VII. MAGNETIC FIELD MODELING TOOL

PG&E will utilize available software to model and calculate the magnetic field environment within and around substations. Currently there are two programs available:

- λ SubCalc from EPRI EMWorkstation (EPRI members only)
- λ 3D-FIELDS from Southern California Edison (public domain software)

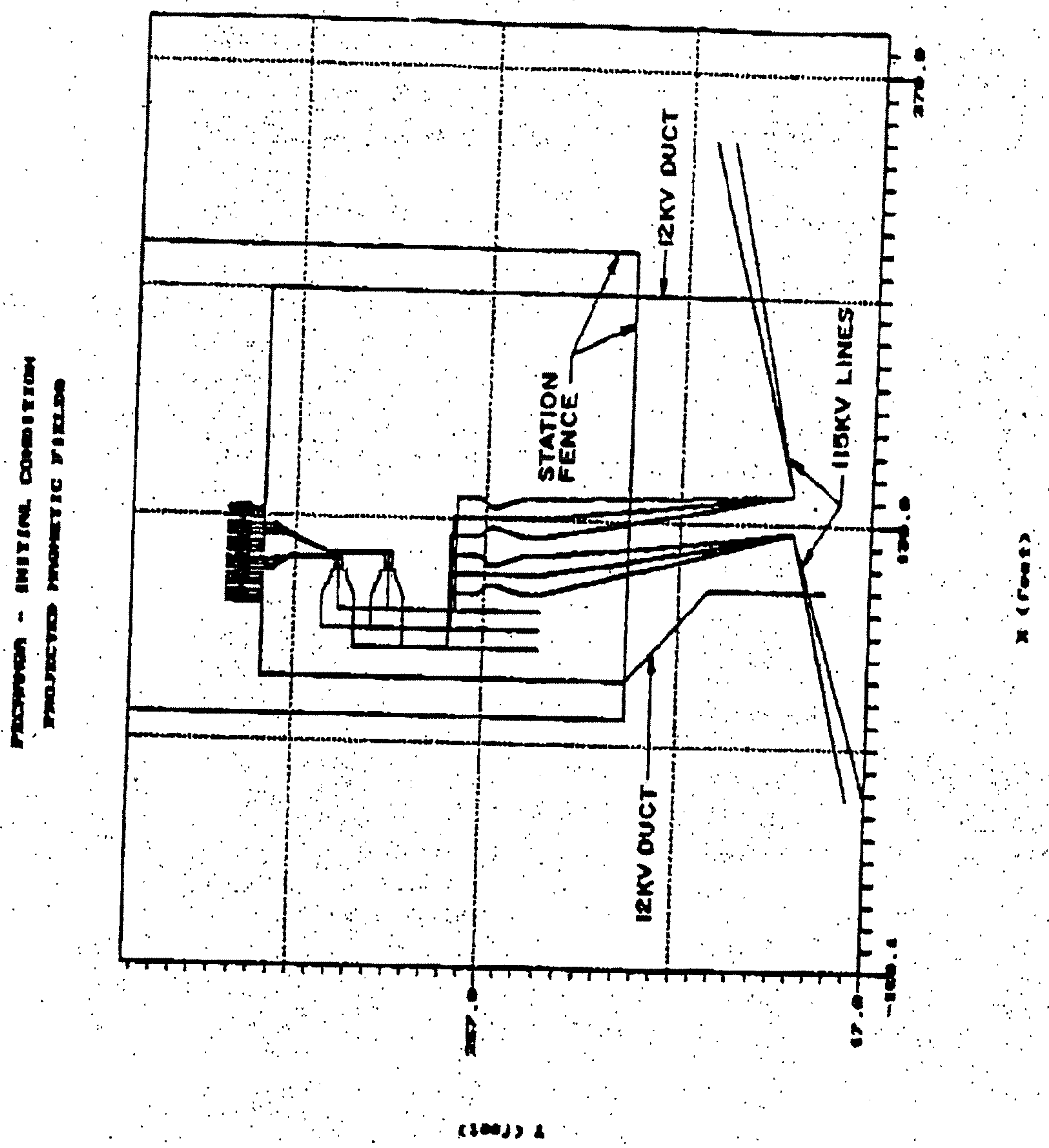
Both programs create a three-dimensional replica of all the conductors in a substation, represented by beginning and ending coordinates in feet. In addition, the engineer enters the phase angles and magnitudes of current on each conductor. The program has the capability of plotting graphic representations of the following information:

Plan View of entered data (see Figure VII-1)
Elevations of entered data along selected profile lines
Contour Plot of calculated Magnetic Fields
3-D Plot of calculated fields
Profile Plot of calculated fields along selected profile lines

By utilizing computer programs, the engineer can determine the layout, phasing, phase configurations, and construction options that provide the lowest levels of magnetic field strength.

