TECHNICAL MEMO
ON POWER-FREQUENCY
ELECTRIC AND MAGNETIC FIELDS

RELATED TO THE

PUGET SOUND ENERGY
ENERGIZE EASTSIDE PROJECT

Prepared for

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Introduction

Puget Sound Energy (PSE) has proposed the Energize Eastside project, which will provide improved electrical service to Eastside communities. The proposed project has four different alternatives under consideration:

Alternative 1: Approximately 18 miles of new 230 kV transmission line and one new transformer at or adjacent to one of three existing substations.

Alternative 2: A mix of energy conservation and generation components which include:

- Energy Efficiency – Reduce peak load demand by upgrading older, less-efficient equipment and better weatherproofing.
- Demand Response – Installation of in-home metering and control equipment to reduce and minimize energy usage.
- Distributed Generation – Installation of gas turbines, anaerobic digesters, reciprocating engines (diesel generators), microturbines, or fuel cells.
- Energy Storage – Construction of a battery facility for energy storage.
- Peak Generation Plant – Construction of three new 20 MW gas-fired generators at existing substations.

Alternative 3: Approximately 60 miles of new 115 kV transmission line and transformer upgrades at several existing substations.

Alternative 4: No action alternative but with the utilization of the Energy Efficiency component of Alternative 2.

A Draft Environmental Impact Statement (DEIS) has been published for the project. Subsequent to this report, Environmental Science Associates (ESA) requested that Enertech Consultants prepare a technical memo to address general topics related to power-frequency (60 Hertz) electric and magnetic field levels associated with the project. This technical memo addresses these general topics.

Corona Interference from Overhead Transmission Lines

Corona can occur at the surface of an overhead high-voltage transmission line conductor, when the electric field intensity at the surface of the conductor exceeds a threshold (the breakdown strength of air). When this situation occurs, a very small electrical discharge is generated that can create audible noise and radio frequency noise. Figure 1 presents a detailed, close-up photograph of a corona discharge on a conductor. Corona effects on high-voltage transmission lines have been studied for over 60 years and engineers take steps in the design of overhead transmission lines to limit corona activity to acceptable levels (EPRI 1982).

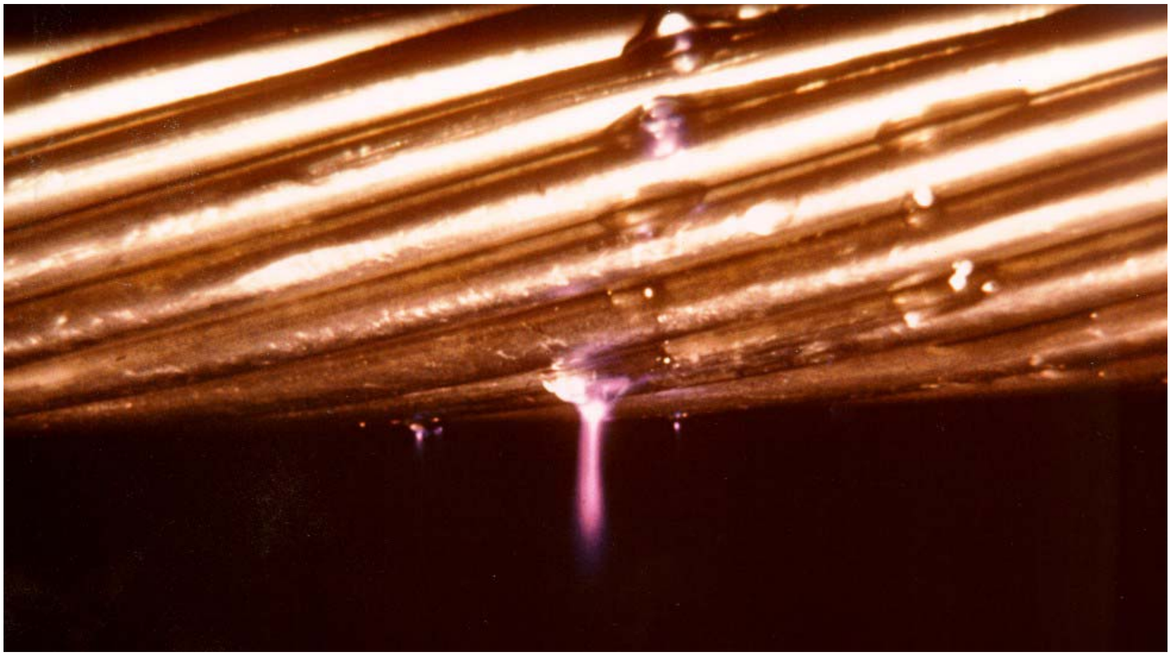

Figure 1. Close-Up Photograph of a Tiny Corona Discharge at the Surface of a Conductor

Corona is affected by the local electric field at the surface of the conductor (called the surface gradient) and is commonly described in units of kilovolts per centimeter (kV/cm). The conductor surface gradient is affected by many factors, including the conductor size, voltage of the line, smoothness or irregularities (such as nicks on the transmission line conductor, water droplets, insects, or debris) on the surface of the conductor, phase configuration, location of other energized conductors, distance to ground, etc. For new projects, such as the Energize Eastside project, electrical engineers will usually design overhead transmission lines to comply with recommended maximum conductor surface gradient values set forth in the Institute of Electrical and Electronics Engineers (IEEE) Radio Noise Design Guide for High-Voltage Transmission Lines (IEEE 1971). The design guide is applicable to overhead ac transmission lines in the voltage range of 115 kV to 800 kV. This design guide is a valuable tool in the design of overhead high-voltage transmission lines because it gives guidelines for acceptable electrical parameters (conductor surface gradients) that engineers can use to evaluate design options. The IEEE guide is based on many years of research and practical experience. Engineers can control the conductor gradients by selection of conductor size (larger conductors have lower gradients), phase spacing and arrangement, and sometimes by bundling (use of multiple conductors per phase lowers the surface gradient).

