The INGAA Foundation, Inc.

Criteria for Pipelines Co-Existing with Electric Power Lines

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Prepared By:
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Objective:

The primary objective of this report is to present the technical background, and provide best practice guidelines and summary criteria for pipelines collocated with high voltage AC power lines. The report addresses interference effects with respect to corrosion and safety hazards, and fault threats.

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EXECUTIVE SUMMARY

The primary objective of this report is to present the technical background, and provide best practice guidelines and summary criteria for pipelines collocated with high voltage AC power lines. The report addresses interference effects with respect to corrosion and safety hazards, and fault threats. The guidelines presented address mitigation and monitoring, encroachment and construction, risk severity classification, and recommendations for further industry development.

This report addresses the technical background to high voltage interference with respect to collocated and crossing pipelines, and presents basic procedures for dealing with interference scenarios. The provisions of this document are recommended to be used under the direction of competent persons, who are qualified in the practice of corrosion control on metallic structures, with specific suitable experience related to AC and/or DC interference and mitigation. This document is intended for use in conjunction with the reference materials cited herein.

Collocated pipelines, sharing, paralleling, or crossing high voltage power line rights-of-way (ROW), may be subject to electrical interference from electrostatic coupling, electromagnetic inductive, and conductive effects. If the interference effects are high enough, they may pose a safety hazard to personnel or the public, or may compromise the integrity of the pipeline. Because of increased opposition to pipeline and power line siting, many future projects propose collocating high voltage alternating current (HVAC) and high voltage direct current (HVDC) power lines and pipelines in shared corridors, worsening the threat.

Predicting HVAC interference on pipelines is a complex problem, with multiple interacting variables affecting the influence and consequences. In some cases, detailed modeling and field monitoring is used to estimate a collocated pipeline's susceptibility to HVAC interference, identify locations of possible AC current discharge, and design appropriate mitigation systems to reduce the effects of AC interference. This detailed computer modeling generally requires extensive data collection, field work, and subject-matter expertise. Basic industry guidelines are needed to help determine when more detailed analysis is warranted, or when detailed analysis can be ruled out based on the known collocation and loading parameters. A consistent technical guidance document will benefit the pipeline industry by increasing public safety and allowing for an efficient approach in assessment and mitigation of threats related to high voltage interference.

The INGAA Foundation contracted Det Norske Veritas (U.S.A), Inc. (DNV GL) to develop this guidance document. The project included a detailed industry literature review to identify applicable technical reports, international standards, existing guidance and operator procedures. In addition to the literature review, numerical modeling was performed to determine the effects of key parameters on the interference levels. The document addresses interference effects with respect to corrosion and safety hazards, mitigation, monitoring, encroachment and construction, prioritization and modeling. It also includes recommendations for further development.

The following severity ranking tables were developed for key variables and their impact on the severity of AC interference. Further background for the development of these rankings is provided throughout the report. Guidelines for determining the need for detailed analysis and applying these severity rankings are provided in Section 6.2.

Separation Distance

Table 3-Severity Ranking of Separation Distance

Separation Distance - D (Feet)	Severity Ranking of HVAC Interference
$D < 100$	High
$100 < D < 500$	Medium
$500 < D < 1{,}000$	Low
$1{,}000 < D \leq 2{,}500$	Very Low

HVAC Power Line Current

Table 4-Relative Ranking of HVAC Phase Current

HVAC Current - I (amps)	Relative Severity of HVAC Interference
$I \geq 1{,}000$	Very High
$500 < I > 1{,}000$	High
$250 < I < 500$	Med-High
$100 < I < 250$	Medium
$I < 100$	Low

Soil Resistivity

Table 5-Relative Ranking of Soil Resistivity

Soil Resistivity - ρ (ohm-cm)	Relative Severity of HVAC Corrosion
$\rho < 2{,}500$	Very High
$2{,}500 < \rho < 10{,}000$	High
$10{,}000 < \rho < 30{,}000$	Medium
$\rho > 30{,}000$	Low

Collocation Length

Table 6-Relative Ranking of Collocation Length

Collocation Length: L (feet)	Relative Severity
$L > 5{,}000$	High
$1{,}000 < L < 5{,}000$	Medium
$L < 1{,}000$	Low

Collocation / Crossing Angle

Table 7-Relative Ranking of Crossing Angle

Collocation/Crossing Angle - θ (°)	Relative Severity
$\theta < 30$	High
$30 < \theta < 60$	Med
$\theta > 60$	Low

The research and analytical studies accentuated the need for accurate power line current load data when assessing the susceptibility of a steel transmission line to high voltage interference. For this reason, collaboration between the respective pipeline and power line operators is advised to accurately determine where detailed assessment is required, and develop efficient mitigation where necessary.

The general safety recommendations and guidelines for interference analysis presented in Section 6 provide guidance on the relative susceptibility of AC interference associated with the selected variables. They primarily address the likelihood or susceptibility of AC interference, and do not address the consequence aspect of an overall risk assessment, as these details are specific to each individual assessment.

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Acronyms

AC	Alternating Current
CAPP	Canadian Association of Petroleum Producers
CFR	Code of Federal Regulation
CP	Cathodic Protection
CSA	Canadian Standards Association
CTS	Coupon Test Station
DC	Direct Current
DCD	DC Decoupler
DOC	Depth of Cover
DOT	Department of Transportation
EMI	Electromagnetic Interference
ER	Electrical Resistance
FBE	Fusion Bonded Epoxy
GPR	Ground Potential Rise
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IF	Isolation Flange
INGAA	Interstate Natural Gas Association of America
LEF	Longitudinal Electric Field
MPY	Mils per year
OSHA	Occupational Safety and Health Administration
PRCI	Pipeline Research Council International
ROW	Right(s) of Way
TLM	Transmission Line Model

1 INTRODUCTION

Trends within both the electric power and pipeline industries have increased the number of projects that co-locate high voltage alternating current (HVAC) and high voltage direct current (HVDC) power lines with steel transmission pipelines in shared rights-of-way (ROW). The primary objective of this report is to provide technical guidance and present best practice guidelines and summary criteria for steel transmission pipelines collocated with high voltage AC power lines.