The magnetic field strength of a substation is dependent upon the location of various devices within the facility. Because of the complexity in modeling the layout of every device's contiguous location, some common industry assumptions may be used to simplify the modeling process:

- λ Loading at nameplate capacity with balanced loading and normal operating conditions
- λ Neutral or Ground currents are not considered
- λ The modeling software currently cannot represent transformer or reactor devices
- λ Underground (UG) distribution circuits are phased in a fixed pattern (no rolling of cables modeled)



EXAMPLE OF SUBSTATION PLAN VIEW (X & Y axis)
AS PLOTED BY *3D-FIELDS* PROGRAM

FIGURE VII-1 PLAN VIEW OF SUBSTATION MODELING

VIII. MAGNETIC FIELD REDUCTION TECHNIQUES AND RECOMMENDATIONS

In general, there are four techniques that may be available to reduce the magnetic field strength levels from AC electric substation facilities. They are:

- Increase Distance from Sources
- Reduce Conductor Spacing
- Minimize Current and Balance Current
- Optimize Phase Configuration

This section contains a detailed discussion of each option and how these techniques can be applied to PG&E substations. The intent of this section is to define the options that may be available. However, the practicality of any particular option must be addressed in the specific case.

Increase Distance from Sources

The strength of the magnetic field decreases as the distance from the source increases. Therefore, one method of reducing the magnetic field strength at a particular location is to increase the distance from the sources to the location of interest. The rate of decrease is dependent on several factors, including substation layout and the current unbalance in the circuit.

The areas of interest where field minimization is desired are those that are accessible to the public. For electric substations, this location will be considered the security fence line. Magnetic fields beyond the fence line are normally dominated by the magnetic fields created by the incoming and outgoing transmission and distribution lines. Southern California Edison modeled a typical distribution substation (Wyle Sub) with and without the influence of these lines. Figure VIII-1 shows the dominating line magnetic fields along the fence line where the lines cross.

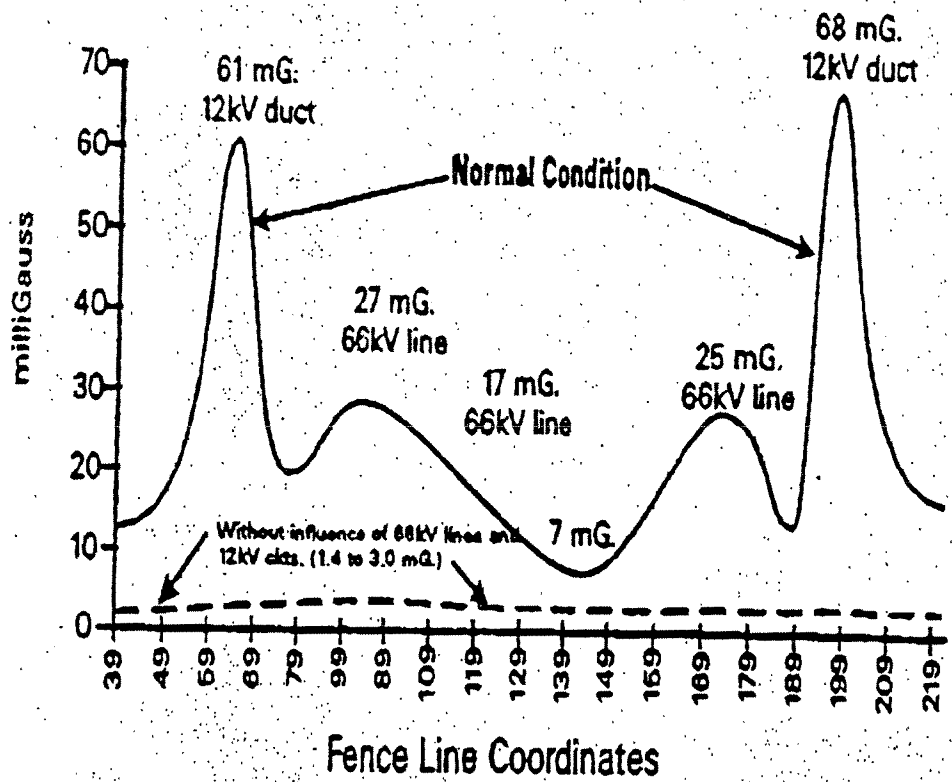


FIGURE VIII-1 MAGNETIC FIELDS ALONG THE SUBSTATION FENCE

Magnetic field reduction may be accomplished in a variety of ways, including:

Siting- taking into account the types of land uses adjacent to substations.