Gap discharges (where electricity crosses tiny gaps between mechanically connected parts) can also generate noise. Generally higher voltage transmission lines (such as the 115 kV and 230 kV transmission lines associated with the Energize Eastside project) do not produce noise due to gap discharges, since these lines would be constructed with modern hardware that eliminates such problems and therefore minimizes gap noise. Gap discharges are typically more common on lower-voltage distribution lines, caused by loose hardware and wires.

Overhead transmission lines do not, as a general rule, interfere with radio or TV reception. Corona-generated radio frequency noise decreases with distance from a transmission line and also decreases with higher frequencies. Whenever corona is a problem, it is usually for amplitude modulation (AM) radio and not the higher frequencies associated with frequency modulation (FM) radio or TV/satellite signals. With the introduction of digital television technology, the broadcast frequencies for affected channels have been raised and corona interference with these television signals is no longer a potential concern (FCC 1999, Smith 2004, EPRI 2006).

In the U.S., electromagnetic interference from transmission systems is governed by the Federal Communications Commission (FCC), which requires the operator of any device that causes "harmful interference" to take prompt steps to eliminate it (FCC 1988). Transmission line owners are also required to resolve interference complaints from licensed operators in accordance with FCC Rules and Regulations (47 CFR Part 15). Electric power companies have been able to work well under the present FCC rule because harmful interference can generally be eliminated. It has been estimated that more than 95 percent of power line sources that cause interference are due to gap-type discharges. These can be found and completely eliminated when required to prevent interference (USDOE 1980). Complaints related to corona-generated interference occur infrequently.

Communication interference is dependent upon the frequency of the system in use, the relative locations of the transmitters and receivers with respect to one another, and other parameters. Generally most modern fire and emergency responder communication systems (such as mobile-radio communications) utilize either FM or digital signals which are not affected by transmission line corona. In addition, interference is unlikely with other communications devices such as cell phones and GPS units which operate with digital signals at much higher microwave frequencies.

Interference from corona-generated noise is generally associated with lines operating at voltages of 345 kV or higher. In general, corona activity is not a problem for transmission lines rated at 230 kV and below, which are the voltage levels under consideration for Alternatives #1 (230 kV) and #3 (115 kV). Because of the lower voltage, the 115 kV transmission line associated with Alternative #3 would generally have less corona than the 230 kV line associated with Alternative #1. Corona levels for these proposed lines would be low, and no corona-generated interference with police and emergency personnel communication/emergency devices is anticipated. Furthermore, if interference should occur and to comply with FCC regulations, PSE would work with owners and operators of communications facilities along the transmission line to identify and implement mitigation measures in the event of interference from the new line. For Alternatives #2 and #4, no overhead transmission lines are proposed so corona is not an issue.

Of course, corona and radio noise are not factors for underground lines or underwater cables since they are not in corona (i.e. they are insulated by a solid dielectric material instead of air and therefore do not generate corona).

Differences in Magnetic Fields from Overhead versus Underground Lines

Magnetic fields are associated with any current-carrying conductor. Transmission lines create magnetic fields, which are generated by the current (amperes) flowing on the phase conductors. The magnetic field is a vector quantity having magnitude and direction. The magnetic field encircles the wire and the direction of the magnetic field is dependent upon the direction of current flow.

Magnetic field strength attenuates rapidly with distance away from a transmission line. However, the rate of attenuation is different from an overhead line configuration versus an underground (or underwater) line configuration. For overhead lines, the air is used as an insulator between each of the phase conductors, resulting in a larger distance separation between the conductors. Whenever energized conductors are spread farther apart, then the magnetic field cancellation between these conductors is diminished. In addition, the height of the conductors above ground level is significant for overhead lines (with higher voltage lines requiring more height). For overhead lines, the magnetic field typically decreases in strength with the square of distance ($1/d^2$) from the power line.

For underground lines, the conductors are encased with insulating material and conductors can therefore be placed in very close proximity to one another (often bundled together within a common pipe or duct). Whenever energized conductors are close together, then the magnetic field cancellation between these conductors is increased significantly. However, the depth below ground level of the conductors is typically much less than the ground clearance for overhead lines. For underground lines, the magnetic field typically decreases in strength as a function of $1/d^3$ in distance from the power line.

Figure 2 presents a generalized diagram of calculated magnetic field strength as a function of distance away from a power line, for both overhead and underground power line configurations (Appendix A presents the assumed overhead and underground line configurations used for these calculations). For overhead lines, the conductor height at midspan is greater in distance than the depth of the underground cables. Therefore, the magnetic field is generally higher directly above an underground cable than it is below an overhead line. However, because the underground cables are in close proximity to one another, the magnetic field strength decreases very rapidly with distance away from the cables due to their magnetic field cancellation. For overhead lines, the magnetic field strength persists farther away from the line (since the conductors are spread farther apart) and decreases more slowly over the distance.

