grids are seen from the edge as if they were embedded in a ceiling. The views extend 2.4 meters (8 ft), or about one residential ceiling height, above and below the grid. The contours clearly show that split return design reduces the magnetic field by at least an order of magnitude for distances greater than a few inches.

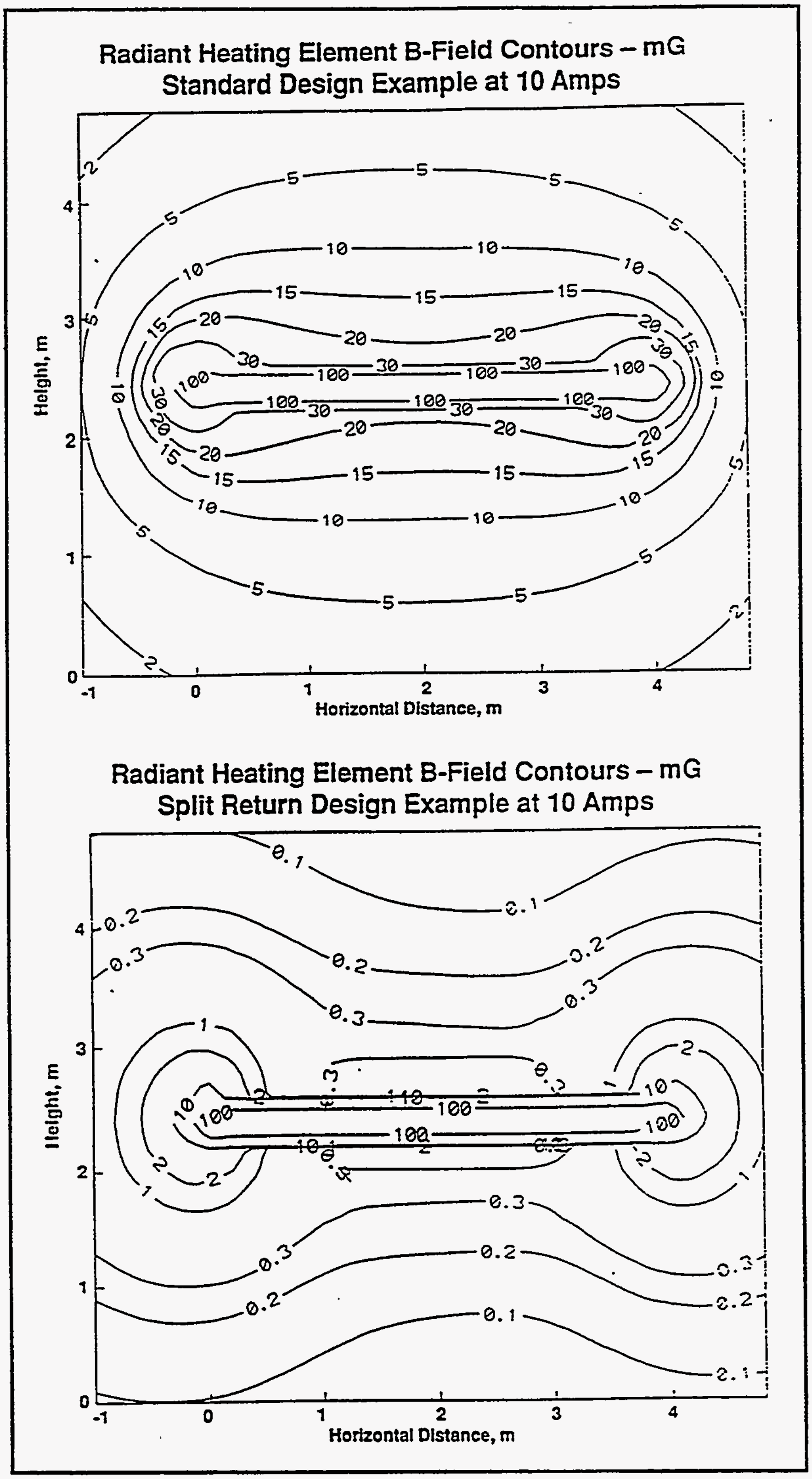


Figure 3.5-4: Radiant heating element calculated B fields.

Several low-field options for small heating elements, such as portable electric heaters, can also be considered. Three of these designs, shown in Figure 3.5-5, are a dual opposing serpentine design, the split return design, and bifilar heating element design that keeps supply and return current as close together as possible. This design is used in the newer, so-call "Low EMF" electric heating blankets that have been commercially available for several years. The calculated magnetic (B) fields along an axis perpendicular to the center of the grids for the two cases are presented in Figure 3.5-6. The curves show that the split return and bifilar designs are the most effective. Both reduce the magnetic field by at least an order of magnitude for distances greater than a few inches.

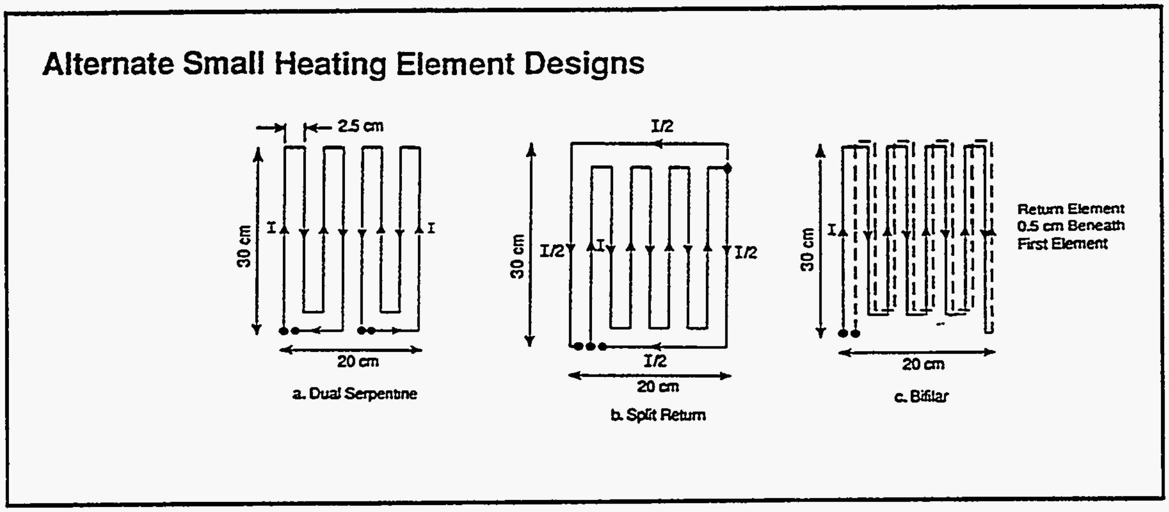


Figure 3.5-5: Small Heating Element Design Options

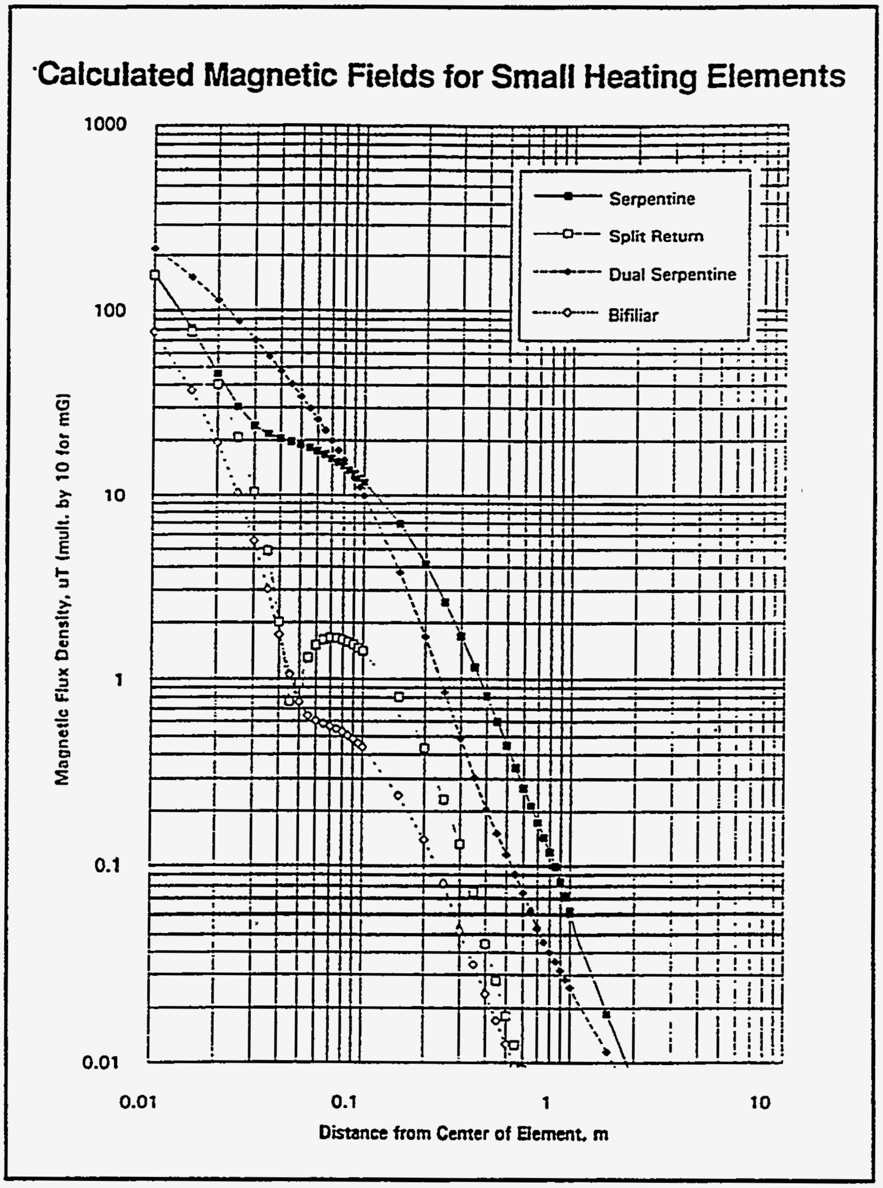


Figure 3.5-6: Small Heating Element Design Option Calculated Magnetic Fields

Electric Motors:

Electric motors use large internal magnetic fields to create forces that usually rotate a shaft. Some motor designs leak more of these magnetic fields than others. The fields from most motors drop off quickly, roughly like a three-dimensional magnetic field dipole.

At least four magnetic field reduction methods are available for electric motors. These include increasing the number of field poles, configuring pole wiring to avoid current loops, use of higher voltage, reduced current models, and shielding.

Gauger showed that common fractional horsepower induction motors often produce higher magnetic fields than their higher horsepower cousins. This is because larger motors often have more poles and are often housed in heavy cast iron or steel housings that provide some shielding. Motors make good shielding subjects because they are small.

Figure 3.5-7 illustrates how proper pole wiring can eliminate current loops in motors [DOD-STD-2146(SH), 1983].

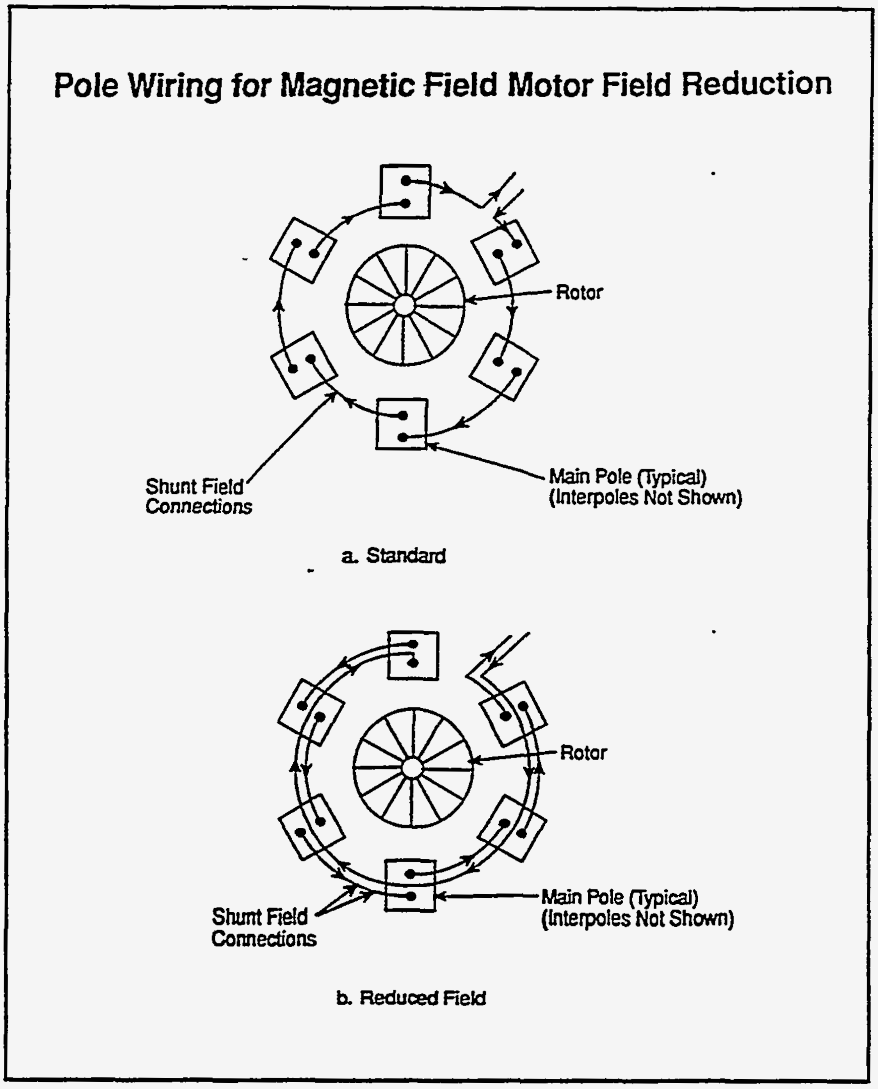


Figure 3.5-7: Pole Wiring for Electric Motor Magnetic Field Reduction

Transformers and Coils:

Transformers, used to step down or step up voltages in appliance power supplies, use large internal magnetic fields to induce current in secondary coils wrapped, along with the primary driving coils, around a ferromagnetic core. Although most of the field is confined to the core, some leakage does occur. These leakage fields drop rapidly with distance, in the fashion of a three-dimensional dipole.

Some core and coil winding topologies are better at confining magnetic fields than others. Figure 3.5-8 shows three common core topologies. The standard "E" and "C" cores are laminated designs composed of interleaved plates of ferromagnetic material. Toroidial cores are less often composed of laminated materials. "E" core windings are usually on the center arm. "C" core windings are usually placed on opposite sides, but primary and secondary windings can be interleaved. Toroidial core windings are usually interleaved.

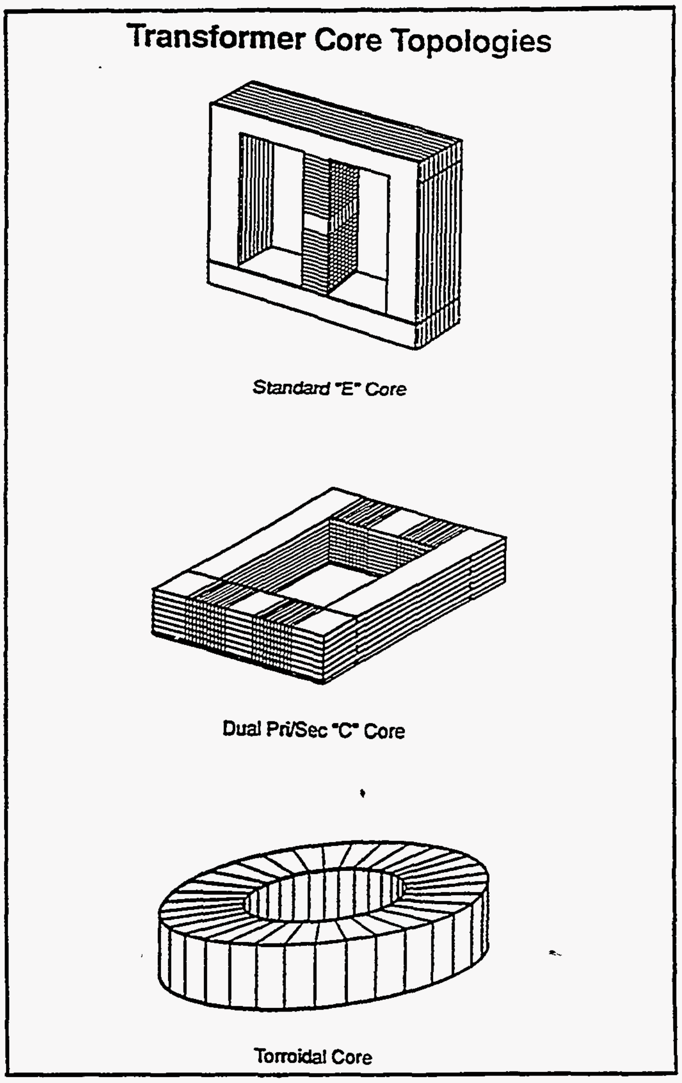


Figure 3.5-8: Transformer Core Topologies

The stray magnetic fields from ten commercially available power supply transformers were measured at IITRI. Three of the designs were "E" cores, two were "C" cores, and five were toroidial cores. All were tested under equal loading conditions. The results, shown in Figure 3.5-9, show that the toroidial designs produced the lowest stray fields. "C" cores produced the highest fields. The best toroidial transformer fields were more than an order of magnitude less than the "C" core fields.

Power Cords and Wiring

Power cords provide current to appliances and machinery and are, therefore, magnetic field sources. Magnetic field reduction methods for power cords are similar to those used for branch circuit wiring. Field reduction methods include reducing conductor spacing, twisting conductors, and shielding. Use of the latter option is unlikely for most small appliances and machines.

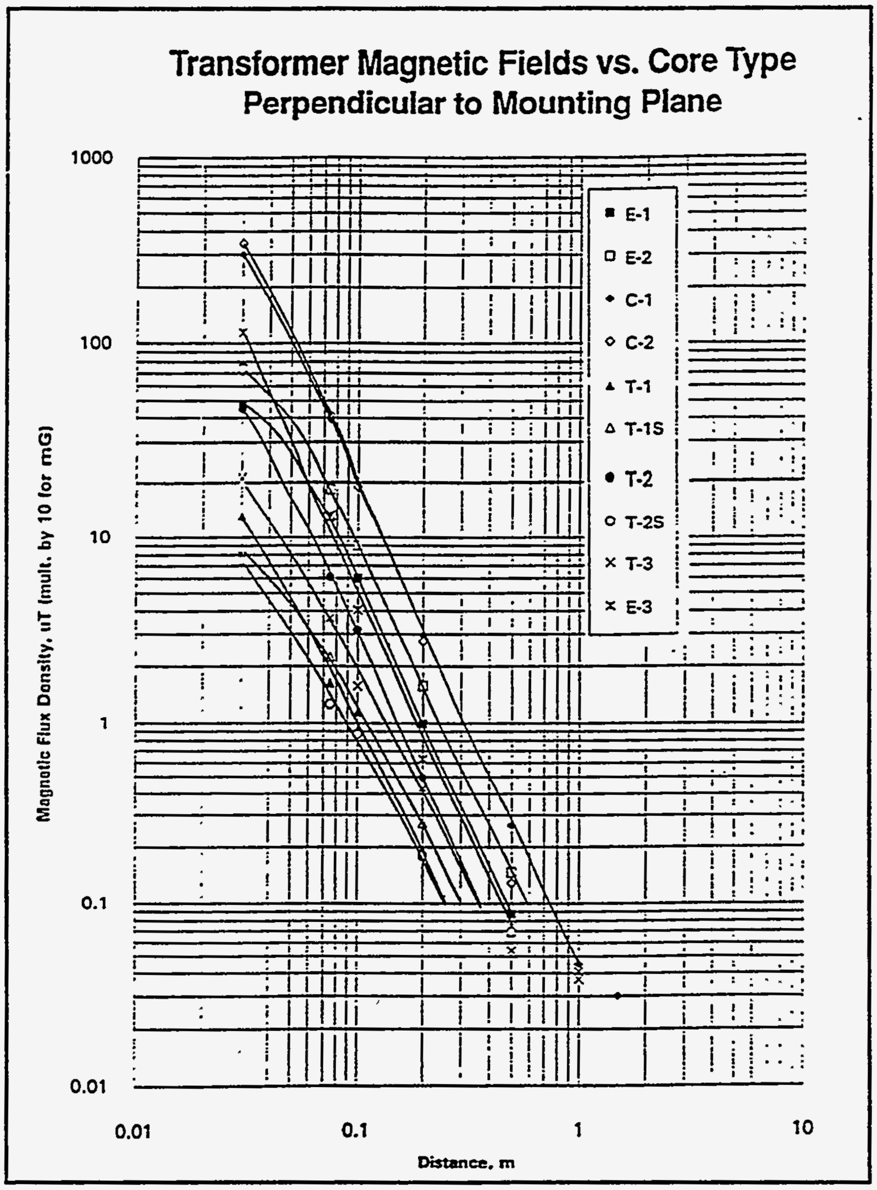


Figure 3.5-9: Transformer Magnetic Fields vs. Core Type: Perpendicular to Mounting Plane

Internal appliance/machinery wiring can be a significant magnetic field source if supply and return conductors are separated. Internal wiring sources can be reduced if some attention is paid to details of both the wiring harness design and the product manufacturing process [Linde, 1995].

Some machines, however, can only be operated with widely separated supply and return current conductors. Examples include manual metal electric arc welding, electric arc welding machines, electric arc furnaces, direct contact electric melting furnaces, and electrogalvanizing processes. These machines can produce large magnetic fields. 60 Hz electric arc welders, for example, can be exposed to fields greater than 4,000 milligauss, with substantial energy at the second (120 Hz) and third harmonics (180 Hz) [Stuchly et al, 1987]. If low magnetic field exposure limits were ever deemed necessary, many of these processes would have to be done remotely or not at all.

Appliance and Machinery Summary

How would power frequency magnetic field exposure limits affect appliances and machines? The answer would depend on the exposure limit values and on how the exposure limits were defined. Exposure limits defined at some distance from a source would be easy to achieve, because most appliance and machinery magnetic fields drop off quickly with distance. On the other hand, exposure limits defined for all points on and near an appliance or machine could be extraordinarily difficult to achieve.

Table 3.5-1 provides a summary of the feasibility and estimated cost of appliances and machines designed to meet one of five theoretical exposure limits: 100 mG, 50 mG, 20 mG, 5 mG and 2 mG. The limits are assumed to be defined at a set distance of perhaps three to six inches from the source. Because such a large variety of magnetic field source types are included in the appliance/machinery category, the cost impact, shown as a multiplier of a baseline cost for each source type, is only a rough estimate.

Table 3.5-1: Appliance and Machinery Magnetic Field Reduction Summary

	<100 mG		<50 mG		<20 mG		<5 mG		<2 mG	
Source Type	**Method**	**Est. Cost Multiplier**	**Method**	**Est. Cost Multiplier**	**Method**	**Est. Cost Multiplier**	**Method**	**Est. Cost Multiplier**	**Method**	**Est. Cost Multiplier**
Applaince Resistive Heating Elements	No Change	1.00	No Change	1.00	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50
Industrial Resistive Heating Elements	No Change	1.00	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar	1.00-1.50	Split Return or Bifiliar+?	1.00-1.50+?	Split Return or Bifiliar+?	1.00-1.50+?
Inexpensive Fractional HP Motors	No Change	1.00	Shield or Replace	1.00-2.00	Shield or Replace	1.00-2.00	Shield or Replace	1.10-2.00	Shield or Replace	1.10-2.00
Heavier-Duty Motors	No Change	1.00	No Change	1.00	Shield or Upgrade	1.00-1.50	Shield or Upgrade	1.00-1.50	Shield or Upgrade	1.00-1.50
Appliance Transformers and Coils	No Change	1.00	No Change	1.00	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50
Industrial Transformers and Coils	No Change	1.00	Shield or Toroid if needed	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50	Shield or Toroid	1.00-1.50
Appliance Power Cords and Wiring	No Change	1.00	No Change	1.00	No Change	1.00	Conductor Twisting/Spacing	1.00-1.10	Conductor Twisting/Spacing	1.00-1.10
Industrial Power Cords and Wiring	No Change	1.00	No Change	1.00	Conductor Twisting/Spacing	1.00-1.10	Conductor Twisting/Spacing	1.00-1.10	Conductor Twisting/Spacing	1.00-1.50
High-Field Industrial Machines (Arc Furnaces, Welding, etc)	Remote Operation ?	1.50+?	Remote Operation ?	1.50+?	Remote Operation?	1.50+?	Remote Operation?	1.50+?	Remote Operation?	1.50+?

3.6 TRANSPORTATION SYSTEMS

Nearly all motorized transportation systems use electric power. Electricity is most often used to control non-electric engines and to power accessory equipment like lighting, heating, and air conditioning. Examples include spark-ignition for internal combustion engines, 400 Hz AC power for controlling aircraft engines and control systems, and 60 Hz or DC "Head End Power" (HEP) used for passenger railway accessories.

For some types of transportation electricity provides the motive power. Examples include electric railway systems; battery-electric road vehicles; "conventional" diesel-electric railway locomotives; diesel-electric construction/excavation equipment; and turbine, diesel, or even nuclear-electric powered seagoing vessels. These all use heavy-duty electric motors, drawing hundreds to thousands of amperes of current, to provide motive power.

Transportation systems represent a specialized use of electricity, but the electromagnetic fields associated with them do not necessarily differ from fields of commercial building power or of industrial appliances. Methods used to reduce fields in other environments could be applied to many transportation-based electromagnetic field sources.

This report examines electric railways as a representative transportation field source type.

Electric Railway Background

Electric railway technology has been in use for more than a century. Although many of its basic tenants remain unchanged, several important developments have appeared during the past decade. Foremost among these is a transition from the time-tested direct current (DC) series-wound traction motor technology to the use of alternating current (AC) variable-frequency three-phase induction traction motors. The expanding use of "high speed" rail electrification systems throughout the world is also notable.

For many years, the electric railway equipment standard was the easy-to-control DC series-wound motor. It was widely used at the turn of the century for streetcar and interurban "trolley" lines; for urban mass-transit "third-rail" subway, elevated, and surface railways; and for mainline "steam" railway electrification projects. Most systems used DC voltages at 600-3000 volts and straightforward series-parallel resistor-based control systems. Some later mainline electrification projects used 25 or 60 Hz AC overhead catenary-supported contact wire feeds energized at up to 12 kV. Even these systems, however, used DC traction motors supplied by on board rectifier or motor-generator equipment.

Electric streetcar and interurban lines all but disappeared in the United States by the 1960s, but most third-rail mass-transit systems remained. Also remaining was extensive main line electrification on the east coast, including the present Amtrak "Northeast Corridor" between Washington, D.C., Baltimore, MD, Philadelphia, PA, New York City, and New Haven, CT.

In recent years, streetcar technology has made a comeback in so-called "light rail" systems. Modern light rail streetcars are now found in San Diego, Los Angeles, San Jose, Sacramento, Portland, St. Louis, Pittsburgh, Boston, Baltimore, and other cities. New third-rail mass transit systems have also appeared during the past several decades in San Francisco, Washington, D.C., Atlanta, Miami, and Los Angeles, among others. Nearly all these systems use DC traction motors and traditional 600-1000 Volt DC feeds. Most of the newer systems use thyristor "choppers" to control traction motor speeds in place of the traditional electromechanical "cam" control systems.

In the United States, new main line electrification appeared during the 1980s on the 30-mile New Jersey Transit line to Long Branch, New Jersey (12.5 kV, 60 Hz); on the 125-mile Black Mesa & Lake Powell Railroad in Arizona (50 kV, 60 Hz); and on the 38-mile Deseret Western between a coal mine at Rangely, Colorado and a power plant at Bonanza, Utah (50 kV, 60 Hz). These systems all used electric locomotives with DC traction motors when they opened [Hayes, 1995][Kneschke, 1985].

Three-phase AC induction motors offer at least two advantages over DC motors. First, they require less maintenance because they do not have commutator brushes. Second, they can provide more torque, or horsepower, than a DC motor of comparable size and weight, especially at low speeds. In the past, their principal weakness was that they were difficult to control because their speed varies with power supply frequency. The recent development of powerful, reliable gate-turn-off (GTO) thyristor finally solved that problem. Inverters use GTO thyristors, which are high-current semiconductor switches, to convert DC to variable frequency AC for motor speed control.

Most of the new electric railway equipment will be delivered with AC motors, including the new Bombardier/GEC Alsthom "American Flyer" 150 mph train sets Amtrak will use on its upgraded Washington, D.C.-Boston Northeast Corridor beginning in 1999. The technology is based on the 186 mph TGV Atlantique used successfully since 1989 in France and on the original Paris-Lyon 164 mph TGV of 1981, which used DC traction motors. Amtrak's Northeast Corridor project involves extending the main line electrification from New Haven to Boston and upgrading the entire Northeast Corridor to 25 kV, 60 Hz. The New Haven-Boston segment represents the most extensive new U.S. rail electrification project in decades.

The delivery of hundreds of AC traction motor diesel-electric freight and passenger locomotives during the past few years is bringing the AC revolution to non-electrified U.S. railroads.

Electric Railway Power Distribution

Railway electrification is a specialized form of electric power distribution. It differs from standard distribution systems in that it is inherently single-phase and that its loads are constantly changing position. It usually consists of a series of substations feeding an overhead contact wire or a "third rail". Electric locomotives or multiple-unit passenger cars collect current through use of an overhead sliding pantograph, an overhead rolling trolley, or from a sliding third rail "shoe." Overhead contact wires are usually supported by a continuous "messenger wire" that also carries current.

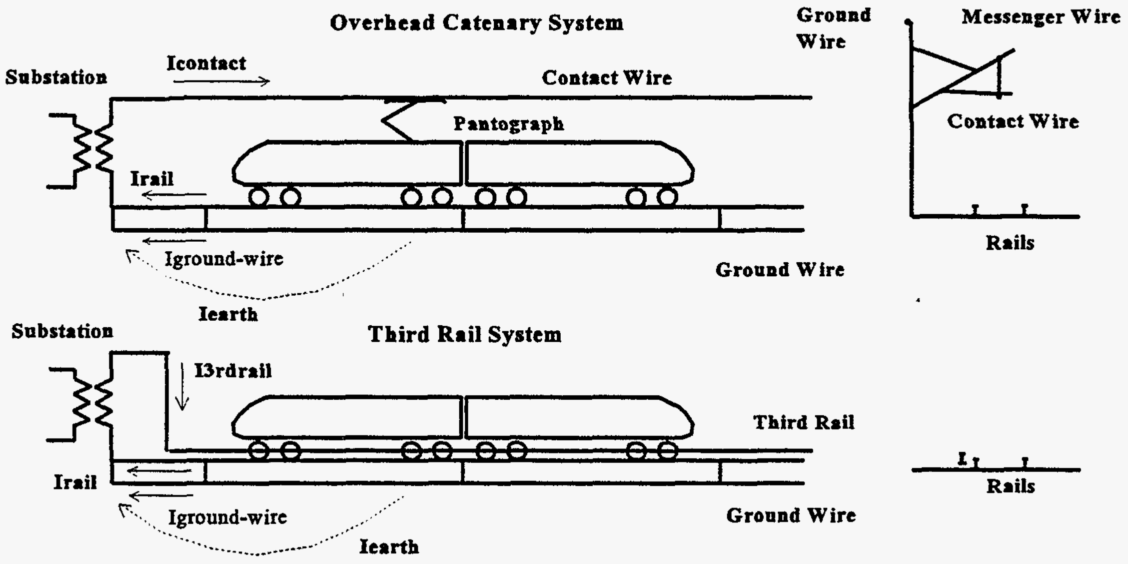


Figure 3.6-1: Principal Electric Railway System Types

Some systems, such as the original Northeast Corridor 11 kV, 25 Hz electrification, use "double-end" feed arrangements. Trains draw current from two substations at once, with most of current coming from the nearest substation [DOT/FRA/ORD-80/66.2, 1981]. Other systems, such as the 12.5 kV, 60 Hz New Jersey Transit Long Branch line, use segmented "single-end" feed systems. The Long Branch line system alternates phases in each segment down the line to balance the overall three-phase utility load.

Current returns to substations by passing through a train's grounded steel axles and wheels to one or both track rails. The current then usually follows several paths. Some current flows through the earth, leaking from the rails through ties and ballast at many points. The impedance of this rail-earth shunt path can become small enough to become the dominant return current path at distances greater than 5-10 miles from a substation [Jacimovic, 1982]. Return current flowing in the rails increases as a train approaches a substation. On modern installations, some return current flows on a buried or pole-mounted ground wire cross-bonded to one or both rails. The ground conductor helps reduce earth current by lowering the track circuit resistance.

If left unchecked, DC earth current can cause electrolytic corrosion of underground metal pipes next to the track. AC earth current can contribute to interference with line side communication conductors. The human safety aspects of AC and DC earth currents must also be considered when electric railways are designed.

Substation spacing depends on feeder voltage. The greater the voltage, the further apart the substations can be. For example, the 38-mile Deseret Western is fed 50 kV power from a single substation at one end of the line. The NJT Long Branch line, a busy double-track commuter railroad, is fed 12.5 kV power from substations that are eight-miles apart.

Electric Railway Magnetic Fields

Two types of electric railway magnetic field exposure environments are of interest. The first is on board a moving train. The second is at stationary track side locations. In both environments, magnetic fields can have complex frequency components and can be highly variable over time.

Modern electric railway equipment creates high-order current harmonics. The harmonics are from nonlinear loads, such as transformers, thyristor rectifiers, thyristor inverters, and the motors themselves. Harmonics are highest when traction equipment is drawing heavy current while accelerating or climbing a grade.

Even systems that have DC power feeds and DC motors can produce extremely low frequency (ELF 30-300 Hz) magnetic field components. These arise from nonlinear rectification, from rapidly changing current levels related to acceleration and deceleration, and, in modern equipment, from thyristor-based "chopper" motor control equipment.

The most thorough assessment of the magnetic field environments of electric railway systems was provided in a series of U.S. Department of Transportation - Federal Railroad Administration studies completed in 1993 [DOT/FRA/ORD-92/09, 93/01, 93/03, 93/04, and 93/05]. The studies considered several electric railway system types. Table 3.6-1 and Figures 3.6-2 and 3.6-3, show a summary of the project's magnetic field measurements on board electric transportation systems.

The data show that magnetic field characteristics of various systems vary significantly. Overall, the high speed railway systems had higher fields than the mass transit subway and "light rail" systems, with one obvious exception. Above average magnetic fields were measured on board Washington, D.C.'s Metrorail subway system. These fields were associated with a "chopper" DC motor control system used by the rail cars. The system controls train speed by "chopping" the motor voltage, or rapidly switching it on and off, at varying duty cycle rates based on train acceleration. Smoothing reactors and capacitors are used to smooth out the current supplied to the motors, but some chopper ripple usually remains.

The Metrorail choppers use a basic switching rate of 273 Hz, creating above average magnetic fields in that frequency range. A smoothing reactor beneath the floor of the car was responsible for the largest fields. By comparison, the Massachusetts Bay Transportation Authority (MBTA) subway system cars, which use traditional electromechanical "cam" controllers, produced lower fields.

Table 3.6-1: Electric Transportation Systems Considered in DOT/FRA Study

System	Type	Electrification	Traction Motor Type	Equipment	Max Speed
Amtrak North East Corridor (NEC) 60 Hz	High Speed Main Line	12.5 kV 60 Hz OH Catenary	DC	AEM-7 Locomotive + Trailer coaches	125 mph
Washington, D.C. Metrorail	Mass Transit	750 VDC Third Rail	DC	Multiple-unit train set	60 mph
New Jersey Transit (NJT) Long Branch	Main Line	12.5 kV 60 Hz Overhead Catenary	DC	AEM-7 Locomotive + trailer coaches	80mph
TGV	High Speed Main Line	25 kV 50 Hz OH Catenary	AC	Articulated train set: 2 power cars, 9 coaches	186 mph
Amtrak North East Corridor (NEC) 25 Hz	High Speed Main Line	11 kV 25 Hz OH Catenary	DC	AEM-7 Locomotive + Trailer coaches	125 mph
MBTA Subway	Mass Transit	600VDC Third Rail	DC	Multiple-unit train set	60mph
MBTA Trolley	Light Rail	600VDC OH Catenary	DC	Two-unit train set	60 mph
MBTA Trolley Bus	Trolley Bus	600 VDC OH Trolley Wire Pair	DC	Single Trolley Bus	40 mph

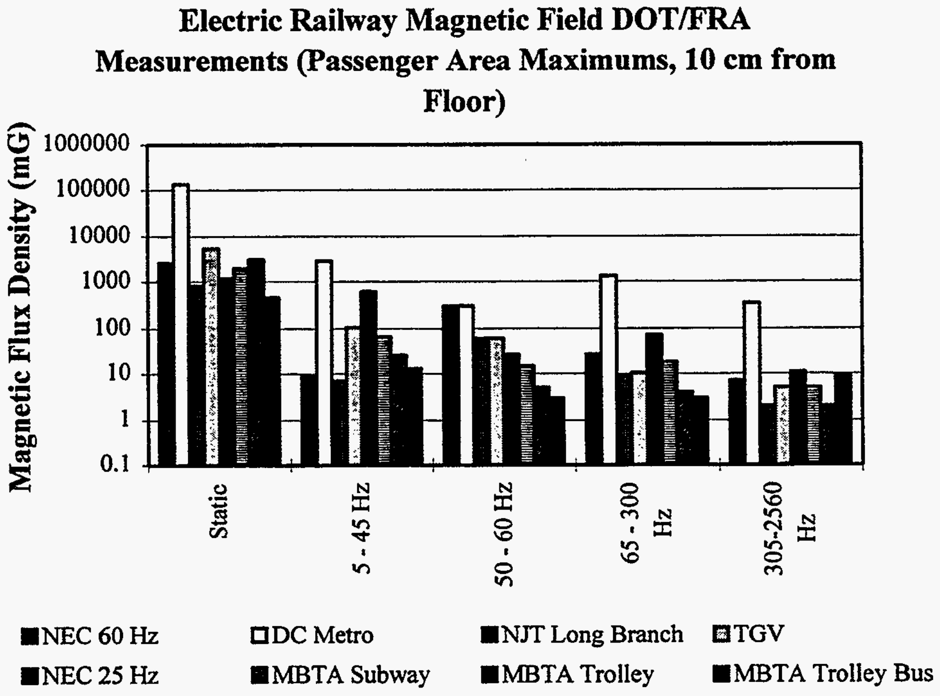


Figure 3.6-2: Electric Railway Magnetic Fields-DOT/FRA Maximum Measurements

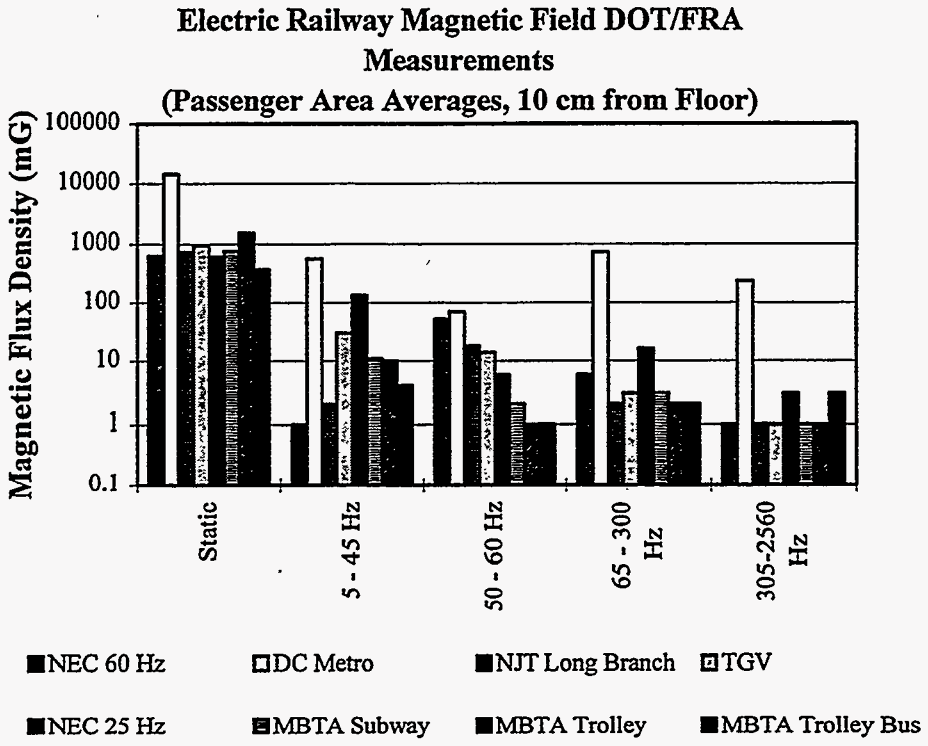


Figure 3.6-3: Electric Railway Magnetic Fields-DOT/FRA Average Measurements

The TGV had lower magnetic fields than those measured on the Northeast Corridor. This was most likely due to the higher voltage feeder system used on the TGV at the time of the measurements. One feature of the TGV power supply system may have offset the lower current/higher voltage system. A TGV train set has a 4,350 Kilowatt (5831 horsepower) "power car" at each end of the train. Each power car has four three-phase AC induction motors. Both power cars are used to provide motive power when the train is running, but only the trailing unit's pantograph collects power from the overhead catenary wire. This is done to avoid creating excessive catenary vibration. A special roof-mounted cable running the length of the train supplies current to the leading power car. This leads to higher magnetic fields in some areas of the passenger "trailer" cars than would occur if both power car pantographs were used. On the other hand, the cable seems to reduce magnetic fields in other areas of the cars.