Access- minimizing public usage around substations.

Equipment Location- locate sources as far from the fence line as possible.

Height- increasing the height of overhead sources.

Property Line- increasing the amount of open "buffer" area around substations.

Siting

In the siting of new substations, the alternative site analysis considers potential land use impacts. A study of the existing and projected magnetic field environments should be performed to investigate how siting considerations may be affected by magnetic field strength. Included in the study should be an analysis of present magnetic fields, computer-generated field strengths for the proposed alternatives and a discussion of how land uses may be impacted. This may result in siting the substation further from the load or causing longer line routes. Any resulting impacts to the line magnetic fields, environmental concerns or costs must be balanced against the substation magnetic field issue.

Locate substations as close to existing transmission right-of-ways as possible. Some designs may even take advantage of some of the existing right-of-way land for the substation facility, thereby lessening the overall land requirement impact.

Access

Public access around substations shall be defined as the fence line and shall never include areas internal to the fence line. PG&E will define the public access boundary on a plot plan of the substation and surrounding property for use in analyzing the field reductions for existing and proposed zoning uses. Agricultural lands should be exempt from consideration as occasional public access points.

It has been a common PG&E practice to allow third party access to substation property outside the security fence for various uses: including jogging, hiking, and bicycle paths; parking lots; nurseries; parks and activity fields; and other similar uses. In light of public concern over the EMF issue, it may not be desirable to encourage those uses that place the public in the magnetic field environment directly under the transmission lines. The Land Department should be consulted on new **substations** regarding how the land purchase documents may be written to provide PG&E with the ability to make these decisions.

Equipment Location

The sources should be located within the facility as far from the fence line as practical. In addition, the higher-current sources should be located closer to the center of the facility if possible, including compaction of the equipment spacing. Any incoming lines to the substation, whether transmission or distribution, should be routed within the property line and as close to the facility as practical.

Figure VIII-2 shows the typical magnetic field intensity in relation to the centerline of an underground (UG) distribution circuit ("duct bank"). The magnetic field decays rapidly (50% of maximum) at a distance of only 6 feet from the centerline, illustrating the importance of locating UG duct banks as far within the perimeter fence line as practical for parallel routing.

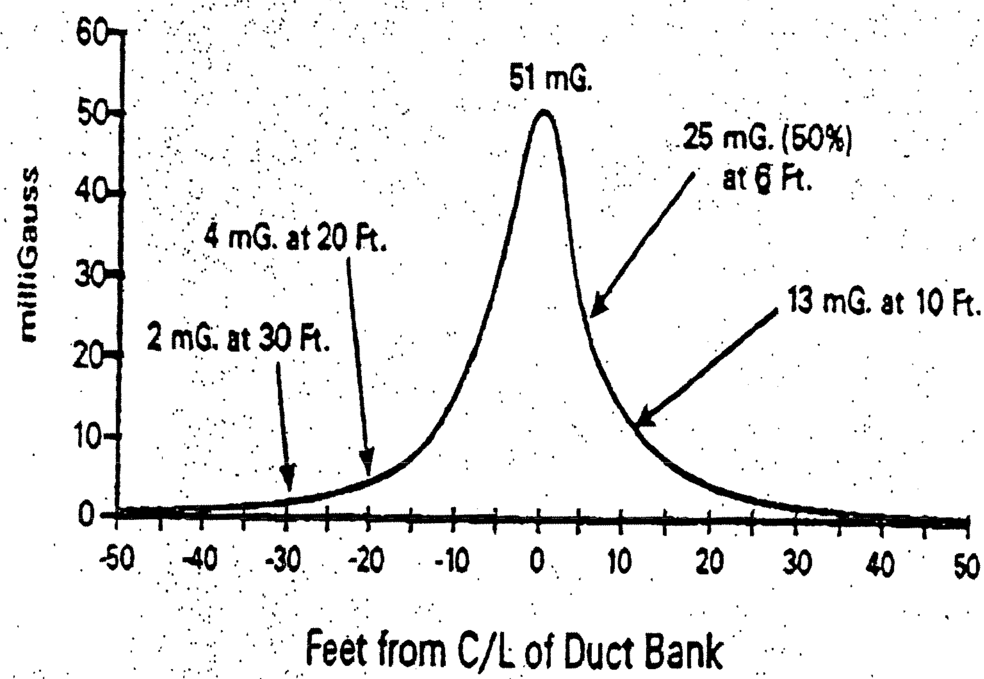


FIGURE VIII - 2 MAGNETIC FIELDS OVER A 12 kV DUCT BANK

Isolating the station ground grid from the perimeter security fence may reduce magnetic fields resulting from circulating ground currents within the station. For safety reasons the fence (if metallic) should be grounded, yet can be "floated" from the remaining station grid more central to the facility. PG&E has typical "floated" the fence grounding from the internal grid and may already be achieving some field reduction from this technique.