Since the magnetic field overhead lines can influence a broader area than underground lines, then one could consider overhead lines as a more significant field source for public exposure than underground lines. However, if the underground line is routed within a more public location (centered along a recreation trail, for example), then the underground line could be a more significant field source than the overhead line. The location of the line route will play an important part for considering which type of line configuration will have the greater level of magnetic field for the general public. In general, underground lines tend to exhibit lower magnetic fields than overhead lines, except directly over the underground cable.

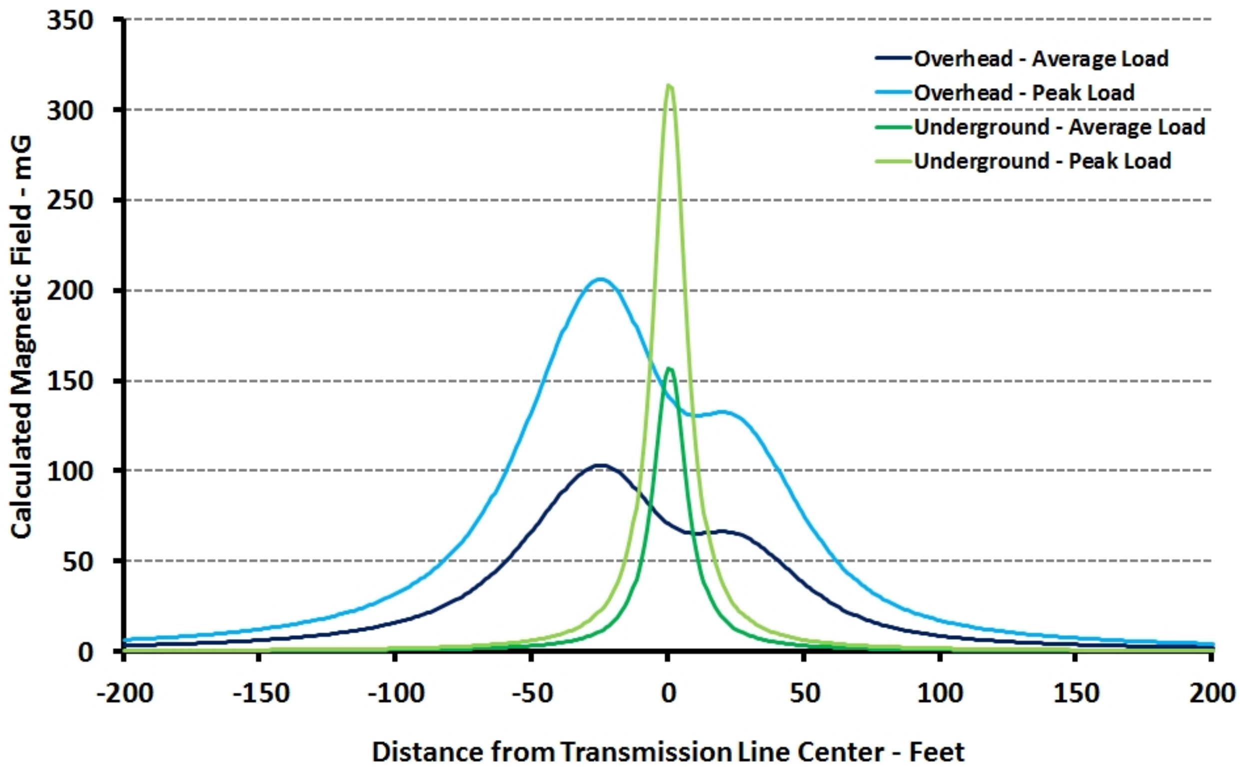

Figure 2. Graph of the Calculated Magnetic Field for a Generalized Overhead Transmission Line Configuration versus a Generalized Underground Transmission Cable Configuration (Given the Same Loading Conditions)

Magnetic Fields Associated with Project Alternatives

Alternative #1

The proposed Alternative 1 consists of approximately 18 miles of new 230 kV transmission line and one new transformer. For the 230 kV overhead transmission line, the spacing between the phase conductors will be increased due to the higher voltage than a 115 kV line. However, the minimum ground clearance at midspan will also be higher for the same reason. Because of the higher voltage, it will require less current (amperes) to transmit the same amount of power (MW) than a lower voltage transmission line would require (hence a lower equivalent magnetic field due to loading).

For magnetic fields, underwater transmission line cables have very similar field attenuation characteristics as those from underground cables. The magnetic field typically decreases in strength as a function of $1/d^3$ in distance from the underwater cable. However, the depth of the water influences the distance at which the general public might encounter these magnetic fields. In shallow water, magnetic field levels would be comparable to underground cables. However in deep water, the underwater cable would be located below the surface of the water (i.e. at the bottom of the lake) and therefore the distance away from the underwater cable would be increased. Since the distance away from the underwater cable is increased, the magnetic field would be significantly reduced (i.e. it would be similar to an underground cable located at the same depth below ground level as the underwater cable is below the surface of the water). Due to their location under water, the general public also has a lower probability of encountering magnetic fields from underwater cables than from land-based underground cables and overhead lines.