Other railway magnetic field sources besides traction motor current can also be important. These include on board equipment; such as lighting, heating, and air conditioning; and transmission lines running along the right of way. For example, power is routed to Northeast Corridor substations on 138 kV transmission lines next to the tracks.

Field Minimization

Electric railway systems would offer a substantial engineering challenge if power frequency magnetic field exposure limits were ever required because their passengers must be within the power distribution system right of way. Active cancellation loops would probably need to be installed in rail cars to reduce passenger exposure, especially on overhead catenary systems. Passive ferromagnetic or eddy current shielding would be difficult to employ because car weight is a critical design factor for high-speed rail systems. Car windows would preclude a complete shielding enclosure, but they are in a critical location compared with the direction of an overhead catenary magnetic field. Wayside magnetic fields might have to be controlled by passive cancellation loops in congested areas. Otherwise, railway systems would have to purchase wider right of ways. This would be costly for existing railways like the Northeast Corridor.

Railway electrification is necessary for mass-transit subways and for high-speed rail greater than 150 mph. It is economically viable only in high-density, high-speed corridors and on a few heavy tonnage freight railroads with heavy mountain grades. If low-level power frequency magnetic field exposure limits were required, the resulting economic realities could lead to de-electrification in some rail corridors.

The MBTA DC Trolley Bus data provides insight into one possible magnetic field reduction scheme for electric railway systems. Trolley buses, which obviously do not have access to a rail-return circuit, use two overhead trolley conductors. One supplies current. The other provides a return path for current. These conductors are close together, usually about one foot apart, so that the supply and return current magnetic fields cancel well. In addition, the return current does not have an opportunity to follow a rail-earth path back toward the substation.

This type of dual-overhead conductor system has not been widely used in rail electrification. One reason is that the addition of an overhead return conductor is more costly than using existing track rails for the return circuit. Another reason is that the dual-overhead system precludes use of the sliding pantograph collector. Instead, traditional trolley collectors must be used. Sophisticated pantograph collectors have been designed and tested for service at speeds greater than 200 mph. Trolley collectors have only seen service at speeds approaching 100 mph, and then only on standard single-overhead conductor designs. Finally, and perhaps most important, dual-overhead conductors would have to be separated by several feet for use in a high-voltage feeder system. An overhead catenary-support system for a high-voltage dual-overhead feeder system would have to be very complex. The overhead contact and messenger wires would have to be separated and supported by many insulators. Trolley bus overhead wires are supported by a less complex suspension system.

Magnetic fields next to a standard electric railway right of way can be reduced if most of the return current can be forced to flow in an overhead ground wire. One approach for doing this, presently used in the TGV electrification and on part of the Northeast Corridor, is shown in Figure 3.6-4.

TGV "Twice 25"Feed System

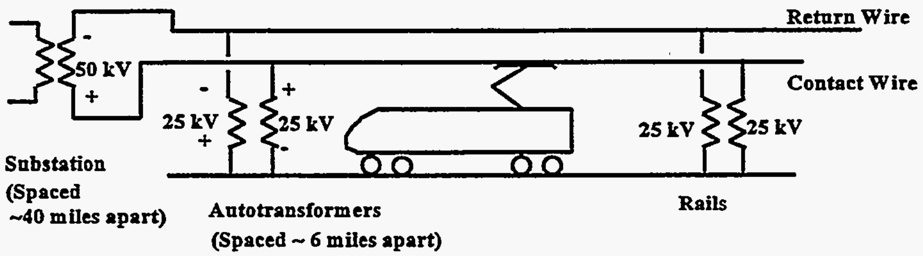


Figure 3.6-4: TGV "Twice 25" Feed System

In this system, widely spaced substations feed power to an overhead single phase circuit formed by the overhead catenary/messenger wire and a second overhead return wire. The overhead wires feed autotransformers placed every few miles along the line, which in turn feed power to contact wire/rail circuit "cells" or "blocks" at half the substation voltage. Current flows in the rails only in active cells. Return current is forced to return in the overhead return wire beyond the active autotransformer cell. The system, called "Twice-25" in its TGV application and "Twice-12.5" on the Northeast Corridor, due to that system's lower voltage, is employed to reduce power losses and to increase substation spacing. Magnetic field reduction is merely a consequence of its employment.

Since the overhead supply voltage is twice the voltage used in an active autotransfomer cell, the overhead supply current is halved in inactive cells. In addition, the overhead ground wire is only a few feet from the contact wire versus the usual 20-foot contact wire-to-rail spacing. Magnetic fields are reduced by roughly an order of magnitude in inactive cells, but the system has no impact on fields in active cells.

Double-ended feed systems, used in the TGV and Northeast Corridor electrifications among others, also provide some magnetic field reduction benefits. Supply current feeds a train from two directions, reducing the overall current, and magnetic field, by as much as one-half at a given location.

The use of higher feed voltages can also serve as a magnetic field reduction method. For example, consider a typical TGV Atlantique train set, which uses a total of eight three-phase AC induction motors with at total continuous rating of 8700 Kilowatts, or 11,662 horsepower. At maximum load, the train would draw 348 amperes of traction current from the French 25 kV, 50 Hz electrification. The same train would draw 696 amperes from the 12.5 kV Northeast Corridor system, but only 174 amperes from a 50 kV electrification used by Deseret Western, Black Mesa & Lake Powell, and South African Railways. The increased costs of transformers and insulators in a higher-voltage railway electrification project are offset by the fact that substations can be spaced further apart.

DC railway electrification might reduce ELF (3-300 Hz) magnetic fields. Most DC systems, however, use low voltages in the 600-700 VDC range, which results in very high current flow. A 4-car Metro North third rail train, for example, has sixteen 162 horsepower traction motors that can draw as much as 3,223 amperes of (mostly) direct current from that system's 600 VDC third rail. Even if the ELF AC components are a small percentage of the total current, they can still effectively exceed hundreds of amperes.

To reduce the ELF current, higher voltage DC systems would be needed. Several higher voltage main line railway electrification systems did once exist in mountainous western U.S. states. For example, the Chicago, St. Paul, Milwaukee & Pacific used a 3,300 VDC system for its now-abandoned line to Seattle, Washington. On it, a typical freight train would be pulled by two 5,600 horsepower E78 electric locomotives that together could draw up to 2,532 amperes from the overhead catenary. A four-car Metro North train would only draw a maximum of 586 amperes on a 3,300 volt system, but the higher voltage would require use of an overhead catenary. An overhead catenary would create larger magnetic fields than a third rail system.

DC voltages higher than roughly 3,300 volts would require the development of new on board high-voltage inverter-rectifier control systems. These would be costly, and would add a significant engineering challenge in that ELF AC current components would have to be extremely well controlled. If ELF magnetic field exposure requirements were ever necessary, however, DC systems would likely have to be considered for railway electrification.

One final method might be considered for reducing passenger exposures in overhead catenary fed railway systems. A single-ended feed variation of the autotransformer catenary feed system, illustrated in Figure 3.6-5, would not draw current in conductors near passenger cars if the train was powered by a single power car, or electric locomotive placed on the "substation side" of the train. The system would require trains to be pushed in one direction and pulled in the opposite direction on single-track lines, unless sophisticated power supply switching systems were employed.

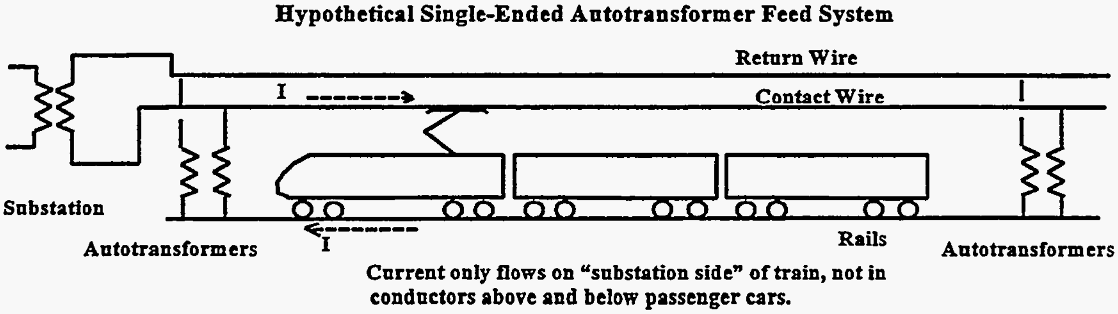


Figure 3.6-5: Hypothetical Single-Ended Autotransformer Feed System

Electric Railway Summary

Power frequency magnetic field exposure limits could substantially affect electric railways and other transportation systems. The limit's impact would depend on what the exposure limit values were and on how they were defined. Exposure limits defined for the edge of right-of-way would require changes like those required for transmission and distribution lines. Exposure limits defined for rail passengers would be more difficult to meet.

Table 3.6-2 provides a summary of the feasibility and estimated cost of electrified railways designed to meet one of five theoretical passenger exposure limits: 100 mG, 50 mG, 20 mG, 5 mG and 2 mG. The limits are assumed to apply to ELF (30-300 Hz) magnetic fields on and along a rail right-of-way. A roughly estimated cost impact for each technology is shown as a multiplier of a baseline cost.

Table 3.6-2: Electric Railway Magnetic Field Reduction Summary

	<100 mG		**<50 mG**		**<20 mG**		**<5 mG**		**<2 mG**	
Source Type	**Methods**	**Est. Cost Multiplier**	**Methods**	**Est. Cost Multiplier**	**Methods**	**Est. Cost Multiplier**	**Methods**	**Est. Cost Multiplier**	**Methods**	**Est. Cost Multiplier**
Light Rail Overhead Catenary	No Change	1.00	No Change	1.00	No Change	1.00	DC, Shielding, or Dual Trolley	1.00-1.50	DC, Shielding, or Dual Trolley+?	1.5-2.00+?
Main Line Overhead Catenary	No Change	1.00	Higher Voltage, Shielding	1.00-1.50	Autotransformer feed, Shielding, DC?	1.00-1.50	Single-ended autotransformer feed, Shielding, DC+?	1.50-2.00+?	Single-ended autotransformer feed, Shielding, DC+?	2.00-3.00+?
High Speed Overhead Catenary	Higher Voltage, Shielding	1.00-1.50	Higher Voltage, Shielding	1.00-1.50	Autotransformer feed, Shielding, DC?	1.00-1.50	Single-ended autotransformer feed, Shielding, DC+?	1.50-2.00+?	Single-ended autotransformer feed, Shielding, DC+?	2.00-3.00+?
Mass Transit Third Rail	No Change	1.00	Higher Voltage, DC, Shielding	1.00-1.50	Higher Voltage, DC, Shielding	1.00-1.50	Higher Voltage, DC, Shielding+?	1.50-2.00+?	Higher Voltage, DC, Shielding+?	2.00-3.00+?

LIST OF REFERENCES

Section 2: Magnetic Field Reduction Overview

S. Ramo, J. Whinnery, T. Duzer. Fields and Waves in Communication Electronics. 2nd edition. New York. John Wiley & Sons, 1984.

L. Zaffanella. "Magnetic Field Management, Overhead Power Lines." Presented at the 1992 EPRI EMF Science and Communication Seminar. San Jose, CA. October 1992.

Magnetic Field Management for Overhead Transmission Lines: Field Reduction Using Cancellation Loops. EPRI TR-105571. Research Project 3959-07 Final Report. December 1995.

Section 3.1: Transmission Lines

H. Nakanishi, H. Inoguchi, I. Hashimoto, Y. Ito, H. Tekehana, N. Nagaoka, A. Ametani. "A Study of Zero-Sequence Current Induced in a Cable System." IEEE Transactions on Power Delivery. Vol. 6, No. 4. October 1991.

U. Jonsson, A. Larsson, J-O. Sjodin. "Optimized Reduction of the Magnetic Field Near Swedish 400 kV Lines by Advanced Control of Shield Wire Currents: Test Results and Economic Evaluation." IEEE Transactions on Power Delivery. Vol. 9, No. 2. April 1994.

R. Olsen, V. Chartier. "The Performance of Reduced Magnetic Field Power Lines: Theory and Measurements on an Operating Line." IEEE Transactions on Power Delivery. Vol. 8, No. 3. July 1993.

R. Walling, J. Paserba, C. Burns. "Series-Capacitor Compensated Shield Scheme for Enhanced Mitigation of Transmission Line Electromagnetic Fields." IEEE Transactions on Power Delivery. Vol. 8, No. 1. January 1993.

IEEE Committee Report. "Magnetic Fields from Electric Power Lines-Theory and Comparisons to Measurements." IEEE Transactions on Power Delivery. Vol. 3, No. 4. October 1988.

Cost Effectiveness Analysis: Mitigation of Electromagnetic Fields. Report to the State of Rhode Island and Providence Plantations. Commonwealth Associates, Inc. 1991.

The Lineman's and Cableman's Handbook, Fifth Edition. McGraw-Hill. 1976.

Magnetic Field Management for Overhead Transmission Lines: Field Reduction Using Cancellation Loops. EPRI TR-105571. Research Project 3959-07 Final Report. December 1995.

Magnetic Field Management for Overhead Transmission Lines: Potential Options for Low Field Designs. EPRI TR-104413. Research Projects 1717-06, 2472-06, 3959-02, -08 Final Report. September 1995.

Transmission Cable Magnetic Field Management. EPRI TR-102003. Project 7898-37 Final Report. September 1993.

Section 3.2: Distribution Lines

D. Mader, L. Zaffanella. "Network Analysis of Ground Currents in a Residential Distribution System." IEEE Transactions on Power Delivery. Vol. 8, No. 1. January 1993.

T. Vinh, T. Jones, C. Shih. "Magnetic Fields Near Overhead Distribution Lines-Measurements and Estimating Techniques." IEEE Transactions on Power Delivery. Vol. 6, No. 2. April 1991.

Ground Current Magnetic Field Study. Empire State Electric Energy Research Corporation. Research Report EP 90-57. January 1993.

Handbook for the Assessment and Management of Magnetic Fields Caused by Distribution Lines. EPRI TR-106003. Research Project 3959-07 Final Report. December 1995.

Section 3.3: Substations

G. Anders, G. Ford, D. Horrocks. "The Effect of Magnetic Field on Optimal Design of a Rigid Bus Substation." IEEE Transactions on Power Delivery. Vol. 9, No. 3. July 1994.

H. Scherer Jr., C. Schwalbe, R. Meyer, J. Dibella. "765 kV Station Design." IEEE Transactions on Power Apparatus and Systems. Vol. PAS-88, No. 9. September 1969.

P. Wong, T. Rind, S. Harvey, R. Scheer. "Power Frequency Electric and Magnetic Fields from a 230 kV Gas-Insulated Substation." IEEE Transactions on Power Delivery. Vol. 9, No. 3. July 1994.

EMF Design Guidelines for New Electrical Facilities: Transmission, Substation, Distribution. Southern California Edison Company. 1994.

Section 3.4: Customer-Side Power Distribution

H. Hofmann, G. Preston. "Reduction of Stray Currents and Magnetic Fields from Single-Phase Power Distribution Systems." IEEE Transactions on Power Delivery. Vol. 10, No. 2. April 1995.

M. Hiles, R. Olsen, K. Holte, D. Jensen, K. Griffing. "Power Frequency Magnetic Field Management Using a Combination of Acitve and Passive Shielding Technology." Presented at the 1995 IEEE/Power Enginering Society Summer Meeting. July 1995.

D. Zipse. "Multiple Neutral to Ground Connections." Presented at the IEEE/Industrial Applications Society Industrial and Commercial Power Systems Technical Conference. May 1972.

1996 Means Electrical Cost Data, 19th Annual Edition. R.S. Means Company, Inc. 1995.

1996 National Electric Code. NFPA 70-1996.

Residential Transient Magnetic Field Research. EPRI TR-103470. Project 2966-07 Interim Report. March 1994.

Section 3.5 Appliances/Machinery

D. Armanini, R. Conti, A. Mantini, P. Nicolini. "Measurements of Power Frequency Electric and Magnetic Fields Around Different Industrial and Household Sources." Presented at CIGRE. 1990.

J. Gauger. "Household Appliance Magnetic Field Survey." IEEE Transactions on Power Apparatus and Systems. Vol.

PAS-104, No. 9. September 1985.

G. Karady, S. Berisha, M. Muralidhar, J. Demcko, M. Samotyj. "Variable Speed Motor Drive Generated Magnetic Fields." IEEE Transactions on Power Delivery. Vol. 9, No. 3. July 1994.

T. Linde, A. Berglund, M. Sandstrom, K. Hansson. "Magnetic Field Reduction by Means of Active Compensation." 1995 Bioelectromagnetic Society Meeting. Poster P-124A.

T. Linde, M. Hansson. "Measurement of ELF Magnetic Fields from GSM Cellular Telephones and Battery Packs." 1995 DOE EMF Contractors Review. Poster P-34.

M. Stuchly and D. Leduyer. "Exposure to Electromagnetic Fields in Arc Welding." Presented at the U.S. Department of Energy/EPRI Contractors Review. 1987.

Complete Guide to Magnetic Field Shielding. Amuneal Manufacturing Corporation Handbook. 1990

Direct Current Generators and Motors, Low Stray Magnetic Field, Design of. U.S. Department of Defense Military Standard. DOD-STD-2146(SH). 1983.

Health Effects of Power Line Electromagnetic Fields. Congressional Research Service Issue Brief IB92118. 1993.

Magnetic Shield Design Handbook. Magnetic Shield Corporation Handbook. 1992.

Power Frequency Magnetic Fields and Public Health. W. Horton and S. Goldberg. CRC Press. 1995.

Survey of Residential Magnetic Field Sources. EPRI TR-102759. 1993

Section 3.6: Transportation Systems

H. Hayes, T. Tolentino. "Special Designs Incorporated into the Electrification of the Deseret Western Railway." Presented at the Joint ASME/IEEE Railroad Conference. 1985.

S. Jacimovic. "Step and Touch Voltages and Potential Distribution on AC 25 kV Single-Phase Electrified Railroads." Presented at Joint ASME/IEEE Railroad Conference. 1982.

T. Kneschke. "Power Supply System for Electrification of the North Jersey Coast Line." Presented at the Joint ASME/IEEE Railroad Conference. 1985.

Magnetic Field Testing of the TR07 MAGLEV Vehicle and System. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-92/09.I and II April 1992.

Magnetic and Electric Field Testing of the Amtrak Northeast Corridor and New Jersey Transit/North Jersey Coast Line Rail Systems. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-93/01.I and II. April 1993.

Magnetic and Electric Field Testing of the French Train A Grande Vitesse (TGV) Rail Systems. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-93/03.I and II. May 1993.

Magnetic and Electric Field Testing of the Washington Metropolitan Area Transit Authority Metrorail System. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-93/04.I and II. June 1993.

Magnetic and Electric Field Testing of the Massachusetts Bay Transportation Authority (MBTA) Urban Transit System. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-93/05.I and II. June 1993.

Summary of E-60CP Road Test Electromagnetic Emission Measurements. U.S. Department of Transportation-Federal Railroad Administration. DOT/FRA/ORD-80/66.2. January 1981.

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Evaluation of Field Reduction Technologies

Volume 2: Appendices

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APPENDIX A

MAGNETIC FIELD SHIELDING

APPENDIX A: MAGNETIC FIELD SHIELDING

Two passive magnetic field shielding mechanisms exist. The first is magnetic flux shunting, provided by materials with high magnetic permeability. The second is inductive, or eddy current, cancellation, provided by highly conductive materials.

Ferromagnetic materials have high permeability. Included in this category are steel, iron, and nickel-iron alloys. The magnetic permeability μ of a ferromagnetic material varies with the applied magnetic field **H**, as shown in Figure A-1.

The magnetic permeability μ is the slope of the magnetization curve. Obviously, μ is lowest at both low at very high applied field strength. It is maximum in the middle of the curve. The low-field value is called "initial permeability" (μ_i). The largest value of μ is called "maximum permeability". At very high field strengths, the material goes into "saturation". Ferromagnetic materials stop working as effective magnetic shields when they enter saturation. Most power-frequency shielding applications are at very low applied field strengths, however.

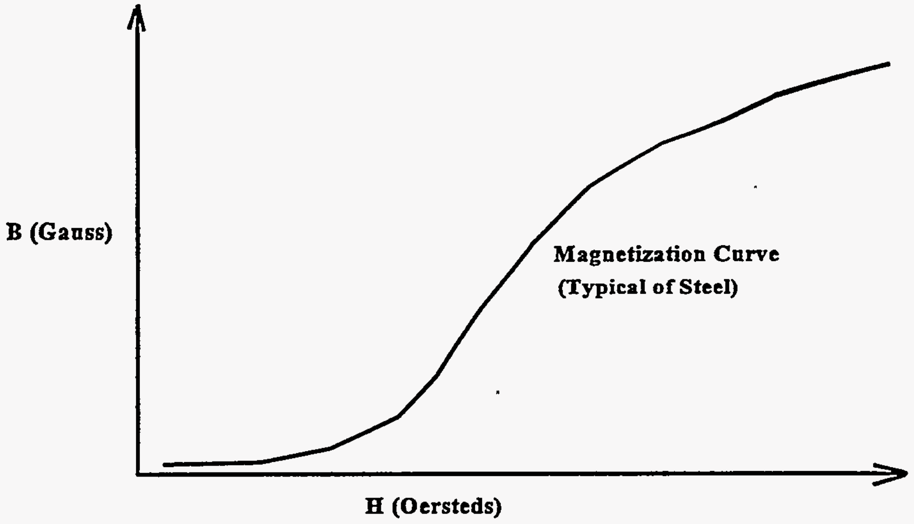

Figure A-1: Typical Ferromagnetic Material Magnetization Curve

The magnetic flux density **B** in a ferromagnetic material exposed to an alternating **H** field follows a hysteresis curve, as shown in Figure A-2. The magnetic permeability μ of a ferromagnetic material in a time-varying field is also time-varying, and is sometimes given as an average, or effective, value over a complete **H** cycle. Magnetic permeability also depends on the frequency of the applied field. In general, μ declines with increasing frequency.

For most low-field power frequency applications, the effective permeability is much less than the maximum permeability. This effect is illustrated in Figure A-2, where several minor time-varying hysterisis loops are imposed on a larger hysteresis loop. In most shielding applications, the large magnetization curve would represent the earth's static magnetic field and the minor loops would represent smaller, time-varying power-frequency fields imposed on the earth's field. The effective time-varying permeability is called "incremental permeability" ($\Delta\mu$) and is given by the slope of the minor hysteresis loop ($\Delta B/\Delta H$). Incremental permeability is usually much less than maximum permeability.

Unfortunately, incremental permeability values are usually not provided by material manufacturers. In their absence, power frequency shield designers usually use the more commonly provided initial permeability values. The initial permeability value is often divided by a design margin number, such as 10. A list of material properties for some common materials are provided in Table A-1.

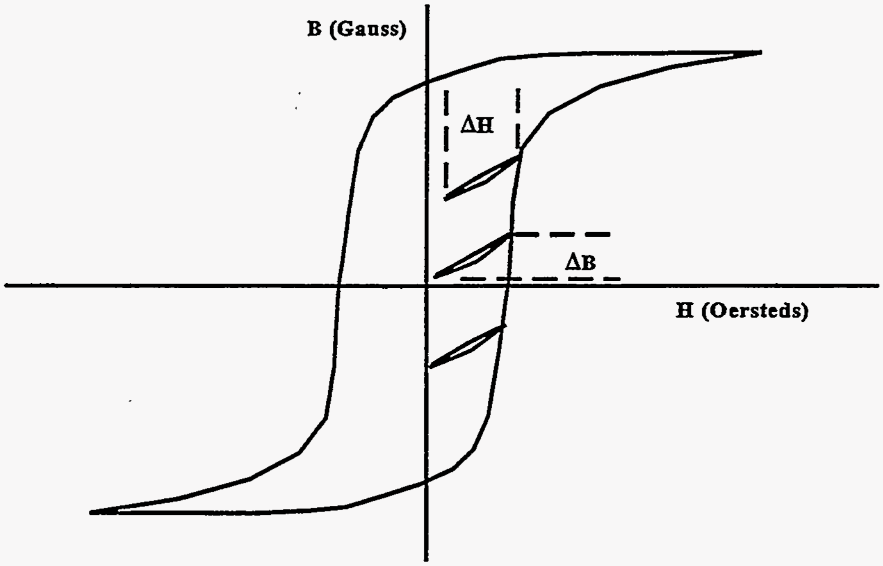

Figure A-2: Ferromagnetic Material Hysteresis

Table A-1: Magnetic Properties of Materials

Material	Conductivity Relative to Copper	Initial Permeability Relative to Copper	Maximum Permeability Relative to Copper
Silver	1.05	1	1
Copper	1.00	1	1
Gold	0.7	1	1
Soft Aluminum	0.61	1	1
Brass	0.26	1	1
Nickel	0.20	50	100
Bronze	0.18	1	1
Cast Iron	0.17	100	600
Silicon Iron	0.17	500	7,000
Steel, SAE 1045	0.10	300	1,000
Carbon Steel, SAE 1010	0.10	1,000	3,000
Silicon Steel	0.10	3,000	5,000
Lead	0.08	1	1
Mumetal	0.03	20,000	100,000
Permalloy 45	0.03	2,500	25,000
Stainless Steel	0.02	1	1

Inductive, or eddy current, cancellation, is provided by materials with high electrical conductivity. Examples of such materials include copper, aluminum, gold, brass, and chromium. Aluminum is usually the shielding material of choice due to its lower cost. Eddy current cancellation only works for time varying (AC) fields.

Eddy current shielding occurs when a magnetic field induces current in a conductive material. The induced current creates its own opposing magnetic field that partially cancels the original field. The eddy current shield appears to "repulse" magnetic fields while a flux shunting shield seems to "attract" them.

The eddy current effect improves with shield conductivity, with shield thickness, with increasing frequency, and with the amount of surface area available for eddy current induction. Eddy current shielding improves as the source moves further from the shield, at least as long as the shield "appears" to be much larger than the source-shield distance, because more shield surface area is exposed to the field.

Some materials provide both flux shunting and inductive cancellation. Iron and steel, for example, have high permeability and are good conductors. They provide flux shunt shielding at DC and at low frequencies and eddy current shielding at higher frequencies. The geometry of source and shield interacts with these materials in a more complex way than with "pure" flux shunting eddy current shields. A change in the source-shield distance may, for example, decrease shielding at low frequencies while improving it at higher frequencies.

Although they are less than 1/5th as conductive as copper or aluminum, the combined permeability-conductivity effect makes iron and steel better shields than copper or aluminum. Iron and steel also compare better than might be expected with high permeability alloys. Mumetal, for instance, has at least ten times higher permeability than iron but is six times less conductive.

Another way to provide both flux shunting and eddy current cancellation is with layered shields of conductive and highly permeable materials. An aluminum/steel "sandwich" can work better than single-material shields of comparable thickness, for example. The layered shield works best if the material closest to the magnetic field source is the more conductive layer.

Shield Design Issues

A shield designer's task is to create shunting paths to divert magnetic fields from some areas while remembering that fields might increase in other areas. The designer strives to make the shield seem as much like an ideal shield as possible from the perspective of the source. Ideal, unobtainable shields are spheres without openings, cylinders of infinite length, and flat plates extending to infinity in all directions. Shields that approximate these are rectangular enclosures with six or fewer sides, cylindrical electrical conduit or pipe, rectangular cable ducts, and flat plate shields.

The shield designer must struggle with several significant problems. First, existing models are inadequate for real shields. Useful shielding effectiveness models have been developed only for ideal cylinders and spheres. Less useful models have been devised to predict infinite flat plate shielding effectiveness.

Second, the models must often be fed with inadequate information. The magnetic permeability of shield materials, for example, vary with incident field strength, with frequency, and sometimes even with position within the material. Manufacturers usually provide maximum and initial permeability data for static fields, but these insufficiently predict how the material will behave.

Finally, a real shield is usually composed of separate pieces joined together. The way these pieces are joined together is crucial. All of these factors make magnetic field shielding design as much an art as a science.

Electrical Conduit Shielding

Shielding effectiveness S is defined as the ratio of the unshielded field magnitude to the shielded field magnitude at a given location. When S = 1.0, no shielding is provided. S = 0.1 indicates a factor of 10 reduction, S = 0.01 a factor of 100 reduction, etc.. In general, shielding effectiveness is a function of shield thickness, magnetic permeability, electrical conductivity, the size and shape of the shield, the configuration of the source, and the distance between the source and the shield.

The magnetic field shielding effectiveness of long cylindrical shields is given by the equations of King [King, 1933] and Shenfeld [Shenfeld, 1968]. The equations predict shielding effectiveness for the case of both a cylinder enclosing a pair of wires carrying equal but opposite currents and for a cylinder exposed to a uniform external field. The symmetry of the cylindrical shield problem gives a constant shielding effectiveness throughout the shielded space.

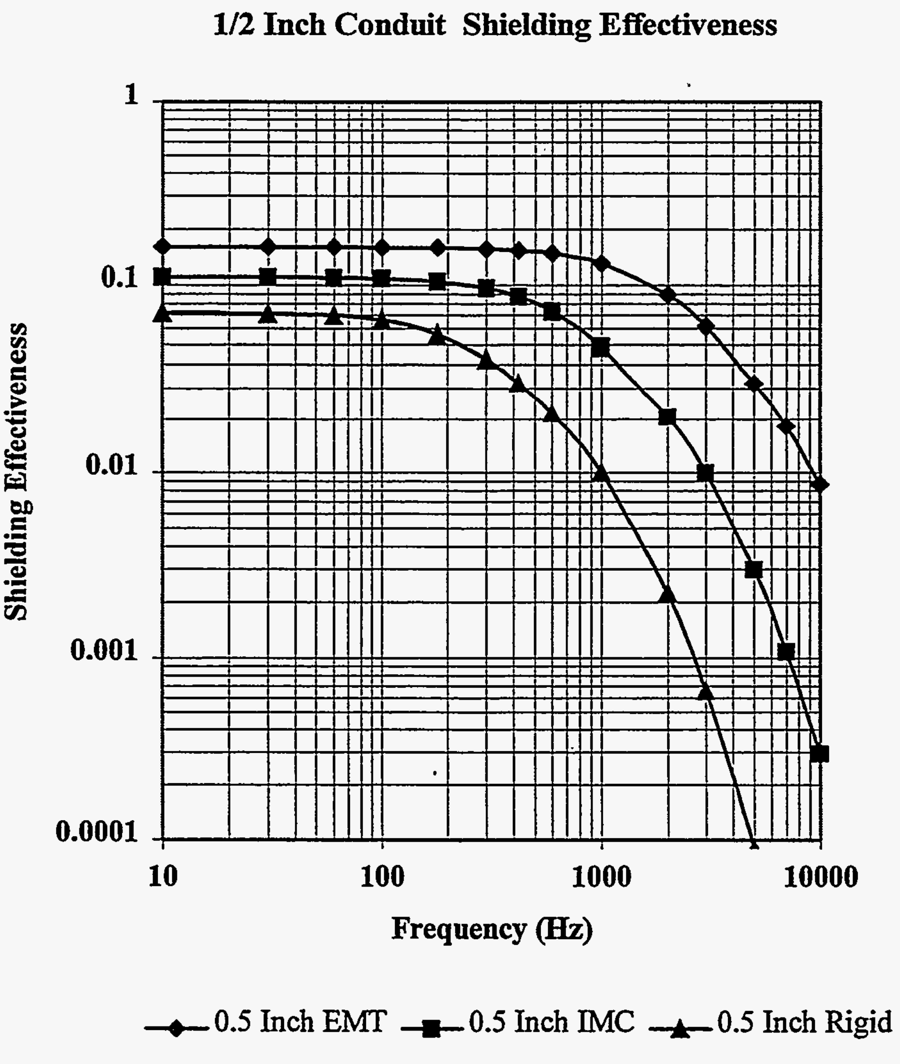

Figure A-3: 0.5 Inch Conduit Shielding Effectiveness

Figure A-3 shows the predicted shielding effectiveness of three types of ½ inch diameter steel conduit versus frequency. The conduits include electrical metal tubing (EMT), intermediate metal conduit (IMC), and rigid metal conduit. For these steel-based conduits, an initial relative permeability of 100 and a conductivity of 5.8×10^6 Siemens/meter is assumed.

Metal conduit shielding effectiveness is fairly constant throughout the lowest frequencies. This is the region where flux shunting dominates. For ½ inch conduit, 60 Hz shielding effectiveness is provided almost entirely by flux shunting and only the rigid metal conduit reduces magnetic fields by more than an order of magnitude.

At higher frequencies, eddy current shielding dominates and shielding improves with increasing frequency. At even higher frequencies, the so-called "skin-effect" dominates. The skin effect causes higher frequency eddy currents to congregate only near the shield surface, making the shield "appear" to be thicker than it is. The skin effect substantially improves shielding at higher frequencies.

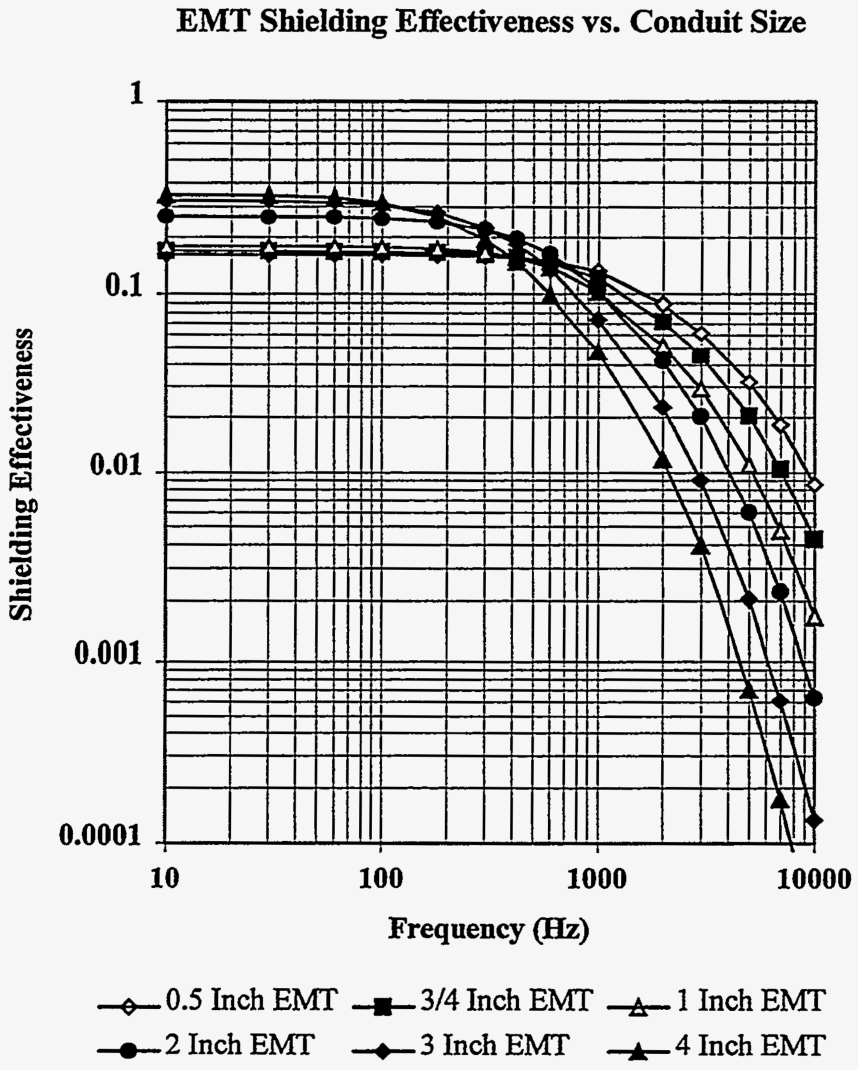

Figure A-4: EMT Shielding Effectiveness vs. Conduit Size

Figure A-4 shows an interesting phenomena. With increasing EMT conduit diameter, the predicted shielding effectiveness *worsens* at low frequencies while *improving* at higher frequencies. This occurs because eddy current shielding improves with diameter while flux shunt shielding becomes less effective. A similar effect occurs for IMC and rigid metal conduit. At the largest IMC and rigid conduit diameters, however, the low frequency shielding effectiveness improves because the relative wall thicknesses increase significantly.

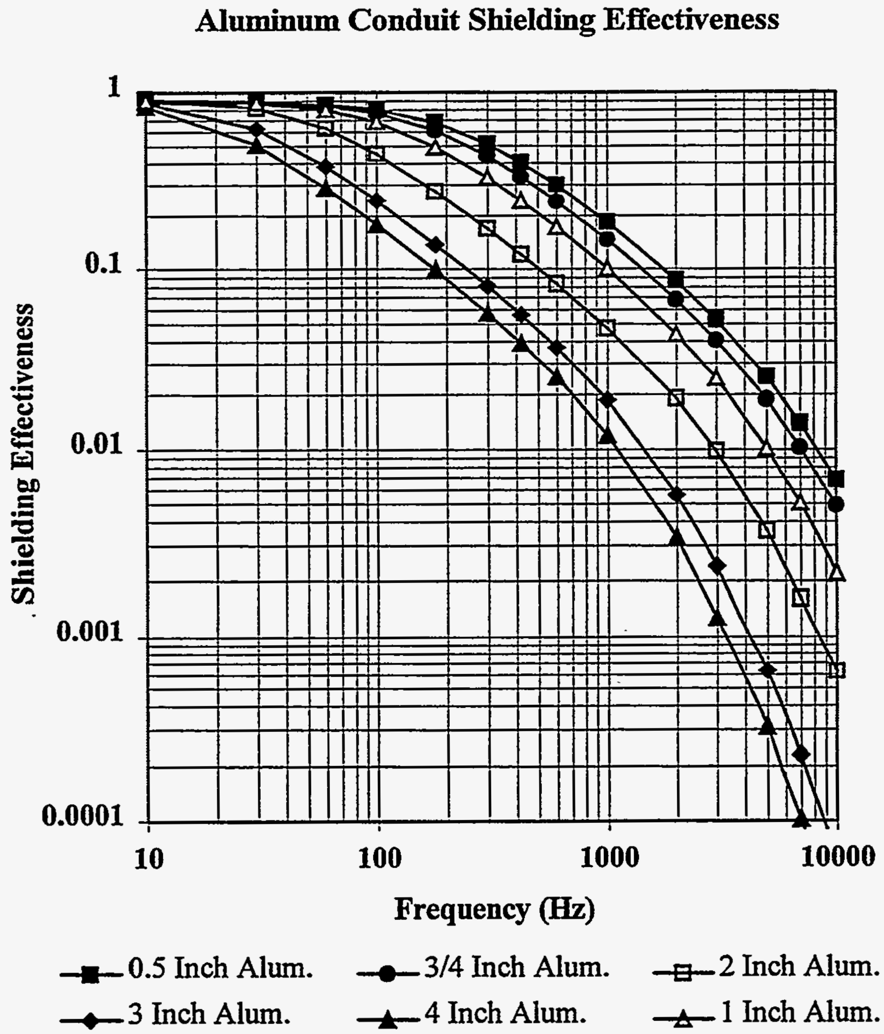

Figure A-5: Aluminum Conduit Shielding Effectiveness

As Figure A-5 illustrates, aluminum conduit only provides eddy current shielding. Its predicted shielding effectiveness improves with conduit diameter at both high and low frequencies. In this example, aluminum conduit is modeled with the same dimensions and wall thickness as rigid metal conduit. Aluminum conductivity is set at 3.77×10^7 Siemens/meter. This theoretical aluminum conduit would perform better than four inch EMT at 60 Hz and almost as well as four inch IMC at 60 Hz, but would not shield as well as four inch rigid metal conduit.

Flat Plate Shielding

One method for approximating the shielding effectiveness of a flat plate was described by Schelkunoff [Schelkunoff, 1943]. Schelkunoff used transmission theory to develop the shielding effectiveness expression **1/S = R + A + B** for an infinite flat plate shield exposed to a uniform transverse magnetic field, where **R** represents reflection loss, **A** represents field attenuation in the shield itself, and **B** represents losses in the shield from internal reflections.

The Schelkunoff equations have been derived for few magnetic field source types. One case, described by Bannister [Bannister, 1968] and Moser [Moser, 1988], involved a flat plate shield near a small circular current loop magnetic field source. The authors found that Shelkunoff's theory predicted experimental results only when the distance between the observation point and the shield was twice the source-shield distance.