Height

Another possible technique to reduce the magnetic field strength at ground level is to increase the distance of the sources from ground. There are two primary methods in which this may be accomplished:

- Raise the height of the substation structures used.
- Suspend sources from existing taller structures.

This is particularly important for sources located near the fence line such as bus conductors, disconnect switches or wave traps. Any resulting impacts to the visual aesthetics of the substation must be considered along with the magnetic field reduction issue.

Fence Line
Increasing the amount of secured property would increase the distance from the sources to the fence line, thereby reducing the magnetic field strength level at the fence line. Land availability for acquisition and the costs associated with the cost of additional property must be taken into consideration when examining this option.

Reduce Conductor Spacing

The magnetic field strength at ground level is a result of the addition of the magnetic field vectors of the various current-carrying conductors. As the phases are moved closer together, there is increased phase-to-phase cancellation of the magnetic field and the total resultant field strength decreases. Therefore, compact spacing designs can result in a lower magnetic field strength than larger, more spread out designs.

For overhead busses, horizontal or vertical configurations typically have a larger phase spacing and hence, produce higher fields under the bus than triangular or delta configurations. For underground busses, self contained systems, where each phase is placed in a separate duct, generally produce greater fields than pipe-type systems, where all three phases are contained in a single duct. Feeder outlets for distribution can typically be installed underground in a single duct, thereby reducing the overall magnetic field strength. PG&E has been undergrounding feeder getaways as an aesthetic technique for years.

For metal-enclosed busses, as in switchgear and GIS, the phase spacing can be greatly reduced, thereby minimizing the overall magnetic field strength. Switchgear devices and busses that utilize vacuum or gas insulation will significantly reduce the phase spacing compared to oil or air insulation.

Due to flashover and reliability considerations for the circuit, there is a practical limit to the reduction in spacing that can be achieved. A reduction in the phase spacing may also impact live line work procedures used to maintain the bus. In general, any spacing reduction should consider the impact to proper electrical clearances, worker safety, utility vehicle traffic, possible contact from small animals, and conductor heating.

Minimize Current and Balance Current

As mentioned in the Overview section (Section III), the magnetic field strength is directly proportional to the magnitude of the current flowing in the conductor. The higher the current, the greater the field strength. This is true for the phase conductor current or the unbalanced neutral current. This section will discuss both.

For phase currents, the amount of power a line transports is proportional to the product of current and voltage, P=V*I. From this equation, it can be seen that the power flow and the voltage of the line are two factors that can be manipulated to reduce the current.

Higher voltage transmission lines can transport the same amount of power with less current than a lower voltage line. As a result, a line operating at the higher voltage will produce a lower magnetic field strength for the same power transfer than a line operating at a lower voltage. It should be noted that an increase in the line voltage will also allow additional power to be transferred without increasing the magnetic field.

Over the past years, PG&E has increased many of the 12kV operating distribution voltages to 21kV when practical. Each increase in voltage level proportionally reduces the magnetic field strength levels.

Another way to minimize the load current is to minimize the power transferred. This may be feasible in selected sites, but it may not be a practical proposition to achieve large scale reductions in load current because the magnitude of power transferred is controlled primarily by the level of customer demand for the electrical power.

It is possible to achieve some reduction in current through Customer Energy Efficiency programs. Adequate reactive load compensation (i.e., capacitors) can be provided to bring the power factor closer to unity at the distribution level, thereby minimizing the reactive power flow on transmission lines. In addition, the current on a particular transmission line may be reduced by providing an alternative path for the power to flow.

This may be accomplished through the switching or reconfiguration of existing facilities or the construction of additional transmission lines. (Any additional facilities may, in association, increase magnetic field in the area and must be properly analyzed to avoid negative tradeoffs).

The magnetic field strength from lines with unbalanced currents decreases less rapidly than the fields from lines with balanced currents. In many cases, the ground level component of the magnetic field strength due to the unbalance is greater than the component due to the phase currents. Therefore, balancing an existing unbalanced line will have a large effect on the ground-level field strength by reducing the amount of return currents to the substation facility.

Unbalanced lines are normally a concern in the distribution system. However, there are local conditions that can cause the phase currents on a transmission line to become unbalanced.