A new transformer would be installed within or adjacent to an existing substation. Transformers are not likely to be a significant source of magnetic field beyond the substation perimeter. While magnetic fields can be high close to these units, the field decreases rapidly with distance away from the equipment. A study of pad-mounted and pole-mounted distribution transformers by the Electric Power Research Institute (EPRI) found that transformers act as point sources and magnetic fields typically decrease as a function of $1/d$ to $1/d^3$ (depending on the size and rating of the transformer). At 5-feet away from pad-mounted transformers, the measured magnetic field had decreased by about 80% to 95% and pole-mounted transformers had decreased by a similar amount (about 90%) (EPRI 2009). Substation transformers should exhibit similar magnetic field attenuation rates and are generally located centrally within a substation. Therefore the magnetic fields from a transformer usually have attenuated to background levels at the substation perimeter – typically other substation sources (such as power lines entering and exiting the station) would be more significant of a magnetic field source than that of a transformer (EPRI 2006). The general public would not have much magnetic field exposure from a substation transformer, since the field has attenuated and people generally do not spend a lot of time near the substation fence.

Alternative #2

The proposed Alternative 2 could include construction of infrastructure such as three 20 MW gas-fired generators at existing substations, one battery storage facility near an existing substation, anaerobic digesters, reciprocating engines (diesel generators), microturbines, and fuel cells. Other new equipment associated with this option could include metering and control equipment at individual homes or facilities. There is no transmission line option associated with this alternative.

Electrical equipment such as the 20 MW gas-fired generators, reciprocating engines (diesel generators) and similar equipment (such as microturbines, which are small combustion/gas turbines/generators) are often present in power generation facilities. Enertech has performed magnetic field measurements for other electric utilities around their power generation facilities. This equipment is very similar to substation transformers with respect to magnetic fields as described for Alternative 1. While magnetic fields can be high close to these units, the field decreases rapidly with distance away from the equipment (typically as a function of $1/d^3$ or $1/d^4$). As previously noted, it is frequently observed that the largest magnetic fields around the perimeter of a substation are those produced by power lines entering or leaving the substation

(EPRI 2006). Generation equipment is usually located centrally within the station and away from the station perimeter.

Anaerobic digester systems use microorganisms to break down biodegradable material, producing a biogas that can then be used as fuel to produce energy. Fuel cells are electrochemical devices that combine hydrogen and oxygen to produce electricity. Neither of these devices have been characterized for magnetic fields by Enertech. If this type of equipment does act as a source for magnetic fields, it is anticipated that the attenuation rate from this equipment would be similar to that of other substation equipment (decreasing rapidly with distance away from the equipment). Similarly, this type of equipment would typically be located centrally within the station and away from the station perimeter.

In-home metering and control equipment is part of the Demand Response Component which would allow PSE and its customers to instantaneously monitor energy usage and control energy usage systems (such as heating and cooling systems). This equipment would have the capability of sending a continuous wireless signal to PSE to transmit energy usage information. It is assumed that this type of equipment would be similar to the smart meter systems (electric meters with wireless information transmission). However, they would have additional features (such as programmatic options and energy control features). The magnetic field from a smart meter (and the nearby electric panel) is similar to standard electric meters and electric panels already in residential and commercial use, with magnetic fields decreasing rapidly with distance away from the equipment. The main difference between a standard meter and a smart meter is that the smart meter broadcasts a radio frequency (RF) signal to the utility to transmit electrical usage information. This RF signal is much higher in frequency than a power frequency (60 Hertz) field and is similar to a wireless computer modem signal.

Finally, the battery storage facility is another component of Alternative 2. This system involves long rows of batteries connected by electrical cables to charge and discharge the batteries. Enertech has measured battery rooms for other utilities and the most significant source of magnetic field are the cables and invertors associated which the battery system. Invertors are very similar to substation transformers with respect to magnetic fields as described for Alternative 1. While magnetic fields can be high close to these units, the field decreases rapidly with distance away from the equipment (typically as a function of $1/d^3$ or $1/d^4$). Cable interconnections are similar to underground cables (except that they can be located above ground) with respect to magnetic fields. Magnetic fields can be high close to cables, but the field decreases rapidly with distance away from the cable (as exemplified for underground cables in Figure 2).

Alternative #3

The proposed Alternative 3 consists of approximately 60 miles of new 115 kV transmission line with transformer upgrades at several existing substations. For the 115 kV overhead transmission line, the spacing between the phase conductors will be less than for the 230 kV option (Alternative 1) due to a lower voltage. However, the minimum ground clearance at midspan may also be lower for the same reason. Because of the lower voltage, it will require more current (amperes) to transmit the same amount of power (MW) than a higher voltage transmission line would require (hence a higher equivalent magnetic field due to loading).

Transformer upgrades would be performed at several existing substations. As discussed for Alternative 1, transformers are not likely to be a significant source of magnetic field beyond the substation perimeter.

Alternative #4

Alternative 4 is the no action alternative. Since no electrical facilities would be constructed, no additional magnetic fields would be created. The Energy Efficiency component of Alternative 2 would be included in the no action alternative, but the process of reducing peak load demand by upgrading older, less-efficient equipment and better weatherproofing should not produce additional magnetic fields.

Comparison of Magnetic Fields Associated with the Four Project Alternatives

A comparison of the power-frequency magnetic fields associated with the four project alternatives is difficult to characterize since specifics regarding components of the project alternatives have not yet been developed (line design information, route locations, equipment specifications, etc.). Therefore, when considering magnetic fields for the general public, a broad conceptual overview of magnetic fields with respect to individual components is basically the only means to provide a comparison. Individual components would include substation and battery storage equipment (transformers, generators, turbines, etc.), residential equipment (metering and controllers), and underground/overhead transmission lines. Figure 3 presents a broad conceptual overview of magnetic field sources. As shown in Figure 3, substation and battery equipment provides little magnetic fields for the general public since they are usually centrally located with substations, their magnetic field decreases rapidly with distance, people do not typically spend a lot of time near the substation fence. Similarly, magnetic fields from residential equipment decrease rapidly with distance. However, since this equipment is more prevalent and located in residences, the general public has a higher probability of encountering magnetic fields from residential sources than from substation equipment.