Figures A-6 through A-8 show Schelkunoff/Bannister/Moser-predicted 60 Hz magnetic field shielding effectiveness versus source-shield distance for flat steel, aluminum, and mumetal plates of varying thickness near a circular current loop magnetic field source. The plots are considered valid only for shielded observation points that are twice as far from the shield as the source. For these examples, conservative initial permeability values of 100 for steel and 10,000 for Mumetal are assumed. Aluminum, steel, and mumetal conductivities were assumed to be 3.77×10^7, 5.8×10^6, and 1.876×10^6 Siemens/meter, respectively.

The Schelkunoff model is limited to cases of infinite flat plates near small circular current loop sources. Although few real-world power frequency shielding problems resemble this example, the model illustrates some fundamental shielding principals. Schelkunoff predicts, for example, that the shielding effectiveness of steel and mumetal plates improve more rapidly with thickness than that of aluminum plates. The model predicts that flat steel shields must be more than 1/4 inch thick to reduce 60 Hz magnetic fields by more than an order of magnitude, something mumetal can do when only 1/50 inch thick. According to the model, aluminum flat plate shields perform nearly as well, if not better than, steel plates because of the source-shield distance involved in this example.

Aluminum plate shielding effectiveness at 60 Hz improves with source-shield distance enough to rival steel at the 0.305 meter source-shield distance for the small circular loop source. Mumetal and steel tend to perform better with decreasing source-shield distance.

The models predict difficulty reducing 60 Hz magnetic fields by more than an order of magnitude with *ideal* infinite flat plate steel or aluminum shields less than 1/4 inch thick. Hoberg [Hoberg, 1995][Hoberg, 1996] and Hiles [Hiles et al, 1995], among others, have shown that multi-layered aluminum/steel shields can perform better than single-layer shields of equivalent thickness. Hoburg predicted, for example, that a two layer pair (four layers) 50/50 aluminum-steel sandwich would perform 2.5 times better than a single steel layer and that a three layer pair would perform five times better than a single steel layer. Hiles performed shielding effectiveness measurements with various combinations of 8 foot by 8 foot steel and aluminum flat plates in front of a large three-phase service panel. A combination of aluminum and steel plates of unspecified thickness reduced the maximum magnetic fields in areas near the panel by a factor of about nine (S = 0.111). Multi layer shields work best when the more conductive aluminum material is nearest the source. This makes the magnetic field ducting steel layer act as if it were closer to the source than it really is. Ferromagnetic materials provide better shielding with decreasing source-shield distance for the loop source. The same effect causes smaller diameter steel conduit to provide better shielding.

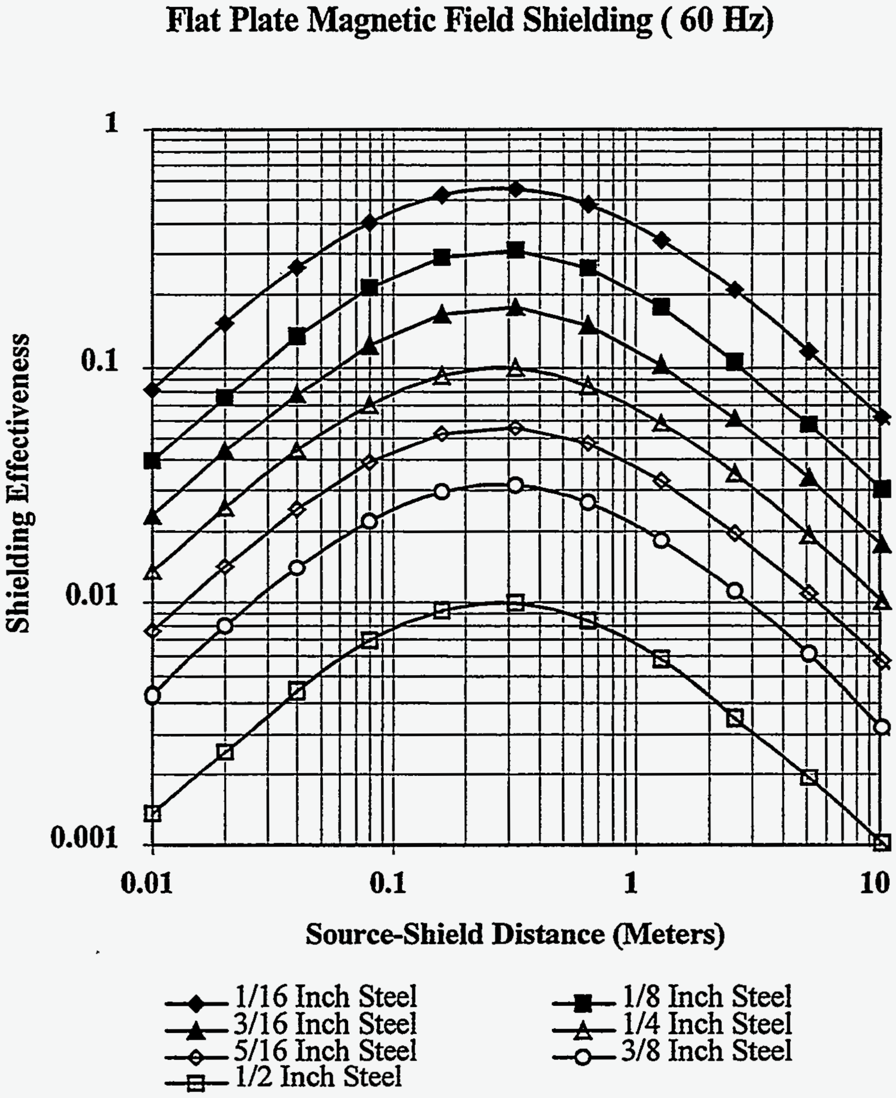

Figure A-6: Steel Plate Shielding vs. Source-Shield Distance

Real shield design can be site-specific and unpredictable. The infinite flat plate models are of little use in most cases. Consider, for example, shielding tests reported by Con Edison in 1995 [Durkin et al, 1995]. The company placed 3/8" thick 4 x 2 foot ASTM 1010 steel plates above underground cable ducts in one test. This simple shield reduced ground-level magnetic fields by a factor of two to four (S = 0.25-0.5). The infinite flat plate Shelkunoff prediction of a 30-fold field reduction (S = 0.03) is of little use for such a shield. Con Ed also shielded a vault and a capacitor bank with large enclosures made from overlapped 1/16 inch thick mumetal sheets joined by screws. These experiments showed that it was possible to achieve a 20-fold magnetic field reduction (S = 0.05) in the field. This compares poorly with the Shelkunoff infinite flat plate prediction of S = 0.008. Shield designers tend to use rules of thumb developed from lab testing and field experience rather than inappropriately apply Shelkunoff theory.

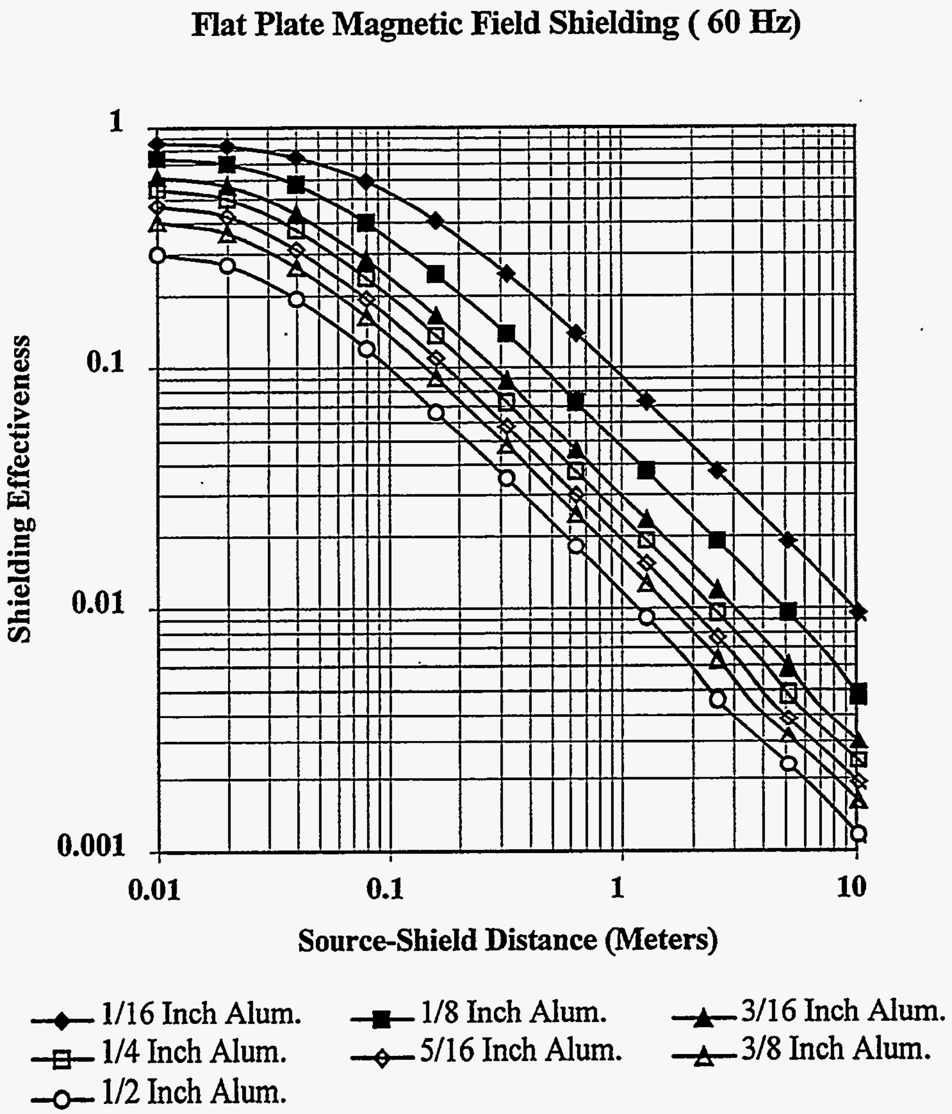

Figure 3.4-13: Aluminum Plate Shielding vs. Source-Shield Distance

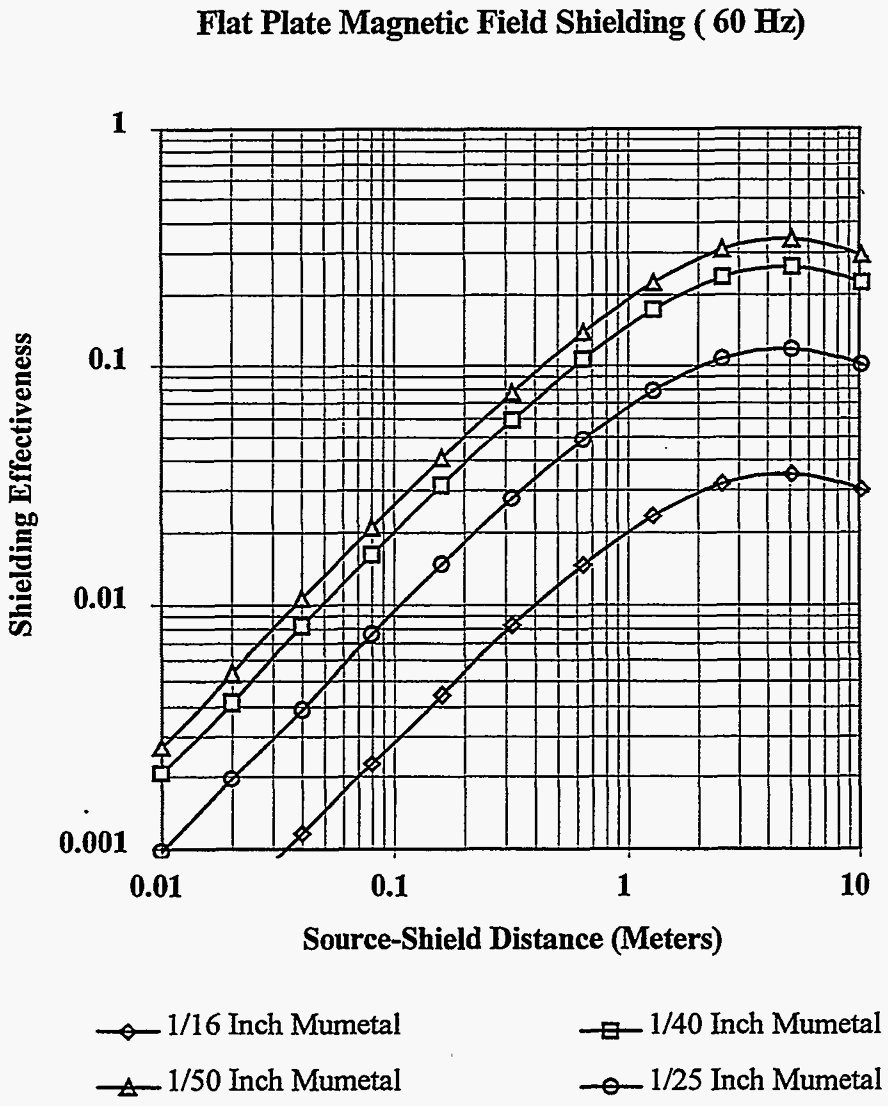

Figure 3.4-14: Mumetal Plate Shielding vs. Source-Shield Distance

List of References for Appendix A

P. Bannister. "New Theoretical Expressions for Predicting Shielding Effectiveness for the Plane Shield Case." IEEE Transactions on Electromagnetic Compatibility. Vol. EMC-10, No. 1. March 1968.

C. Durkin, R. Fogarty, T. Halleran, D. Mark, A. Mukhopadhyay. "Five Years of Magnetic Field Management." IEEE Transactions on Power Delivery. Vol. 10, No. 1. January 1995.

J. Hoburg. "A Computational Methodology and Results for Quasistatic Multilayered Magnetic Field Shielding." IEEE Transactions on Electromagnetic Compatibility. Vol. 38, No. 1. February 1996.

J. Hoburg. "Principles of Quasistatic Magnetic Shielding with Cylindrical and Spherical Shields." IEEE Transactions on Electromagnetic Compatibility. Vol. 37, No. 4. November 1995.

L. King. "Electromagnetic Shielding at Radio Frequencies." Phil. Mag. J. Sci.. Vol. 15. February 1933.

J. Moser. "Low-Frequency, Low-Impedance Electromagnetic Field Shielding." IEEE Transactions on Electromagnetic Compatibility. Vol. 30, No. 8. August 1988.

S. Shelkunoff. Electromagnetic Waves. Princeton, N.J. Van Nostrand. 1943

S. Shenfeld. "Shielding of Cylindrical Tubes." IEEE Transactions on Electromagnetic Compatibility. Vol. EMC-10, No. 1. March 1968.

R. Schulz. "Shielding Theory and Practice." IEEE Transactions on Electromagnetic Compatibility. Vol. 30, No. 3. August 1988.

Handbook of Shielding Principles for Power Frequency System Magnetic Fields. EPRI TR-103630. Research Project 3335-02 Final Report. April 1994.

APPENDIX B

HIGH VOLTAGE TRANSMISSION LINE

DESIGN ASSUMPTIONS
AND
PREDICTED MAGNETIC FIELDS

APPENDIX B

HIGH VOLTAGE TRANSMISSION LINE

DESIGN ASSUMPTIONS
AND
PREDICTED MAGNETIC FIELDS

Table_1 - General Design Assumptions - Overhead Transmission

1. Nominal Voltages: 69, 115, 230, 345, 500 and 765 kV.

2. Reference Load Level

69 kV	600 amps	72 MVA
115 kV	600 amps	120 MVA
230 kV	600 amps	239 MVA
345 kV	1200 amps	717 MVA
500 kV	1800 amps	1559 MVA
765 kV	2400 amps	3180 MVA

3. All designs will include overhead ground wires

4. All designs are based on NESC Heavy Load

5. Costs are provided for typical rural and suburban locations.
   <u>Rural Assumptions</u>
   a. Line traverses cross country with long spans and few bends
   b. No distribution underbuild
   <u>Suburban Assumptions</u>
   a. Line along streets and roadways
   b. Line would have many turns and short spans
   c. Poles would provide clearances and strength for underbuild of distribution or communication wires.
   d. Poles will be located on property lines (250 ft spans)

6. For preparing cost estimates the length of line and the number of medium angle and dead end structures are listed in the table below.

	Voltage kV	Miles	Med. Angle	Dead End
Suburban	all *	10	20	10
Rural	69	25	10	5
Rural	115	25	10	5
Rural	230	25	10	5
Rural	345	50	16	8
Rural	500	75	24	12
Rural	765	100	32	16

* 500 kV and 765 kV systems have no suburban configurations and no provision for distribution underbuild.

Table_2 Conductor Characteristics

Conductor Physical Characteristics

Conductor			Cable	Weight	Rated	Resist.
Code Word	Size kcmil	Strand Al/St	Diameter inches	/1000 ft lbs	Strength lbs	50°C ohm/mi
Linnet	336.4	26/7	0.720	463.0	14,100	0.2996
Drake	795.0	26/7	1.108	1094.0	31,500	0.1278
Cardinal	954.0	54/7	1.196	1229.0	33,800	0.1100

Conductor Ampacity and Temperature

Conductor		100°C Conduct.[1] Amps	Conductor Temperature[2] in °C			
Code Word	Size kcmil		300 A	360 A	600 A	900 A
Linnet	336.4	574	45.0	50.9	-	-
Drake	795.0	993	-	-	50.8	-
Cardinal	954.0	1085	-	-	47.8	66.8

[1] Conductor ampacity at 100°C conductor temperature and 40°C (104°F)ambient.

[2] Conductor temperature at given amps and 25°C (77°F) ambient.

Conductor Sag (feet)

Span ft.	Final Sag for listed spans and conductor temp. of 100°C			Final Sag for listed spans and conductor temp. of 50°C		
	Linnet 336.4	Drake 795.0	Cardinal 954.0	Linnet 336.4	Drake 795.0	Cardinal 954.0
Bare Conductor						
250	4.39	4.25	4.78	3.31	3.21	3.76
400	8.10	7.97	8.79	6.61	6.52	7.06
600	13.70	13.96	15.20	11.68	11.94	12.36
800	20.26	21.09	22.80	17.70	18.18	18.81
1200	-	-	41.36	-	-	35.35

Table 3.1 69 kV Transmission Design Assumptions

		Conduct/Phase		Norm. Pwr Transfer				Phase Spacing	
Id No.	Descr.	No.	kcmil	Amps	MVA	Struct	Insul.	Horiz	Vertical
1.1.1	69-Delta	1	795	600	72	WP	Post	4.6	6.0
1.1.2	69-Vertical	1	795	600	72	WP	Post	0.0	8.0
1.1.3	69-Splt Phs	2	336	600	72	WP	Post	4.6	8.0
1.1.4	115-Delta	1	336	360	72	WP-Davit	Susp.	12.0	6.0
1.1.5	69-5-Wire	2	336	600	72	WH	Post	9.6	6.0
	center wire	1	795					4.6	

Rural Configuration - Longer spans and no distribution underbuild

					Lowest Conductor Elevation (ft)			Min
						Mid Span		
Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	At Struct.	Design 100°C	Norm 50°C	ROW Width ft.
1.1.1A	69-Delta	400	60 ft Cl 2	52.0	30.0	22.0	23.5	27
1.1.2A	69-Vertical	400	65 ft Cl 1	56.5	30.5	22.5	24.0	27
1.1.3A	69-Splt Phs	400	65 ft Cl 2	56.5	30.5	22.4	23.9	30
1.1.4A	115-Delta	400	70 ft Cl 2	56.5	31.5	23.4	24.9	41
1.1.5A	69-5-Wire	600	2-65 ft Cl 1	56.5	38.5	24.8	26.8	43

Suburban Configuration - Shorter spans with pole height and strength to accommodate distribution underbuild

					Lowest Conductor Elevation (ft)			Min
						Mid Span		
Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	At Struct.	Design 100°C	Norm 50°C	ROW Width ft.
1.1.1B	69-Delta	250	75 ft Cl 1	65.5	43.5	39.3	40.3	25
1.1.2B	69-Vertical	250	80 ft Cl 1	70.0	44.0	39.8	40.8	25
1.1.3B	69-Splt Phs	250	80 ft Cl H-1	70.0	44.0	39.6	40.7	26
1.1.4B	115-Delta	250	80 ft Cl 1	70.0	45.0	40.6	41.7	38
1.1.5B	69-5-Wire	250	2-75 ft Cl 3	65.5	47.5	43.1	44.2	31

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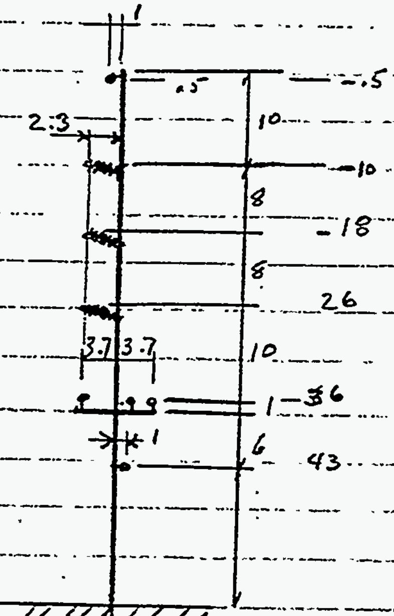

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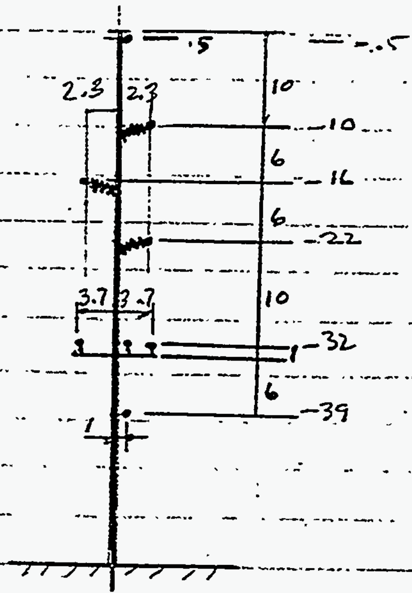

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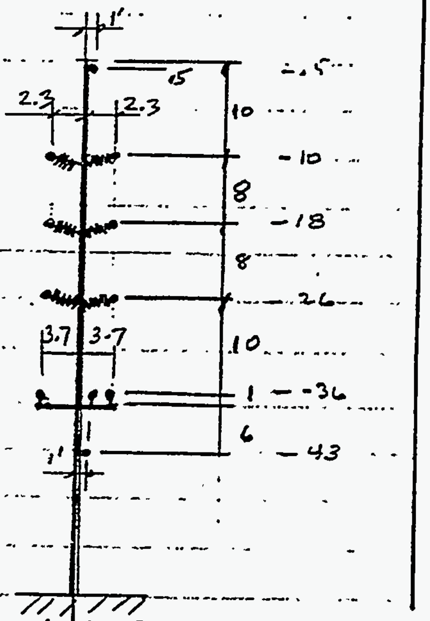

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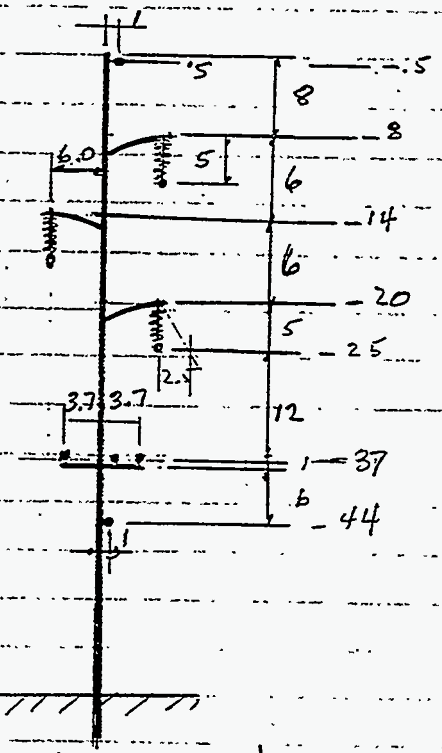

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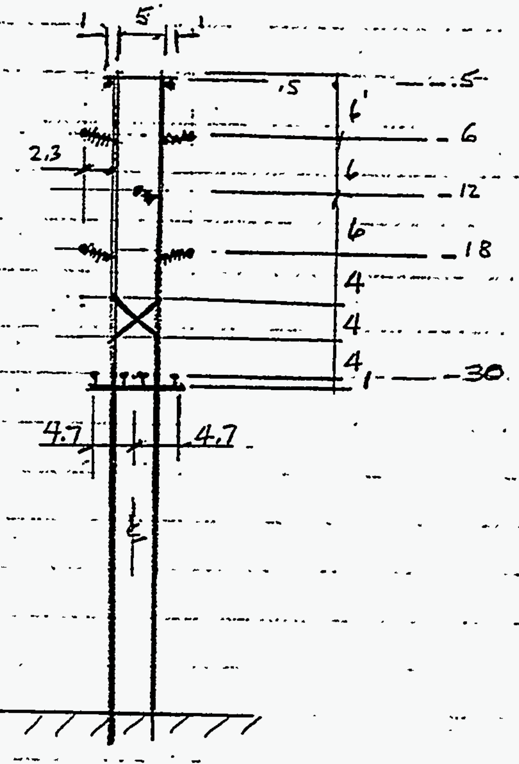

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69 KV

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CALCULATION SHEET

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SHEET OF

SUBJECT 69 kV Underground Transm - Config + Dimen.

JOB NUMBER 115001

CALC. BY/DATE D. Shafer 2/1/97

CHECKED BY/DATE

REV.

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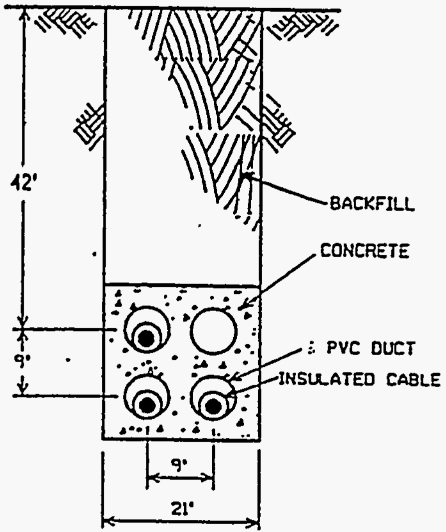
2×2-5" Duct Bank
3-1c Cables in 3 Ducts



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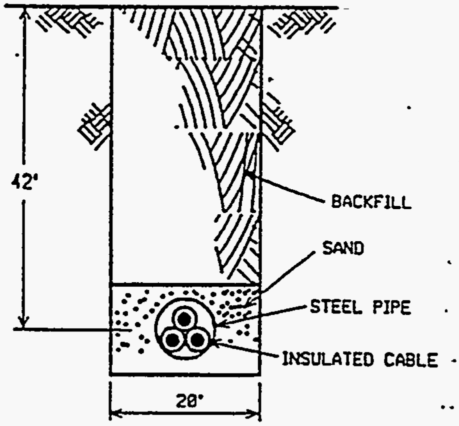
HPGF Pipe-Type Cable
3-1c Cables in 6" Pipe



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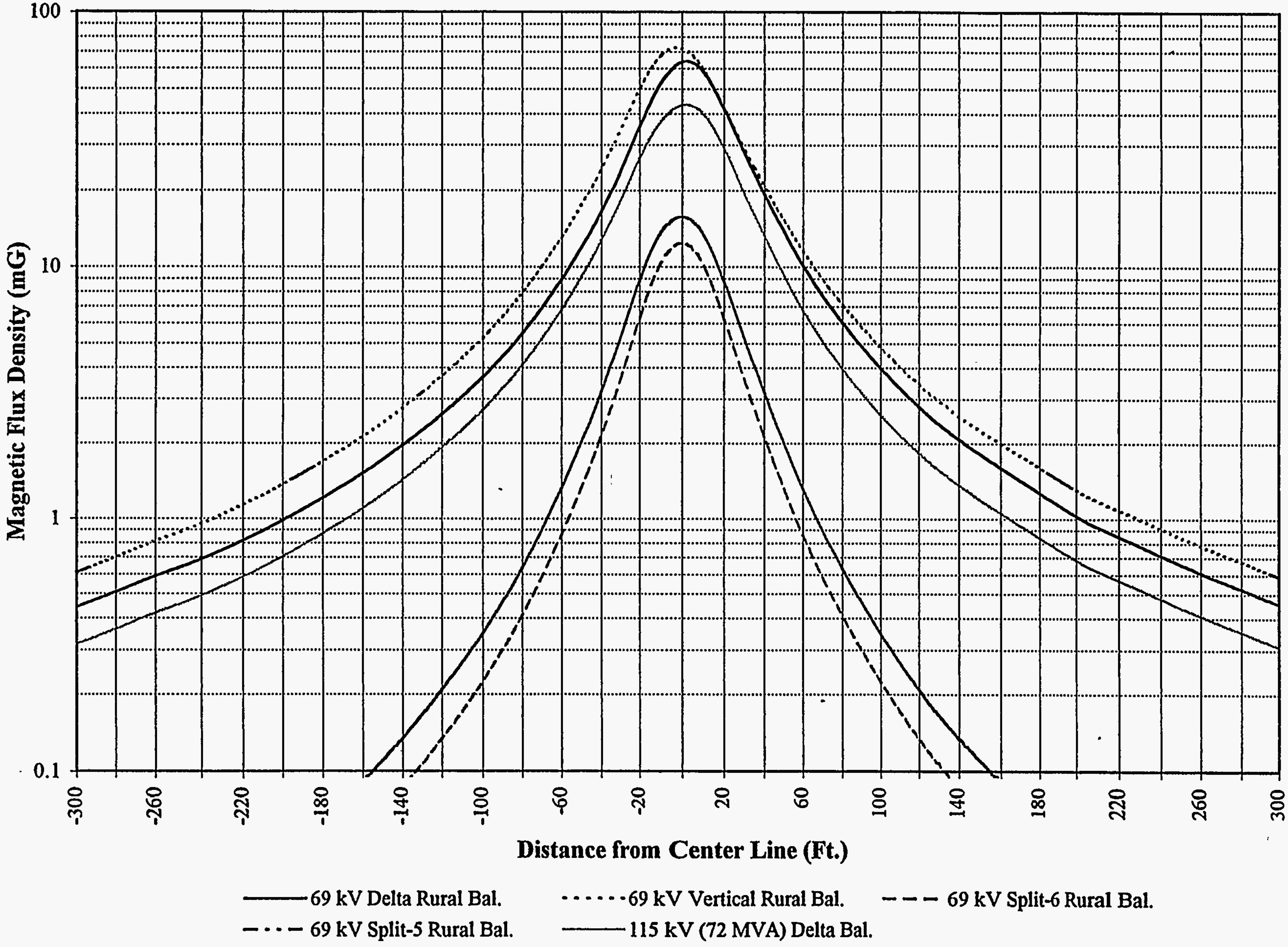

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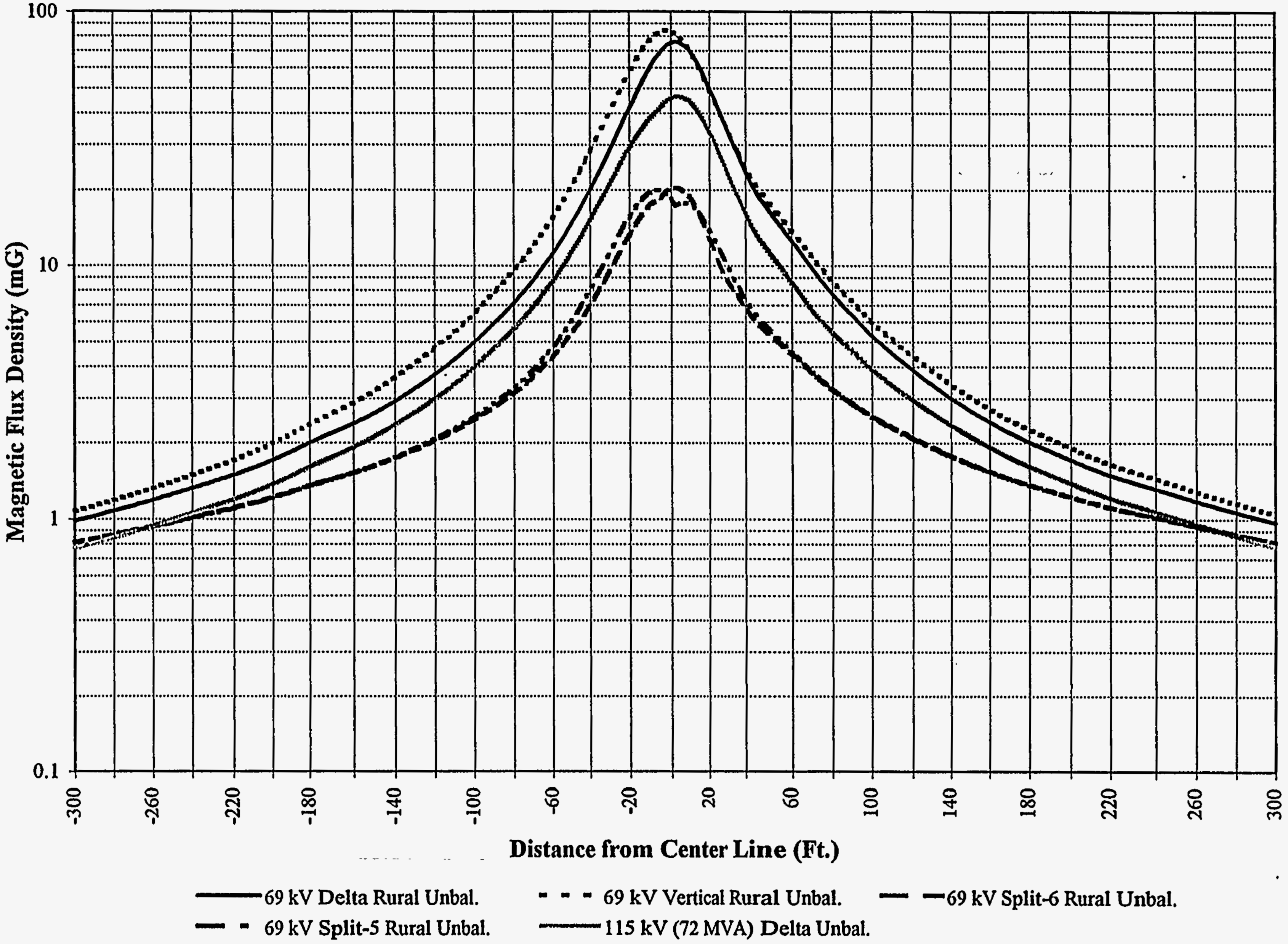
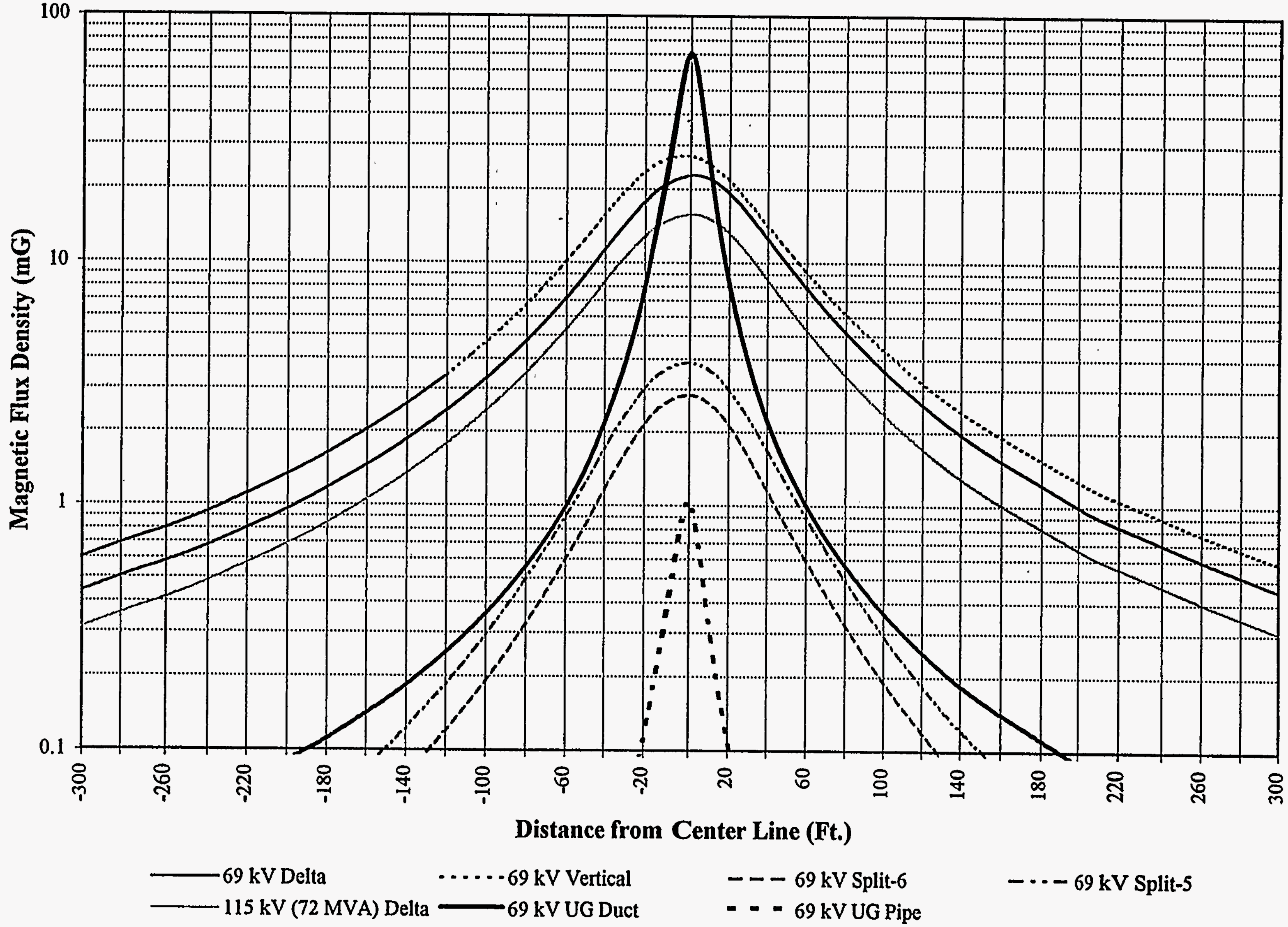


69 kV Suburban Transmission Lines (Balanced)



69 kV Suburban Transmission Lines (Unbalanced)