Phase Configuration

Selective use of some phase configurations can be used as a field cancellation technique. Since the resultant magnetic field strength at any one point in space is the vector sum of the individual fields of the three phases of the bus, alternate phase orientations other than the typical horizontal configuration can be used. Other configurations worth considering are vertical or delta or a variation of those.

The phasing relationship between all busses in a substation must be evaluated to determine the optimum phasing for the busses that results in the lowest combined field strength. It should be kept in mind when doing this evaluation that the loading and direction of current flow on each bus may vary with time. Therefore, there may not be one single "optimum" low field phasing combination for the substation. It is recommended that in this case the phasing configuration that results in the lowest average field strength should be used.

PG&E has historically used an A-B-C:C-B-A phase relationship for the double bus designs in many substations. This phasing may already achieve significant magnetic field reductions compared to other configurations.

Preferred Field Reduction Techniques

The following design techniques are expected to have the most impact on reducing magnetic fields around substations and will receive priority focus by design personnel:

- Compacting the equipment spacing within the facility and locating the high-current sources as close to the center as possible.
- Increasing the property area within the security fencee
- Reducing the phase spacing on distribution busses by utilizing metal-enclosed switchgear technology.

PG&E does not expect suggested design techniques for Conductor Height, Phase Location, Minimizing Current, Siting and Transmission Bus Phase Spacing to have an appreciable impact on reducing overall magnetic fields around expanded or new PG&E substations. These other techniques will be utilized if the primary techniques do not achieve the desired reductions.

IX. FIELDS FROM DEVICES

The remaining section of this document provides magnetic field information on the various standard PG&E substation devices. This section only discusses devices currently used by PG&E and does not attempt to present alternative design options that may be available elsewhere in the industry. PG&E does not currently have much specific field information for this section, although several studies are underway. Information listed here has been obtained from other referenced utilities. Information not available yet will be provided later from verified field test cases.

This section is arranged according to the following substation device categories:

- **Transformers**
- **Switchgear**
- **High and Low Voltage Busses**
- **Wave Traps**
- **Other**

All of the magnetic field strength numbers to be provided in this section are computed at a 3-foot height above ground level and are based on a balanced current flow.

There are various general loading conditions often used for magnetic field strength calculations. These include:

- Normal Current (time weighted average current)
- Heavy Load Current (system peak, all lines in service)
- Maximum Steady State Design Current (the design capability of the line)
- Emergency Maximum Current (System peak, with one line out of service)

It is recommended that the present year Heavy Load value be used for magnetic field strength calculations. This condition gives the highest realistic strength value. When presenting the magnetic field strength data, it should be noted if the load varies significantly over the time of day or throughout the year. If it does, it may be desirable to perform some type of averaging on the current or differentiate between the current levels for the various time intervals.

In addition to determining the appropriate current value to use, it is important to use the correct conductor height. To maintain consistency and provide the highest realistic value, it is recommended that the midspan conductor height be used, although within substations the spans are typically short enough that sag of the conductors at midspan is negligible.

Transformers

No information is currently available for transformer devices within substations

Switchgear

San Diego Gas & Electric (SDG&E) has done a study on phase compaction of the distribution bus. Modeled fields from a 12kV open-air 3-phase horizontal bus were compared to modeled fields from metal-enclosed switchgear. The reduced phase spacing showed a 76% reduction in magnetic fields at 25 feet from the center of the modeled phases (see Figure IX-1). PG&E is currently performing a similar case study to model reductions from a similar design (Bantam Sub). These models do not include shielding from the metal cabinets.

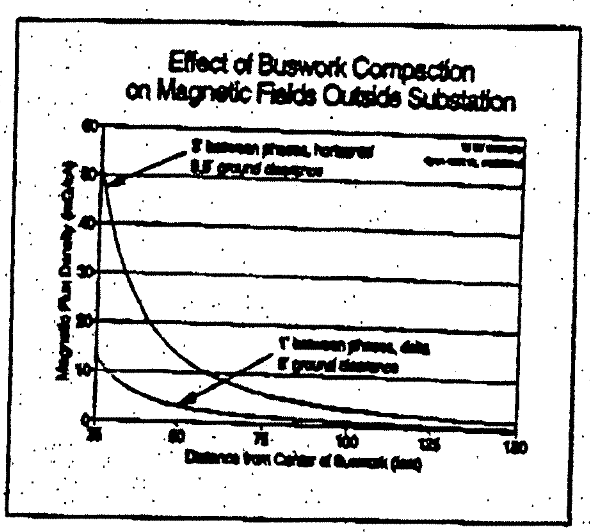


Figure IX- 1 Magnetic Field Effects of 12kV Bus Compaction

High and Low Voltage Busses

SDG&E has also done some studies on increasing the property area from the buswork to the security fence line. Modeled fields from conductor busses show substantial magnetic reductions by increasing the property from the outer-most phase by an additional 25 feet. Table 2 below shows calculated magnetic flux densities (mG/kA) at 25 feet a way and the reduced densities at 25 feet further away (Flux Density is away of modeling magnetic fields without inputting specific bus current levels. It is a helpful technique to "normalize" general field reductions--simply multiply the density by expected bus current in "thousand amps" to convert to magnetic field levels in "milligauss"):