Topography, permitting requirements, land access, increasingly vocal public opposition to infrastructure projects, and environmental concerns, including protected regions, all have led to an increase in sharing of common utility corridors. While there are numerous benefits to common utility corridors, there are also many concerns. Collocated steel transmission pipelines that share, parallel, or cross high voltage power line ROW may be subject to electrical interference from electrostatic coupling, electromagnetic inductive, and conductive effects. If these interference effects are high enough, they may pose a safety hazard to personnel or compromise the integrity of the pipeline.

Pipelines collocated with overhead HVAC lines account for a significant portion of the high voltage interference conditions encountered in the transmission pipeline industry. However, interference effects due to buried power lines and HVDC are also of concern to pipeline operators where close collocations exist. As aboveground HVAC is still the primary concern for pipeline interference, it is the primary focus of this report. However, comparison background and technical discussion is included related to HVDC and buried power line interference as well, and the effects of both should be considered on a case-by-case basis when steel transmission pipelines are closely collocated with these systems.

Numerous methodologies exist to analyze alternating current (AC) interference for specific collocations and crossings, but the analysis generally requires extensive data collection and detailed computational modeling. The accuracy of these models is sensitive to the HVAC power line operating parameters, which can often be difficult or costly for pipeline operators to obtain from electric power companies. Basic guidelines and prioritization criteria have been established in this report to provide guidance for pipeline operators to aid in a risk-based decision-making process and help prioritize regions for detailed modeling and mitigation design, or exclude further modeling analysis for a given region.

This report addresses interference effects related to encroachment and construction, corrosion and safety hazards, mitigation, and monitoring. This project included a detailed industry literature review to identify applicable technical reports, international standards and, guidance documents. Several INGAA members provided procedures. In addition to the literature review, numerical models were developed and trends presented detailing the effects of critical variables on interference levels under the conditions defined.

2 INDUSTRY LITERATURE REVIEW

There has been extensive research performed to understand the risks of high voltage interference and to develop efficient mitigation techniques. The effects of HVAC interference from a personnel safety and corrosion standpoint are a risk identified in much of the literature. Case studies in North America, the UK, and continental Europe have identified and documented AC corrosion concerns. Through-wall defects have been reported with corrosion rates greater than 50 mils/year (mpy) observed.[1]

In development of this guidance document a literature review identified and reviewed more than fifty technical references, US and International standards, existing guidance documents, research theses, journal manuscripts, and technical symposia papers. Additionally, INGAA collected operating procedures and guidelines from 10 member companies for review and comparison.

Where published, historically identified corrosion defects and pipeline failures associated with AC corrosion degradation have been reviewed and a selection are presented as case studies in Appendix A, demonstrating the magnitudes and variability in corrosion rates possible with AC accelerated corrosion.

The primary finding from this review is that there is significant variation in operating procedures and technical literature with respect to AC interference. Various companies' procedures were compared with published industry guidance, historical project data, and project experience to determine a best practice approach. Details and cross references are presented in each of the subsections of this document with a detailed review of the technical literature, case studies, and company procedures provided in Appendix A.

3 HIGH VOLTAGE INTERFERENCE ON ADJACENT PIPELINES

3.1 HVAC Interference Modes

Electrical interference from capacitive, electromagnetic inductive, and conductive coupling can affect pipelines collocated in close proximity to HVAC power lines. The subject of AC interference has been a growing concern across multiple industries in recent decades as improved pipeline coatings and utility ROW congestion has contributed to an increase in identified AC corrosion incidents. Recent trends in the high voltage electric power transmission industry are leading to increased power capacity and higher operating currents in certain systems, in part to overcome long distance transmission line losses.[2] This increase in operating current has a direct effect on the level of electromagnetic interference (EMI) and the corresponding magnitude of AC interference on affected pipelines. This trend toward elevated operating currents may present a significant challenge for achieving adequate mitigation on pipelines crossing or collocated with the high voltage power lines.

The three primary physical phenomena by which AC can interfere or "couple" with pipelines are through capacitive, resistive, or inductive coupling as detailed in Sections 3.1.1 through 3.1.3. High voltage interference can occur during normal operation, generally referred to as steady state, or during a power line fault. HVAC power line faults are any abnormal current flow from the standard intended operating conditions, and discussed further in Section 3.1.4.

3.1.1 Capacitive Coupling

Capacitive coupling, or electrostatic interference, occurs due to the electromagnetic field produced by AC current flowing in the conductors of a high voltage power line, which can induce a charge on an above ground steel pipeline that is electrically isolated from the ground. Capacitive effects are primarily a concern during construction when sections of the pipeline are aboveground on insulating supports, as indicated in Figure 1. The pipeline can build up charge as a capacitor with the surrounding air acting as the dielectric, which can maintain the electric field with a minimum loss in power, resulting in a potential difference with surrounding earth.

The magnitude of potential is primarily dependent on the pipeline proximity to the HVAC conductors, the magnitude of power line current, and the individual phase arrangement. If the potential buildup due to capacitive coupling is significant, electrostatic interference may present a risk of electric shock or arcing. While elevated capacitive voltages may exist, the corresponding current is generally low, resulting in low shocking consequence[3,4].

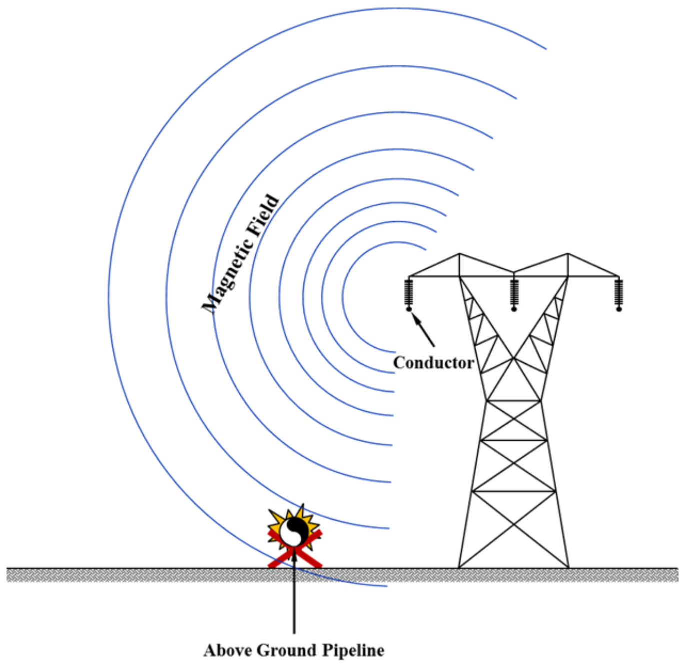

Figure 1. Illustration of Capacitive Coupling

3.1.2 Inductive Coupling

Electromagnetic induction is the primary interference effect of an HVAC power line on a buried steel pipeline during normal steady state operation. EMI occurs when AC flowing along power line conductors generates an electromagnetic field around the conductor, which can couple with adjacent buried pipelines, inducing an AC voltage, and corresponding current, on the structure as depicted in Figure 2. This induced AC potential may present a safety hazard to personnel, and can contribute to AC corrosion of the pipeline, as discussed in Section 3.3.1.