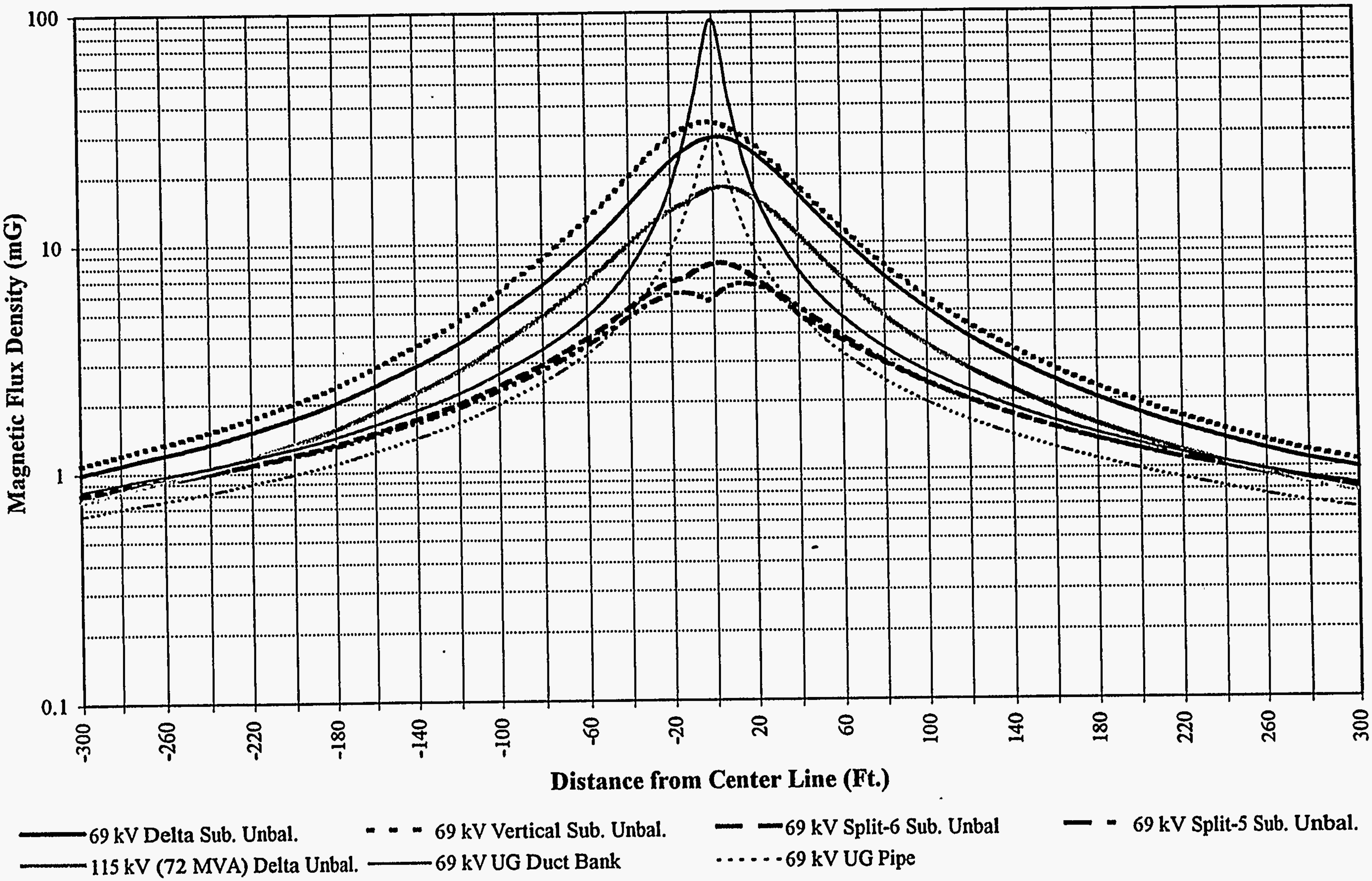


Table 3.2 115 kV Transmission Design Assumptions

Id No.	Descr.	Conduct/Phase No.	Conduct/Phase kcmil	Norm. Pwr Transfer Amps	Norm. Pwr Transfer MVA	Struct	Insul.	Phase Spacing Horiz	Phase Spacing Vertical
1.2.1	115-H Frame	1	795	600	120	WP	Susp.	12.5	0.0
1.2.2	115-Delta	1	795	600	120	WP-Davit	Susp.	12.0	6.0
1.2.3	115-Dlta Cpct	1	795	600	120	WP	Post	6.0	6.0
1.2.4	115-6W Splt Phs	2	336	600	120	WP-Davit	Susp.	12.0	12.0
	center arm							16.0	
1.2.5	115-6W Splt Cpc	2	336	600	120	WP	Post	6.0	12.0
1.2.6	69-6W Splt Phs	2	795	1000	120	WP	Post	4.6	8.0
1.2.7	230-Delta	1	336	300	120	WP-Davit	Susp.	16.0	8.0
1.2.8	115-5-Wire	2	336	600	120	WH	Susp.	13.0	10.0
	center wire	1	795					6.0	10.0
1.2.9	115 HF w/cancel.	1	795	600	120	WP	Susp.	12.5	0.0
	Cancellation Loop		795			WP	Post	31.0	

Rural Configuration - Longer spans and no distribution underbuild

Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	Lowest Conductor Elevation (ft) At Struct.	Lowest Conductor Elevation (ft) Mid Span Design 100°C	Lowest Conductor Elevation (ft) Mid Span Norm 50°C	Min ROW Width ft.
1.2.1A	115-H Frame	800	2-65 ft Cl H-1	56.5	45.5	24.4	27.3	52
1.2.2A	115-Delta	400	65 ft Cl 1	56.5	31.5	23.5	25.0	39
1.2.3A	115-Dlta Cpct	400	60 ft Cl 1	52.0	30.0	22.0	23.5	30
1.2.4A	115-Splt Phs	400	80 ft Cl H-1	70.0	33.0	24.9	26.4	47
1.2.5A	115-Splt Cpct	400	75 ft Cl H-1	65.5	31.5	23.4	24.9	34
1.2.6A	69-Splt Phs	400	65 ft Cl H-2	56.5	30.5	22.5	24.0	27
1.2.7A	230-Delta	400	75 ft Cl 2	65.5	32.5	24.4	25.9	52
1.2.8A	115-5-Wire	600	2-80 ft Cl 1	70.0	40.0	26.3	28.3	49
1.2.9A	115 HF w/cancel.	800	2-65 ft Cl H-1	56.5	45.5	24.4	27.3	65
	Cancellation Loop	400	35 ft Cl 5	29.5	29.5		23.0	

Suburban Configuration - Shorter spans with pole height and strength to accommodate distribution underbuild

Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	Lowest Conductor Elevation (ft) At Struct.	Lowest Conductor Elevation (ft) Mid Span Design 100°C	Lowest Conductor Elevation (ft) Mid Span Norm 50°C	Min ROW Width ft.
1.2.1B	NONE	-	-	-	-	-	-	-
1.2.2B	115-Delta	250	80 ft Cl 1	70.0	45.0	40.8	41.8	37
1.2.3B	115-Dlta Cpct	250	80 ft Cl 1	70.0	48.0	43.8	44.8	29
1.2.4B	115-Splt Phs	250	95 ft Cl H-1	83.5	46.5	42.1	43.2	44
1.2.5B	115-Splt Cpct	250	95 ft Cl H-2	83.5	49.5	45.1	46.2	31
1.2.6B	69-Splt Phs	250	80 ft Cl H-2	70.0	44.0	39.8	40.8	25
1.2.7B	230-Delta	250	95 ft Cl 1	83.5	50.5	46.1	47.2	49
1.2.8B	NONE	-	-	-	-	-	-	-

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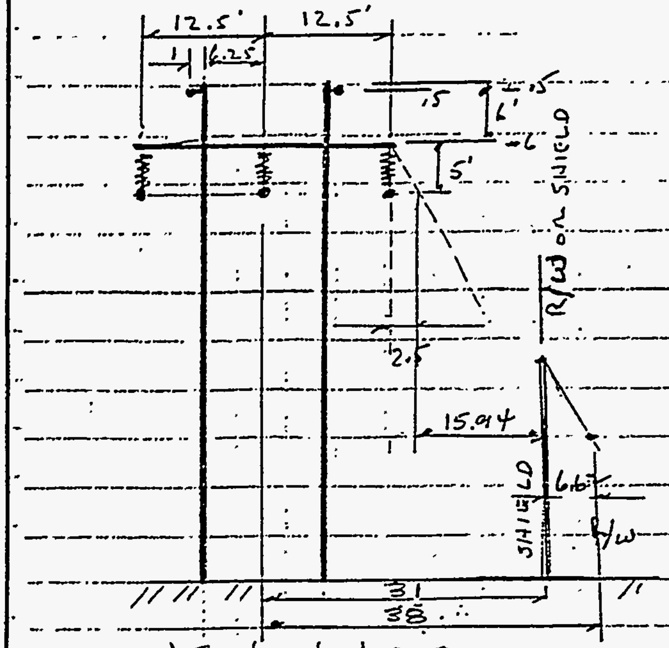

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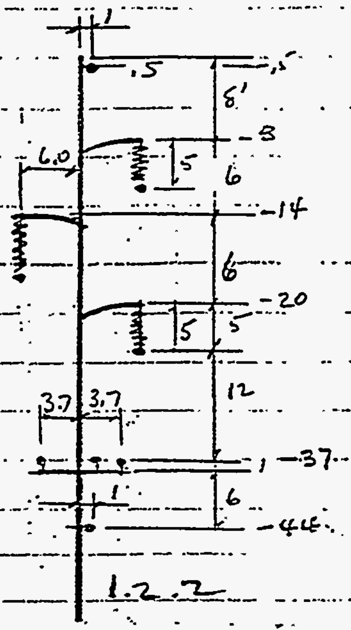

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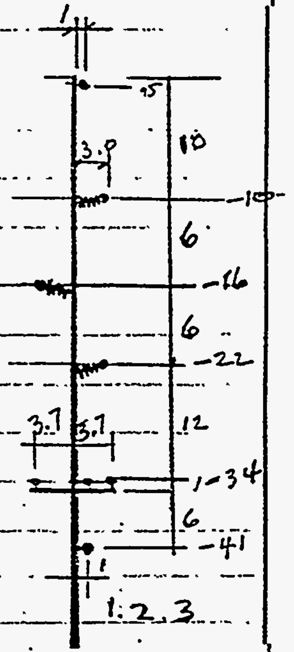

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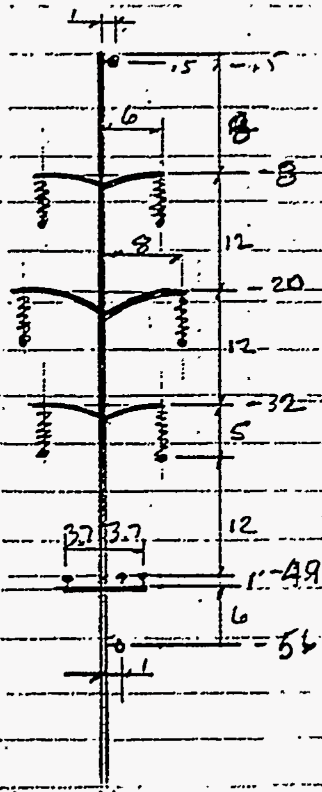

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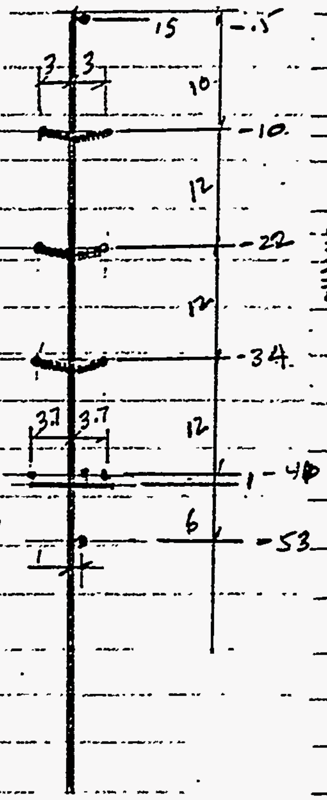

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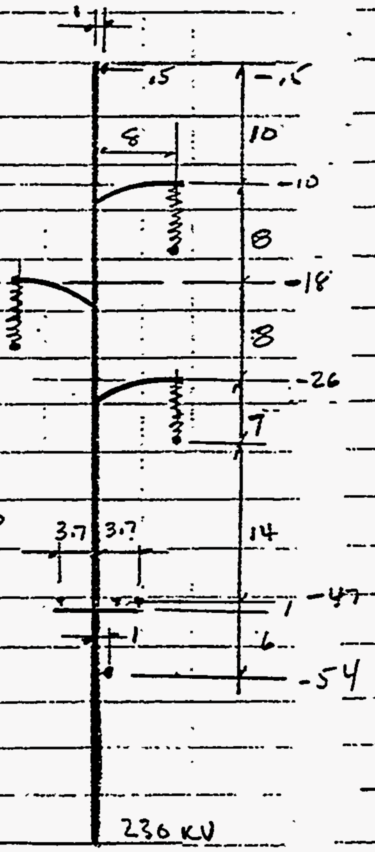

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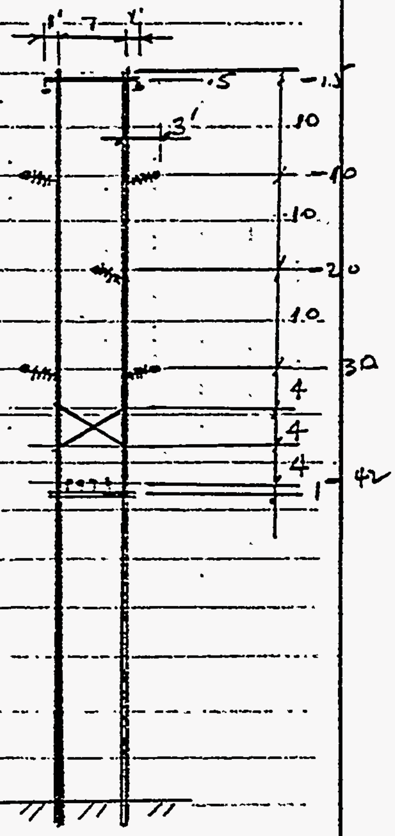

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SUBJECT 115 kV UNDERGROUND TRANSM. CONFIG + DIMENS.	JOB NUMBER 115001
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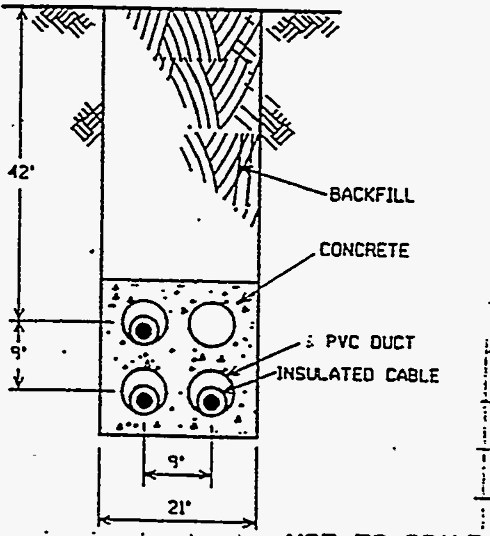
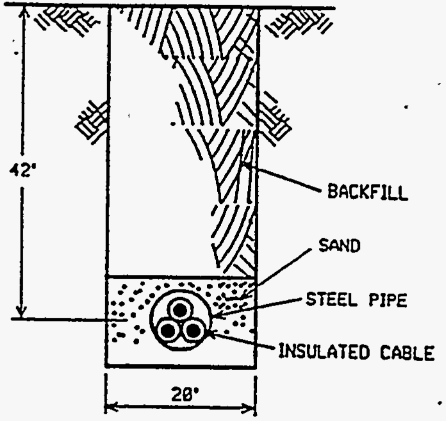
2×2-5" DUCT BANK
3-1c CABLES IN 3 DUCTS



NOT TO SCALE

1.2.11

HPGF PIPE-TYPE CABLE
3-1c CABLES IN 6" PIPE



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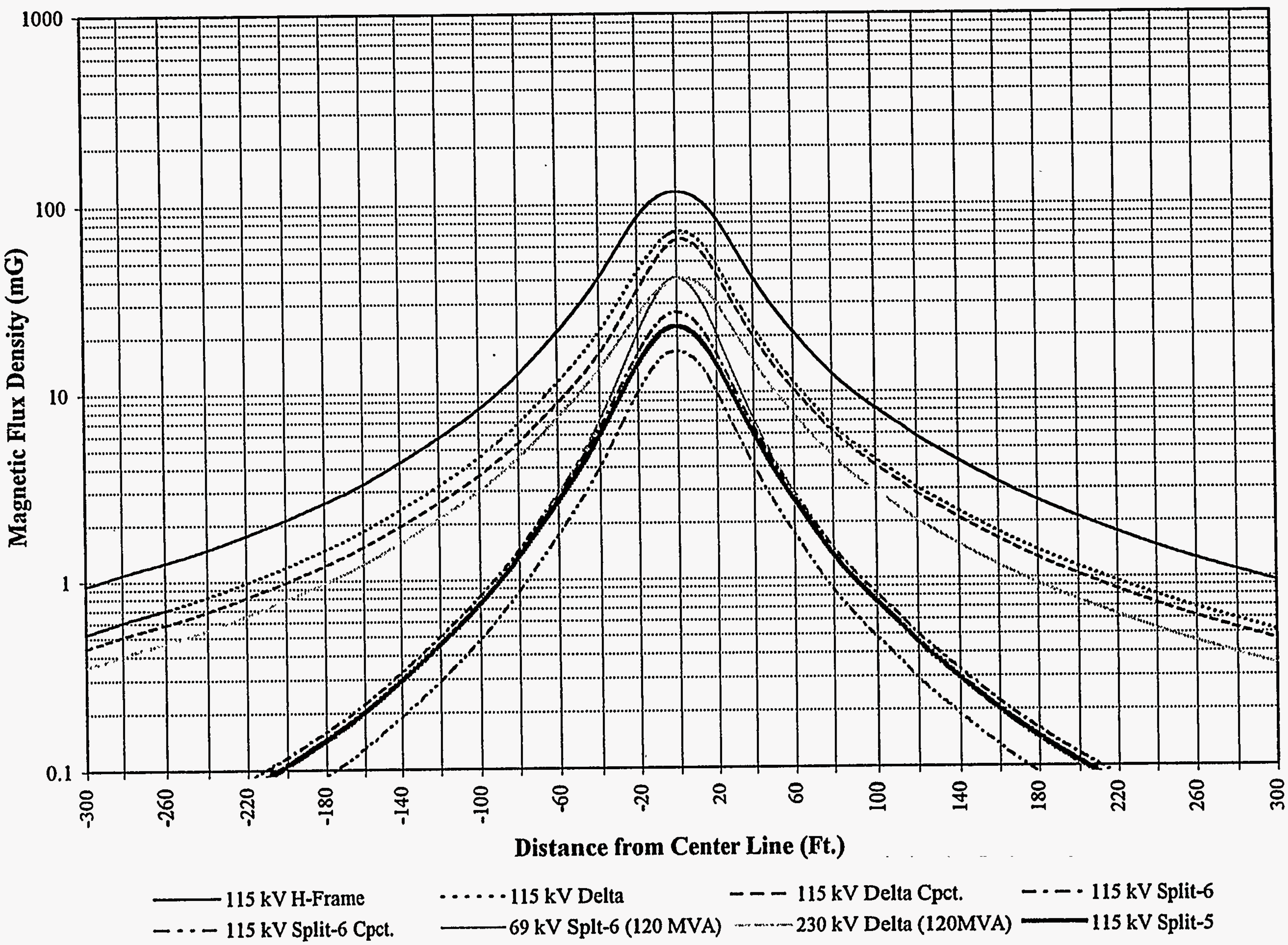
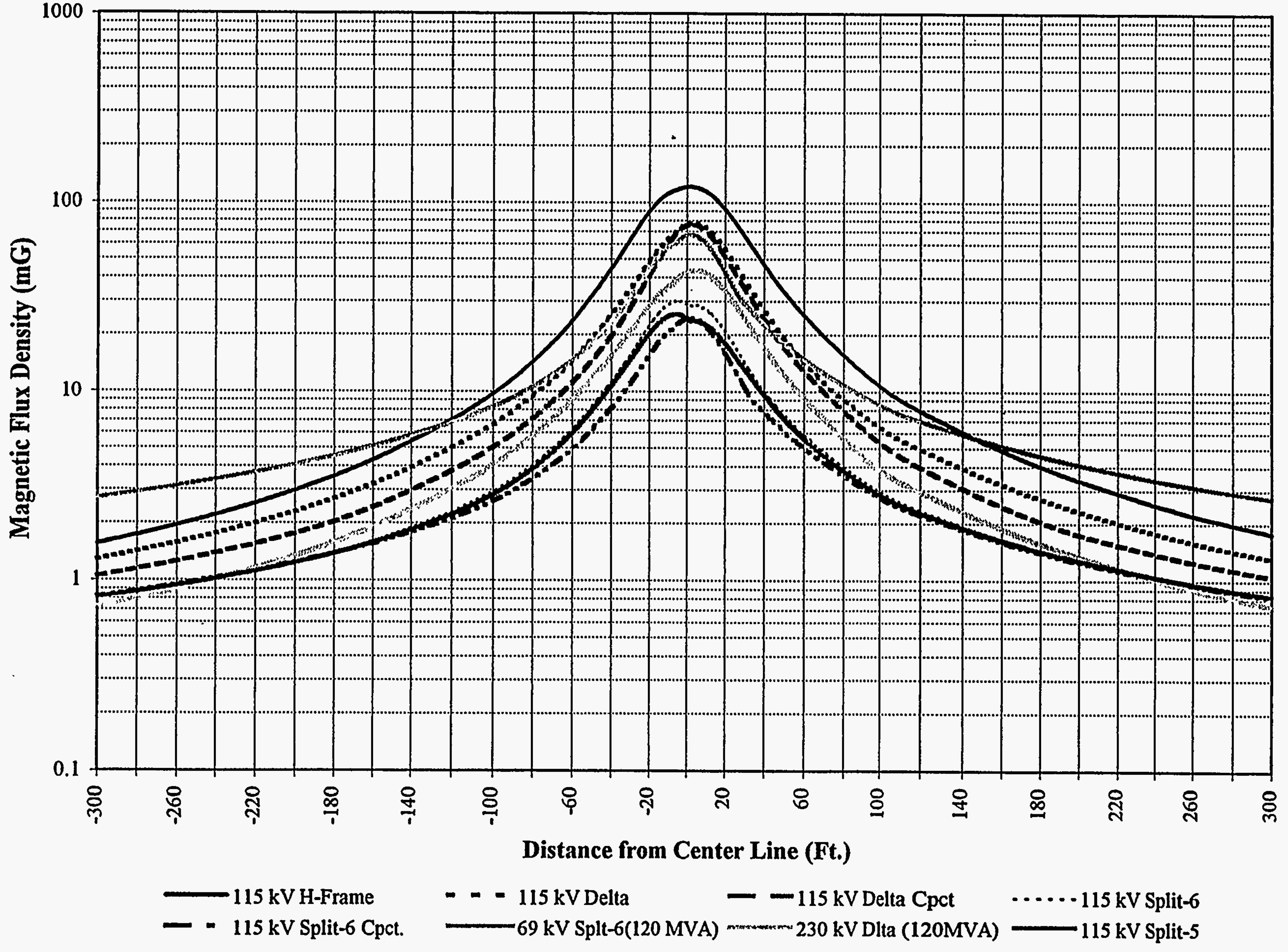
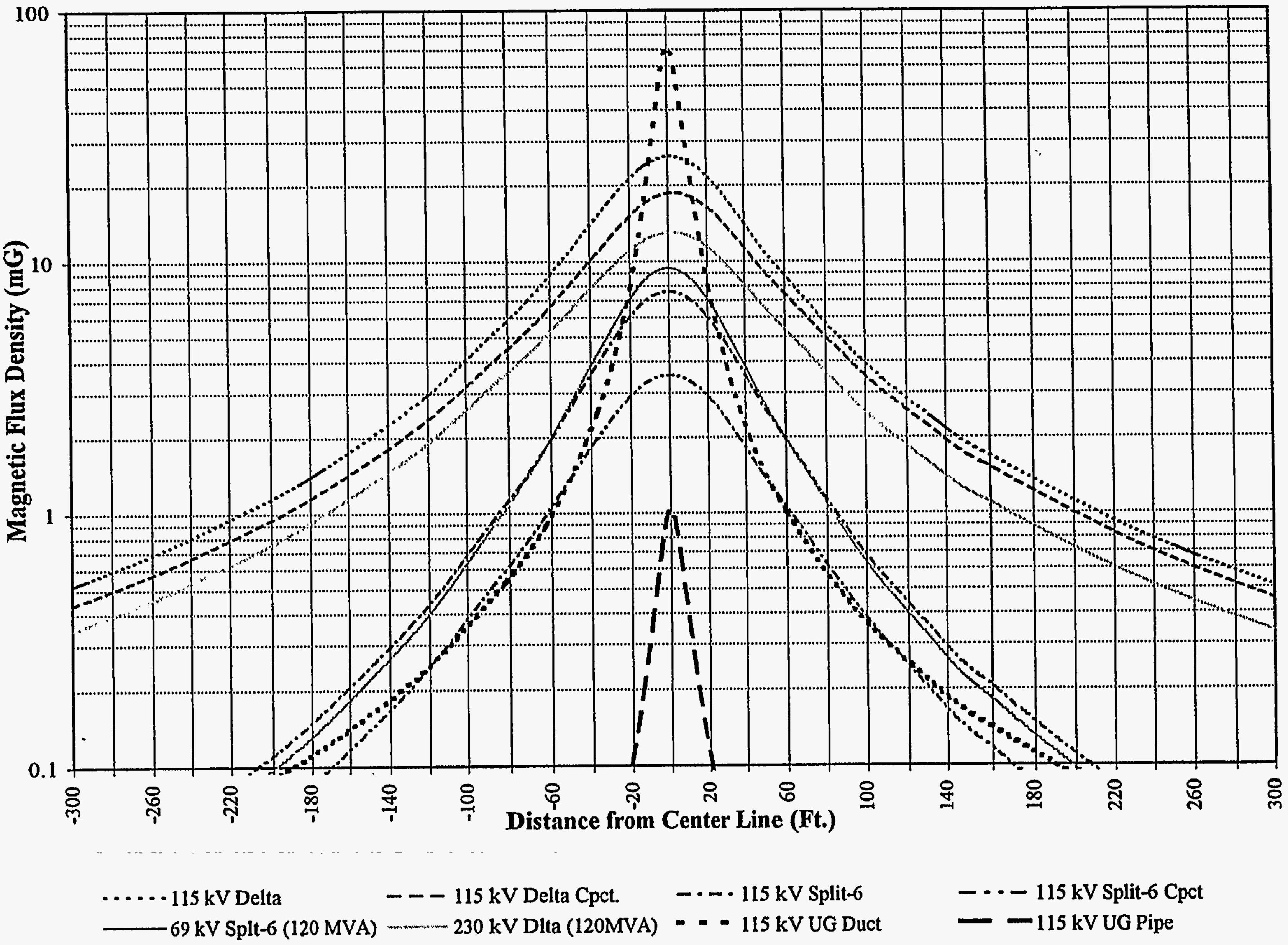
115 kV Rural Transmission Lines (Balanced)





115 kV Rural Transmission Lines (Unbalanced)

115 kV Suburban Transmission Lines (Balanced)



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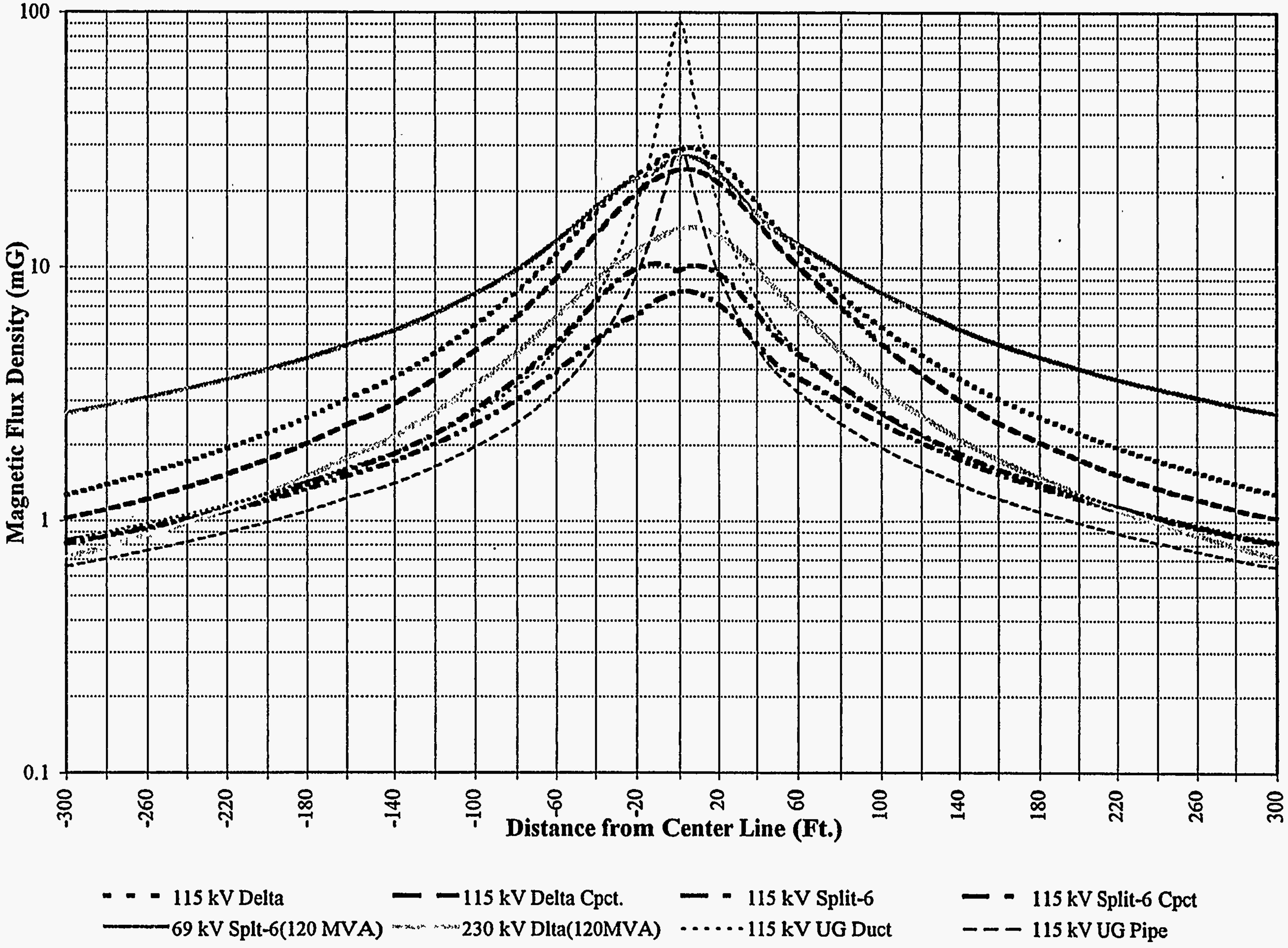


Table 3.3 230 kV Transmission Design Assumptions

		Conduct/Phase		Norm. Pwr Transfer				Phase Spacing	
Id No.	Descr.	No.	kcmil	Amps	MVA	Struct	Insul.	Horiz	Vertical
1.3.1	230-H Frame	1	954	600	239	WP	Susp.	20.0	0.0
1.3.2	230-Delta	1	954	600	239	WP-Davit	Susp.	16.0	8.0
1.3.3	230-Dlta Cpct	1	954	600	239	WP	Post	15.0	8.0
1.3.4	230-Splt Phs	2	795	600	239	WP-Davit	Susp.	16.0	16.0
	center arm							20.0	
1.3.5	230-Splt Cpct	2	795	600	239	WP	Post	15.0	16.0
1.3.6	115-Splt Phs	2	795	1200	239	WP-Davit	Susp.	12.0	12.0
	center arm							16.0	
1.3.7	115-Splt Cpct	2	795	1200	239	WP	Post	6.0	12.0
1.3.8	230-5-Wire	2	795	600	239	WH	Susp.	31.0	8.0
	center wire	1	954				Post	15.0	
1.3.9	230 HF w/cancel.	1	954	600	239	WP	Susp.	20.0	0.0
	Cancellation Loop		954			WP	Post	41.0	

Rural Configuration - Longer spans and no distribution underbuild

				Installed	Lowest Conductor Elevation (ft)	Mid Span		Min
		Span	Stucture	Pole Ht.	At Struct.	Design	Norm	ROW Width
Id No.	Descr.	ft.	Descript.	ft.		100°C	50°C	ft.
1.3.1A	230-H Frame	800	2-75 ft Cl H-1	65.5	50.5	27.7	31.7	80
1.3.2A	230-Delta	400	80 ft Cl H-1	70.0	37.0	28.2	29.9	49
1.3.3A	230-Dlta Cpct	400	70 ft Cl H-1	61.0	33.0	24.2	25.9	45
1.3.4A	230-Splt Phs	400	95 ft Cl H-2	83.5	34.5	26.5	28.0	55
1.3.5A	230-Splt Cpct	400	90 ft Cl H-2	79.0	35.0	27.0	28.5	46
1.3.6A	115-Splt Phs	400	80 ft Cl H-3	70.0	33.0	25.0	26.5	44
1.3.7A	115-Splt Cpct	400	75 ft Cl H-2	65.5	31.5	23.5	25.0	31
1.3.8A	230-5-Wire	600	2-80 ft Cl H-2	70.0	42.0	28.0	30.1	68
1.3.9A	230 HF w/cancel.	800	2-75 ft Cl H-1	65.5	50.5	27.7	31.7	93
	Cancellation Loop	400	35 ft Cl 5	29.5	29.5		22.4	

Suburban Configuration - Shorter spans with pole height and strength to accommodate distribution underbuild

				Installed	Lowest Conductor Elevation (ft)	Mid Span		Min
		Span	Stucture	Pole Ht.	At Struct.	Design	Norm	ROW Width
Id No.	Descr.	ft.	Descript.	ft.		100°C	50°C	ft.
1.3.1B	NONE							
1.3.2B	230-Delta	250	95 ft Cl 1	83.5	50.5	45.7	46.7	48
1.3.3B	230-Dlta Cpct	250	85 ft Cl 1	74.5	46.5	41.7	42.7	43
1.3.4B	230-Splt Phs	250	110 ft Cl H-1	97.0	48.0	43.8	44.8	53
1.3.5B	230-Splt Cpct	250	105 ft Cl H-1	92.5	48.5	44.3	45.3	44
1.3.6B	115-Splt Phs	250	95 ft Cl H-2	83.5	46.5	42.3	43.3	42
1.3.7B	115-Splt Cpct	250	90 ft Cl H-1	79.0	45.0	40.8	41.8	29
1.3.8B	NONE							
1.3.9B	NONE							

CAI COMMONWEALTH ASSOCIATES INC.

CALCULATION SHEET

CLIENT IIT Research

SHEET 3 OF

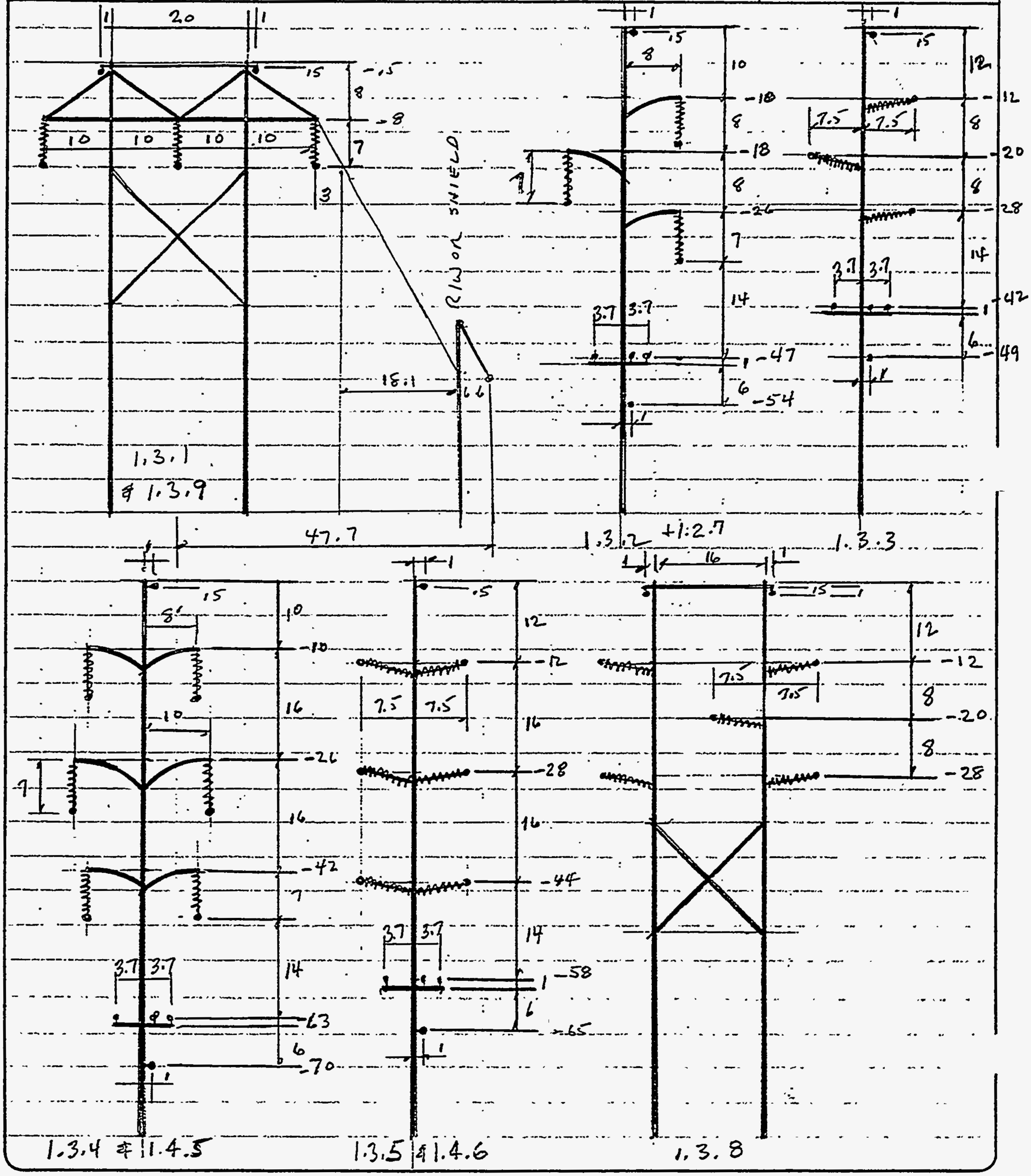
SUBJECT 230 kV Structure Configurations & Dimensions

JOB NUMBER 155001

CALC. BY/DATE RWW

CHECKED BY/DATE

REV.

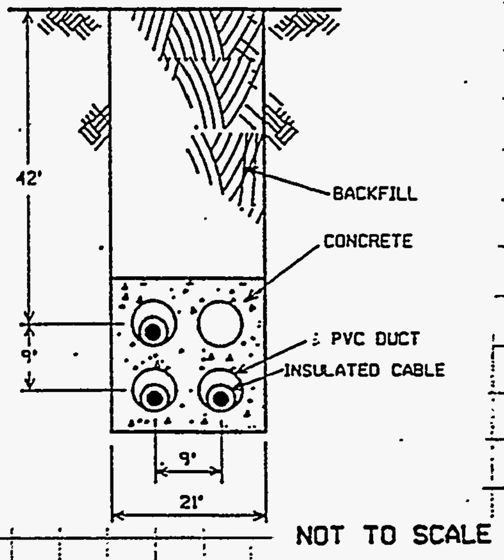


CAI COMMONWEALTH ASSOCIATES INC.

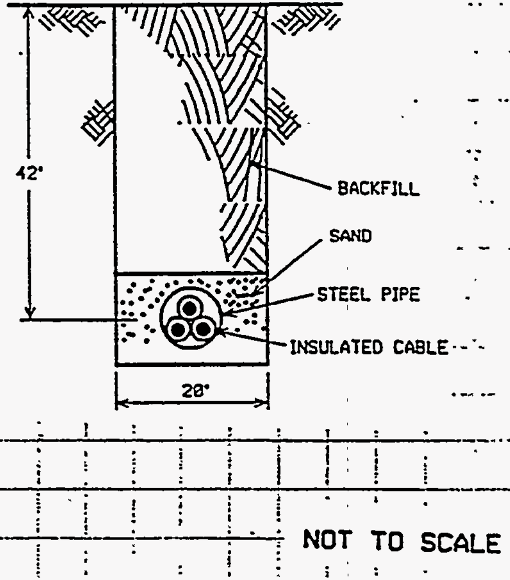
CALCULATION SHEET

CLIENT IIT RESEARCH		SHEET OF
SUBJECT 230 kV UNDERGROUND TRANSM - CONFIG + DIMENS		JOB NUMBER 115001
CALC. BY/DATE D. SHAFER 2/1/97	CHECKED BY/DATE	REV.