Equipment Type	Magnetic Flux Density (mG/ka)		Field Reduction
	at 25 away	at 50 feet away	
12kV Switchgear	12	4	67%
12kV Bus	51	14	73%
138kV Bus	53	24	55%
138kV Bus (5% Unbalance)	60	30	50%

Table 2 -- Substation Bus Flux Densities

A case study by Southern California Edison (SCE) of a 66/12 kV distribution substation (Wyle Sub) showed through modeling that fields along a critical fence line could be reduced by adding additional property and relocating UG duct banks further within the fence line. The 12kV duct banks were relocated 25 feet within parallel fence lines, and the critical fence line was moved 20 feet further out. Fields previously modeled ranged from 17 to 24 mG based on SCE's projected load currents. Modeled fields were reduced to levels from 8 to 9 mG along the fence line profile--a reduction of 53 to 63% (see Figure IX-2 for graphical representation of the field comparisons).

Wave Traps

No information is currently available for wave trap devices within substations

Other

No information is currently available for other devices within substations

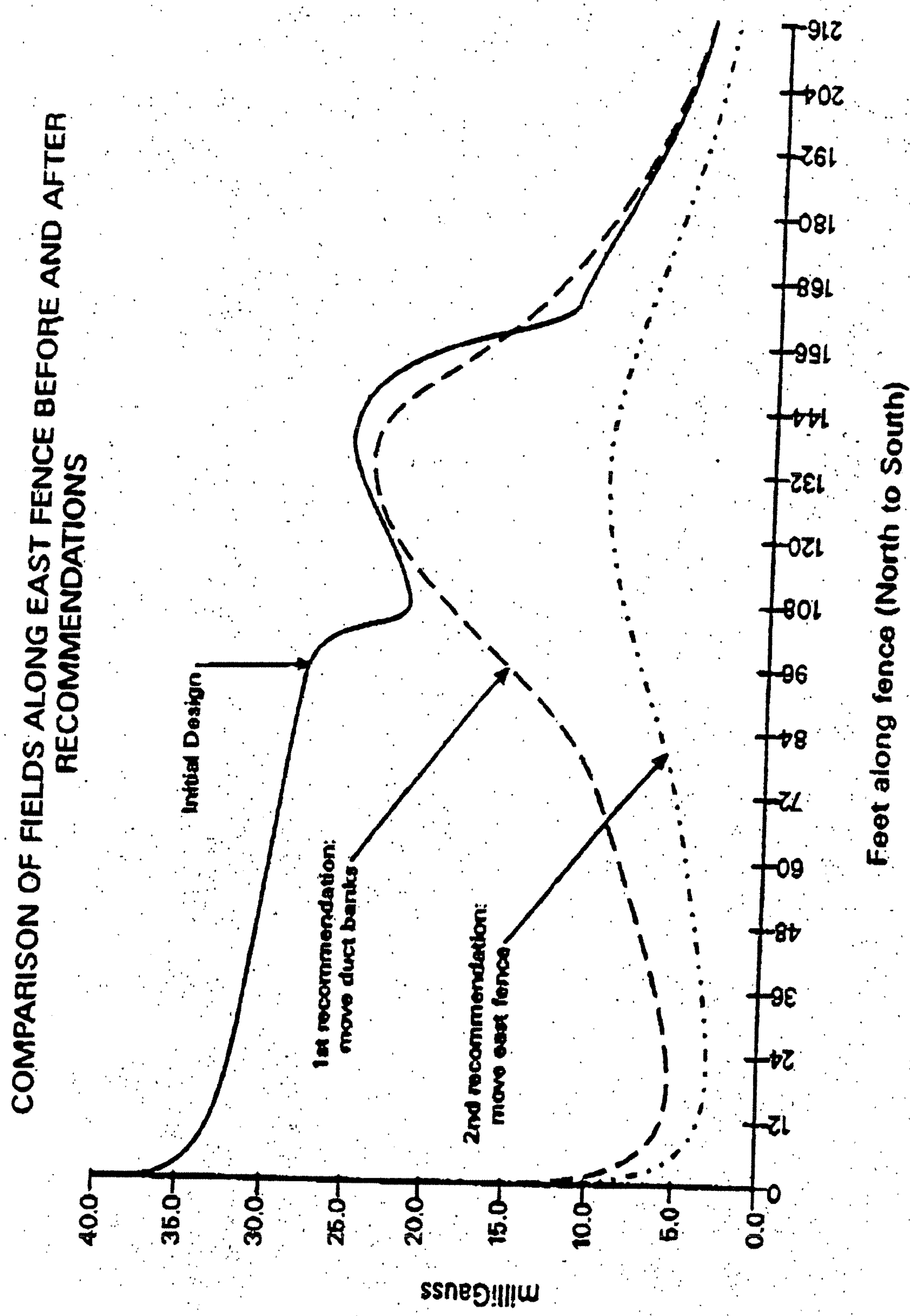


FIGURE IX - 2 MAGNETIC FIELD COMPARISON AT WYLE SUB

APPENDIX A -- References

"High Voltage Transmission Lines, Summary of Health Effect Studies," California Energy Commission, July 1992.

Marshall, Stanley V. and Skitek, Gabriel G., Electromagnetic Concepts and Applications, Prentice Hall, Englewood Cliffs, New Jersey, Third Edition, 1990.

Electric Power Research Institute, Transmission Line Reference Book 345kV and Above, Second Edition, 1982.

Olsen, Robert G. and Wong, Paul S., "Characteristics of Low Frequency Electric and Magnetic Fields in the Vicinity of Electric Power Lines", IEEE Transactions on Power Delivery Volume 7, Number 4, pp. 2046-2055, October 1992.

Kaune, W.T. and Zaffanella, L.E., "Analysis of Magnetic Fields Produced Far From Electric Power Lines", IEEE Transactions on Power Delivery Volume 7, Number 4, pp. 2082-2091, October 1992.

Schmus, W.R. and Lai, A.W., "Distribution Designs To Manage Electric and Magnetic Fields". Presented at Pacific Coast Electrical Association 1992 Engineering and Operating Conference, March 19, 1992.

Goldberg, S., Horton, W.F., and King, P. B., "Characterizing the Magnetic Fields of Household Appliances" in The Proceedings of the Twenty-Fourth Annual North American Power Symposium, pp. 403-412, October 1992.