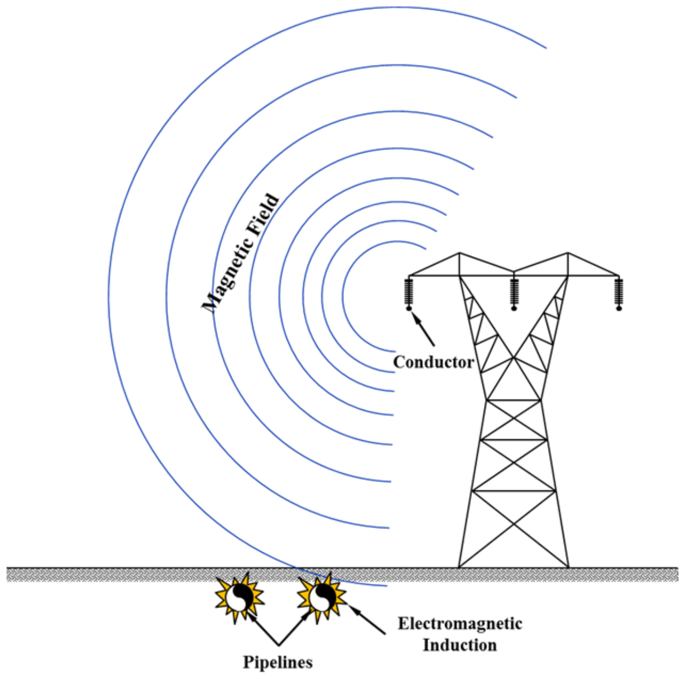

Figure 2. Illustration of Steady State HVAC Inductive Interference

The inductive effects of the HVAC power line on an adjacent pipeline are a function of geometry, soil resistivity, coating resistance, and the power line operating parameters. The geometry characteristics include separation distance between the pipeline and the towers, depth of cover (DOC), pipe diameter, angle between pipeline and power line, tower footing design, and phase conductor configuration. These parameters remain relatively constant over the life of the installation. The coating resistance, power system resistance, and soil resistivity may vary with the seasonal changes and as the installations age, but they are considered constants for most analyses. However, the operating parameters of the power line – such as phase conductor load, phase balance, voltage, and available fault current – all have an influence on the effects of AC interference, and can vary significantly. The individual conductor current load and phase balance is dynamic and changes with load requirements and switching surges. These variations in operating parameters contribute to variations in levels of AC interference. During normal HVAC operation, the current load varies as the load demand changes both daily and seasonally.[3,5] While normal operating conditions are often referred to as "steady state" throughout the industry, the term is somewhat misleading as the current loads and corresponding induced AC potentials can be continuously varying, adding further complexity to quantifying interference magnitude.

For a straight, parallel, homogenous collocation, induced potentials are highest at the ends of the collocated segment, and fall exponentially with distance past the point of divergence.[6] For more complex collocations, voltage peaks may occur at geometric or electrical discontinuities, where there is an abrupt change in the collocation geometry or electromagnetic field. Specifically, voltage peaks commonly occur where the pipeline converges or diverges with the HVAC power line, separation distance or soil resistivity changes significantly, isolation joints are present on the pipeline, or where the electromagnetic field varies such as at phase transpositions.[3,7,8,9]

3.1.3 Resistive Coupling

Current traveling through the soil to a pipeline can cause resistive or conductive coupling. As the grounded tower of an HVAC power system shares an electrolytic path with adjacent buried pipelines through the soil, fault currents may transfer to adjacent steel pipelines if the pipeline presents a lower resistance electrical path. Resistive interference is primarily a concern when a phase-to-ground fault occurs in an area where a pipeline is in close proximity to an HVAC power line, and magnitudes of fault currents in the ground are high. However, a phase imbalance on an HVAC system with a grounded neutral can contribute to resistive interference as return currents will travel through the ground and may transfer to a nearby pipeline.

During a fault condition (see Section 3.1.4), the primary concern is the resistive interference transferred through the soil. However, inductive interference can also be a concern as the phase current, and corresponding EMI, of at least one conductor can be high, as depicted in Figure 3. In other words, during a fault, the inductive effects during normal operation as described in Section 3.1.2 increase due the elevated EMI during the fault period.

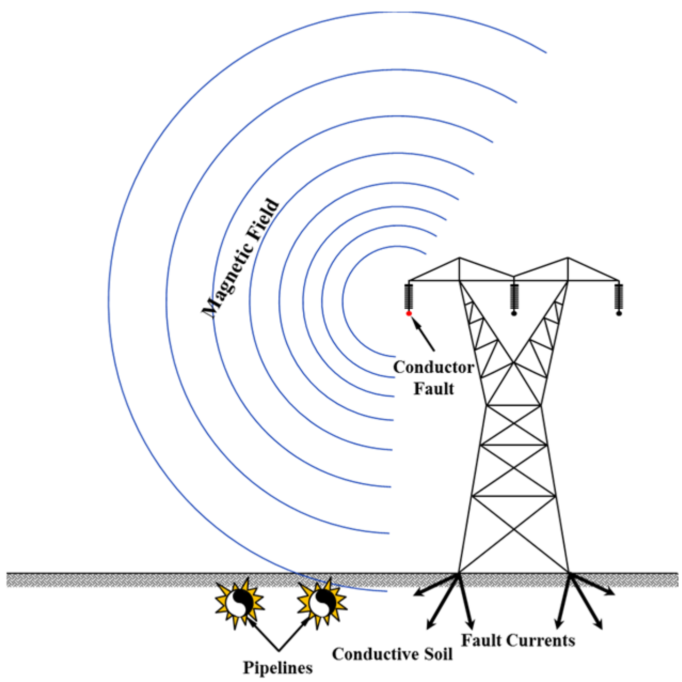

Figure 3. Illustration of HVAC Fault Condition – Inductive and Conductive Interference

If any of these electrical effects are high enough during operation, a possible shock hazard exists for anyone that touches an exposed part of the pipeline such as a valve, cathodic protection (CP) test station, or other aboveground appurtenance. During steady state normal power line operation, AC current density at a coating holiday (flaw) above a certain threshold may cause accelerated external corrosion damage to the pipeline. In addition, damage to the pipeline or its coating can occur if the voltage between the pipeline and surrounding soil becomes excessive during a fault condition.