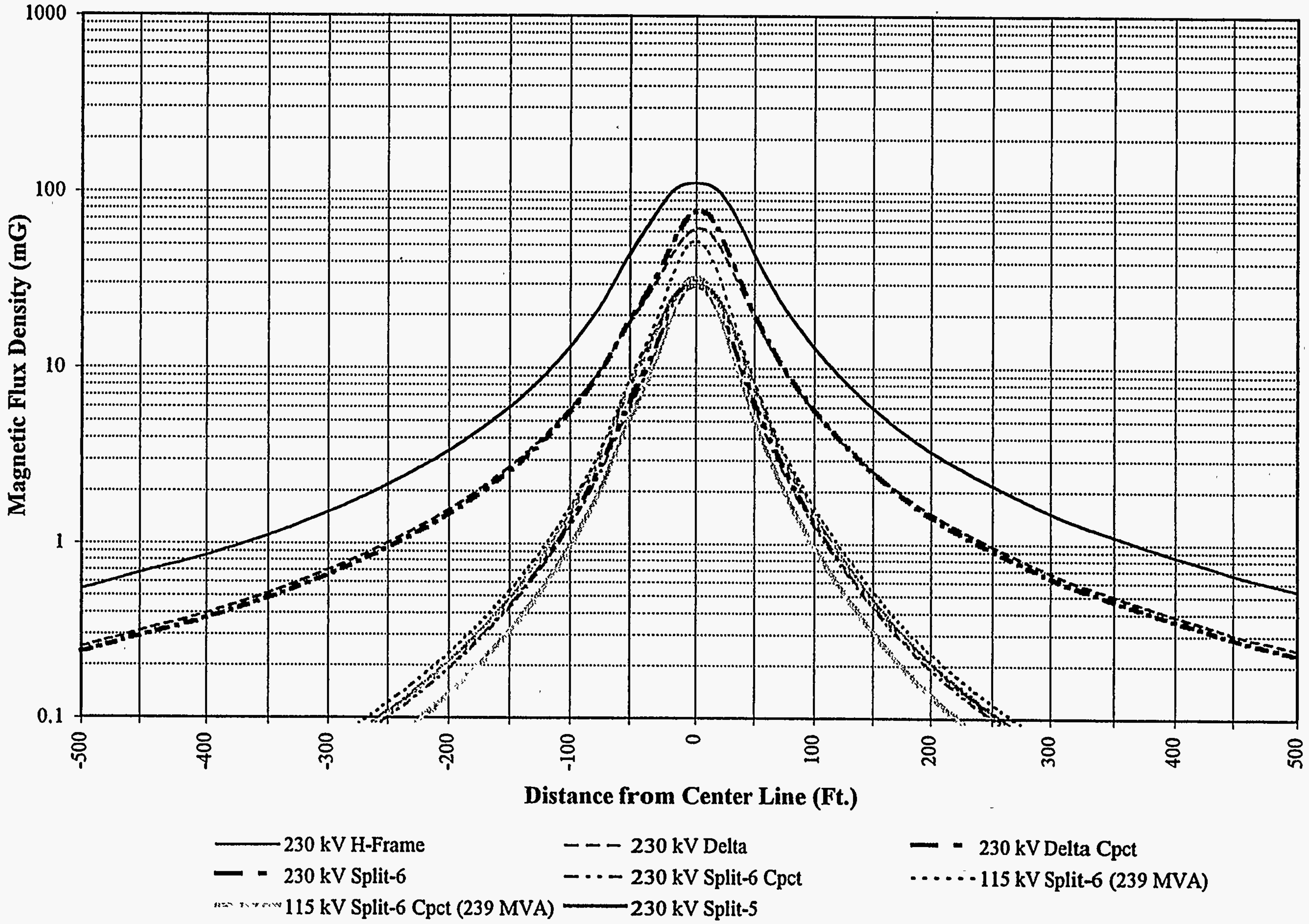
2×2 - 5" DUCT BANK
3-1c CABLES IN 3 DUCTS

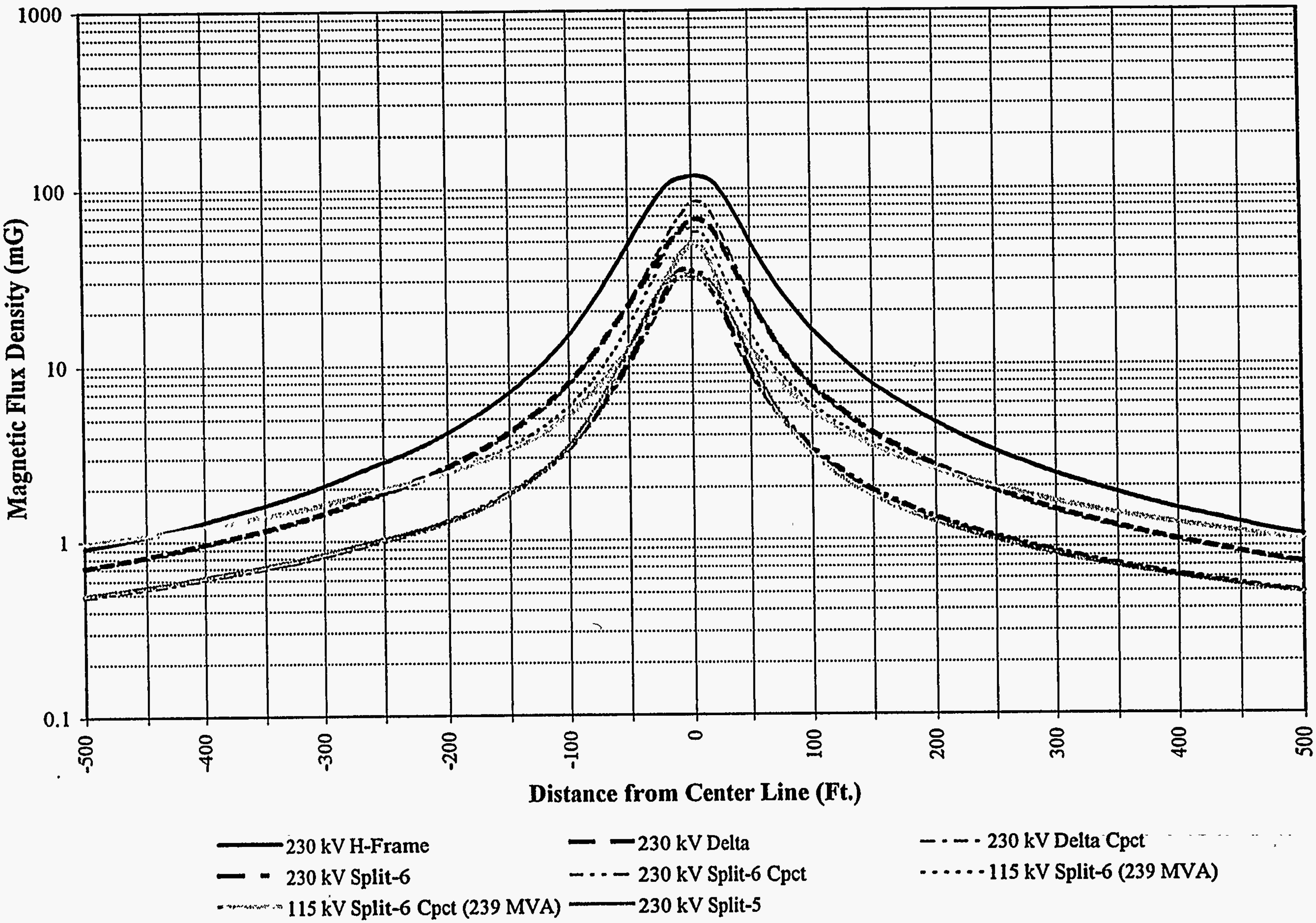


HPFF PIPE-TYPE CABLE
3-1c CABLES IN 8" PIPE



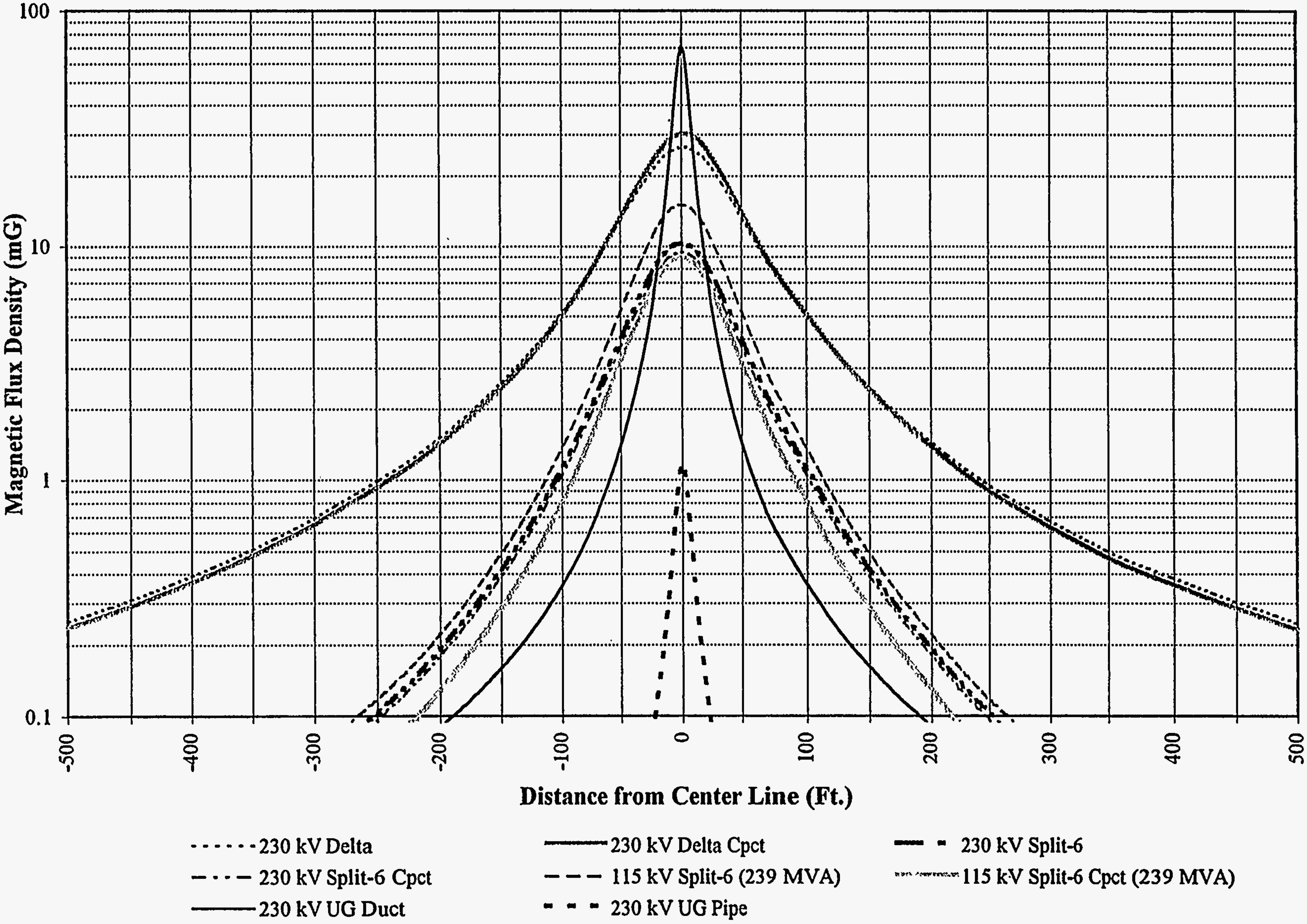
230 kV Rural Transmission Lines (Balanced)





230 kV Rural Transmission Lines (Unbalanced)

230 kV Suburban Transmission Lines (Balanced)



230 kV Suburban Transmission Lines (Unbalanced)

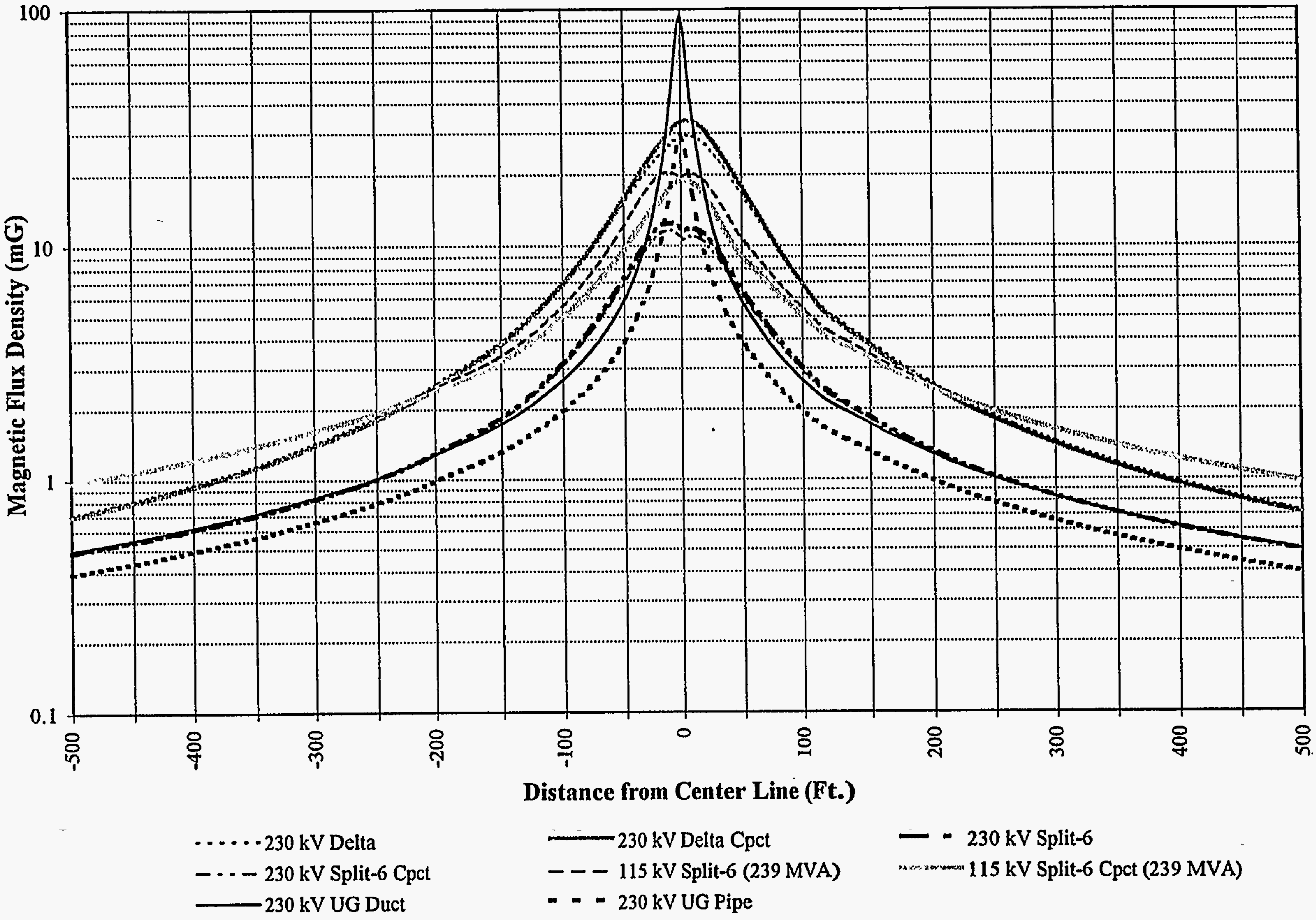


Table 3.4 345 kV Transmission Design Assumptions

		Conduct/Phase		Norm. Pwr Transfer				Phase Spacing	
Id No.	Descr.	No.	kcmil	Amps	MVA	Struct	Insul.	Horiz	Vertical
1.4.1	345-H Frame	2	954	1200	717	WH	Susp.	26.00	0.00
1.4.2	345-Delta	2	954	1200	717	WP-Davit	Susp.	25.00	12.00
1.4.3	345-Dlta Cpct	2	954	1200	717	WH	V-Str.	20.00	25.00
1.4.4	345-Splt Phs	4	954	1200	717	Steel	V-Str.	20.00	24.00
	center arm							28.00	
1.4.5	230-Splt Phs	2	954	1800	717	WP-Davit	Susp.	16.00	16.00
	center arm							20.00	
1.4.6	230-Splt Cpct	2	954	1800	717	WP	Post	15.00	16.00
1.4.7	345-5-Wire	4	954	1200	717	WH	V-Str.	20.00	20.00
	center wire	2	954					0.00	
1.4.8	345 HF w/cancel	2	954	1200	717	WH	Susp.	26	0.00
	Cancellation Loop		954			WP	Post	53.0	

Rural Configuration - Longer spans and no distribution underbuild

					Lowest Conductor Elevation (ft)			Min
				Installed		Mid Span		ROW
		Span	Stucture	Pole Ht.	At Struct.	Design	Norm	Width
Id No.	Descr.	ft.	Descript.	ft.		100°C	50°C	ft.
1.4.1A	345-H Frame	800	2-80 ft Cl H-4	70.0	50.5	27.7	31.7	100
1.4.2A	345-Delta	400	95 ft Cl H-3	83.5	38.0	29.2	30.9	68
1.4.3A	345-Dlta Cpct	600	2-110 ft Cl H-3	97.0	46.0	30.8	33.6	62
1.4.4A	345-Splt Phs	400	125 ft Cl H-6	110.5	36.5	27.7	29.4	69
1.4.5A	230-Splt Phs	400	95 ft Cl H-3	83.5	34.5	25.7	27.4	55
1.4.6A	230-Splt Cpct	400	90 ft Cl H-2	79.0	35.0	26.2	27.9	49
1.4.7A	345-5-Wire	600	2-125 ft Cl H-4	110.5	44.5	29.3	32.1	63
1.4.8A	345 HF w/cancel	800	2-80 ft Cl H-4	70.0	50.5	27.7	31.7	115
	Cancellation Loop	400	35 ft Cl 5	29.5	29.5		22.4	

Suburban Configuration - Shorter spans with pole height and strength to accommodate distribution underbuild

					Lowest Conductor Elevation (ft)			Min
				Installed		Mid Span		ROW
		Span	Stucture	Pole Ht.	At Struct.	Design	Norm	Width
Id No.	Descr.	ft.	Descript.	ft.		100°C	50°C	ft.
1.4.1B	NONE							
1.4.2B	345-Delta	250	110 ft Cl H-2	97.0	51.5	46.7	47.7	67
1.4.3B	NONE							
1.4.4B	345-Splt Phs	250	120 ft Steel	120.0	46.0	41.2	42.2	67
1.4.5B	230-Splt Phs	250	110 ft Cl H-1	97.0	48.0	43.2	44.2	53
1.4.6B	230-Splt Cpct	250	105 ft Cl H-1	92.5	48.5	43.7	44.7	44
1.4.7B	NONE							
1.4.8B	NONE							

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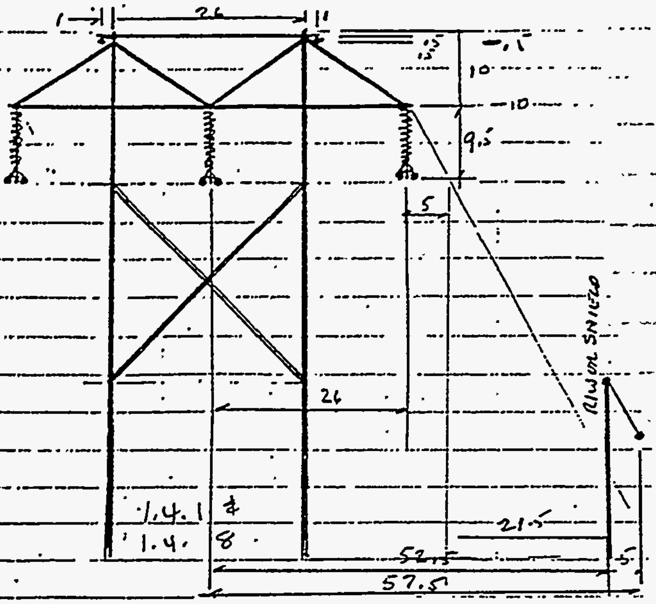
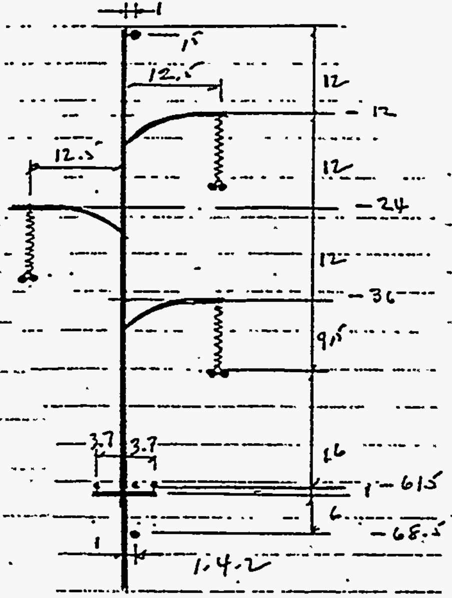
CALCULATION SHEET

CLIENT IIT RESEARCH		SHEET 4 OF
SUBJECT 345 KV STRUCTURE CONFIGURATIONS & DIMENSIONS		JOB NUMBER 15500K
CALC. BY/DATE	CHECKED BY/DATE	REV.



1.4.1 & 1.4.8



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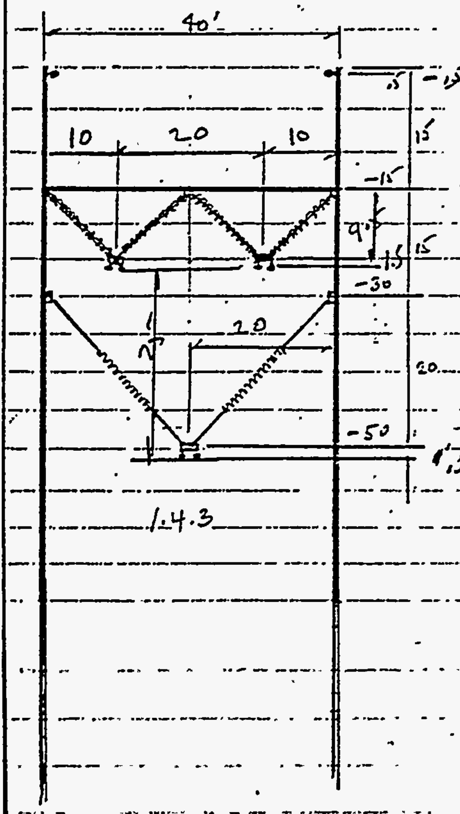

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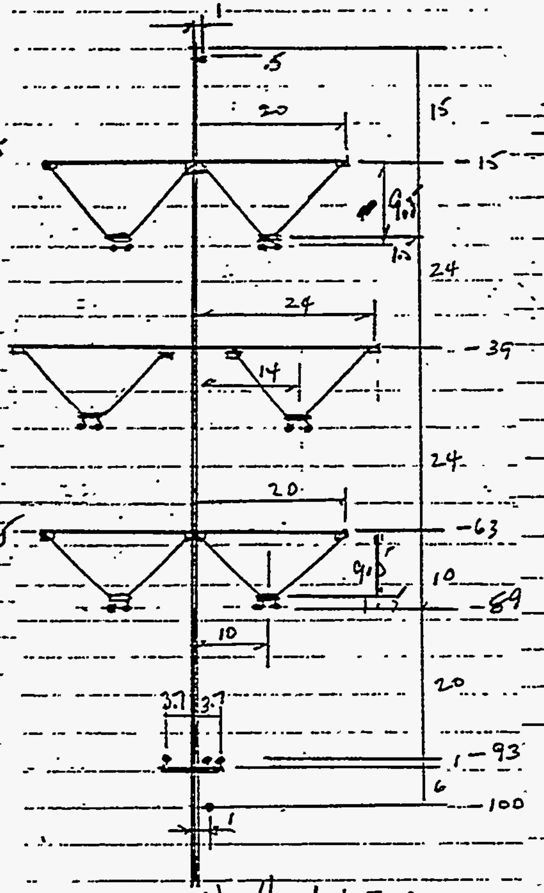

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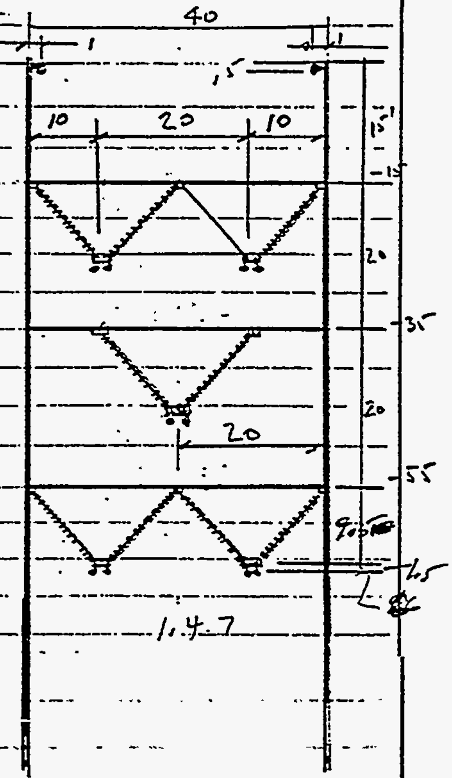


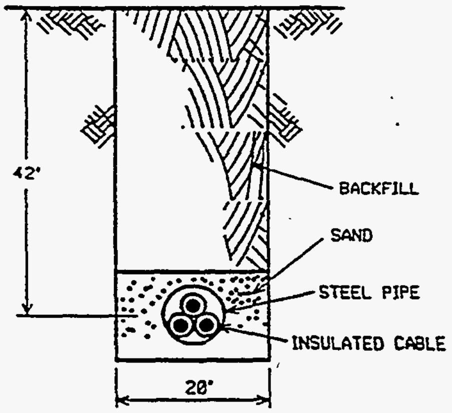
1.4.7

CALCULATION SHEET

CLIENT IIT RESEARCH		SHEET OF
SUBJECT 345 KV UNDERGROUND TRANSMI CONF & DIMENS		JOB NUMBER 115001
CALC. BY/DATE D. SHAFER 2/1/97	CHECKED BY/DATE	REV.

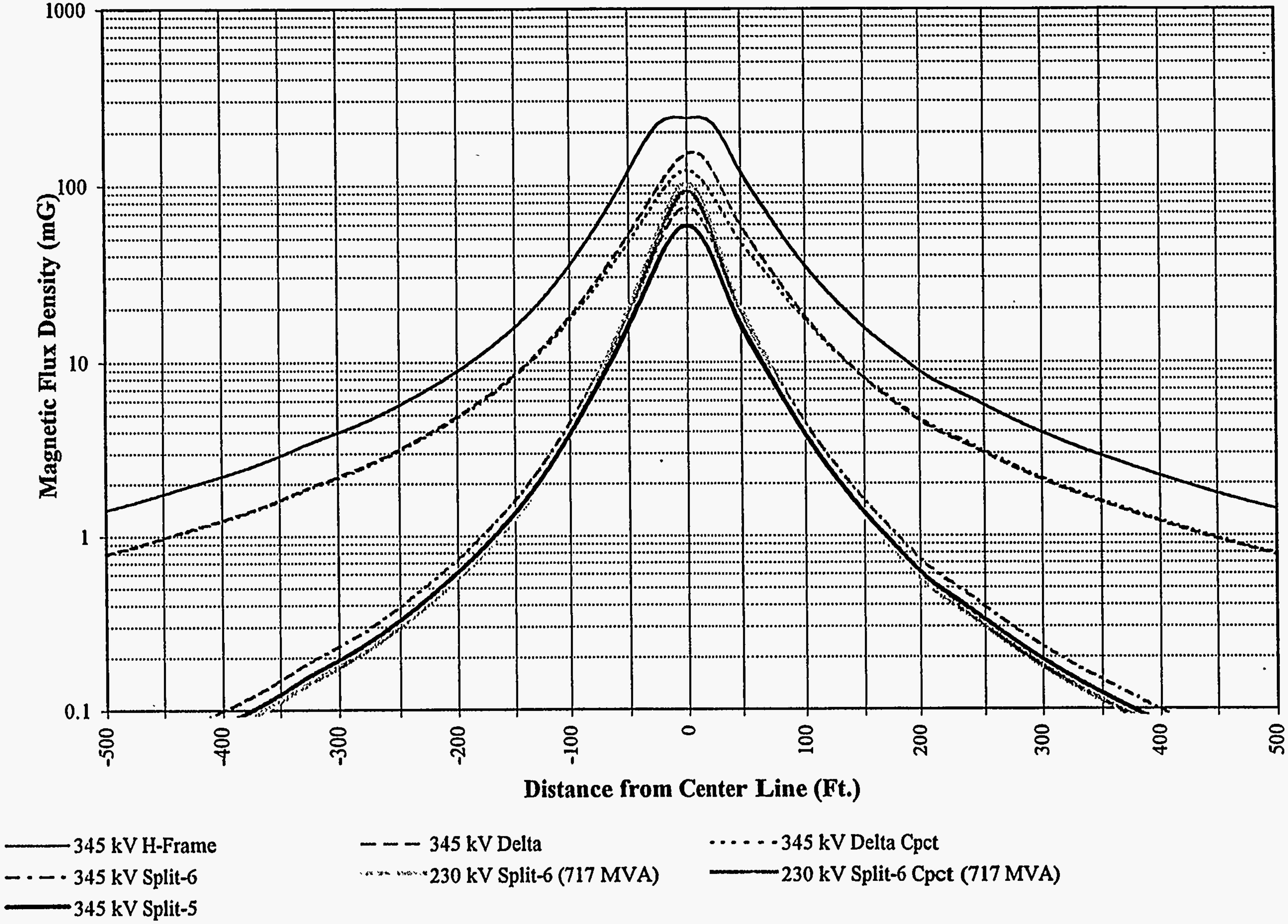
1.4.9

HPFF PIPE-TYPE CABLE
3-1C CABLES IN 10" PIPE

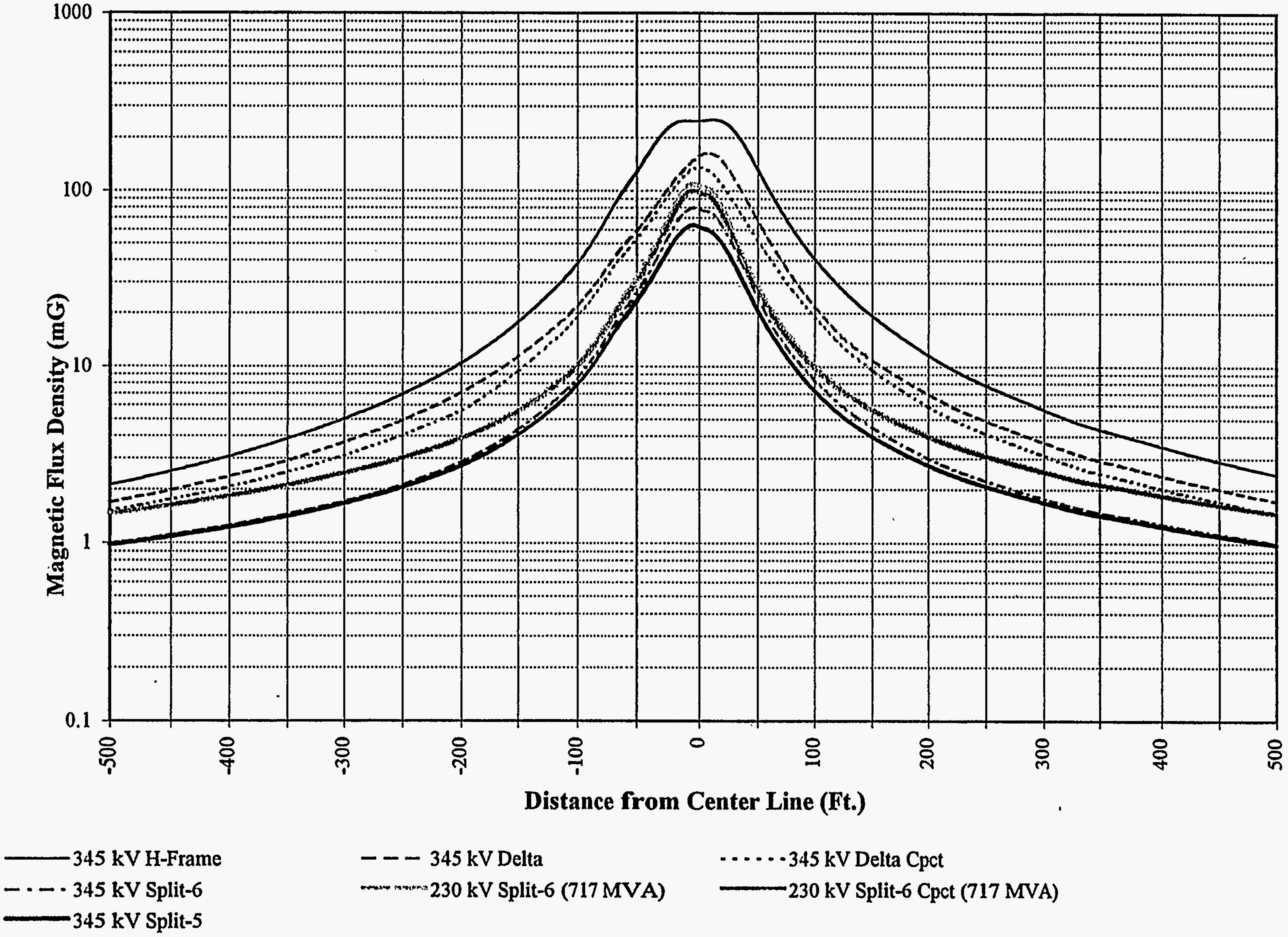


NOT TO SCALE

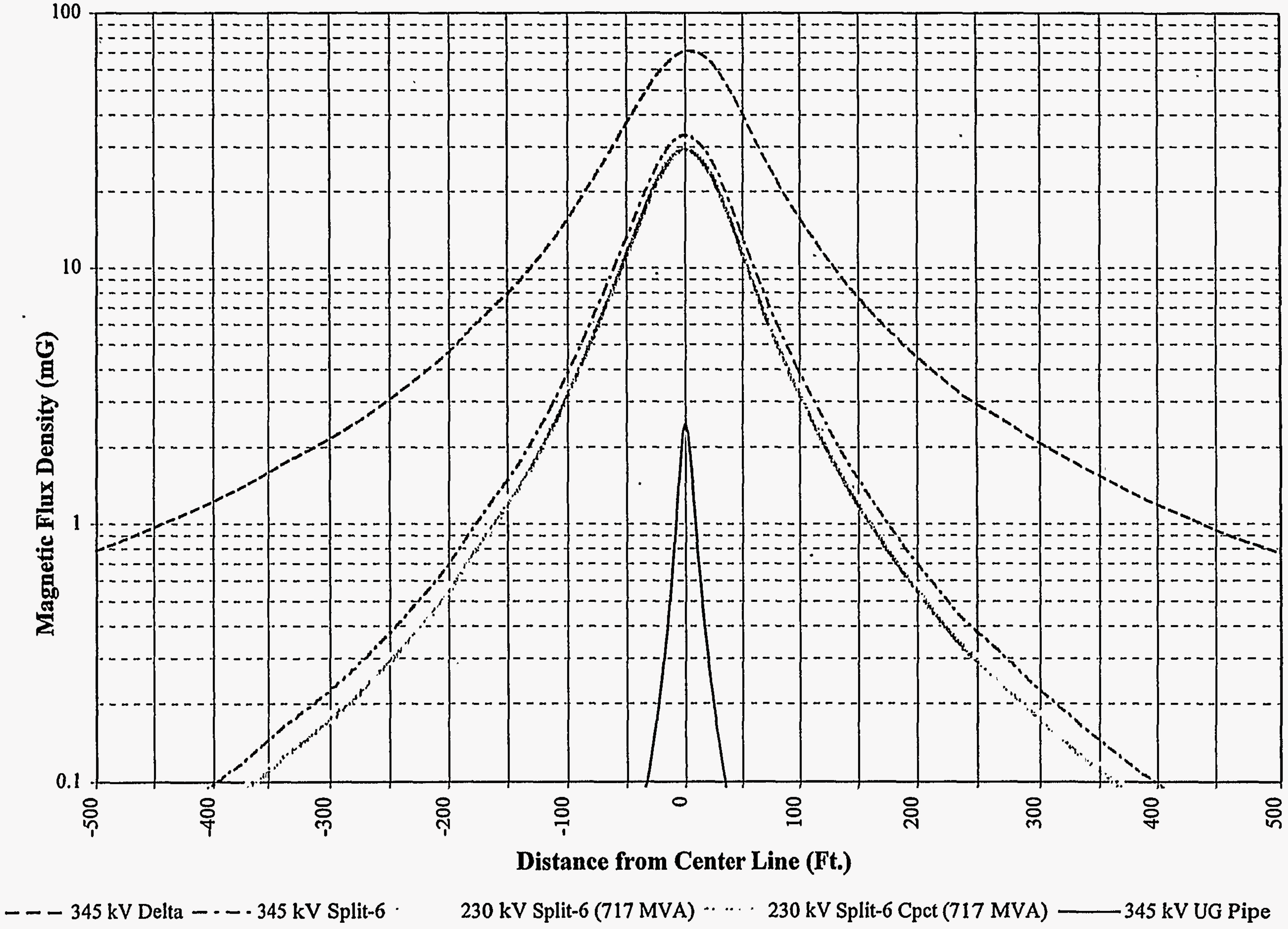
345 kV Rural Transmission Lines (Balanced)



345 kV Rural Transmission Lines (Unbalanced)



345 kV Suburban Transmission Lines (Balanced)



345 kV Suburban Transmission Lines (Unbalanced)

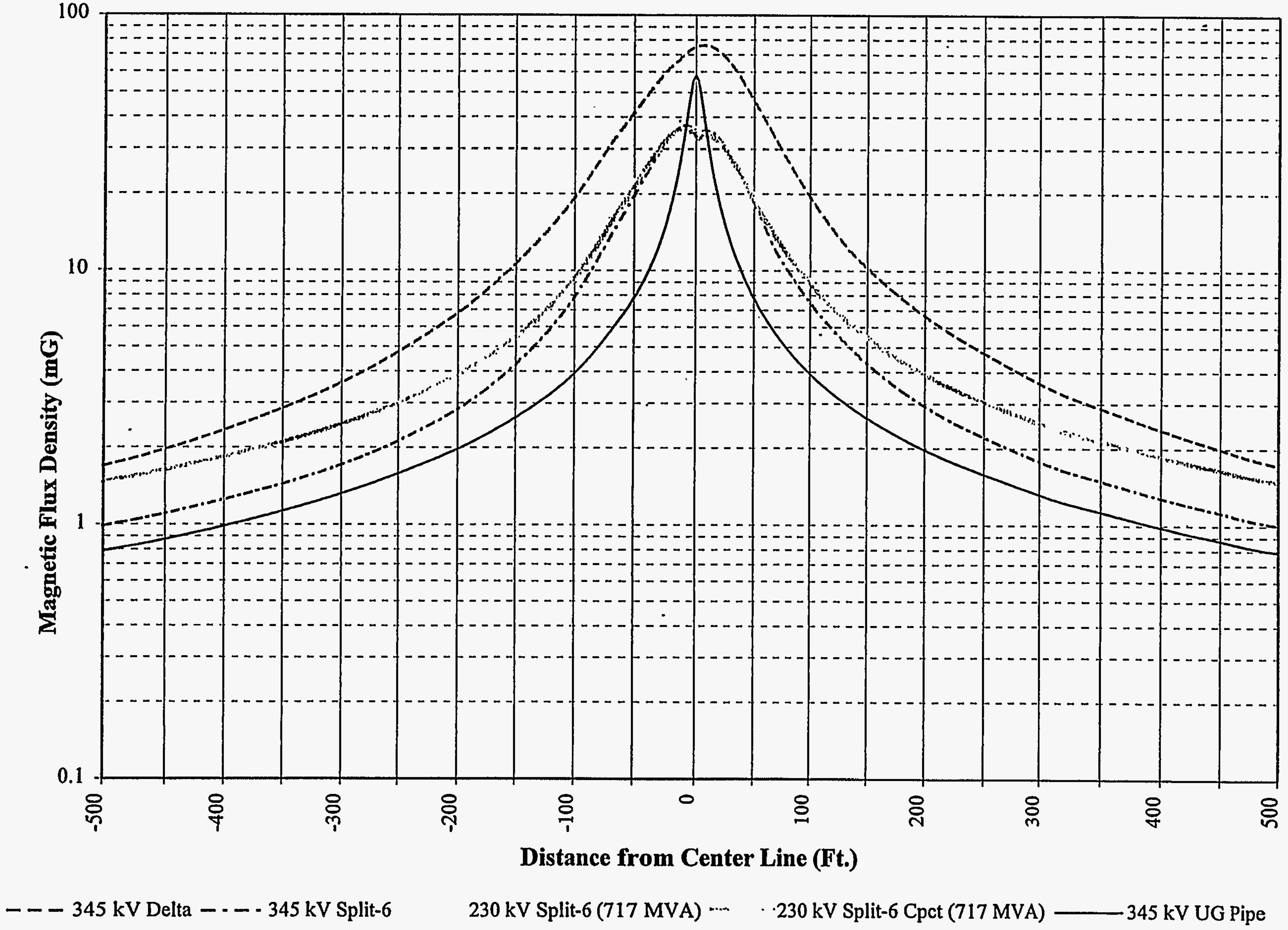


Table 3.5 500 kV Transmission Design Assumptions

		Conduct/Phase		Norm. Pwr Transfer				Phase Spacing	
Id No.	Descr.	No.	kcmil	Amps	MVA	Struct	Insul.	Horiz	Vertical
1.5.1	500-H Frame	3	954	1800	1559	SH	V-Str.	24.00	0.00
1.5.2	500-Delta	3	954	1800	1559	LS	V-Str.	35.00	30.00
1.5.3	500-Vertical	3	954	1800	1559	SP-Davit	V-Str.	0.00	25.00
1.5.4	500-Splt Phs	6	954	1800	1559	SP-Davit	V-Str.	25.00	25.00
	center arm							40.00	
1.5.5	345-Splt Phs	4	954	2609	1559	WP-Davit	V-Str.	20.00	24.00
	center arm							28.00	
1.5.6	500-HF w/cancel.	3	954	1800	1559	SH	V-Str.	24.00	0.00
	Cancellation Loop		954			WP	Post	58.0	

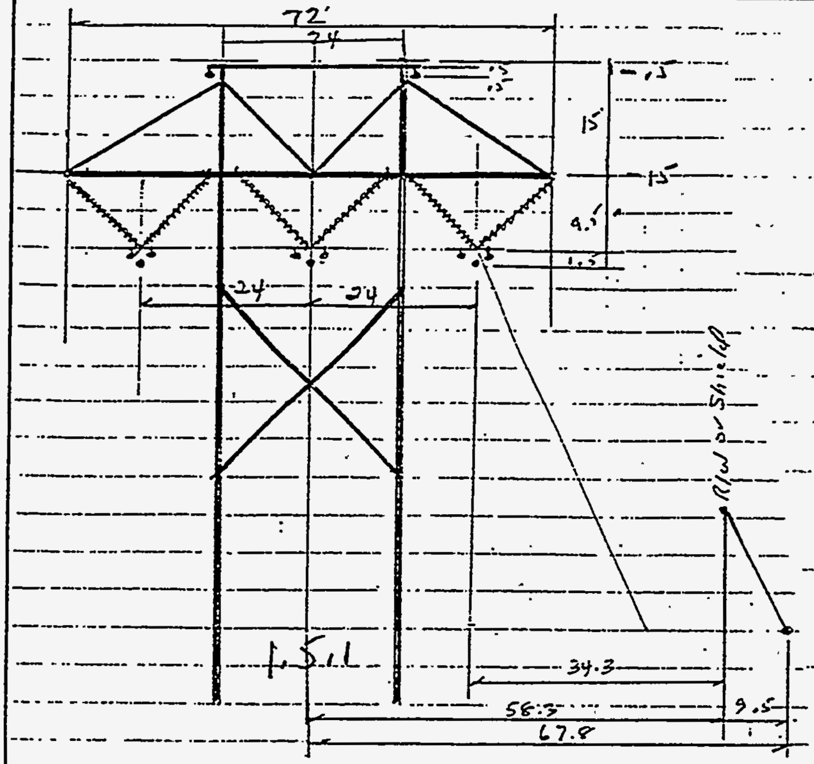
Rural Configuration - Longer spans and no distribution underbuild

					Lowest Conductor Elevation (ft)			Min
				Installed		Mid Span		ROW
		Span	Stucture	Pole Ht.	At Struct.	Design	Norm	Width
Id No.	Descr.	ft.	Descript.	ft.		100°C	50°C	ft.
1.5.1	500-H Frame	1200	100 ft SH	100.0	74.0	32.6	38.7	117
1.5.2	500-Delta	1200	120 ft LS	120.0	74.0	32.6	38.7	117
1.5.3	500-Vertical	800	130 ft SP	130.0	54.0	31.2	35.2	74
1.5.4	500-Splt Phs	800	130 ft SP	130.0	54.0	31.2	35.2	103
1.5.5	345-Splt Phs	400	125 ft Cl H-6	110.5	36.5	27.7	29.4	71
1.5.6	500-HF w/cancel.	1200	100 ft SH	100.0	74.0	32.6	38.7	136
	Cancellation Loop	600	45 ft Cl 5	38.5	38.5		26.1	

CAI COMMONWEALTH ASSOCIATES INC.