Underground transmission lines have higher magnetic fields directly above the cable, while overhead transmission lines have lower magnetic fields directly beneath the conductors but can influence a larger area (assuming similar loading conditions). In general, magnetic fields from overhead lines attenuate as a function of 1/d2 while magnetic fields from underground lines as a function of 1/d3 (reference Figure 2 and its discussion). Since overhead lines generally influence a broader area than underground lines, then one could consider overhead lines as a more significant magnetic field source than underground lines. However, if the underground line is routed within a more public location (centered along a recreation trail, for example), then the underground line could be a more significant source than the overhead line. Therefore, the route location of a transmission line plays a significant role in assessing magnetic field levels with respect to the general public.

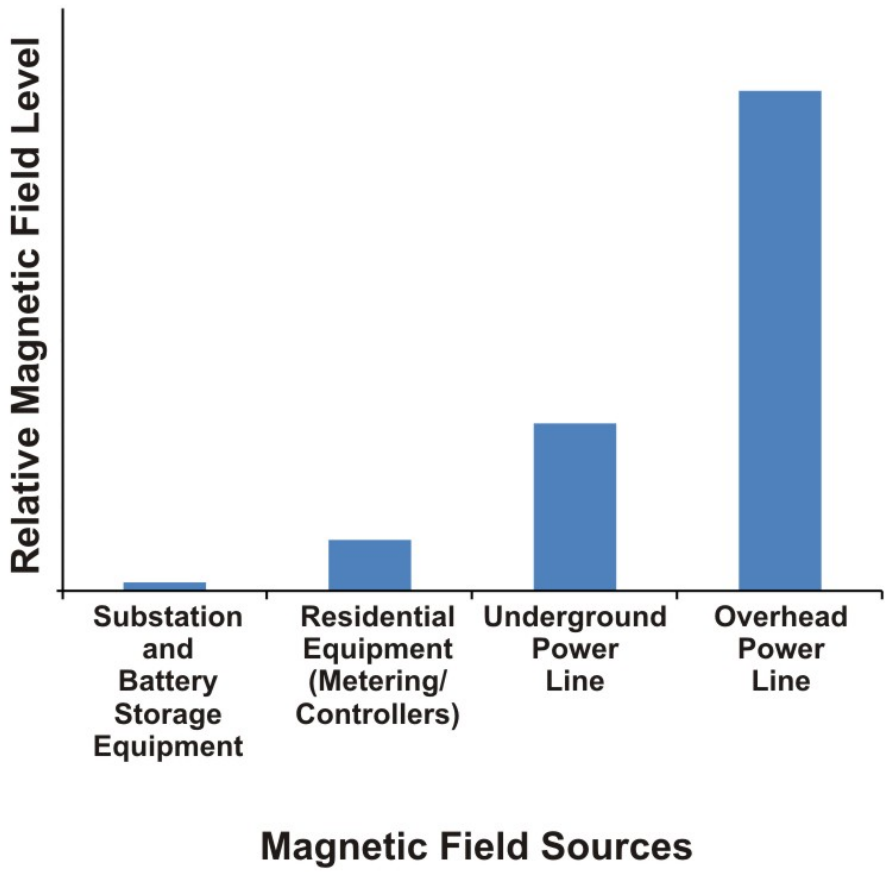

Figure 3. Broad Conceptual Overview of Magnetic Field Levels from Various Sources

Overhead Transmission Line Magnetic Field Reduction

It is usually difficult to mitigate magnetic fields from overhead transmission lines (EPRI 1999). Reduction options could include those researched by the Washington State Legislature (Waller and Geissinger 1992), as well as others:

- Load Restrictions
- Line Relocation
- Increased Line Height
- Split-Phase Arrangement of Conductors
- Line Compaction
- Undergrounding the Line
- Active or Passive Cancellation Loop System

Load Restrictions

Reduce or restrict the loading (current) on the transmission line. Because magnetic fields are directly related to line loading (current), limiting the load might also limit the levels of magnetic field created by the line (depending upon line geometry). In certain circumstances, load limiting could actually increase magnetic field levels (particularly on a double circuit transmission line with unlike phasing and only one circuit is load limited).

However, transmission line loading may be controlled by entities other than PSE (for example, an Independent System Operator). Therefore, the controlling entity would have to be identified and also approve a load limiting scheme. Furthermore, PSE would probably have difficulty approving a scheme which would not allow them to maximize the use of their lines (and hence their investment). The controlling entity would probably state similar concerns. Even if enacted, load restrictions would probably have to be temporarily lifted under certain conditions (such as peak or emergency load conditions, or for line maintenance). Because of these conditions, this is usually not a viable option.

Line Relocation

Move the proposed transmission line to other locations farther away from the general public. This action requires alternate routing evaluations (which is typically performed for this type of project), as well as load and power delivery analyses. While route alternatives are typically evaluated as part of the project process, usually there are limited routing options (particularly within major cities and developed areas). Relocation of a transmission line route may also affect other/different public locations.