3.1.4 AC Faults

For HVAC power lines, a fault is any abnormal current flow from the standard intended operating conditions. A fault can occur between one or more phase wires and the ground, or simply between adjacent phase wires. Faults can occur when one or more of the conductors are grounded or come in contact with each other, or due to other unforeseen events. This may be due to vegetation contacting the conductors, conductors contacting the towers or each other during high winds, physical damage to a tower, conductor, or insulator, flashover due to lightning strikes, or other abnormal operating condition. A phase-to-ground fault on a power line causes large currents in the soil at the location of the fault and large return currents on the phase conductor and ground return.

Faults are generally short duration transient events. Typical clearing times for faults range from approximately 5 to 60 cycles (0.08 to 1.0 seconds for 60-hertz transmission) depending on the location of the fault, breakers and type of communications. While the fault effects are transient, high-induced potentials or resistive coupled voltages along the ROW present a possible shocking hazard for personnel or anyone who may be in contact with above grade pipeline or appurtenances.

3.2 HVAC – Personnel Safety Hazards

An evaluation of the possible safety hazards for those working on a pipeline should take place whenever a pipeline is operating or constructed in close proximity to a HVAC power line. Personnel safety hazards are present during both pipeline construction and maintenance, and during normal steady state operation.

3.2.1 Hazards During Operation

Touch and Step Potential Limits

Personnel safety is of concern when a person is touching or standing near a pipeline when high voltages are present. The “touch potential” is defined as the voltage between an exposed feature of the pipeline, such as a CP test station or valve, and the surrounding soil or a nearby isolated metal object, such as a fence that can be touched at the same time. The touch potential is the voltage a person may be exposed to when contacting a pipe or electrically continuous appurtenance. The “step potential” is the voltage across a person’s two feet and defined as the difference in the earth’s surface potential between two spots one meter apart. The touch potential can be a concern during both normal steady state inductive and fault conductive/inductive conditions. Typically, the step potential is a concern during conductive fault conditions due to high currents and voltage gradients in the soil.

The Canadian Standards Association (CSA) and NACE International (NACE) have published standards addressing HVAC interference hazards. Both NACE and CSA standards[10,12] recommend reducing the steady state touch and step potential below 15 volts at any location where a person could contact the pipeline or any electrically continuous appurtenance. The 15-volt threshold is designed to limit the available maximum current through a typical human body to less than 10 mA. An 8 to 15 mA current results in a painful shock but is still in the maximum ”let go” current range, for which a person can release an object or withdraw from contact.[10] The Institute of Electrical and Electronics Engineers (IEEE) Guide for Safety in AC Substation Grounding, indicates that a current in the range of 9 to 25 mA range may produce painful shock and involuntary muscular contraction, making it difficult to release an energized object.[13] Elevated body current in the range of 60 to 100 mA may cause severe injury or death as it can induce ventricular fibrillation, or inhibition of respiration. Current lower than nine (9) mA will generally result in a mild shock, but involuntary movement could still cause an accident.[10]

The touch potential is equal to the difference in voltage between an object and a contact point some distance away, and may be nearly the full voltage across the grounded object if that object is grounded at a point remote from where the person is in contact with it. For example, a crane that was grounded to the system neutral and that contacted an energized line would expose any person in contact with the crane or its un-insulated load line to a touch potential nearly equal to the full fault voltage.

The step potential may pose a risk during a fault simply by standing near the grounding point due to large potential gradients present in the soil, typically during a short duration fault condition.

A risk evaluation of the possible hazards to personnel for those working on the pipeline and possible pipeline coating damage should take place whenever a pipeline is in close proximity to a HVAC power line. This assessment should consider the possible likelihood and consequence of HVAC interference hazards to determine if further analytical assessment or mitigation is necessary. NACE International Standard Practice SP0177-2014 (Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems) indicates mitigation is necessary in those cases where step or touch potentials are in excess of 15 volts. Mitigation is further discussed in Section 5.

3.2.2 Encroachment and Construction Hazards

There are multiple safety hazards to consider associated with pipeline construction near a high voltage power line, the most obvious of which is the possibly lethal hazard of equipment directly contacting an energized overhead conductor.[3] The Occupational Safety and Health Administration (OSHA) has multiple regulations for safety requirements and limitations for working near power lines that must be considered in addition to pertinent company standards, and industry best practice guidelines. These include, but are not limited to the following:

- 29 CFR 1910.269: Electric power generation, transmission, and distribution
- 29 CFR 1910.333: Selection and use of work practices
- 29 CFR 1926, SUBPART V: Power Transmission and Distribution

The OSHA standards address requirements for working near energized equipment, overhead power lines, underground power lines, and construction nearby.

Elevated capacitive potentials generated on pipeline sections isolated from the ground on insulating skids as described in Section 3.1.1 can pose a safety hazard. Pipeline segments that are supported aboveground during pipeline construction near an HVAC power line are subject to EMI and electrical capacitance can build up between the pipeline segments and earth. If no electrical path to ground is present, even a relatively short section of piping may experience elevated AC potential, presenting a shock hazard to personnel near the pipeline.

Cases presented in published literature indicate scenarios of measured potentials greater than 1,000 volts on a pipeline segment exposed to an HVAC corridor.[4] In general, while the capacitive coupled voltages can exceed the NACE 15 volt touch potential safety threshold, the corresponding current is low reducing shocking hazard. However, arcing due to capacitive coupling may present a possible safety hazard, as an arc may be a possible ignition source for construction vehicles refueling along the ROW. Grounding pipelines in HVAC ROW will reduce the possibility of shocking or arcing.

Capacitive coupling is generally mitigated by connecting temporary grounding or bonding during construction to provide a low resistance path to ground for any electrostatic interference. Section 6 addresses further mitigation techniques and guidance for construction practices.