CALCULATION SHEET

CLIENT IIT Research		SHEET 5 OF
SUBJECT 500 kV Structure Configurations & Dimensions		JOB NUMBER 155001
CALC. BY/DATE	CHECKED BY/DATE	REV.



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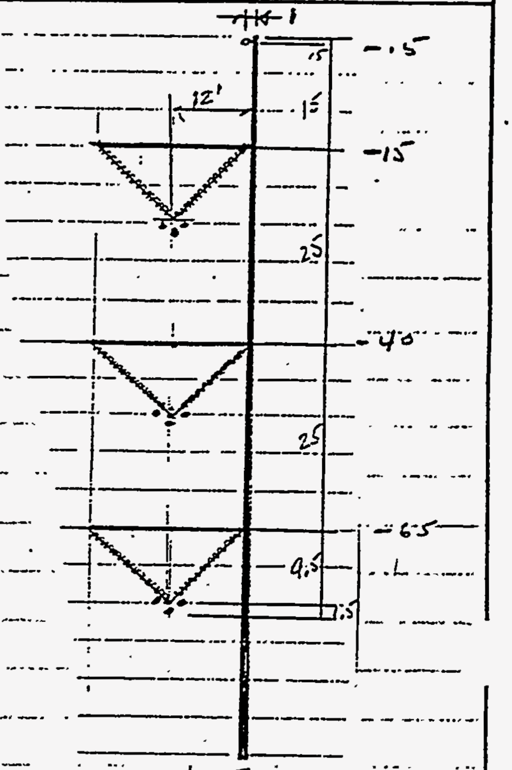

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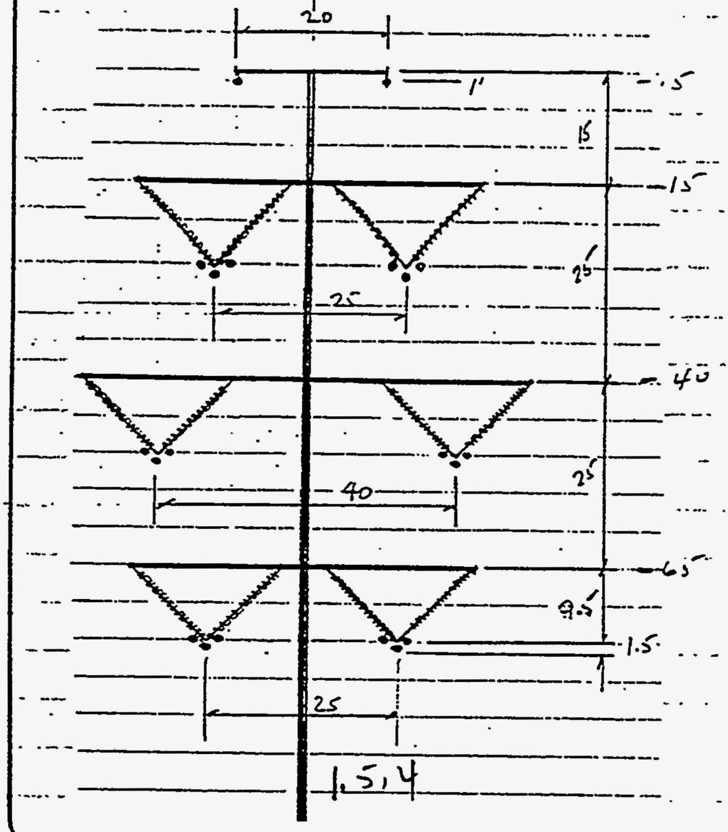

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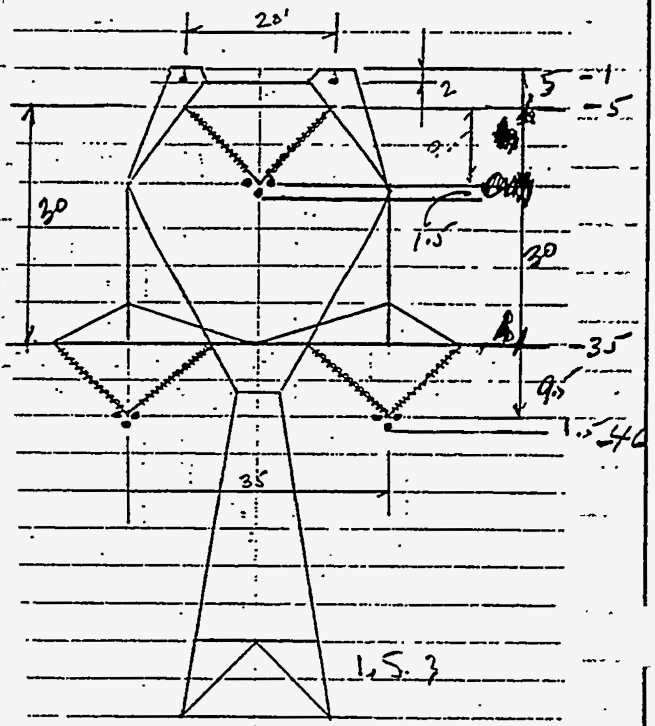
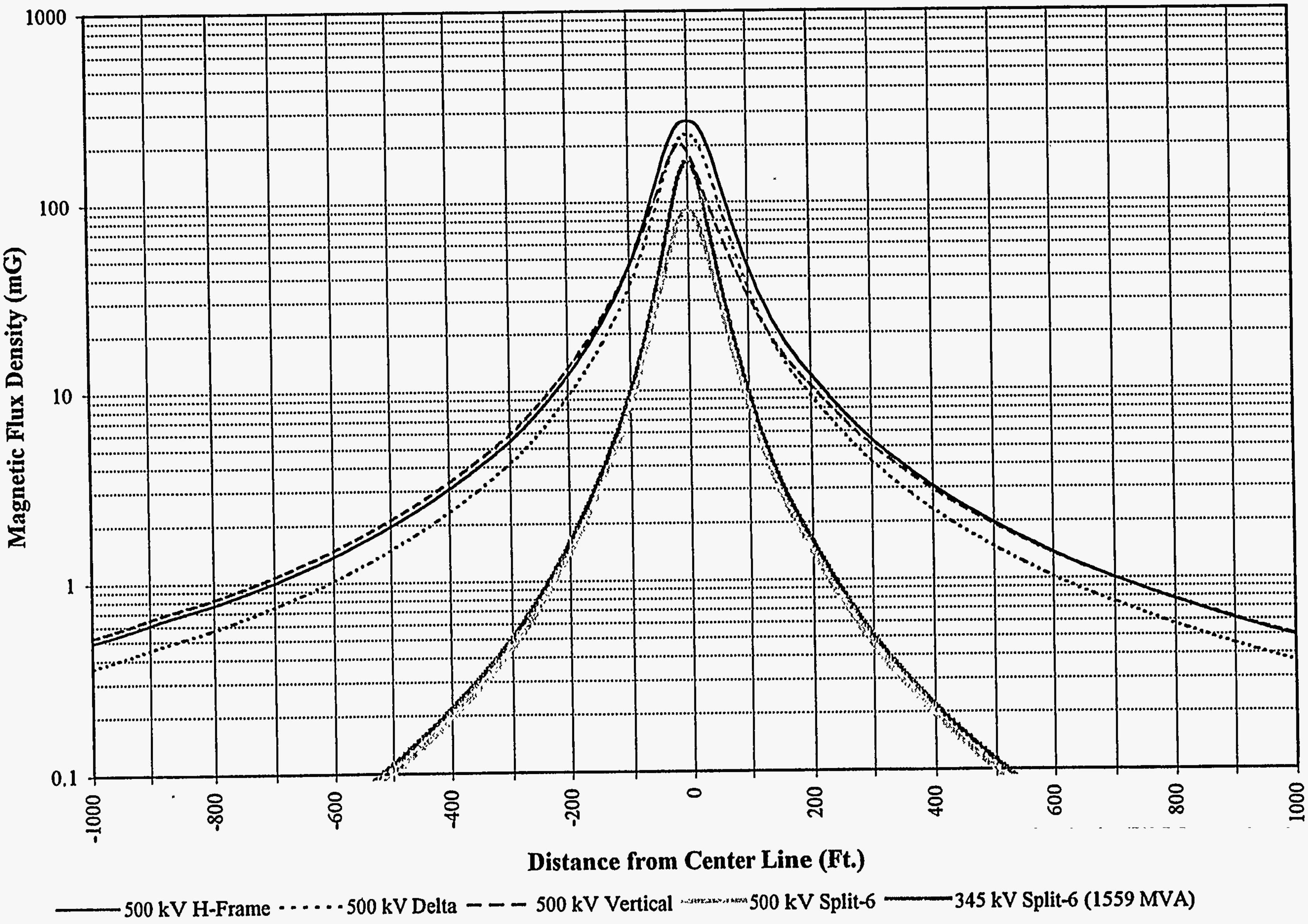


1.5.3

500 kV Transmission Lines (Balanced)



500 kV Transmission Lines (Unbalanced)

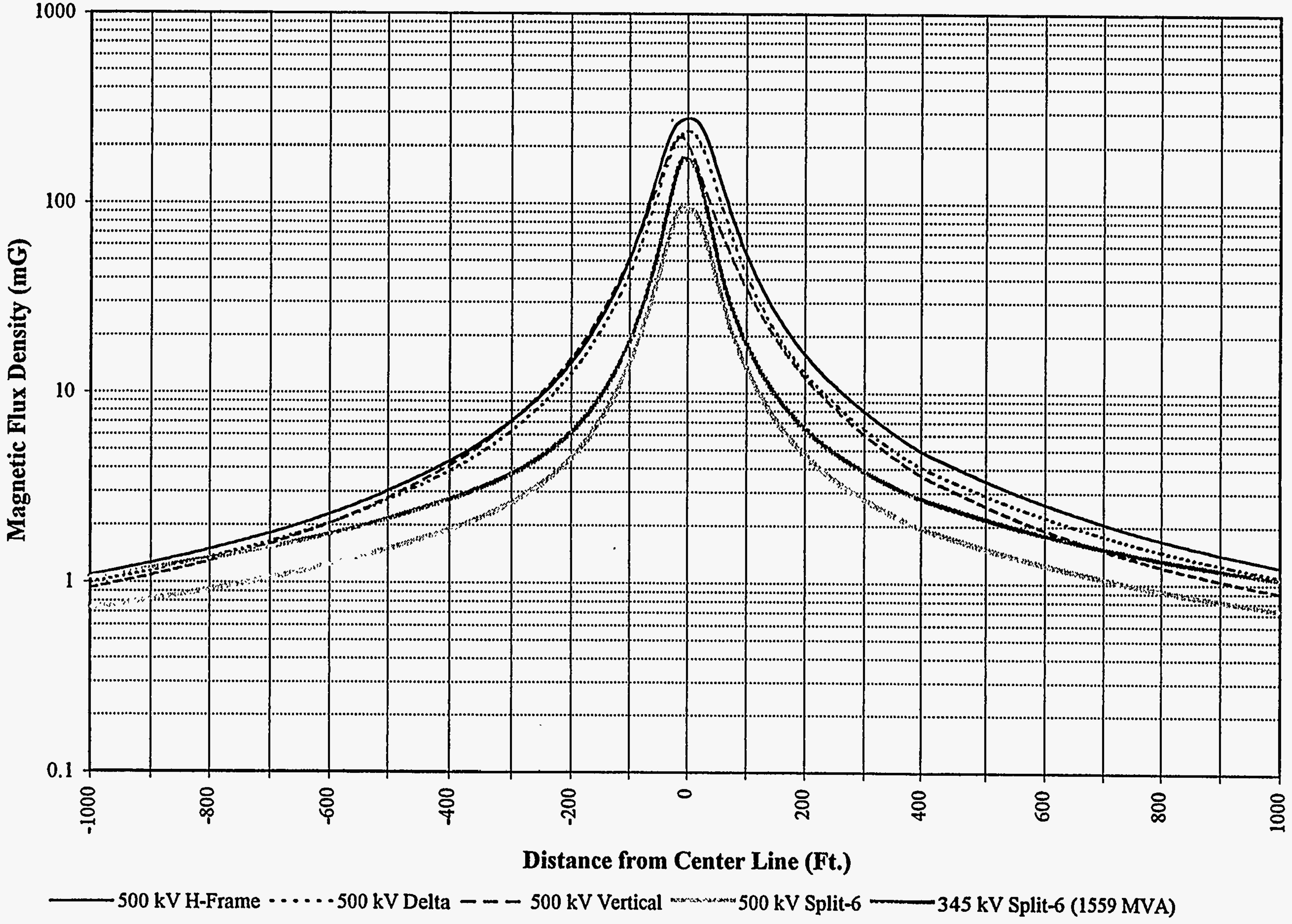


Table 3.6 765 kV Transmission Design Assumptions

		Conduct/Phase		Norm. Pwr Transfer				Phase Spacing	
Id No.	Descr.	No.	kcmil	Amps	MVA	Struct	Insul.	Horiz	Vertical
1.6.1	765-H Frame	4	954	2400	3180	SH	V-Str.	32.00	0.00
1.6.2	500-Splt Phs	6	954	3672	3180	SP-Davit	V-Str.	25.00	25.00
	center arm							40.00	
1.6.3	765 HF w/cance	4	954	2400	3180	SH	V-Str.	32.00	0.00
	Cancellation Loop		954			WP	Post	69.0	

Rural Configuration - Longer spans and no distribution underbuild

					Lowest Conductor Elevation (ft)			
						Mid Span		
Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	At Struct.	Design 100°C	Norm 50°C	ROW Width ft.
1.6.1A	765-H Frame	1200	115 ft SH	115.0	80.0	38.6	44.7	138
1.6.2A	500-Splt Phs	800	130 ft SP	130.0	54.0	31.2	35.2	103
1.6.3A	765 HF w/cancel	1200	115 ft SH	115.0	80.0	38.6	44.7	158
	Cancellation Loop	600	45 ft Cl 5	38.5	38.5		26.1	

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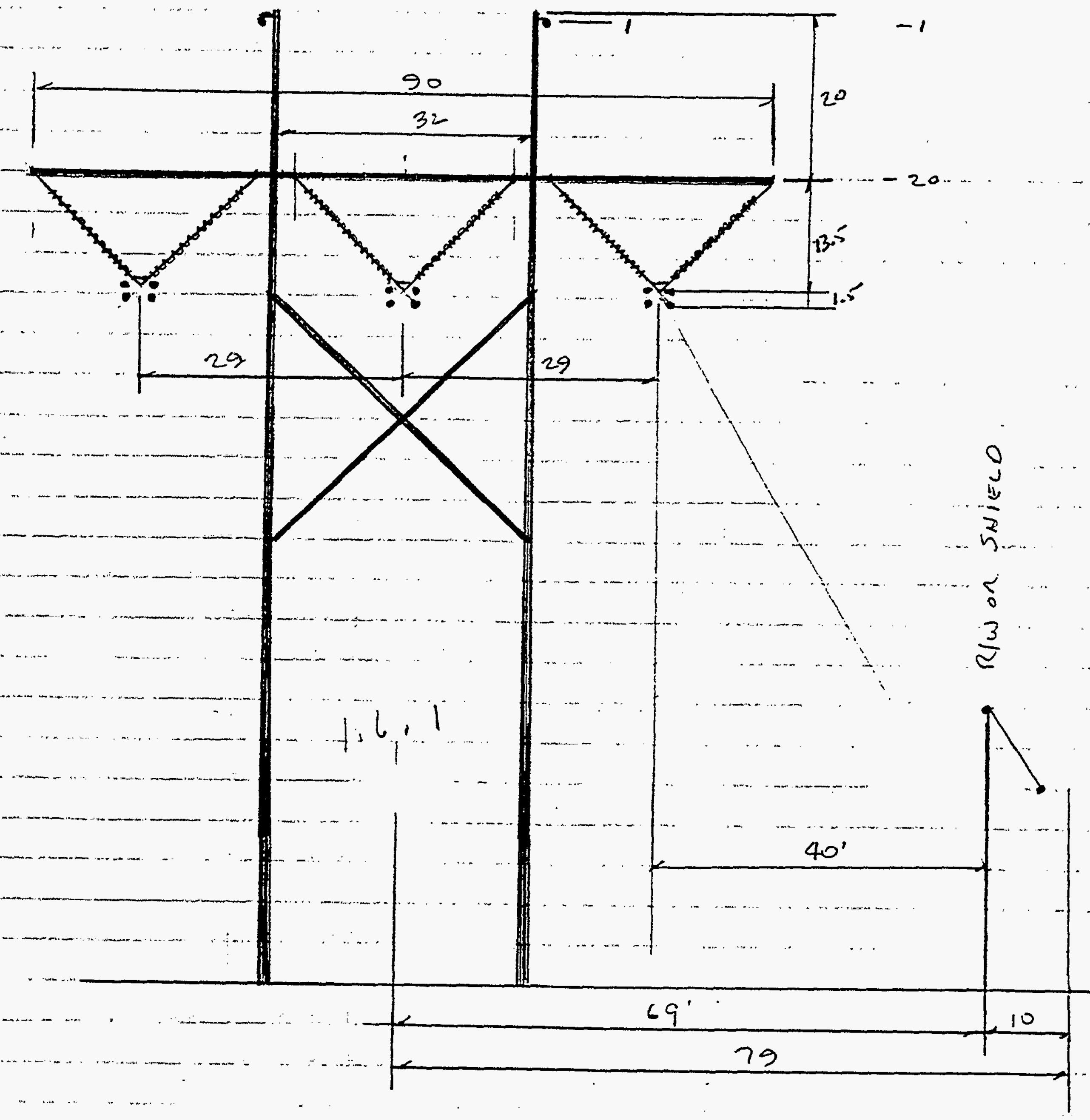
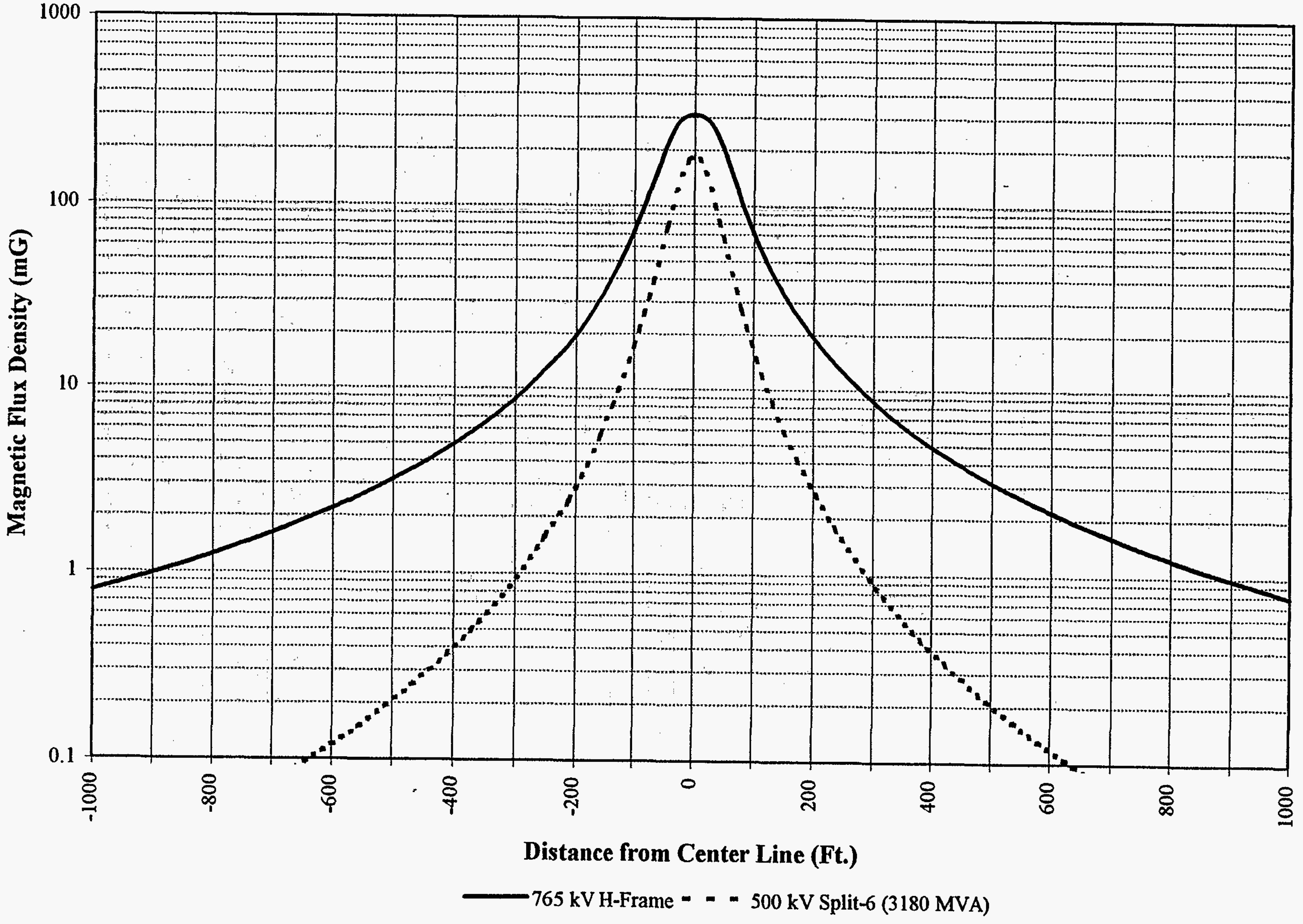
CALCULATION SHEET

CLIENT IIT Research		SHEET 6 OF
SUBJECT 765 kV STRUCTURE CONFIGURATION & DIMENSIONS		JOB NUMBER 155001
CALC. BY/DATE RGM	CHECKED BY/DATE	REV.



765 kV Transmission Lines (Balanced)



765 kV Transmission Lines (Unbalanced)

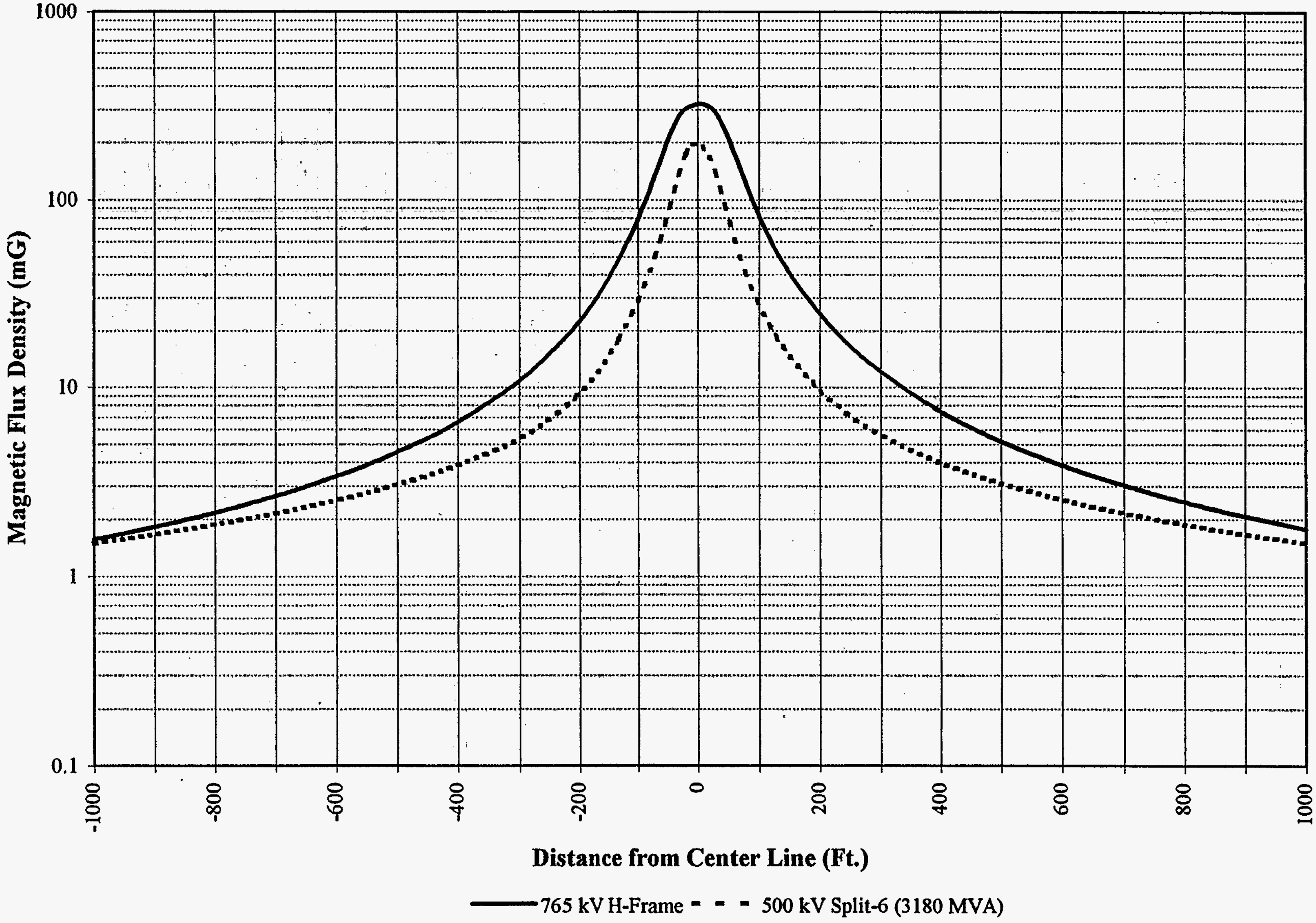


Table_4 - General Design Assumptions - Underground Transmission

1. Nominal Voltages: 69, 115, 230, and 345

2. Reference Load Level

69 kV	600 amps	72	MVA
115 kV	600 amps	120	MVA
230 kV	600 amps	239	MVA
345 kV	1200 amps	717	MVA

3. The following solid dielectric cables options are considered:

69 kV	500 kcmil, cu XLP	2x2 - 5" PVC Duct
115 kV	750 kcmil, al XLP	2x2 - 5" PVC Duct
230 kV	1000 kcmil, al XLP	2x2 - 5" PVC Duct

4. The following pipe-type options are considered:

69 kV	HPGF	500 kcmil, cu	6" Steel pipe
115 kV	HPGF	750 kcmil, cu	6" Steel pipe
230 kV	HPFF	1000 kcmil, cu	8" Steel pipe
345 kV	HPFF	2500 kcmil, cu	10" Steel pipe

5. Costs are provided for suburban and urban locations.

<u>Suburban Assumptions</u>

a. 10 mile line located on street right-of-way but not under pavement.
b. 90% of line requires normal excavation, 10% requires rock excavation
c. Line crosses 2 major roads or railroads and 9 other road crossings

<u>Urban Assumptions</u>

a. 5 mile line underneath street, requiring removal and replacement of pavement
b. 90% of line requires normal excavation, 10% requires rock excavation

APPENDIX C

HIGH VOLTAGE DISTRIBUTION LINE

DESIGN ASSUMPTIONS
AND
PREDICTED MAGNETIC FIELDS

Table_5 - General Design Assumptions - Overhead Distribution

1. Nominal Voltages:
   7.6 kV single phase
   13.2 kV three-phase
   34.5 kV three-phase

2. Reference Load Level - amps

		Rural	Suburban
7.6 kV	single-phase	100	200
13.2 kV	three-phase	300	600
34.5 kV	three-phase	300	600

3. All designs do <u>not</u> include overhead ground wires

4. All designs are based on NESC Heavy Load

5. Costs are provided for typical rural and suburban locations.
   Rural Assumptions
   a. 10 mile line with average span of 400 feet
   b. One deadend or 90° angle every two miles
   c. Two angle structures every two miles

   Suburban Assumptions
   a. 5 mile line with average span 250 feet
   b. One deadend or 90° angle every mile
   c. Two angle structures every mile

6. Cost estimates do not include, transformers, switches, capacitors, arresters, secondary wiring, service drops, meters, and related equipment which typically comprise a distribution system.

Table_6 Distribution Conductor Characteristics

Conductor Physical Characteristics

Conductor			Cable	Weight	Rated	Resist.
Code Word	Size	Strand Al/St	Diameter inches	/1000 ft lbs	Strength lbs	50°C ohm/mi
Penguin	4/0 AWG	6/1	0.563	290.8	8,350	0.5530
Linnet	336.4 kcmil	26/7	0.720	463.0	14,100	0.2996
Drake	795.0 kcmil	26/7	1.108	1094.0	31,500	0.1278

Conductor Ampacity and Temperature

Conductor		100°C Conduct.[1] Amps	Conductor Temperature[2] in °C			
Code Word	Size		100 A	200 A	300 A	600 A
Penguin	4/0 AWG	374	34.2	42.6	59.5	-
Linnet	336.4 kcmil	574	33.7	37.8	45.0	-
Drake	795.0 kcmil	993	-	-	37.9	50.8

[1] Conductor ampacity at 100°C conductor temperature and 40°C (104°F)ambient.

[2] Conductor temperature at given amps and 25°C (77°F) ambient.

Conductor Sag (feet)

Span ft.	Final Sag for listed spans and conductor temp. of 100°C			Final Sag for listed spans and conductor temp. of 50°C		
	Penguin 4/0 AWG	Linnet 336.4	Drake 795.0	Penguin 4/0 AWG	Linnet 336.4	Drake 795.0
Bare Conductor						
250	4.70	4.39	4.25	3.60	3.31	3.21
400	8.33	8.10	7.97	6.82	6.61	6.52

Span ft.	Final Sag for listed spans and conductor temperature of 120°F			
Hendrix Aerial Cable (Total Sag of messenger and cable)				
	336.4 15 kV	795.0 15 kV	336.4 35 kV	795.0 35 kV
250	7.19	7.74	7.92	8.25

Table 7.1 13.2 kV Distribution Design Assumptions

- See sketch for phase spacing dimensions

		Conduct/Phase		Neutral	Norm Load - Amps			
Id No.	Description	No	kcmil	Conductor	Rural	Suburban	Struct	Insul.
	Three-phase options							
2.1.1	13 kV X- Arm	1	795	4/0	300	600	WP	Pin
2.1.2	13 kV Delta	1	795	4/0	300	600	WP	Post
2.1.3	13 kV Hendrix	1	795H1	795H1-mssg	300	600	WP	
2.1.4	13 kV 6-W X-Arm	2	336	4/0	300	600	WP	Pin
2.1.5	13 kV 6-W Hendri	2	336H1	336H1-mssg	300	600	WP	
2.1.6	34 kV X-Arm	1	336	4/0	115	230	WP	Pin
2.1.7	13 kV 5-Wire	2	336	4/0	300	600	WP	Pin/Post
	center wire	1	795	4/0				
	Single-phase options		AWG					
2.3.1	7.6 kV 1-ph	1	4/0	4/0	100	200	WP	Pin
2.3.2	7.6 kV 1-ph Tall	1	4/0	4/0	100	200	WP	Post

RURAL CONFIGURATIONS

					Lowest Conductor Elevation (ft)			
					Phase Conductor		Neutral Conductor	
Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	At Struct.	Mid Span Norm 50°C	At Struct.	Mid Span Norm 50°C
Three-phase options								
2.1.1A	13 kV X- Arm	400	45 ft Cl H-1	38.5	37.5	31.0	31.5	24.7
2.1.2A	13 kV Delta	400	50 ft Cl 1	43.0	38.0	31.5	32.0	25.2
2.1.3A	13 kV Hendrix	250	40 ft Cl 4	34.0	32.0	24.3	33.0	25.3
2.1.4A	13 kV 6-W X-Arm	400	50 ft Cl H-3	43.0	38.0	31.4	32.0	25.2
2.1.5A	13 kV 6-W Hendrix	250	40 ft Cl H-1	34.0	32.0	24.8	33.0	25.8
2.1.6A	34 kV X-Arm	400	45 ft Cl 1	38.5	37.5	30.9	31.5	24.7
2.1.7A	13 kV 5-Wire	400	55 ft Cl H-2	47.5	38.5	31.9	32.5	25.7
Single-phase options								
2.3.1A	7.6 kV 1-ph	400	45 ft Cl 5	38.5	38.5	31.7	32.5	25.7
2.3.2A	7.6 kV 1-ph Tall	400	55 ft Cl 4	47.5	46.5	39.7	46.5	39.7

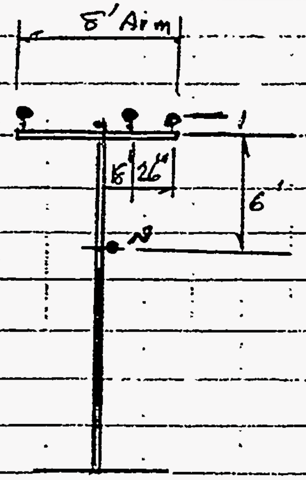
SUBURBAN CONFIGURATIONS

					Lowest Conductor Elevation (ft)			
					Phase Conductor		Neutral Conductor	
Id No.	Descr.	Span ft.	Stucture Descript.	Installed Pole Ht. ft.	At Struct.	Mid Span Norm 50°C	At Struct.	Mid Span Norm 50°C
2.1.1B	13 kV X- Arm	250	40 ft Cl 3	34.0	33.0	29.8	27.0	23.4
2.1.2B	13 kV Delta	250	45 ft Cl 3	38.5	33.5	30.3	27.5	23.9
2.1.3B	13 kV Hendrix	250	40 ft Cl 4	34.0	32.0	24.3	33.0	25.3
2.1.4B	13 kV 6-W X-Arm	250	45 ft Cl 1	38.5	33.5	30.2	27.5	23.9
2.1.5B	13 kV 6-W Hendrix	250	40 ft Cl H-1	34.0	32.0	24.8	33.0	25.8
2.1.6B	34 kV X-Arm	250	40 ft Cl 3	34.0	33.0	29.7	27.0	23.4
2.1.7B	13 kV 5-Wire	250	50 ft Cl 2	43.0	34.0	30.7	28.0	24.4
Single-phase options								
2.3.1B	7.6 kV 1-ph	250	40 ft Cl 5	34.0	34.0	30.4	28.0	24.4
2.3.2B	7.6 kV 1-ph Tall	250	50 ft Cl 5	43.0	42.0	38.4	42.0	38.4

CAI COMMONWEALTH ASSOCIATES INC.

CALCULATION SHEET

CLIENT IIT RESEARCH		SHEET OF
SUBJECT 13.2 KV DISTRIB CONFIG & DIMENSIONS		JOB NUMBER 115001
CALC. BY/DATE RGM	CHECKED BY/DATE	REV.



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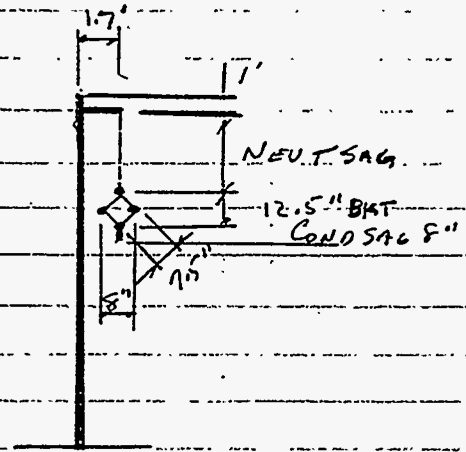

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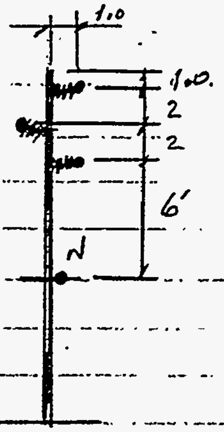
HENDRIX



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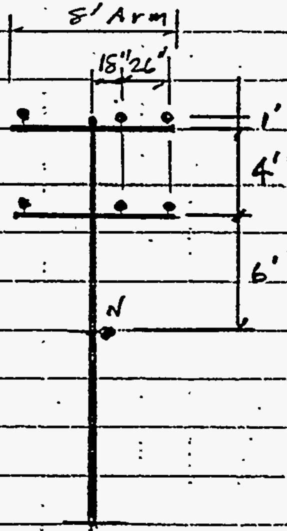

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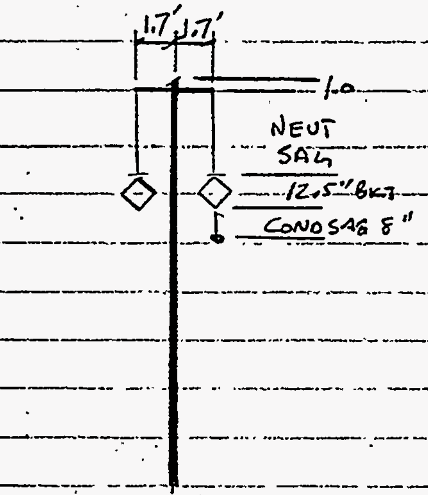

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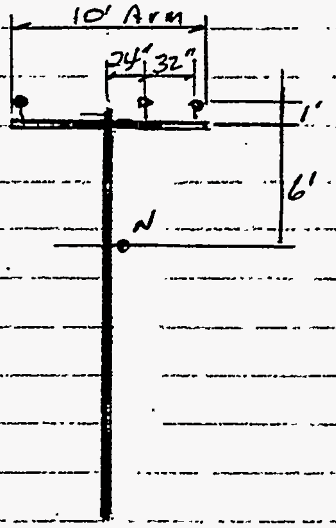
Hendrix



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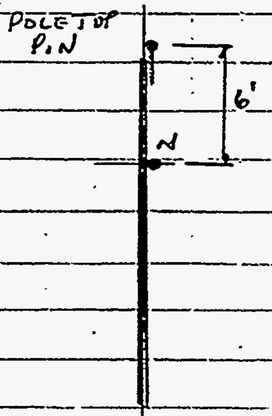
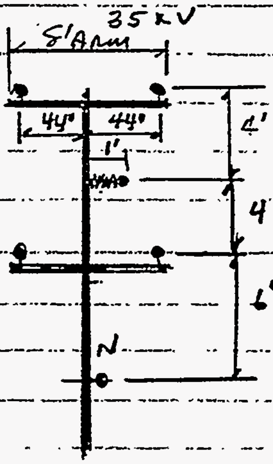
35 KV



2.1.6

2.1.7



2.1.10

CAI COMMONWEALTH ASSOCIATES INC.