Increased Line Height

Increase the heights of the line (conductors) along portions of the route to increase distance and reduce magnetic field levels directly beneath the transmission line. The decrease in magnetic field is greatest directly underneath of the transmission line conductors; at the right-of-way edge and beyond, the level of magnetic field reduction is minimal. Also, there may be city and/or county height restrictions which can limit the usefulness of this option (depending upon the route location). Other issues, such as transmission line maintenance, may also be an important consideration. Because of these conditions, this may not be a viable option.

Split-Phase Arrangement of Conductors

Create a double circuit line configuration to increase magnetic field cancellation with conductor phasing. If the proposed transmission line is a double circuit configuration, then the phasing arrangement of the conductors can be used to increase the magnetic field cancellation. If the proposed transmission line is a single circuit line, then portions of the line may be modified to simulate a double circuit configuration. Conductor and tower/pole support structures need to be evaluated to determine additional weight and stress requirements. Engineering studies would have to be performed to determine phase separation requirements, associated NESC requirements, and other operating parameters. However, if this is an unusual or unique configuration to PSE, then safety issues can arise for utility line crews during line maintenance. Finally, the cost associated with implementing a split-phase conductor arrangement (additional conductors, stronger towers, additional cross-arms, etc.) can approach almost twice that of a single circuit design. Because of these concerns, this option is usually not viable.

Line Compaction

Re-arrange the conductor configuration to locate each of the phase conductors as close as possible to one another. Other factors, which limit line compaction, include spacing distance, sag of the conductors, increased audible noise and radio/TV interference due to corona, and maintenance requirements. In addition, system reliability, safety, integrity and operating flexibility cannot be diminished. Because of these conditions, this is usually not viable.

Undergrounding the Line

Convert the overhead power line to a buried underground line configuration. While magnetic fields may be higher directly above the buried cables, the field level would attenuate much faster with distance away from the line. This option was previously discussed and examples of magnetic field attenuation are shown in Figure 2.

Active or Passive Cancellation Loop System

Install either an active or passive cancellation loop along the transmission line right-of-way edge to provide field cancellation and reduce magnetic fields beyond the right-of-way. Loop systems are experimental in nature and have only been tested in a limited number of situations. This action would require additional support structures to be located along the right-of-way edge with a current-carrying conductor loop installation. Figure 4 presents a diagram of a cancellation loop system which shows the additional support structures and wires. Also, utility worker safety is again a concern for line maintenance with the use of a cancellation loop. For these reasons, a cancellation loop system is usually not a viable magnetic field reduction option.