Douglas, John, "Taking the Measure of Magnetic Fields", Electric Power Research Institute Journal, April\May 1992, pp. 16-17.

APPENDIX B -- GLOSSARY

Alternating Current (AC) - Electric current that reverses its direction at regular intervals or periods. An AC field also changes strength and direction in a rhythmically repeating cycle.

Ampere (A)- The unit of measure of electric current; specifically, a measure of the rate of flow of electrons past a given point in an electric conductor such as a power line.

$\bar{B}$ - The magnetic flux density vector, a vector field, expressed in tesla (SI units) or milligauss (Gaussian units).

Balanced Currents - A set of conductors whose currents instantaneously sum to zero are said to have balanced currents. A three-phase electric power transmission line is said to have balanced currents if the phase currents are equal in magnitude and at 120 electrical degrees with respect to each other (only positive-sequence symmetric components).

Circuit - A closed conducting path for the flow of current. For AC electrical circuit, there are three phases per circuit.

Conductor - A material that allows the flow of charge. The wires on transmission lines are conductors.

Current - The flow of electrically charged particles. The unit is ampere (A).

Direct Current (DC) - Electric current that flows in a single direction and at a constant voltage. A DC field is also steady and does not change strength or direction over time.

Electric Field ($\bar{E}$) - A vector field describing the electrical force on a unit charge in space. Electrical charges are a source of electric fields. The electric field from a power line is an alternating, 60-Hz field due to charges on the conductors. The intensity of the electric field is expressed in volts per meter (V/m) or kilovolts per meter (kV/m).

Extremely Low Frequency (ELF) - ELF denotes the frequency range below 300 Hz.

EMF - A non-scientific term in popular use to refer to Electric and Magnetic Fields (or, Electro Magnetic Fields). This term is often used to describe magnetic fields only.

Ferromagnetic Materials - Materials exhibiting a strong magnetic moment which can be aligned with an applied magnetic field. Ferromagnetic materials exhibit large values of relative permeability (e.g., iron alloys).

Field - Any physical quantity that takes on different values at different points in space.

Frequency - The number of complete cycles of a periodic wave form per unit time. The units of frequency are Hertz (Hz).