CALCULATION SHEET

CLIENT IIT RESEARCH

SHEET OF

SUBJECT 13kV DISTR. UNDERGR. CONFIG + DIMENSIONS

JOB NUMBER 115001

CALC. BY/DATE D. SHAFER 2/1/97

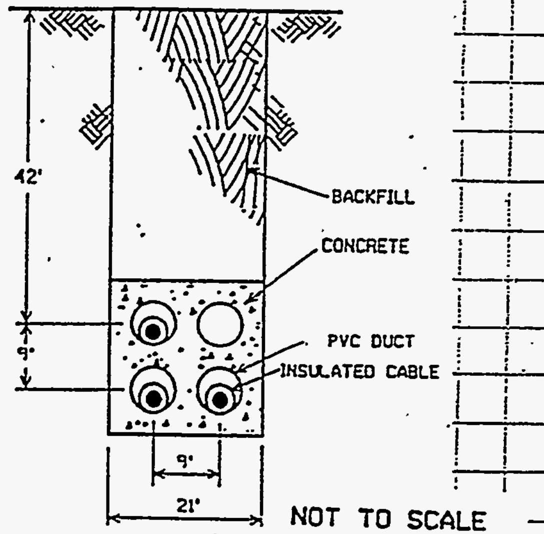
CHECKED BY/DATE

REV.

2.1.8

2×2 - 5" DUCT BANK

3-1c CABLES IN 3 DUCT

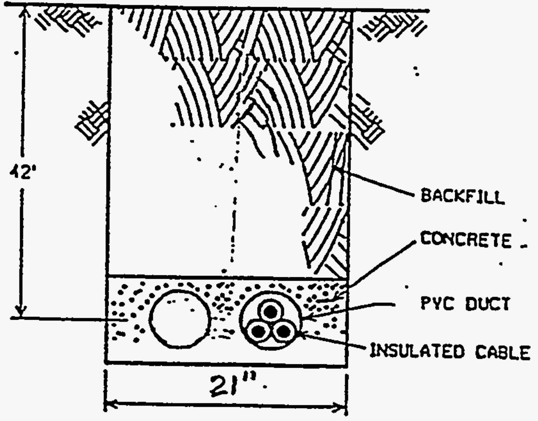


NOT TO SCALE

2.1.9

1×2 - 6" DUCT BANK

3-1c CABLES IN 1 DUCT



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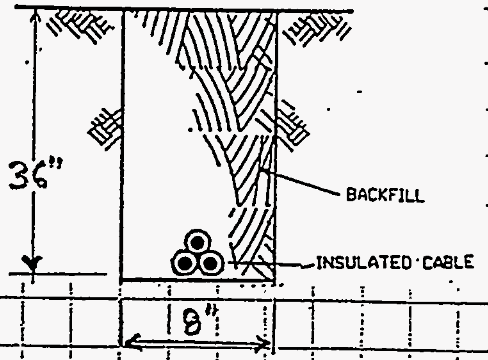
2.1.10

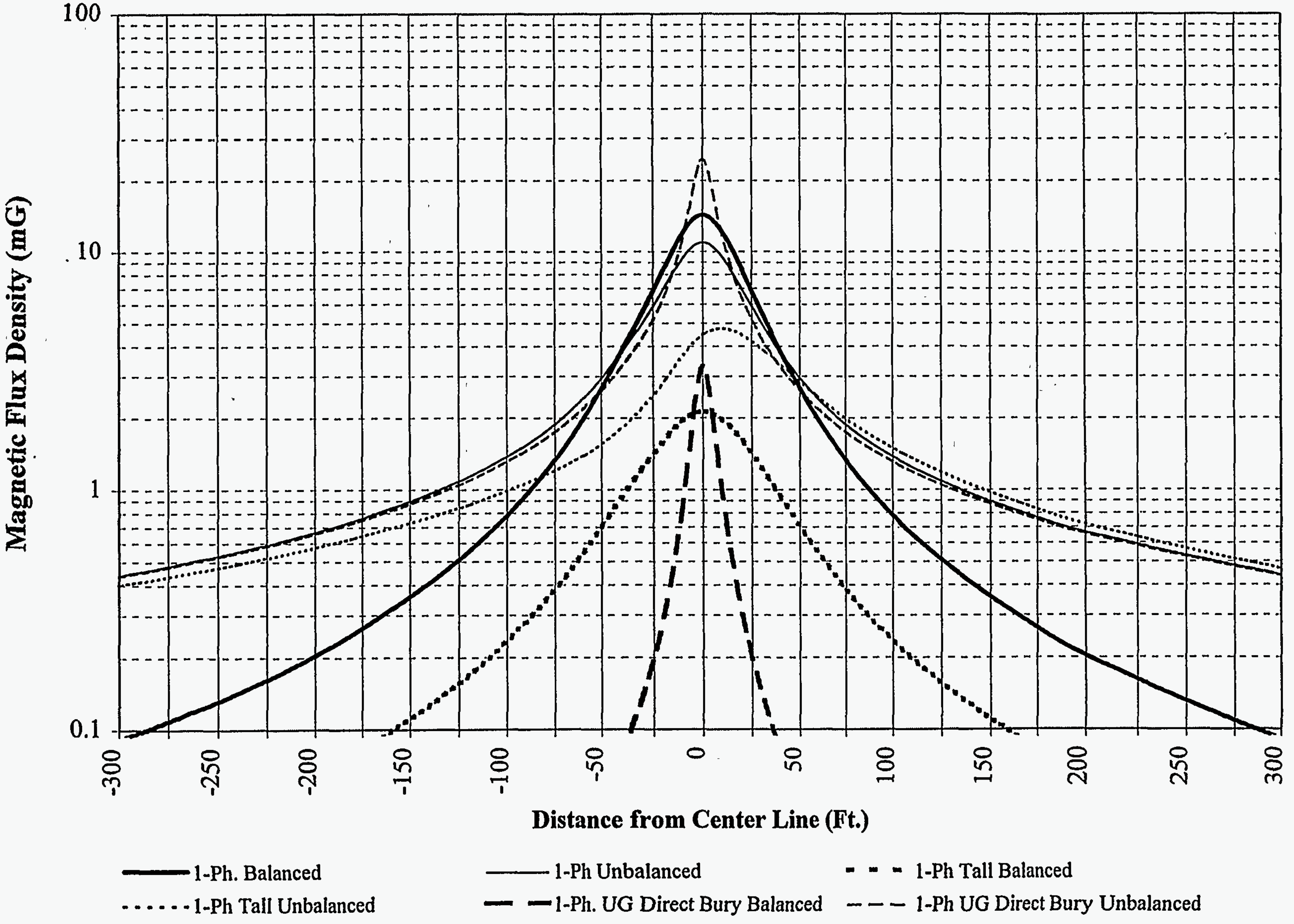
DIRECT BURY

3-1c URD

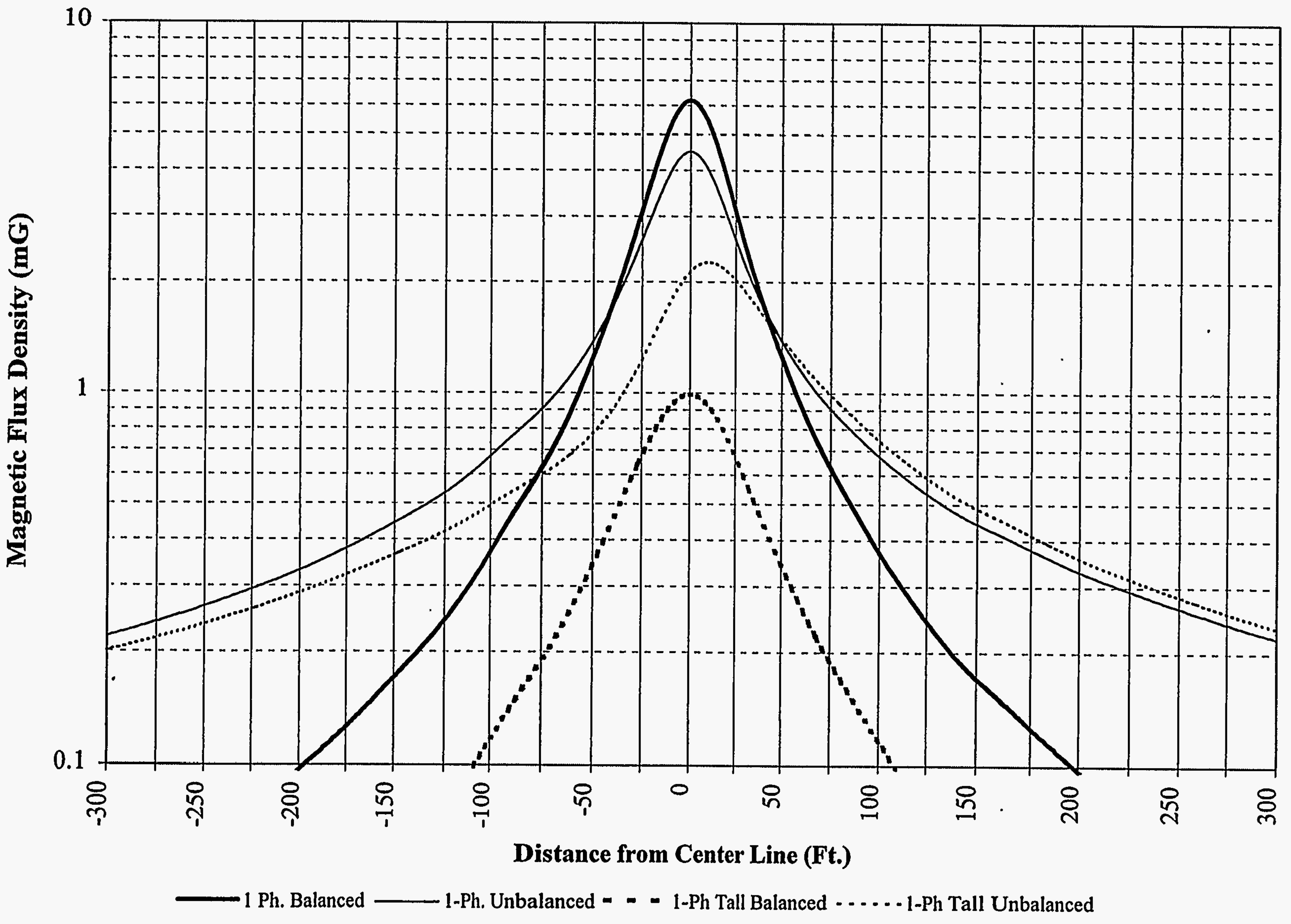


NOT TO SCALE

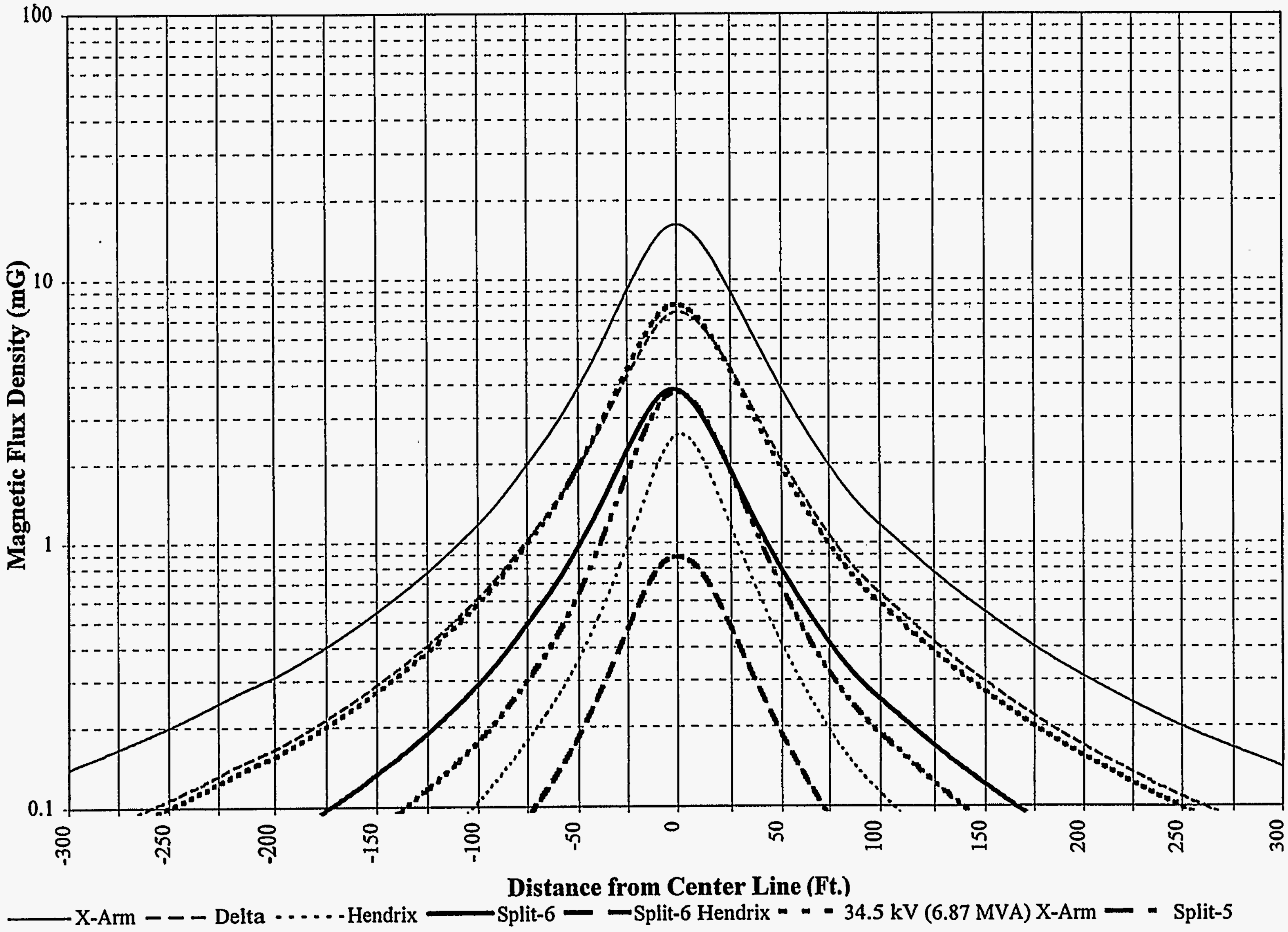
7.6 kV Single Phase Suburban Distribution Line Magnetic Fields



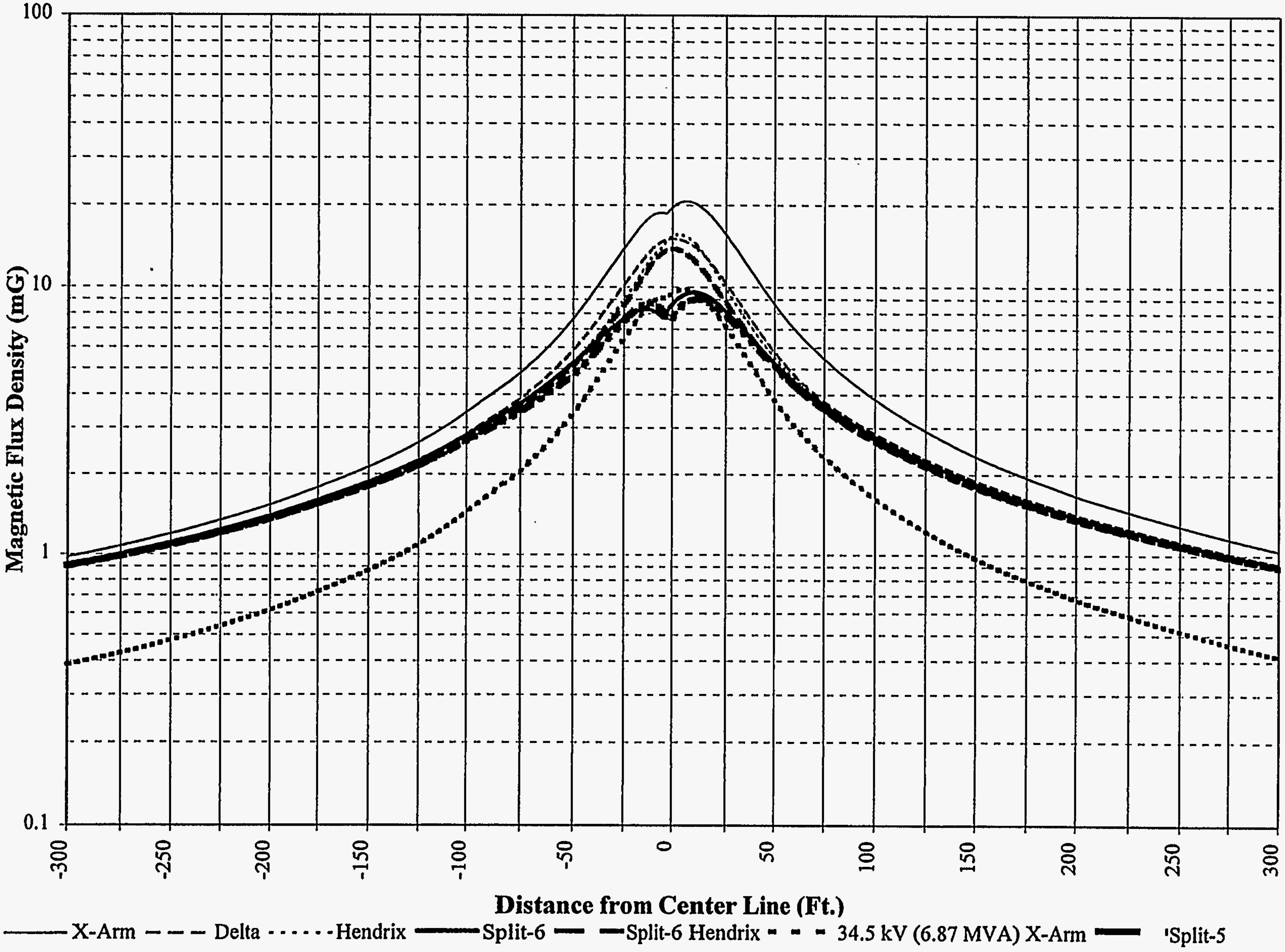
7.6 kV Single Phase Rural Distribution Line Magnetic Fields



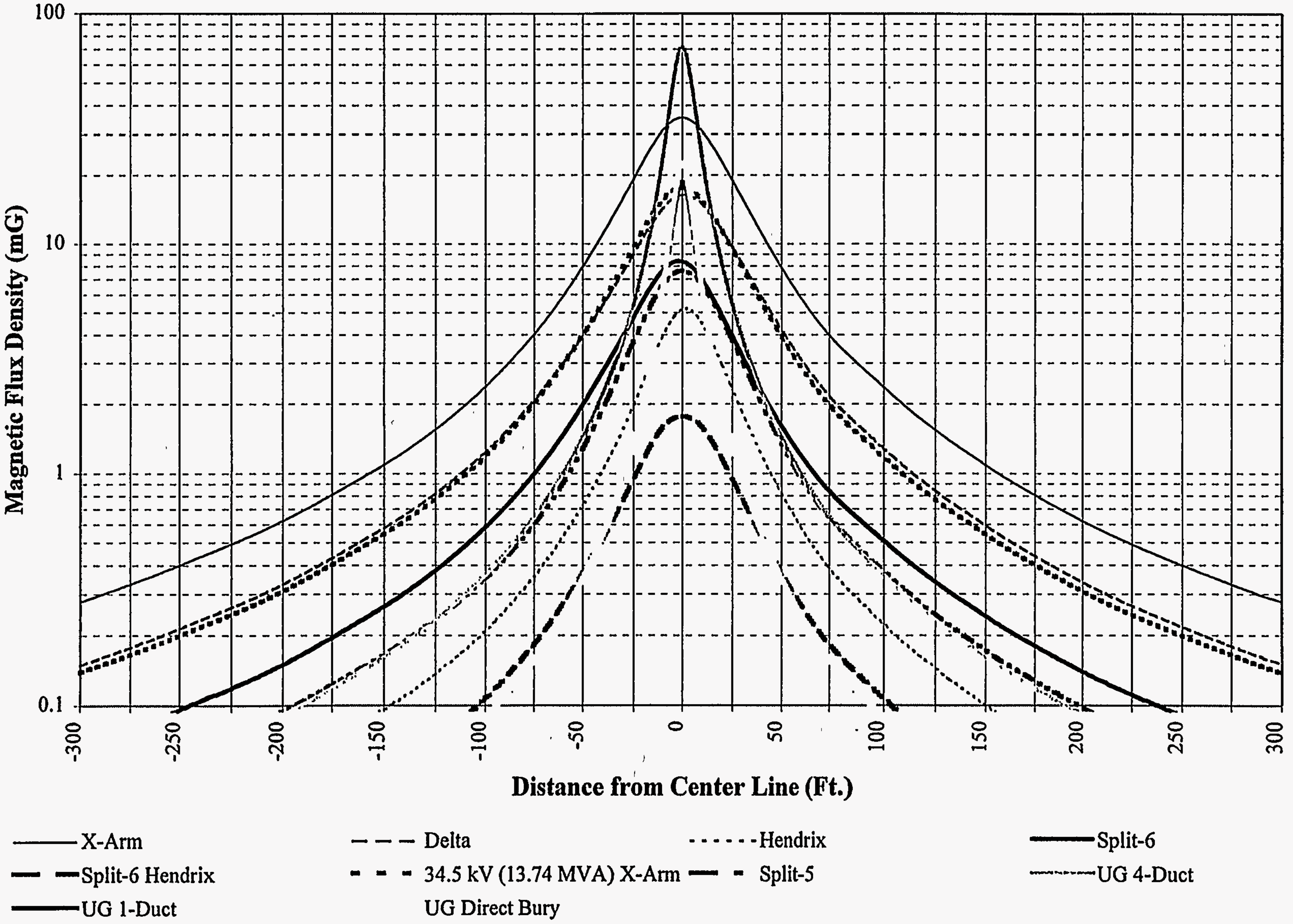
13.2 kV Rural Distribution Line Magnetic Fields (Balanced)



13.2 kV Rural Distribution Line Magnetic Fields (Unbalanced)



13.2 kV Suburban Distribution Line Magnetic Fields (Balanced)



13.2 kV Suburban Distribution Line Magnetic Fields (Unbalanced)

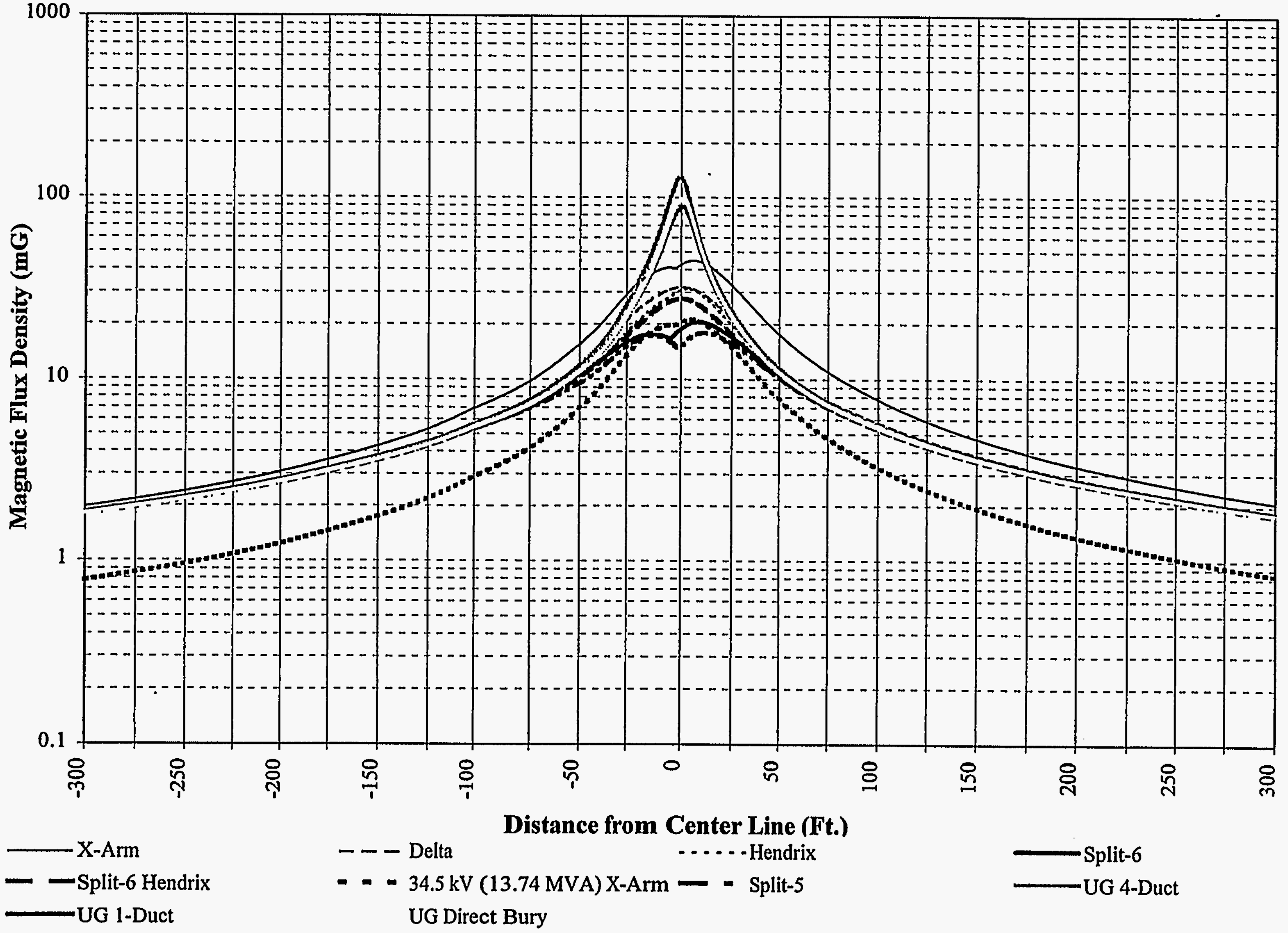


Table 7.2 34.5 kV Distribution Design Assumptions

*** See sketch for phase spacing dimensions**

		Conduct/Phase		Neutral	Norm Load - Amps			
Id No.	**Description**	**No**	**kcmil**	**Conductor**	**Rural**	**Suburban**	**Struct**	**Insul.**
	Three-phase options							
2.2.1	34 kV X- Arm	1	795	4/0	300	600	WP	Pin
2.2.2	34 kV Delta	1	795	4/0	300	600	WP	Post
2.2.3	34 kV Hendrix	1	795H1	95H1-mssg	300	600	WP	
2.2.4	34 kV 6-W X-Arm	2	336	4/0	300	600	WP	Pin
2.2.5	34 kV 6-W Hendri	2	336H1	36H1-mssg	300	600	WP	
2.2.6	34 kV 5-Wire	2	336	4/0	300	600	WP	Pin/Post
	center wire	1	795	4/0				

RURAL CONFIGURATIONS

					Lowest Conductor Elevation (ft)			
					Phase Conductor		Neutral Conductor	
Id No.	**Descr.**	**Span ft.**	**Stucture Descript.**	**Installed Pole Ht. ft.**	**At Struct.**	**Mid Span Norm 50°C**	**At Struct.**	**Mid Span Norm 50°C**
Three-phase options								
2.2.1A	34 kV X- Arm	400	45 ft Cl H-1	38.5	37.5	31.0	31.5	24.7
2.2.2A	34 kV Delta	400	50 ft Cl 1	43.0	38.0	31.5	32.0	25.2
2.2.3A	34 kV Hendrix	250	40 ft Cl 1	34.0	31.5	23.8	33.0	25.3
2.2.4A	34 kV 6-W X-Arm	400	50 ft Cl H-3	43.0	37.0	30.4	31.0	24.2
2.2.5A	34 kV 6-W Hendrix	250	40 ft Cl H-2	34.0	31.5	24.3	33.0	25.8
2.2.6A	34 kV 5-Wire	400	55 ft Cl H-2	47.5	36.5	29.9	30.5	23.7

SUBURBAN CONFIGURATIONS

					Lowest Conductor Elevation (ft)			
					Phase Conductor		Neutral Conductor	
Id No.	**Descr.**	**Span ft.**	**Stucture Descript.**	**Installed Pole Ht. ft.**	**At Struct.**	**Mid Span Norm 50°C**	**At Struct.**	**Mid Span Norm 50°C**
2.2.1B	34 kV X- Arm	250	40 ft Cl 2	34.0	33.0	29.8	27.0	23.4
2.2.2B	34 kV Delta	250	45 ft Cl 3	38.5	33.5	30.3	27.5	23.9
2.2.3B	34 kV Hendrix	250	40 ft Cl 1	34.0	31.5	23.8	33.0	25.3
2.2.4B	34 kV 6-W X-Arm	250	45 ft Cl 1	38.5	32.5	29.2	26.5	22.9
2.2.5B	34 kV 6-W Hendrix	250	40 ft Cl H-2	34.0	31.5	24.3	33.0	25.8
2.2.6B	34 kV 5-Wire	250	50 ft Cl 2	43.0	32.0	28.7	26.0	22.4

CALCULATION SHEET

CLIENT IITRESEARCH		SHEET OF
SUBJECT 34.5 KV DISTRIB CONFIG & DIMENSIONS		JOB NUMBER 115001
CALC. BY/DATE RWM	CHECKED BY/DATE	REV.

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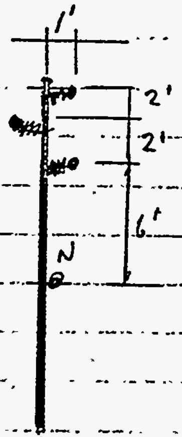

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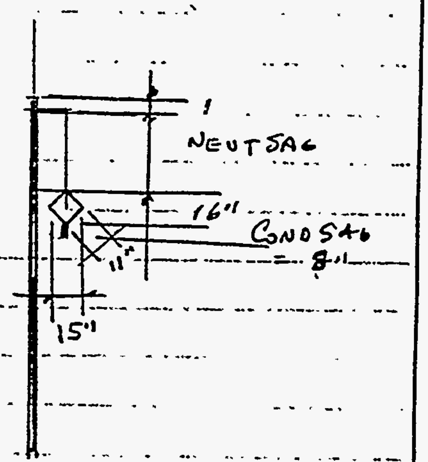
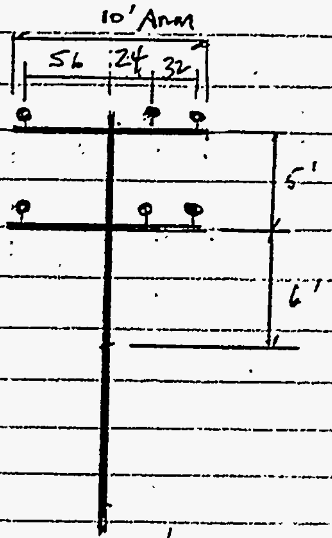


2.2.3
HENDRIX



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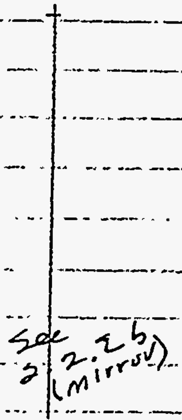

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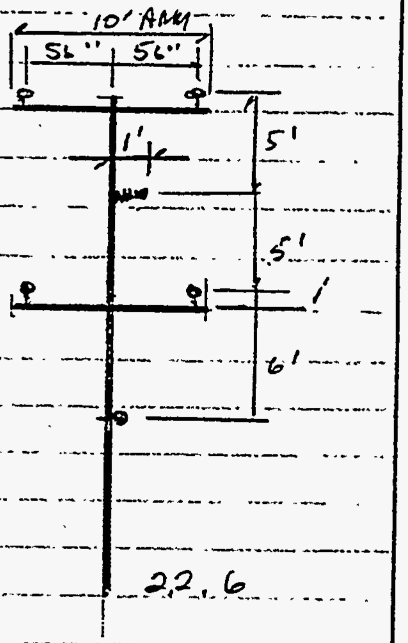
HENDRIX



2.2.6

CAI COMMONWEALTH ASSOCIATES INC.

CALCULATION SHEET

CLIENT IIT RESEARCH

SHEET OF

SUBJECT 34.5 kV DISTR. UNDERGR. CONFIG + DIMEN.

JOB NUMBER 115001

CALC. BY/DATE D. SHAFER 2/1/97

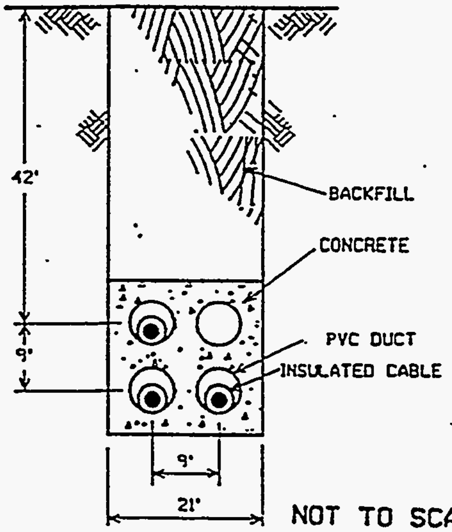
CHECKED BY/DATE

REV.

2.2.7

2×2 - 5" DUCT BANK

3-1c CABLES IN 3 DUCT

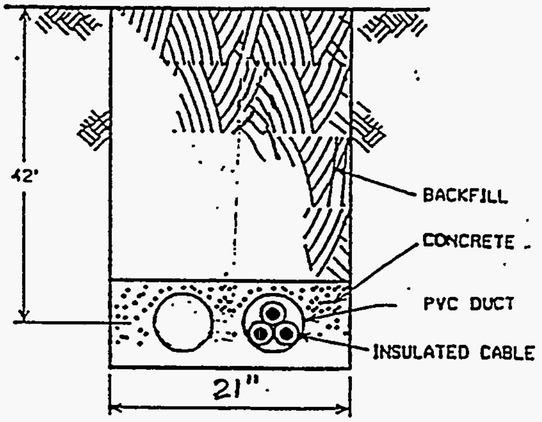


NOT TO SCALE

2.2.8

1×2 - 6" DUCT BANK

3-1c CABLES IN 1 DUCT

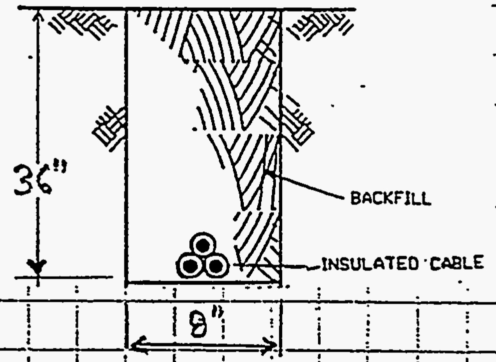


NOT TO SCALE

2.2.9

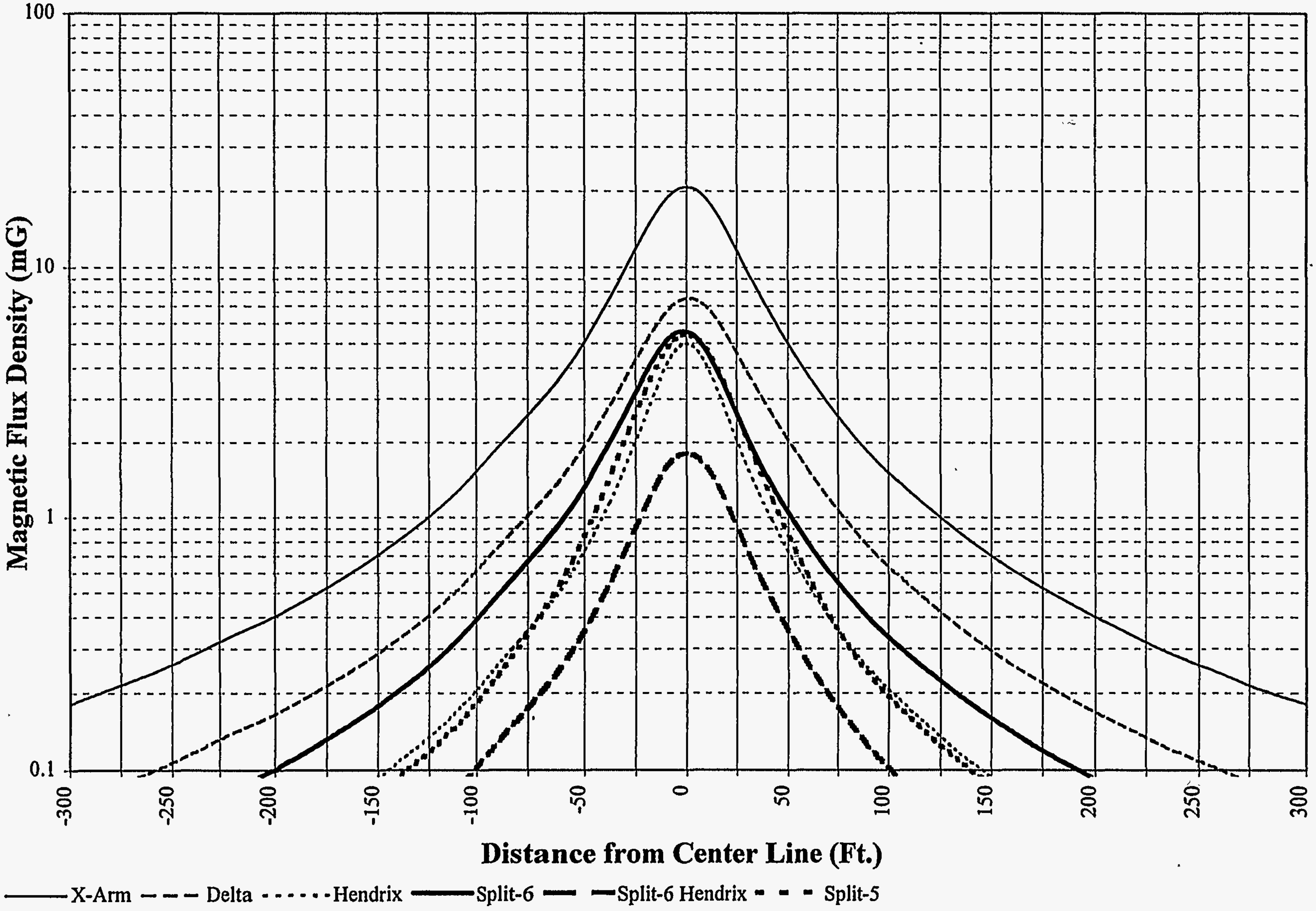
DIRECT BURY

3-1c URD

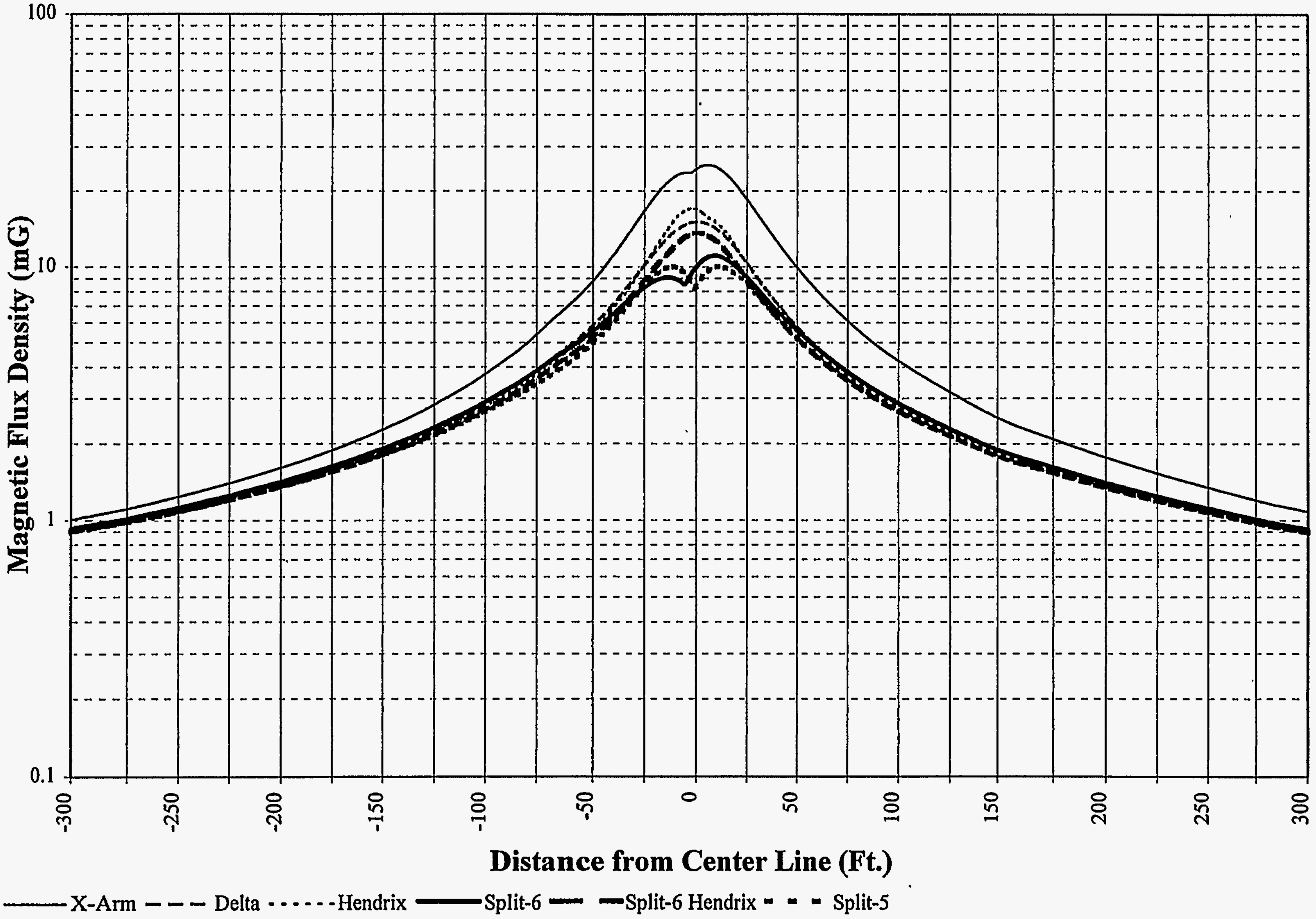


NOT TO SCALE

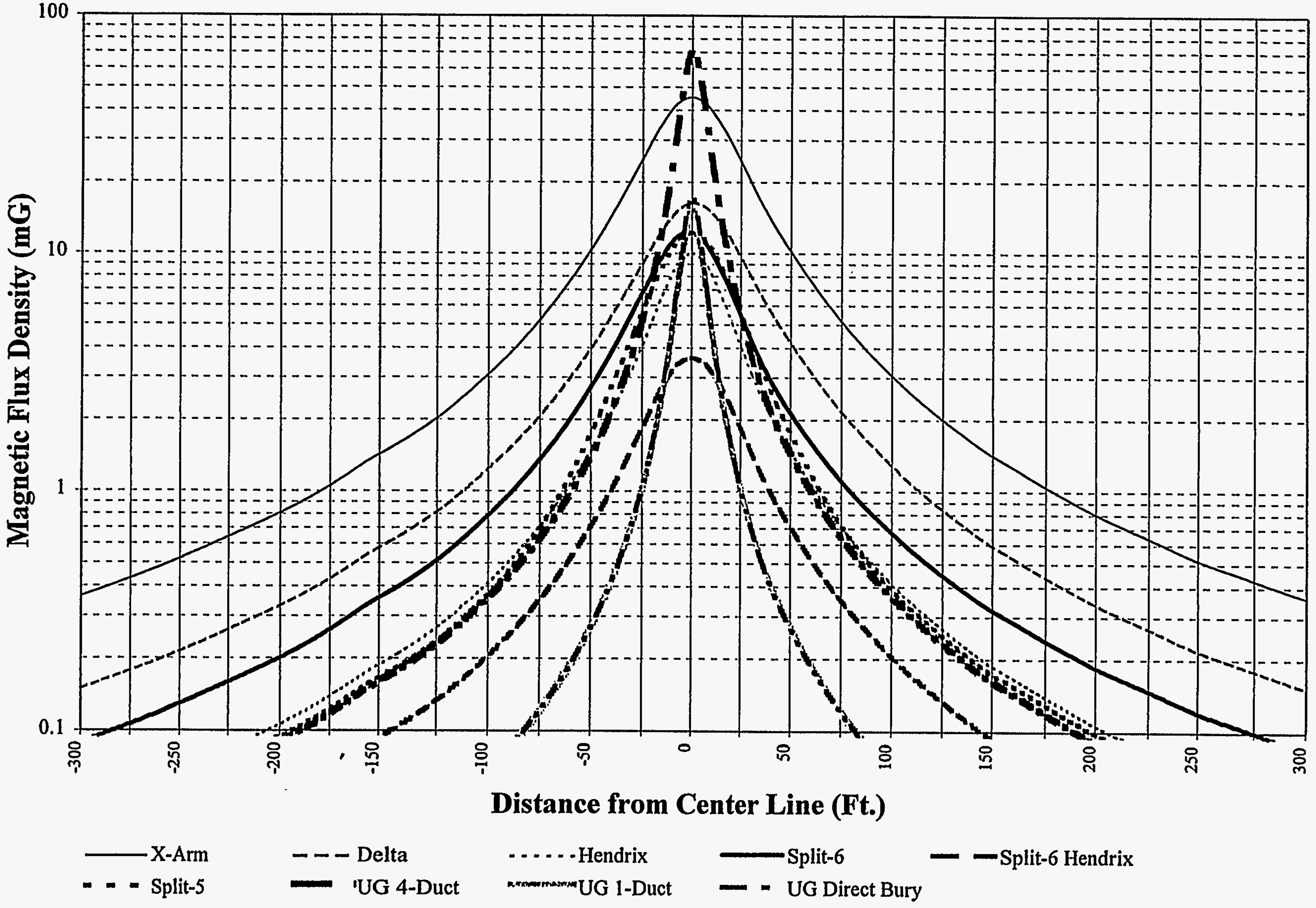
34.5 kV Rural Distribution Line Magnetic Fields (Balanced)