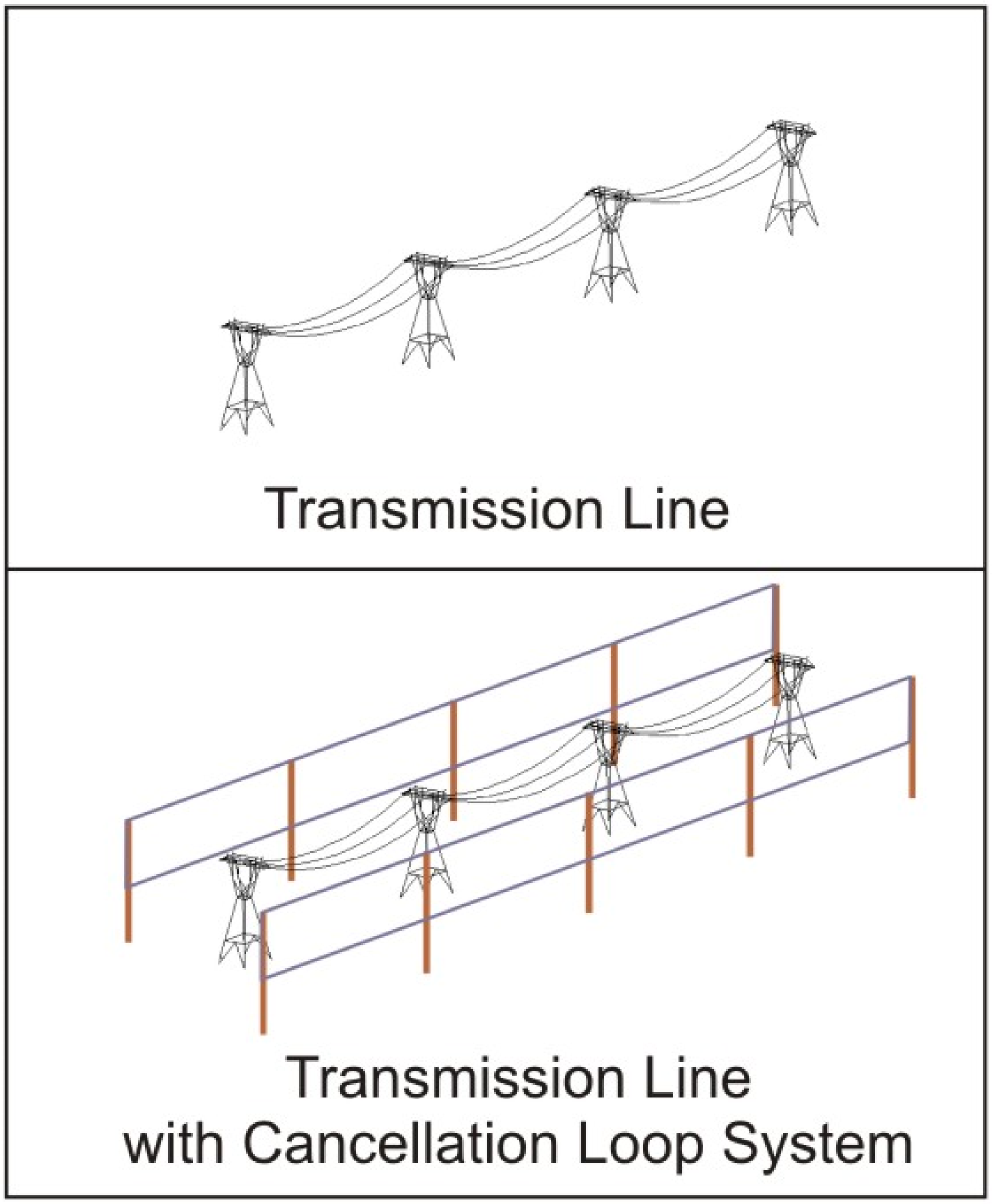

Figure 4. Diagram of a Cancellation Loop System

References

EPRI 1982. "*Transmission Line Reference Book: 345 kV and Above - Second Edition"*, Electric Power Research Institute (EPRI), 1982.

EPRI 1999. "Electric and Magnetic Field Management Reference Book", First Edition, Electric Power Research Institute (EPRI), Technical Report 114200, December 1999.

EPRI 2006. *"AC Transmission Line Reference Book—200 kV and Above"*, Third Edition, Electric Power Research Institute (EPRI), Technical Report 1011974, January 23, 2006.

EPRI 2009. *"Characterization of Magnetic Fields from Power Distribution Transformers"*, Electric Power Research Institute (EPRI), Technical Report 1019010, Palo Alto, CA, 2009.

FCC 1988. Federal Communications Commission (FCC) Rules and Regulations, Volume II, Part 15, 47 CFR, Chapter 1, October 10, 1988.

FCC 1999. *"DTV REPORT ON COFDM AND 8-VSB PERFORMANCE"*, Federal Communications Commission (FCC), Office of Engineering and Technology, September 30, 1999.

IEEE 1971. *"Radio Noise Design Guide for High-Voltage Transmission Lines"*, Institute of Electrical and Electronics Engineers (IEEE), IEEE Transactions on Power Apparatus and Systems, pp 833-842, Vol. PAS-90, No. 2, March/April, 1971.

Smith 2004. Smith, David R., *"Digital Transmission Systems"*, Third Edition, ISBN 1-4020-7587-1, Kluwer Academic Publishers, 2004.

USDOE 1980. *"A Practical Handbook for the Correction of Radio Interference from Overhead Powerlines and Facilities"*, U.S. Department of Energy (USDOE), Portland, OR, 1980.