3.3 HVAC Threat to Pipeline Integrity

High voltage interference poses multiple threats to pipeline integrity for collocated and crossing pipelines under both steady state and fault conditions. During normal steady state HVAC power line operation, the inductive interference can contribute to accelerated external corrosion damage to the pipeline. Under faulted conditions, elevated potentials can lead to coating damage or a direct arcing to the pipeline.

The steady state 15 VAC threshold presented in NACE and CSA standards[10,12] considers personnel safety and does not necessarily address corrosion issues. Research and experience has shown that AC accelerated corrosion can occur in low resistivity soils at AC voltages well below this threshold.[3,6,14]

3.3.1 AC Corrosion

External corrosion, whether controlled by AC or DC, may pose a threat to the integrity of an operating pipeline. DC corrosion protection utilizes a system of corrosion resistant coatings and a CP system to provide electrochemical protection at coating holidays to reduce corrosion rate. However, AC corrosion is possible even in the presence of cathodically protected DC potentials due to high AC current density at coating holidays.

The concept of AC corrosion has been around since the early 1900s with only minor effects expected for many years.[3,10] AC accelerated corrosion has been recognized as a legitimate threat for collocated steel since the early 1990s, after several occurrences of accelerated pitting and leaks, ultimately associated with HVAC interference, were reported on cathodically protected pipelines.

Historically, there has been little consensus on specific mechanisms driving AC corrosion, and the severity of degradation attributed. However, several recent publications show tentative agreement in a plausible mechanism.[6,15,17] The explanation presented by Buchler, Tribollet, et al, suggests that AC corrosion on cathodically protected pipelines may be attributed to destabilization of pseudo-passive film that can normally form on exposed steel at a coating holiday under DC cathodic protection polarization. Due to the cyclic nature of AC current, the charge at the steel surface is continuously varying between anodic and cathodic polarization, which acts to reduce the passive film at the steel surface as shown in Figure 4. It is not the intention of this report to identify the specific mechanism driving material degradation due to AC corrosion, but rather to summarize a previously proposed mechanism and clarify the risks and contributing factors associated with AC corrosion.

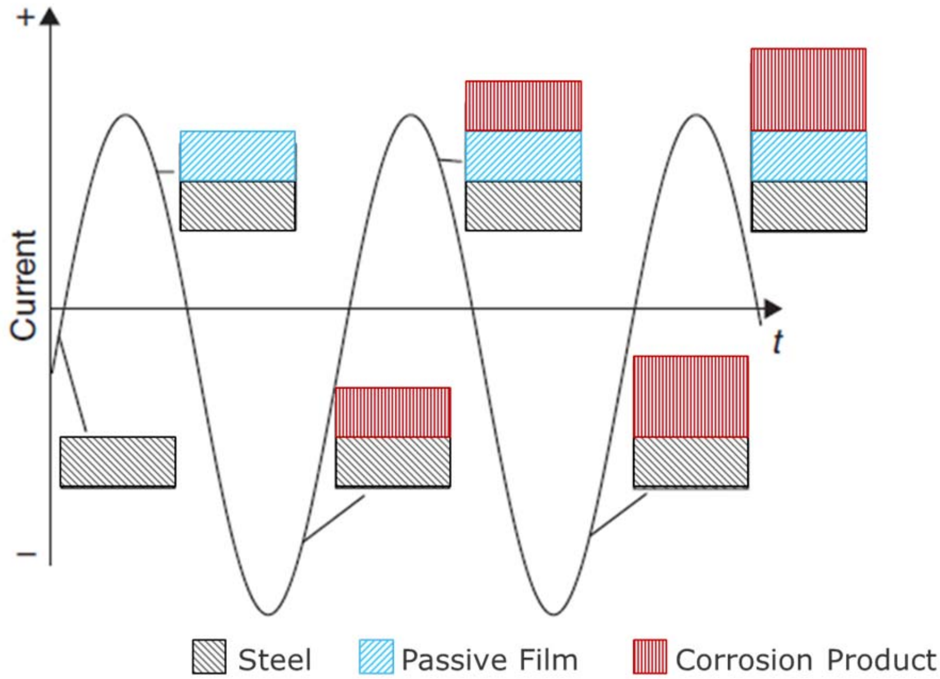

Figure 4. Graphical representation of proposed processes occurring during AC corrosion. Reproduced from Tribollet.[6]

3.3.1.1 AC Current Density

While there may be disagreement regarding the specific mechanism driving AC corrosion, AC current density is generally recognized as being an indicator of the likelihood of AC corrosion for a given location. In January of 2010, NACE International prepared and published a report entitled "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements," which provides the following insight on AC corrosion current density.

> *"In 1986, a corrosion failure on a high-pressure gas pipeline in Germany was attributed to AC corrosion. This failure initiated field and laboratory investigations that indicated induced AC-enhanced corrosion can occur on coated steel pipelines, even when protection criteria are met. In addition, the investigations ascertained that above a minimum AC density, typically accepted levels of CP would not control AC-enhanced corrosion. The German AC corrosion investigators' conclusions can be summarized as follows:*
>
> - *AC-induced corrosion does not occur at AC densities less than 20 A/m^2 (1.9 A/ft^2).*
> - *AC corrosion is unpredictable for AC densities between 20 to 100 A/m^2 (1.9 to 9.3 A/ft^2).*
> - *AC corrosion occurs at current densities greater than 100 A/m^2 (9.3 A/ft^2)."3[1]*

The AC density for a given location is dependent on soil resistivity, induced voltage, and the size of a coating holiday. Research has indicated that the highest corrosion rates occur at holidays with surface areas of 1 to 3 cm^2 (0.16 to 0.47 in^2).[1] AC current density is best obtained through direct measurement of a correctly sized coupon or probe. However, the theoretical AC current density can be calculated, utilizing the soil resistivity and AC potential on a pipeline, in conjunction with Equation 1, presented in the State of the Art Report.[1]

$$I_{AC} = \frac{8V_{AC}}{\rho \pi d} \qquad \text{Equation (1)}$$

Where:

I_{AC}	=	Theoretical AC Current Density (A/m^2)
V_{ac}	=	Pipe AC Voltage to Remote Earth (V)
ρ	=	Soil Resistivity (ohm-m) (*1 ohm-m = 100 ohm-cm*)
d	=	Diameter of a circular holiday having an area equal to that of the actual holiday (m)