34.5 kV Rural Distribution Line Magnetic Fields (Unbalanced)



34.5 kV Suburban Distribution Line Magnetic Fields (Balanced)



34.5 kV Suburban Distribution Line Magnetic Fields (Unbalanced)

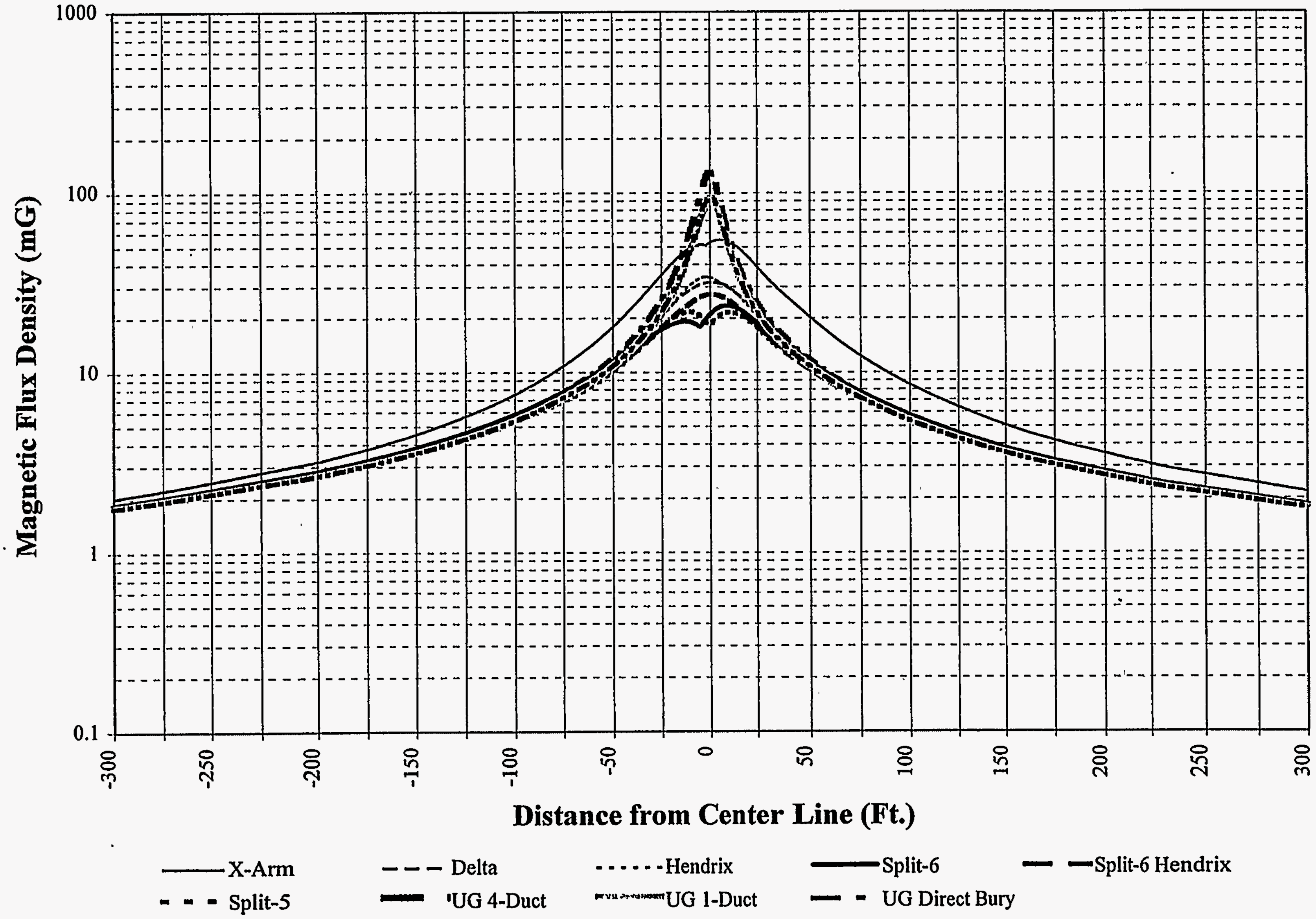


Table_8 - General Design Assumptions - Underground Distribution

1. Nominal Voltages: 4.16 kV, 13.2 kV and 34.5 kV (Three-phase circuits)
   2.4 kV, 7.6 kV (Single-phase circuits)

2. Reference Load Level (amps)

	amps
4.16 kV three-phase	600
13.2 kV three-phase	600
34.5 kV three-phase	600
2.4 kV single-phase	200
7.6 kV single-phase	200

3. The following solid dielectric cables options are considered:

4.16 kV	500 kcmil, cu XLP	2x2 - 5" PVC Duct
4.16 kV	750 kcmil, cu XLP	1x2 - 5" PVC Duct
4.16 kV	750 kcmil, cu XLP	Direct Bury
13.2 kV	500 kcmil, cu XLP	2x2 - 5" PVC Duct
13.2 kV	750 kcmil, cu XLP	1x2 - 5" PVC Duct
13.2 kV	750 kcmil, cu XLP	Direct Bury
34.5 kV	500 kcmil, cu XLP	2x2 - 5" PVC Duct
34.5 kV	750 kcmil, cu XLP	1x2 - 5" PVC Duct
34.5 kV	750 kcmil, cu XLP	Direct Bury
2.4 kV	1/0, cu XLP	Direct Bury
7.6 kV	1/0, cu XLP	Direct Bury

4. Costs are provided for suburban and urban locations.

   Suburban Assumptions for Three-phase Cable in Duct Systems
   a. 5 mile line at 13.2 kV and 8 mile at 34.5 kV
   b. Located on street right-of-way but not under pavement.
   c. 90% of line requires normal excavation, 10% requires rock excavation
   d. Line crosses 1 major road or railroad and 4 other road crossings

   Suburban Assumptions for Three-phase Direct Bury Options
   a. 5 mile line at 13.2 kV and 8 mile at 34.5 kV
   b. Located on street right-of-way but not under pavement.
   c. 100% of line requires normal excavation (trenching)
   d. Line crosses no major road or railroad and 5 other road crossings

   Suburban Assumptions for Single-phase Direct Bury Options
   a. 0.6 mile line
   b. 100% of line requires normal excavation (trenching)
   c. Line crosses no major road or railroad and 2 other road crossings

   Urban Assumptions for Three-phase Cable in Duct Systems
   a. 4 mile line underneath street, requiring removal and replacement of pavement
   b. 90% of line requires normal excavation, 10% requires rock excavation

5. Cost estimates do not include: transformers, switches, capacitors, arresters, secondary and service cables, meters and related equipment which typically comprise a distribution system.

APPENDIX D

HIGH VOLTAGE TRANSMISSION LINE

COST ESTIMATES

INTRODUCTION

This appendix provides the assumptions and details of the transmission and distribution cost estimates. It should be noted that every power line must be custom designed to fit the terrain, landscape and local requirements. The cost estimates contained in this report are based on generic assumptions. These estimates are useful for making comparisons between options and for providing order of magnitude costs. However, costs for actual lines can vary considerably from these estimates.

For each option, three estimates are provided: material and labor, project, and life-cycle.

Material and Labor

The material and labor estimate provides the costs for the poles, insulators, wires, and all other necessary materials and the labor to construct the power line. Cost estimate details provided in this report show the development of material and labor estimate in the categories of conductors and structures.

The design of the power line begins with a determination of the amount of power that needs to be transmitted. Once this is decided, the voltage of the line and its conductor size can be selected. Knowing the conductor size and its length, the cost of conductors can be estimated.

Also, knowing the conductor size, line route and terrain, the supporting structures can be designed. The supporting structures are designed on the basis of maintaining conductor ground clearances and meeting code requirements with regard to strength. For example, the supporting structures need to support the weight of the wires and wind and ice loads on the wires. Another factor affecting cost is the number of tangent, angle and deadend structures required. A tangent structure is the lightest structure located in the straight portion of the line. It is designed primarily to hold the wires in the air. Angle structures are required where the line turns a corner and deadend structures are needed where it is necessary to resist the full tension of the conductors. Angle and deadend structures must be stronger than tangent structures, hence more costly. For the purpose of making our generic estimates we have assumed that the line will be over relatively flat terrain and that a certain number of angles and deadends are required.

Development of material and labor costs is the first step in the estimating process. Sometimes it is sufficient for comparing the relative differences in alternatives. We have provided this first level of comparison of the alternatives in this report.

Project Costs

A utility constructing a power line incurs many other costs than material and labor. These would include costs to purchase land or land rights, clearing of brush and trees from the right-of-way, restoration of right-of-way after construction. In some cases, the construction of access roads are required to build and maintain the power line. For the purpose of making our estimates we have assumed costs for land, clearing and restoration. We have assumed that we would not need access roads. These costs can be highly variable from project to project. We have made similar assumptions for all our options to provide a basis for comparison.

Other costs incurred by the utility include licensing and permits, labor and expenses to acquire land and land rights (in addition to actual costs of land as described above), engineering and surveying, inspections during construction, and the owner's administrative costs. Utility accounting practices also account for the interest of the money tied up during the construction of the project. This is called allowance for funds used during construction (AFUDC). Since each line is custom designed to fit the location, it is necessary to add a contingence to cover unforeseen items.

The material and labors costs plus the other costs as described above are the project cost estimate. This is the total amount of capital that the utility will need to construct the power line and place it in service. The project cost estimates provide a second level of comparison between alternatives. Also, the project estimate gives an order of magnitude estimate of the total cost of constructing a power line project. Remember, that this estimate would need to be tuned to local costs.

Life-cycle Costs

The third level of comparison of the alternatives is provided with the life-cycle cost. The life-cycle cost is the present worth of all costs incurred over the lifetime of the project. For a power line these costs are defined in three categories: fixed costs, cost of losses, and O&M costs. For the purpose of this analysis we have assumed all projects to have a life-time of 35 years and a net salvage value of zero at the end of the project life.

The annual fixed costs of owning the power line are calculated using a 16% fixed charge rate. The fixed charge rate can vary from utility to utility and from one region to another. However, 16% is representative of the utility industry. Included in the fixed charge rate, is the recovery of the investors initial capital investment (depreciation of the asset), return on this investment (interest or dividends paid to investors), and the utility's annual costs to own the asset including such items as property taxes and insurance. As shown in the detailed tables, the fixed costs are the major component of the life-cycle cost.

The second component in the life-cycle cost is power line losses in operating the power line. The power loss costs are calculated on the basis of an assumed power loading on the line and a cost of power. As shown in the detail sheets the power losses can be a significant portion of the life-cycle costs (5 to 30%).

The third component of life-cycle cost is operation and maintenance costs (O&M). A portion of O&M cost is related to the power line structures and conductors. Another portion is related to maintaining the right-of-way clear of brush and trees. These costs can vary considerably from location to location. For the purpose of our analysis we have used the industry average of approximately 1%. Fortunately, these costs are a relatively small portion of the life-cycle costs and, thus, have little influence on the comparative life-cycle costs.

Table 1.1.1A shows an example cost estimating sheet for transmission lines. It shows cost estimate details for the 69 kV rural delta design. The table is followed by a set of cost comparison summary sheets for each transmission line voltage category. These include 69 kV, 115 kV, 230 kV, 345 kV, 500 kV, and 765 kV.

COST ESTIMATE DETAILS
1.1.1A - 69 kV Delta
Rural location with no distribution

Assumptions:

Length of line	25 miles
Average span	400 feet
One Deadend (or 90° Angle every)	5 miles
Ratio of angle to deadend structures	2 angles/deadend
Right-of-way (ROW) width	75 feet
Percentage of ROW Requiring Clearing	40%

Structures (including insulators)			Unit Costs		Construction Costs		
Type	WP davit arms	Units	Material	Labor	Material	Labor	Total
Tangent	60 Ft Cl 1	316	1,996	2,100	630,736	663,600	1,294,336
Angle	65 Ft Cl H-1	10	2,648	2,700	26,480	27,000	53,480
Deadend	65 Ft Cl H-1	5	4,210	3,700	21,050	18,500	39,550
Subtotal Structures		331			$678,266	$709,100	$1,387,366
Conductors (Units in miles)							
Conductor	3-795 Drake	25	20,800	40,000	520,011	1,000,000	1,520,011
Shield wire	1-3/8" EHS	25	1,320	10,000	33,000	250,000	283,000
Subtotal Conductors					$553,011	$1,250,000	$1,803,011
Contractor Mobilization						50,000	50,000
Total Material & Labor					$1,231,277	$2,009,100	$3,240,377
Total Material & Labor per Mile					**$49,251**	**$80,364**	**$129,615**

Clearing of ROW	90.9 acres @	2,000 per acre		181,818
Restoration of ROW	25 miles @	5,000 per mile		125,000
Construction of Access Roads	0.0 miles @	25,000 per mile		0
Subtotal clearing, restoration and access roads				$306,818
Right-of-way Costs	227.3 acres @	3,500 per acre		795,455
Overhead Costs				
Licensing & permits				10,000
Right-of-way Procurement	50% of right-of-way costs			397,727
Engineering	6% of labor and material			194,423
Soil Borings	0 sites @	$1,000 site		0
Surveying	25 miles @	$12,500 per mile		312,500
Construction Inspection	3 month @	$10,000 month		30,000
Owner's Admin. Costs				120,000
Subtotal Overhead Costs				$1,064,650
Project Subtotal				$5,407,300
Allowance for Funds Used During Construction (AFUDC)			5%	270,365
Project Contingency			15%	811,095
Total Project Cost				$6,488,760
Average Project Cost per mile				**$259,550**

LIFE CYCLE COST ANALYSIS
1.1.1A - 69 kV Delta
Rural location with no distribution

Assumptions for Calculation of Fixed Charges

Economic Life	35 years	Fixed Charge Rate	16.0%
Capital Costs	259,550 $/mi		
		Fixed Costs	$ 41,528 $/mi/yr

Assumptions for Calculation of Line Losses

Conductor			
1-795 kcmil ACSR "Drake"		0.1278 ohms/mi	
Peak Loading	600 amps	Load Factor	60.0%
Peak Losses	138.0 kW/mi.	Loss Factor	40.8%
Annual Losses	493,309 kWh/mi		
Cost of Power	0.03 $/kwH		
		Cost of Losses	$ 14,799 $/mi/yr

Assumptions for Calculation of O&M Costs

L & M Costs	129,615 $/mi		
O&M Costs	0.5% of L & M		
		O&M Costs	$ 648 $/mi/yr

Assumptions for Life-Cycle Cost

Economic Life	35 years
Present Worth Discount Rate	10.0%

LIFE-CYCLE COSTS

	First Year Costs $/mi		Escalation per year	Life Cycle Cost $/mi.	
Fixed Costs	41,528	72.9%		400,503	69.0%
Cost of Losses	14,799	26.0%	2.0%	171,826	29.6%
O&M Costs	648	1.1%	3.0%	8,331	1.4%
Total	$ 56,975	100.0%		$ 580,661	100.0%

COST COMPARISON OF 69 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.1.1A - 69 kV Delta	130	100%	260	100%	581	100%
1.1.2A - 69 kV Vertical	132	102%	263	101%	586	101%
1.1.3A - 69 kV 6 Wire Split Phase	153	118%	290	112%	659	113%
1.1.4A - 115 kV Delta Davit Arm	110	85%	235	91%	515	89%
1.1.5A - 69 kV 5 Wire Split Phase	170	131%	311	120%	682	118%
Suburban Options						
1.1.1B - 69 kV Delta	189	100%	336	100%	702	100%
1.1.2B - 69 kV Vertical	197	104%	346	103%	718	102%
1.1.3B - 69 kV 6 Wire Split Phase	253	134%	417	124%	861	123%
1.1.4B - 115 kV Delta Davit Arm	191	101%	339	101%	680	97%
1.1.5B - 69 kV 5 Wire Split Phase	289	153%	463	138%	925	132%
1.1.6B - 69 kV 3-1c Cables in 3 Ducts	646	342%	916	273%	1,632	233%
1.1.7B - 69 kV HPGF Cable System	635	336%	901	268%	1,551	221%
Urban Options						
1.1.6c - 69 kV 3-1c Cables in 3 Ducts	853	100%	1,212	100%	2,102	100%
1.1.7C - 69 kV HPGF Cable System	802	94%	1,143	94%	1,935	92%

COST COMPARISON OF 115 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.2.1A - 115 kV H-Frame	128	100%	280	100%	613	100%
1.2.2A - 115 kV Delta Davit Arm	130	102%	283	101%	617	101%
1.2.3A - 115 kV Delta Compact	117	92%	267	95%	591	96%
1.2.4A - 115 kV 6 Wire Split Phase Davit Arm	196	153%	367	131%	781	127%
1.2.5A - 115 kV 6 Wire Split Phase Compact	169	132%	332	119%	725	118%
1.2.6A - 69 kV 6 Wire Split Phase	213	166%	365	130%	816	133%
1.2.7A - 230 kV Delta Davit Arm	130	101%	282	101%	545	89%
1.2.8A - 115 kV 5 Wire Split Phase	179	140%	345	123%	736	120%
1.2.9A - Cancellation Loop for 115 kV H-Frame	78	61%	165	59%	266	43%
Suburban Options						
NONE						
1.2.2B - 115 kV Delta Davit Arm	211	100%	377	100%	767	100%
1.2.3B - 115 kV Delta Compact	200	95%	363	96%	745	97%
1.2.4B - 115 kV 6 Wire Split Phase Davit Arm	320	152%	516	137%	1,018	133%
1.2.5B - 115 kV 6 Wire Split Phase Compact	289	137%	476	126%	954	124%
1.2.6B - 69 kV 6 Wire Split Phase	307	145%	485	129%	1,007	131%
1.2.7B - 230 kV Delta Davit Arm	293	139%	482	128%	863	113%
NONE						
1.2.10B - 115 kV 3-1c Cables in 3 Ducts	843	400%	1,182	314%	2,073	270%
1.2.11B - 115 kV HPGF Cable System	704	334%	994	264%	1,705	222%
Urban Options						
1.2.10C - 115 kV 3-1c Cables in 3 Ducts	1,063	100%	1,494	100%	2,569	100%
1.2.11C - 115 kV HPGF Cable System	881	83%	1,249	84%	2,110	82%

COST COMPARISON OF 230 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.3.1A - 230 kV H-Frame	153	100%	334	100%	673	100%
1.3.2A - 230 kV Delta Davit Arm	166	108%	350	105%	699	104%
1.3.3A - 230 kV Delta Compact	159	104%	342	102%	685	102%
1.3.4A - 230 kV 6 Wire Split Phase Davit Arm	265	173%	477	143%	839	125%
1.3.5A - 230 kV 6 Wire Split Phase Compact	236	154%	439	131%	779	116%
1.3.6A - 115 kV 6 Wire Split Phase Davit Arm	235	154%	417	125%	1,001	149%
1.3.7A - 115 kV 6 Wire Split Phase Compact	208	136%	382	114%	946	141%
1.3.8A - 230 kV 5 Wire Split Phase	238	156%	442	132%	804	119%
1.3.9A - Cancellation Loop for 230 kV H-Frame	88	58%	177	53%	290	43%
Suburban Options						
1.3.2B - 230 kV Delta Davit Arm	254	100%	443	100%	848	100%
1.3.3B - 230 kV Delta Compact	244	96%	430	97%	828	98%
1.3.4B - 230 kV 6 Wire Split Phase Davit Arm	402	158%	631	142%	1,085	128%
1.3.5B - 230 kV 6 Wire Split Phase Compact	359	141%	576	130%	998	118%
1.3.6B - 115 kV 6 Wire Split Phase Davit Arm	354	139%	558	126%	1,228	145%
1.3.7B - 115 kV 6 Wire Split Phase Compact	322	127%	519	117%	1,165	137%
1.3.10B - 230 kV 3-1c Cables in 3 Ducts	1,110	437%	1,543	348%	2,599	306%
1.3.11B - 230 kV HPFF Cable System	1,106	435%	1,537	347%	2,555	301%
Urban Options						
1.3.10C - 230 kV 3-1c Cables in 3 Ducts	1,344	100%	1,876	100%	3,129	100%
1.3.11C - 230 kV HPFF Cable System	1,321	98%	1,845	98%	3,043	97%

COST COMPARISON OF 345 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.4.1A - 345 kV H-Frame	251	100%	486	100%	1,061	100%
1.4.2A - 345 kV Delta Davit Arm	283	113%	526	108%	1,126	106%
1.4.3A - 345 kV H-Frame Compact Delta	351	140%	613	126%	1,265	119%
1.4.4A - 345 kV 6 Wire Split Phase Davit Arm	987	392%	1,428	294%	2,416	228%
1.4.5A - 230 kV 6 Wire Split Phase Davit Arm	282	112%	520	107%	1,486	140%
1.4.6A - 230 kV 6 Wire Split Phase Compact	243	97%	471	97%	1,408	133%
1.4.7A - 345 kV 5 Wire Split Phase	527	210%	839	173%	1,525	144%
1.4.8A - Cancellation Loop for 345 kV H-Frame	87	34%	182	38%	337	32%
Suburban Options						
1.4.2B - 345 kV Delta Davit Arm	423	100%	685	100%	1,381	100%
1.4.4B - 345 kV 6 Wire Split Phase Davit Arm	1,737	410%	2,356	344%	3,896	282%
1.4.5B - 230 kV 6 Wire Split Phase Davit Arm	432	102%	697	102%	1,769	128%
1.4.6B - 230 kV 6 Wire Split Phase Compact	369	87%	616	90%	1,639	119%
1.4.9B - 345 kV HPFF Cable System	1,767	417%	2,436	355%	4,112	298%
Urban Options						
1.4.9C - 345 kV HPFF Cable System	2,023	100%	2,804	100%	4,696	100%

COST COMPARISON OF 500 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.5.1A - 500 kV H-Frame	649	100%	1,017	100%	2,054	100%
1.5.2A - 500 kV Delta	623	96%	983	97%	2,001	97%
1.5.3A - 500 kV Vertical Davit Arm	727	112%	1,116	110%	2,213	108%
1.5.4A - 500 kV 6 Wire Split Phase Davit Arm	1,123	173%	1,624	160%	2,799	136%
1.5.5A - Cancellation Loop for 500 kV H-Frame	74	11%	166	16%	330	16%
1.5.6A - 345 kV 6 Wire Split Phase Davit Arm	990	152%	1,453	143%	3,005	146%

COST COMPARISON OF 765 KV TRANSMISSION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options						
1.6.1A - 765 kV H-Frame	905	100%	1,368	100%	2,761	100%
1.6.2A - 500 kV 6 Wire Split Phase Davit Arm	1,119	124%	1,643	120%	3,531	128%
1.6.3A - Cancellation Loop for 765 kV H-Frame	88	10%	184	13%	440	16%

APPENDIX E

HIGH VOLTAGE DISTRIBUTION LINE

COST ESTIMATES

INTRODUCTION

This appendix provides the assumptions and details of the transmission and distribution cost estimates. It should be noted that every power line must be custom designed to fit the terrain, landscape and local requirements. The cost estimates contained in this report are based on generic assumptions. These estimates are useful for making comparisons between options and for providing order of magnitude costs. However, costs for actual lines can vary considerably from these estimates.

For each option, three estimates are provided: material and labor, project, and life-cycle.

Material and Labor

The material and labor estimate provides the costs for the poles, insulators, wires, and all other necessary materials and the labor to construct the power line. Cost estimate details provided in this report show the development of material and labor estimate in the categories of conductors and structures.

The design of the power line begins with a determination of the amount of power that needs to be transmitted. Once this is decided, the voltage of the line and its conductor size can be selected. Knowing the conductor size and its length, the cost of conductors can be estimated.

Also, knowing the conductor size, line route and terrain, the supporting structures can be designed. The supporting structures are designed on the basis of maintaining conductor ground clearances and meeting code requirements with regard to strength. For example, the supporting structures need to support the weight of the wires and wind and ice loads on the wires. Another factor affecting cost is the number of tangent, angle and deadend structures required. A tangent structure is the lightest structure located in the straight portion of the line. It is designed primarily to hold the wires in the air. Angle structures are required where the line turns a corner and deadend structures are needed where it is necessary to resist the full tension of the conductors. Angle and deadend structures must be stronger than tangent structures, hence more costly. For the purpose of making our generic estimates we have assumed that the line will be over relatively flat terrain and that a certain number of angles and deadends are required.

Development of material and labor costs is the first step in the estimating process. Sometimes it is sufficient for comparing the relative differences in alternatives. We have provided this first level of comparison of the alternatives in this report.

Project Costs

A utility constructing a power line incurs many other costs than material and labor. These would include costs to purchase land or land rights, clearing of brush and trees from the right-of-way, restoration of right-of-way after construction. In some cases, the construction of access roads are required to build and maintain the power line. For the purpose of making our estimates we have assumed costs for land, clearing and restoration. We have assumed that we would not need access roads. These costs can be highly variable from project to project. We have made similar assumptions for all our options to provide a basis for comparison.

Other costs incurred by the utility include licensing and permits, labor and expenses to acquire land and land rights (in addition to actual costs of land as described above), engineering and surveying, inspections during construction, and the owner's administrative costs. Utility accounting practices also account for the interest of the money tied up during the construction of the project. This is called allowance for funds used during construction (AFUDC). Since each line is custom designed to fit the location, it is necessary to add a contingence to cover unforeseen items.

The material and labors costs plus the other costs as described above are the project cost estimate. This is the total amount of capital that the utility will need to construct the power line and place it in service. The project cost estimates provide a second level of comparison between alternatives. Also, the project estimate gives an order of magnitude estimate of the total cost of constructing a power line project. Remember, that this estimate would need to be tuned to local costs.

Life-cycle Costs

The third level of comparison of the alternatives is provided with the life-cycle cost. The life-cycle cost is the present worth of all costs incurred over the lifetime of the project. For a power line these costs are defined in three categories: fixed costs, cost of losses, and O&M costs. For the purpose of this analysis we have assumed all projects to have a life-time of 35 years and a net salvage value of zero at the end of the project life.

The annual fixed costs of owning the power line are calculated using a 16% fixed charge rate. The fixed charge rate can vary from utility to utility and from one region to another. However, 16% is representative of the utility industry. Included in the fixed charge rate, is the recovery of the investors initial capital investment (depreciation of the asset), return on this investment (interest or dividends paid to investors), and the utility's annual costs to own the asset including such items as property taxes and insurance. As shown in the detailed tables, the fixed costs are the major component of the life-cycle cost.

The second component in the life-cycle cost is power line losses in operating the power line. The power loss costs are calculated on the basis of an assumed power loading on the line and a cost of power. As shown in the detail sheets the power losses can be a significant portion of the life-cycle costs (5 to 30%).

The third component of life-cycle cost is operation and maintenance costs (O&M). A portion of O&M cost is related to the power line structures and conductors. Another portion is related to maintaining the right-of-way clear of brush and trees. These costs can vary considerably from location to location. For the purpose of our analysis we have used the industry average of approximately 1%. Fortunately, these costs are a relatively small portion of the life-cycle costs and, thus, have little influence on the comparative life-cycle costs.

Table 2.1.1A shows an example cost estimating sheet for distribution lines. It shows cost estimate details for the 13.2 kV horizontal crossarm rural design. The table is followed by a set of cost comparison summary sheets for each distribution line voltage category. These include 7.6 kV single-phase, 13.2 kV three-phase, and 34.5 kV three-phase.

COST ESTIMATE DETAILS
2.1.1A - 13.2 kV Horizontal Crossarm
Rural location

Assumptions:

Length of line	10	miles
Average span	400	feet
One Deadend (or 90° Angle every)	2	miles
Ratio of angle to deadend structures	2	angles/deadend
Right-of-way (ROW) width	50	feet
Percentage of ROW Requiring Clearing	40%	

Structures (including insulators)			Unit Costs		Construction Costs		
Type	WP X-arms	Units	Material	Labor	Material	Labor	Total
Tangent	45 Ft Cl H-1	118	943	1,182	111,267	139,527	250,794
Angle	45 Ft Cl H-2	10	1,397	1,599	13,972	15,990	29,961
Deadend	50 Ft Cl H-2	5	2,007	2,101	10,035	10,506	20,540
Subtotal Structures		133			$135,274	$166,022	$301,295
Conductors (Units in miles)							
Conductor	3-795 kcmil + 4/0 Ne	10	22,645	42,000	226,449	420,000	646,449
Shield wire	- none-						
Subtotal Conductors					$226,449	$420,000	$646,449
Contractor Mobilization						10,000	10,000
Total Material & Labor					$361,722	$596,022	$957,744
Total Material & Labor per Mile					**$36,172**	**$59,602**	**$95,774**

Clearing of ROW	24.2 acres @	2,000 per acre		48,485
Restoration of ROW	10 miles @	5,000 per mile		50,000
Construction of Access Roads	0.0 miles @	25,000 per mile		0
Subtotal clearing, restoration and access roads				$98,485
Right-of-way Costs	60.6 acres @	3,500 per acre		212,121
Overhead Costs				
Licensing & permits				5,000
Right-of-way Procurement	50% of right-of-way costs			106,061
Engineering	6% of labor and material			57,465
Soil Borings	0 sites @	$1,000 site		0
Surveying	10 miles @	$12,500 per mile		125,000
Construction Inspection	1.0 month @	$10,000 month		10,000
Owner's Admin. Costs				30,000
Subtotal Overhead Costs				$333,525
Project Subtotal				$1,601,875
Allowance for Funds Used During Construction (AFUDC)			3%	48,056
Project Contingency			15%	240,281
Total Project Cost				$1,890,213
Average Project Cost per mile				**$189,021**

LIFE CYCLE COST ANALYSIS
2.1.1A - 13.2 kV Horizontal Crossarm
Rural location

Assumptions for Calculation of Fixed Charges

Economic Life	35 years	Fixed Charge Rate	16.0%
Capital Costs	189,021 $/mi		
		Fixed Costs	**$ 30,243 $/mi/yr**

Assumptions for Calculation of Line Losses

Conductor			
1-795 kcmil ACSR "Drake"		0.1278 ohms/mi	
Peak Loading	300 amps	Load Factor	60.0%
Peak.Losses	11.5 kW/mi.	Loss Factor	40.8%
Annual Losses	41,109 kWh/mi		
Cost of Power	0.03 $/kwH		
		Cost of Losses	**$ 1,233 $/mi/yr**

Assumptions for Calculation of O&M Costs

L & M Costs	95,774 $/mi		
O&M Costs	0.5% of L & M		
		O&M Costs	**$ 479 $/mi/yr**

Assumptions for Life-Cycle Cost

Economic Life	35 years
Present Worth Discount Rate	10.0%

LIFE-CYCLE COSTS

	First Year Costs $/mi		Escalation per year	Life Cycle Cost $/mi.	
Fixed Costs	30,243	94.6%		291,672	93.4%
Cost of Losses	1,233	3.9%	2.0%	14,319	4.6%
O&M Costs	479	1.5%	3.0%	6,156	2.0%
Total	$ 31,956	100.0%		$ 312,147	100.0%

COST COMPARISON OF 4.16 - 13.2 KV DISTRIBUTION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options - Three-Phase						
2.1.1A - 13.2 kV Horizontal Crossarm	96	100%	189	100%	312	100%
2.1.2A - 13.2 kV Delta - Posts Insulators	104	108%	199	105%	328	105%
2.1.3A - 13.2 kV Hendrix Cable	124	129%	224	118%	368	118%
2.1.4A - 13.2 kV 6 Wire Split Phase Crossarm	118	123%	217	115%	359	115%
2.1.5A - 13.2 kV 6 Wire Hendrix Cable	154	161%	262	139%	431	138%
2.1.6A - 34.5 kV Horizontal Crossarm	77	81%	166	88%	266	85%
2.1.7A - 13.2 kV 5 Wire Split Phase	121	126%	220	117%	364	117%
Rural Options - Single Phase						
2.3.1A - 7.6 kV Single Phase	33	100%	107	100%	172	100%
2.3.2A - 7.6 kV Single Phase Tall Compact	42	130%	119	111%	192	111%
Suburban Options - Three-Phase						
2.1.1B - 13.2 kV Horizontal Crossarm	103	100%	194	100%	363	100%
2.1.2B - 13.2 kV Delta - Posts Insulators	119	116%	214	110%	396	109%
2.1.3B - 13.2 kV Hendrix Cable	127	123%	224	116%	411	113%
2.1.4B - 13.2 kV 6 Wire Split Phase Crossarm	131	127%	229	118%	429	118%
2.1.5B - 13.2 kV 6 Wire Hendrix Cable	157	152%	261	135%	480	132%
2.1.6B - 34.5 kV Horizontal Crossarm	87	84%	173	89%	293	81%
2.1.7B - 13.2 kV 5 Wire Split Phase	134	129%	232	120%	431	118%
2.1.8B - 13.2 kV 3-1c Cables in 3 Ducts	448	434%	630	324%	1,059	291%
2.1.8(5kV)B - 4.16 kV 3-1c Cables in 3 Ducts	433	419%	610	314%	1,027	283%
2.1.9B - 13.2 kV 3-1c Cables in 1 Duct	408	395%	576	297%	956	263%
2.1.9(5kV)B - 4.16 kV 3-1c Cables in 1 Duct	388	375%	550	283%	913	251%
2.1.10B - 13.2 kV 3-1c URD Direct Bury	127	123%	203	104%	380	105%
2.1.10(5kV)B - 4.16 kV 3-1c URD Direct Bury	110	106%	180	93%	344	95%
Suburban Options - Single-Phase						
2.3.1B - 7.6 kV Single Phase	43	100%	115	100%	199	100%
2.3.2B - 7.6 kV Single Phase Tall Compact	55	129%	130	113%	223	112%
2.3.3B - 7.6 kV 1c URD Direct Bury	57	134%	123	107%	214	107%
2.3.3(5kV)B - 2.4 kV 1c URD Direct Bury	48	113%	111	97%	195	98%
Urban Options						
2.1.8C - 13.2 kV 3-1c Cables in 3 Ducts	662	100%	921	100%	1,522	100%
2.1.8(5kV)C - 4.16 kV 3-1c Cables in 3 Ducts	647	98%	900	98%	1,489	98%
2.1.9C - 13.2 kV 3-1c Cables in 1 Duct	623	94%	869	94%	1,420	93%
2.1.9(5kV)C - 4.16 kV 3-1c Cables in 1 Duct	602	91%	841	91%	1,377	90%

COST COMPARISON OF 34.5 KV DISTRIBUTION ALTERNATIVES
1996 DOLLARS PER MILE

Description	Material & Labor Cost $x1,000		Project Costs $x1,000		Life-Cycle Costs $x1,000	
Rural Options - Three-Phase						
2.2.1A - 34.5 kV Horizontal Crossarm	96	100%	189	100%	313	100%
2.2.2A - 34.5 kV Delta - Posts Insulators	104	109%	200	105%	329	105%
2.2.3A - 34.5 kV Hendrix Cable	145	151%	251	133%	411	131%
2.2.4A - 34.5 kV 6 Wire Split Phase Crossarm	120	124%	219	116%	362	116%
2.2.5A - 34.5 kV 6 Wire Hendrix Cable	181	189%	296	156%	485	155%
2.2.6A - 34.5 kV 5 Wire Split Phase	121	126%	221	117%	365	117%
Suburban Options - Three-Phase						
2.2.1B - 34.5 kV Horizontal Crossarm	106	100%	198	100%	369	100%
2.2.2B - 34.5 kV Delta - Posts Insulators	120	113%	215	109%	397	108%
2.2.3B - 34.5 kV Hendrix Cable	148	140%	250	127%	453	123%
2.2.4B - 34.5 kV 6 Wire Split Phase Crossarm	133	125%	231	117%	433	117%
2.2.5B - 34.5 kV 6 Wire Hendrix Cable	185	174%	296	150%	536	145%
2.2.6B - 34.5 kV 5 Wire Split Phase	135	127%	234	118%	433	117%
2.2.7B - 34.5 kV 3-1c Cables in 3 Ducts	482	454%	672	340%	1,126	305%
2.2.8B - 34.5 kV 3-1c Cables in 1 Duct	462	436%	646	327%	1,066	289%
2.2.9B - 34.5 kV 3-1c URD Direct Bury	158	149%	241	122%	442	120%
Urban Options						
2.2.7C - 34.5 kV 3-1c Cables in 3 Ducts	699	100%	966	100%	1,594	100%
2.2.8C - 34.5 kV 3-1c Cables in 1 Duct	681	97%	941	97%	1,536	96%