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

APPENDIX A

TRANSMISSION LINE GEOMETRY ASSUMED FOR MAGNETIC FIELD CALCULATIONS

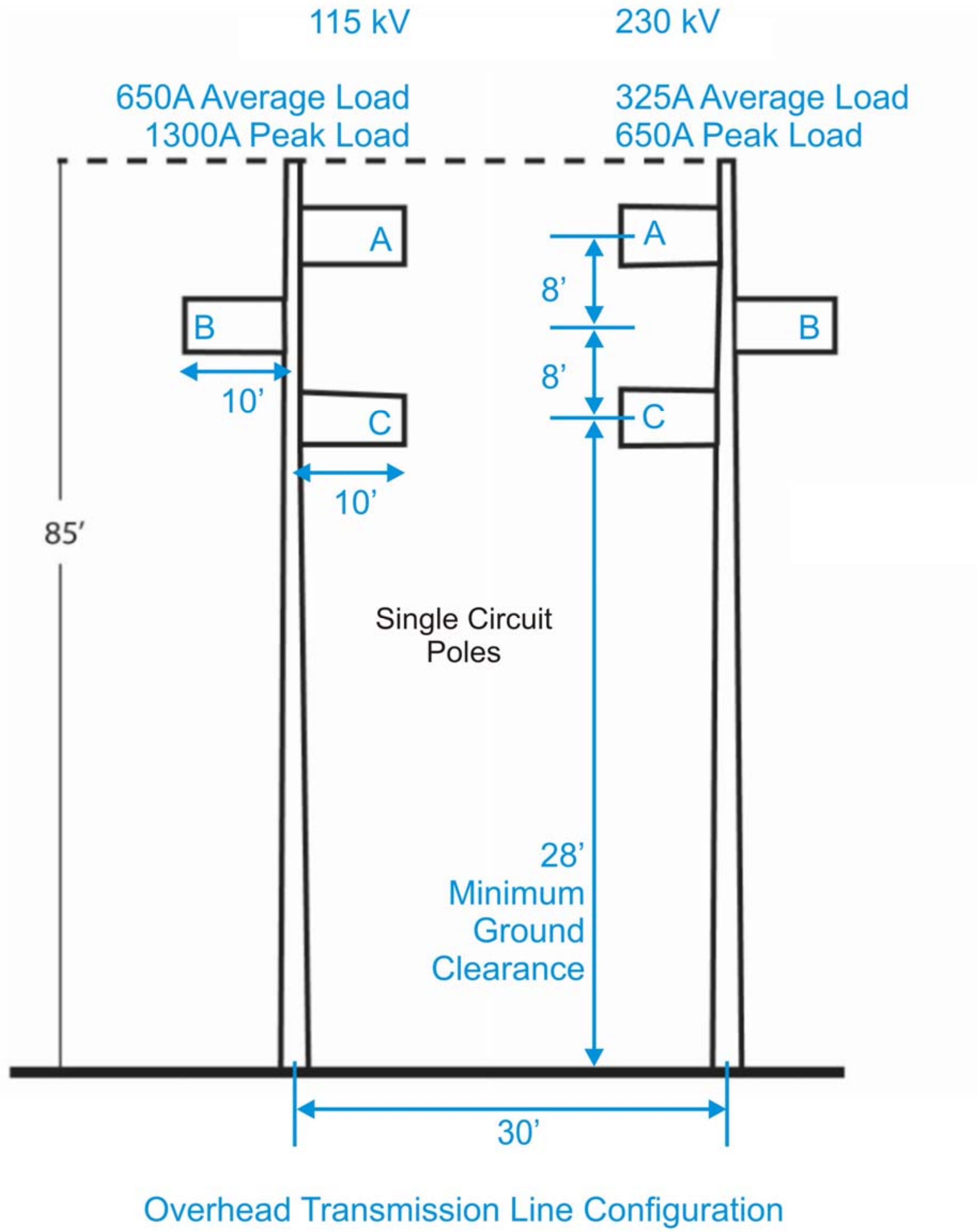

Figure A-1. Overhead Transmission Line Geometry Assumptions for Magnetic Field Calculations (reference Figure 2 in report)

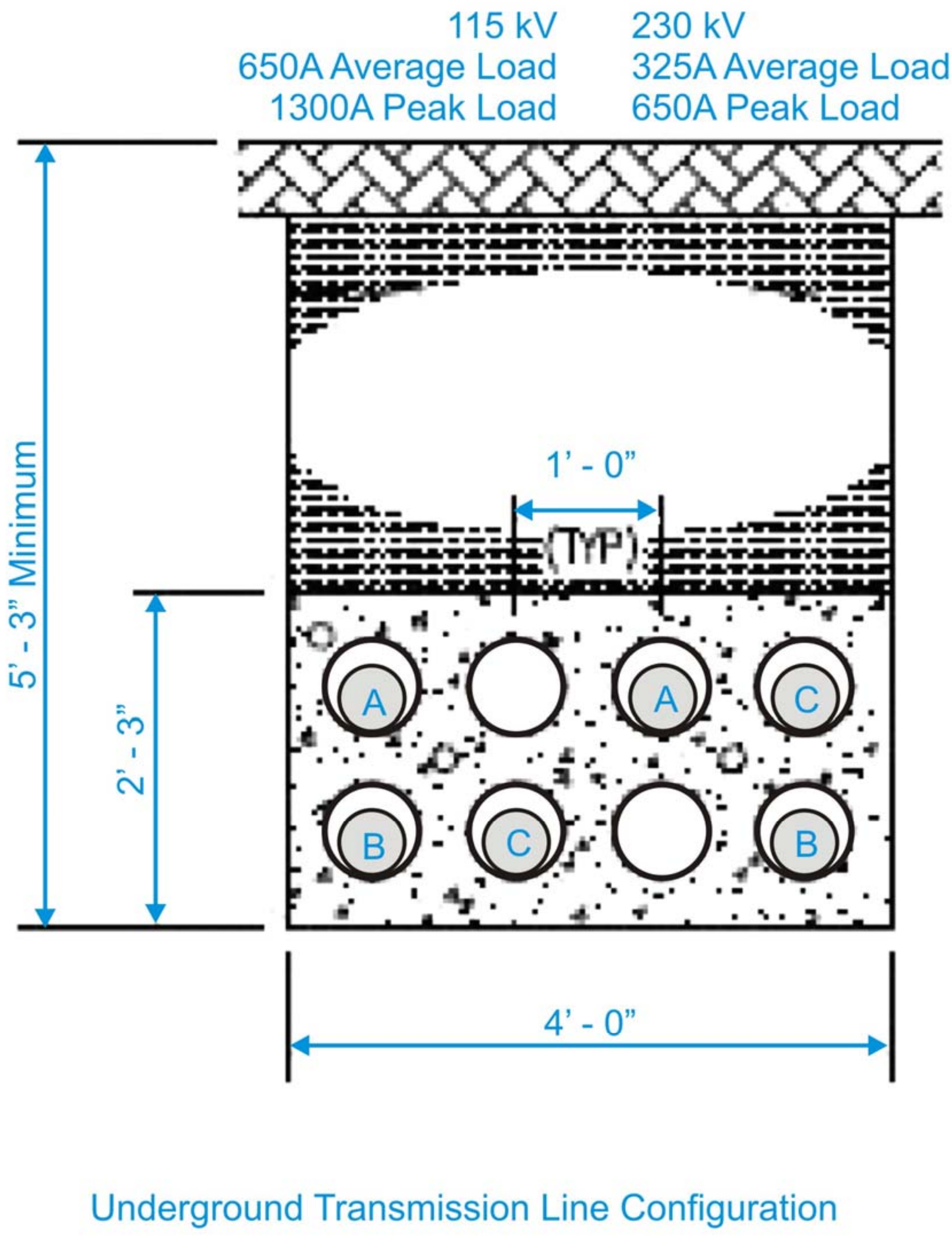

Figure A-2. Underground Transmission Line Geometry Assumptions for Magnetic Field Calculations (reference Figure 2 in report)