Multiple industry references discuss a current density threshold below which AC corrosion is not a significant factor; however, there is still disagreement on the magnitude of this threshold. While the majority of technical literature indicates AC corrosion is possible at current densities between 20 to 30 A/m^2, there is experimental evidence presented by Goidanich, et al[14] indicating that AC current densities as low as 10 A/m^2 can contribute to a measureable increase in corrosion rate[14]. A significant conclusion of study published by Yunovich and Thompson in 2004[9], reiterated in the NACE AC Corrosion State of the Art Report in 2010, indicated that there might not be a theoretical threshold below which AC corrosion is active. The focus should rather be on a practical limit, below which the contribution of AC interference to the overall corrosion rate is low, or rate of corrosion due to AC is not appreciably greater than the free corrosion rate for the particular conditions.[3,9] The results of the experimental study showed that a current density of approximately 20 A/m^2 produced a 90% or greater increase in the corrosion rate versus the control, in the absence of CP.[9] Experimental studies performed by Goidanich, Lazzari, et al in 2010 and 2014, in the presence of CP, concluded that while it was apparent AC current density greater than 30 A/m^2 showed a considerable increase in the corrosion rate, a current density as low as 10 A/m^2 resulted in a corrosion rate nearly double that of the specimens without AC.[14, 18]

For reference, the European Standard EN 15280:2013, "Evaluation of AC corrosion Likelihood of Buried Pipelines Applicable to Cathodically Protected Pipelines" adopted the 30 A/m^2 current density magnitude as a lower threshold, below which the likelihood of AC corrosion likelihood is low. In an effort to address the practical application seen in operation, considering interaction effects of CP current and AC interference, recent research has assessed the likelihood of AC corrosion in terms of the ratio between AC and DC current density (I_{AC}/I_{DC}).

3.3.1.2 Current Density Ratio

Recent research has shown that the likelihood of AC corrosion on pipelines is dependent on both the level of AC interference and the level of cathodic current from either CP or other stray current sources.[3, 15, 18] In general, AC current density values below the previously cited 20 A/m^2 recommended limits were shown to accelerate corrosion rates in the presence of elevated DC current density due to excessive CP overprotection.

The latest revision of EN 15280:2013 was revised to present criteria based upon the AC interference and DC current due to CP. Alternative acceptance criteria are presented in terms of limiting cathodic current density, or limiting the AC to DC current density ratio (I_{AC}/I_{DC}) below a specified level.

Current density obtained by use of coupons or electrical resistance (ER) probes will provide this ratio. However, both AC and DC current density data required to utilize these limits are often not available or easily obtained along the pipeline in practice. Therefore, the current density ratio limits provided within the EN 15280 standard are not widely used or easily applicable criteria. This reference demonstrates the recognized interaction of AC interference and CP systems, presenting an alternative approach that may be valuable for specific scenarios where data is available.

As mentioned previously, the measurement or calculation of AC current density has been the primary indicator to determine the likelihood of AC corrosion across industry in North America. It is possible to measure AC current density on a representative holiday through the installation and use of metallic coupons. A coupon representative of the pipe material, with a defined bare surface area, buried near the pipeline and connected to the pipeline routed through a test station will allow the measurement of current. These current measurements along with the known surface area of the coupon, allow for calculation of a representative current density. In many cases, the coupons are supplemented with additional instrumentation such as ER probes and reference electrodes to provide additional pertinent information. The ER probes provide a time based corrosion rate while the reference electrodes provide both and AC and DC pipe-to-soil potentials.

Section 6 provides further details related to mitigation and monitoring methods for to AC corrosion. Appendix A includes additional details related to literature review, historical AC corrosion rates, and industry case studies.

3.3.2 Faults

During a phase-to-ground fault on a power line, an adjacent or crossing pipeline may be subject to both resistive and inductive interference. Although these faults are normally of short duration (generally less than one second), pipeline damage can occur from high potential breakdown of the coating and conductive arcing across the coating near the fault. Further, the fault current is typically carried by a single conductor, resulting in short term elevated induced voltages that can reach thousands of volts or greater. This presents a significant risk to personnel in contact with the pipeline or electrically continuous appurtenance during a fault.

A phase-to-ground fault, or a lightning strike, on an HVAC power line can result in large potential differences with respect to the adjacent or crossing pipelines. If the potential gradient through the soil is sufficient, a direct arc to a collocated or crossing pipeline is possible, which can result in coating damage, or arc damage to the pipe wall up to the point of burn-through. Even if an arc is not sustained long enough to cause burn through, a short duration elevated current can cause molten pits on the pipe surface that may lead to crack development as the pipe cools. Fault arcing is generally a concern where fault potentials are greater than the dielectric strength of the coating, or at coating holidays within the possible arcing distance. Section 7.3 provides guidance limits for both issues. Where necessary, installation of grounding and shield wires can be used to mitigate the fault hazards as discussed in Section 6.

3.3.2.1 Coating Stress Voltage

During fault conditions, damage to the pipeline or its coating can occur if the voltage between the pipeline and surrounding soil becomes excessive. Fault conditions that produce excess coating stress voltages across the coating are of concern for dielectric coatings. The main factors to consider are the magnitude of the voltage gradient and the dielectric strength of the coating type. It should be noted that there are several parameters that are utilized to assess these issues: magnitude of the fault current, distance between the pipeline and fault, soil resistivity, coating age/quality, duration of the fault and coating thickness.

Guidance on allowable coating stress voltage varies across references. NACE SP0177-2014 indicates, "Limiting the coating stress voltage should be a mitigation objective." Multiple references offer varying coating stress limits and are generally considered to be in the range of 1 to 1.2 kV for bitumen, as low as 3 kV for coal tar and asphalt, and 3 to 5 kV for fusion-bonded epoxy (FBE) and polyethylene, for a short-duration fault."[10]

For reference, NACE SP0490-2007 "Holiday Detection of Fusion-Bonded Epoxy External Pipeline Coating of 250 to 760 μm (10 to 30 mil)" uses an equation for calculating test voltages which recommends a 15 mil (14 to 16 mils is a common specification for FBE coatings) fusion bonded coating (FBE) be tested at 2,050 volts.