Gauss (G) - A common unit cf measure for magnetic fields. Abbreviated G. A milligauss (mG) is one thousandth of a gauss. There are 10,000 gauss in one tesla. The gauss is a unit (in the CGS system) used to describe magnetic flux density (B), or magnetic flux lines () per unit of cross-sectional area. The gauss is one maxwell (one flux line) per square centimeter, or webers per square meter. One gauss equals tesla (MKS or SI units) and 1 mG equals 0.1 T

$\bar{H}$ - The magnetic field intensity vector, a vector field, usually expressed in ampere per meter.

Hertz (Hz)- the unit of frequency; equivalent to one cycle per second. In America, AC power has a frequency of 60 Hz. In most of Europe, AC power has a frequency of 50 Hz. Radio waves have frequencies of many thousands or millions of hertz. Abbreviated Hz.

Magnetic Field - A magnetic field (H) exists in the region near a permanent magnet or current semi-major axis represents the magnitude and direction of the maximum value of the magnetic field, and whose semi-minor axis represents the magnitude and direction of the field a quarter cycle later at its minimum value. The unit of magnetic field strength in the MKS (SI) system is the ampere-turn per meter, or simply, the ampere per meter (A/m), which is mmf per unit length. One ampere-turn per meter is the magnetic field strength in the interior of an elongated, uniformly wound solenoid that is excited with a linear current density in its winding of one ampere per meter of axial distance. (In the CGS system, the oersted is the unit of magnetic field strength:
Sometimes the magnetic field is described (incorrectly) using the units of its magnetic flux density (B) with MKS (SI) units of tesla and CGS units of gauss (or mG). One milligauss equals 0.1 microtesla. Magnetic field and magnetic flux density are related by the permeability of the material or medium in which they are characterized. The ratio of flux density (B) to field (H) is the permeability.

Neutral - Neutral is the wire at ground potential carrying the return current of energized wires.

Phase - The measure of the progression of a periodic wave form in time of space from a chosen instant or position. Most high voltage, ac transmission lines have three conductors or conductor bundles with the phase of the voltage in each advanced 120 degrees or one-third of a cycle relative to the others.

Polarization - The description of the angular variation with time of either the electric or the magnetic field vector at a fixed point is the field polarization. If the spatial components of the field are all in phase with each other, the field is said to be linearly polarized (the field vector will oscillate back and forth along a line with time). If, on the other hand, the individual spatial components of the field are not all in phase, the field will be elliptically polarized (the field vector traces out an ellipse with time). An elliptically polarized field can be described by its semi-major axis (or maximum value) and its semi-minor axis (minimum value) a quarter cycle later. The field ellipse is completely specified by its degree of polarization (ratio of minor/major axis) and its orientation (the spatial direction of its major axis). A polarized field with a degree of polarization of unity (major and minor axes are equal) is said to be circularity polarized since its field ellipse will trace out a circle with time.

Power - The time rate at which work is done. Electrical power is proportional to the product of current and voltage. The unit is the Watt (W).

Profile (of magnetic field) - A plot of the magnitude of the field as a function of horizontal distance, usually at a height of three feet from the ground plan.

Resultant Value of Magnetic Flux Density - The square root of the sum of the squares of the three orthogonal (x, y, and z) field vectors.

r.m.s (root mean square) - The square root of the average of the squares of individual values. For a sinusoidal variable, such as the amplitude of 60Hz alternating current, the r.m.s. value equals the peak value divided by the square root of two. Measured and calculated E&M field levels are usually r.m.s values.

Vectors - Vector quantities, or vectors, are those which can be represented on a map or a model by a directed line segment, where the length of the line represents the magnitude and the arrow represents the direction.

Voltage (V) the electrical potential energy difference per unit charge between two points. The unit is the volt .

APPENDIX C

Management Plan for Substation Magnetic Fields

Description of existing substation design:

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____
____
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____

<u>No Cost MF Mitigation</u>

Description of design technique(s)	%MF reduction
______________________________	_____
______________________________	_____
______________________________	_____
______________________________	_____
Overall % MF reduction	_____

<u>Low-Cost MF Mitigation</u>

Description of design technique(s)	% MF reduction	% cost increase
______________________	_____	_____
______________________	_____	_____
______________________	_____	_____
______________________	_____	_____
______________________	_____	_____
______________________	_____	_____

Overall % of MF reduction _____
Overall % cost increase _____

Pacific Gas & Electric Company

APPENDIX C

Management Plan for Substation Magnetic Fields

Descripition of existing substation design:

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____

<u>No Cost MF Mitigation</u>

Description of design technique(s)	%MF reduction
Overall % MF reduction	

<u>Low-Cost MF Mitigation</u>

Description of design technique(s)	% MF reduction	% cost increase

Overall % of MF reduction _____
Overall % cost increase _____

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