NACE SP0188 2006 "Discontinuity (Holiday) Testing of New Protective Coatings" also uses an equation for calculating test voltages for coatings in general.

$$TV=1{,}250\sqrt{T} \qquad \text{Equation (2)}$$

Where:

TV = Test Voltage (V)

T = Average coating thickness in mils

This results in a test voltage of 8,840 volts +/- 20% for a pipeline coated with a 50-mil coal tar coating.

The first standard above is the subject of AC mitigation and the following two standards are the recommendations for holiday testing; however, there appear to be inconsistences as to what voltage will actually damage the various pipeline coatings. The inconsistences appear to be due to the unidentified coating thickness in SP0177-2014 and actual duration of the fault resulting in conservative values.

Gummow et al. in their paper "Pipeline AC Mitigation Misconceptions"[19] present data that include the duration and coating thickness in the analysis resulting in values that are more practical. They conclude that FBE coatings with a 16 mil thickness should conservatively use a voltage gradient limit of 5,000 volts and that the 3kv to 5 kV range indicated in NACE SP0177-2014 would be more applicable in the range of 7.5 kV to 12.5 kV.

3.4 HVDC / Underground HVAC

High voltage power interference is primarily a concern for pipelines collocated with HVAC overhead power lines, due to the widespread sharing of common ROW, and the interference effects associated. However, there are associated concerns across industry regarding interference effects of aboveground HVDC transmission and underground AC power lines. Presently, the U.S. transmission grid consists of approximately 200,000 miles of 230 kV or greater high voltage transmission lines, with an estimate that underground transmission lines account for less than 1% of this total.[20] Industry trends indicate that due to significant disparity in overall installation costs, it is expected that while buried transmission lines will continue to be developed and implemented, overhead transmission will remain the primary means for electric transmission for the foreseeable future.[2]

In general, the level of interference from buried HVAC power lines is typically lower as the proximity between the individual phase conductors acts to balance electromagnetic fields, reducing EMI on foreign structures. Depending on the type of construction, sheathing or conduit may offer some level of electromagnetic shielding, further reducing inductive interference effects.

As aboveground HVAC is still the primary concern for pipeline interference, it is the primary focus of this report. However, the effects of both aboveground HVDC and buried transmission cables require review on a case-by-case basis when pipelines are closely collocated. There are currently less than 30 identified high voltage direct current (HVDC) transmission lines operating in the United States[21]. Although there are few relative to overhead HVAC, and the interference effects on a pipeline are different from HVAC transmission lines, they do warrant a brief discussion so that pipeline operators are aware of potential issues. The Canadian Association of Petroleum Producers (CAPP)[22] have produced a technical document that addresses in detail the issues associated with HVDC transmission lines influence on metallic pipelines. Due to the technical differences, the detailed extent of HVDC transmission line interference on steel pipelines necessitates its own study, beyond the scope of this document, however a summary overview of design and interference comparisons follows.

HVDC transmission systems in operation today are typically of monopole or bipole design. In each case, the systems consist of a transmission line between stations with the major components being DC-AC convertors and large ground electrodes. In monopole systems, a single conductor transports the power with an earth return, as depicted in Figure 5. It should be noted that where HVDC systems use a ground return, the interference concerns are similar to typical DC stray current interference, which is addressed in NACE SP0169 and is outside the scope of this document.

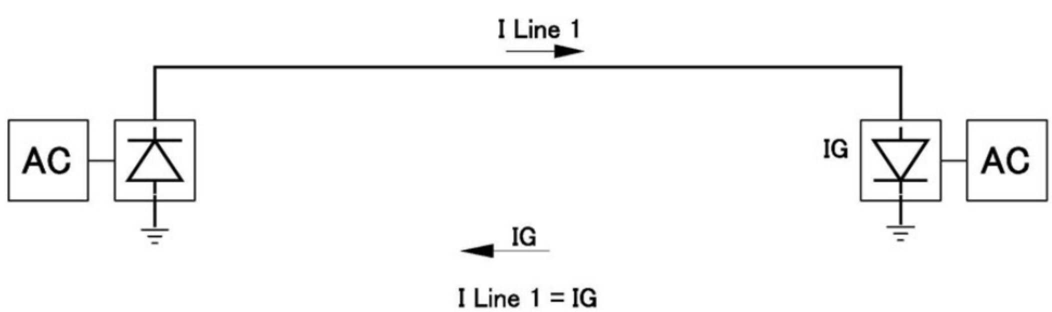

Figure 5. Monopole System [34]

In bipole systems, two conductors between stations allow the system to transport power through both conductors, one conductor and an earth return, or a combination of both, as depicted in Figure 6. The most common use of monopole systems is in submarine applications using the seawater as the earth return. The most common use of bipole systems consist of onshore overhead transmission towers to transport the power.

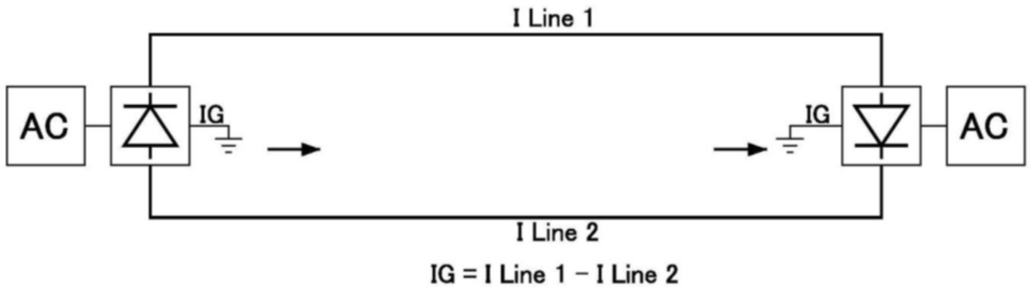

Figure 6. Bipole System (34)

Tripole configurations have been considered and reviewed in research, but have not seen widespread use in practice. There are several types of designs and operation modes within the broad parameters of the monopole and bipole systems. During emergencies and in maintenance of the bipole system, an earth return is used. In an earth return mode there is a potential gradient generated and metallic objects, such as pipelines, can be subject to varying potentials and become a conductor of the return current if they provide a low resistance path. Where current is collected or received by the pipeline generally no damage occurs, unless the current is high enough to damage the coating. However, corrosion will occur at current discharge locations. The amount of corrosion is dependent on the amount of current and duration of discharge. In the case of large discharge current, significant corrosion damage can occur in relatively short time periods. The effects are similar to the interference currents caused by other DC power sources such as traction systems, cathodic protection systems or welding with an improper ground.

HVDC transmission lines also have the same coupling modes with pipelines that occur with HVAC transmission lines capacitive, inductive, and resistive. Although under typical circumstances these effects may be negligible. However, interference levels under faulted conditions can be significant.

3.4.1.1 Capacitive coupling

The results of research presented by Koshcheev indicate the electrical field below HVDC transmission lines does not generally require significant safety measures during construction when the pipe is isolated on skids, as the electric field influence associated with HVDC transmission is limited compared to HVAC.[21]

3.4.1.2 Inductive coupling

CAPP indicates the voltages induced due to HVDC, under steady state conditions tend to be negligible. The magnitude of induction may contribute to minor interference problems with telephone lines, and possibly other communications systems, but is typically low enough that neither pipeline integrity nor safety hazards are considered likely under steady state conditions. However, during fault conditions, there is a possibility for short duration of elevated inductive coupling.

3.4.1.3 Resistive coupling

During faulting both HVAC and HVDC transmission systems can present personnel safety issues and compromise pipeline integrity, with possible damage to the pipeline, coating, and associated equipment. A faulted HVDC power line presents a possible integrity concern for nearby pipelines. CAPP indicates that the fault current discharged to ground at the power line tower causes a ground potential rise (GPR) near the ground electrode. A voltage gradient exists relative to remote earth. A pipeline within the voltage gradient will experience a coating stress voltage as discussed in Section 3.3.2.1. If high enough, the voltage stress could puncture the insulating coating possibly damaging the pipeline.

3.5 Industry Procedure Summary

The lack of industry consensus on the subject of AC corrosion guidelines has led to varied practices among pipeline operators in regards to mitigating AC interference on pipelines. As part of this study, The INGAA Foundation requested a review of industry practices and procedures related to AC interference. Based upon this review, all of the procedures address a safety concern and define a maximum allowable AC pipe-to-soil potential limit for above-grade appurtenances. For pipelines in close proximity to HVAC power lines, faults are identified as a hazard in almost all of the procedures. However, few addressed coating stress limit above which mitigation is required. For current density criteria, several procedures had clearly defined limits, while others addressed it as a concern for AC corrosion but did not specify a targeted limit of AC current density or define limits for mitigation. Table 1 provides a summary comparison of the industry procedures reviewed.

Table 1 - Industry Procedure Summary

Induced AC Potential Limit Requiring Mitigation	*Fault Protection/Coating Stress Voltage Limit Requiring Mitigation*	*Current Density Criteria Requiring Mitigation*
In accordance with NACE: 15 V	Not specified	Not Specified
15 V	2500 V	Not Specified
15 V	Mentions damage possible from faults but no limit	Not Specified
15 V or higher - No work unless approved by area supervisor	Not specified	Not Specified
Modeling Required > 2 V	Consider with Modeling	30 A/m^2
15 V	5000 V	75 A/m^2 requires mitigation, 50 A/m^2 requires further evaluation
10-15 V	150-2000 V depending on fault duration	30 A/m^2
15 V	Faults to be considered along with a minimum separation distance, but no limit specified	20 A/m^2
15 V	Faults to be considered during mitigation analysis, but no limit specified	50 A/m^2
15 V	Faults to be considered during mitigation analysis, but no limit specified	50 A/m^2

4 NUMERICAL MODELING

Predicting high voltage interference is a complex problem, with multiple interacting variables affecting the influence and impact. In recent decades, development of advanced calculation methods and computer-based tools for simulation of interference effects, analysis of faults, and development of mitigation methods has been significant.2[3,5,9,10] Computer based numerical modeling can be utilized to examine the collocated pipeline's susceptibility to HVAC interference, help identify locations of possible AC current discharge, and where necessary design appropriate mitigation systems to reduce the effects of AC voltage, fault currents, and AC current density to meet accepted industry standards. These numerical models are capable of analyzing the interacting contribution of multiple variables to the overall magnitude of AC interference.

Computer modeling is used to analyze the interactions and sensitivity of the variables that affect the magnitude of AC induction on pipelines. This section provides a brief review of numerical modeling software in general, as well as the results of the individual variable analyses.

4.1 Modeling Software

Previous research has compared the benefits of specific industry standard software; literature is available for each of the common software packages.[3,9,2023] This review addresses the generalizations concerning the present industry standard software, but does not aim to address or endorse specific software packages.

For the majority of simple collocations considering a single pipeline and single HVAC power line numerous industry-accepted models have shown to be consistent in the assessment of HVAC interference. Often, for these simple cases, the benefit of a more complex model is not gained due to uncertainty in the analysis inputs. That is to say that for a majority of simple collocations, any of several industry accepted models are capable of providing an accurate analysis. The applicability is limited by the accuracy of the input data, and expertise of the analyst in utilizing the specific model. Often the uncertainty in critical input variables, such as the HVAC load current and phasing, outweighs the benefits gained from a more complex model. However, as the collocation complexity increases, both in terms of the number of structures and geometric routing, the limitations of some basic models support the benefits of the more detailed modeling software.

Typical industry standard software packages that were reviewed use a transmission line model (TLM) to calculate longitudinal electrical field (LEF), based on established fundamental Carson or Maxwell equations for electromagnetic fields. The geometry and routing of the complete pipeline and transmission line network incorporated in the model considers multiple pipelines, transmission lines, tower sections, and other collocation parameters. Collocations are simplified as a connected series of finite sections and nodes, with appropriate parameters applied simulating the pipeline, soil, and transmission load-ins. The modeling software can then calculate the LEF for each section and solve the fundamental equations to calculate the potential, current, and theoretical current density along a given collocation.

Calculation of the EMI and corresponding effects on buried pipelines requires a thorough understanding of the variables involved. Detailed modeling requires knowledge of electric field interactions, transmission current, tower design, bulk and local soil resistivity, and pipeline parameters such as geometry, coating, depth, diameter, electrical connections or isolations, and existing CP. All of these variables may significantly affect the AC interference model, and similarly the analogous real world interference. Likewise, the assumptions and simplifications made during the model setup can have significant impact on the accuracy and applicability of the outputs.

While most of the available models are able to analyze each of these variables, either directly or indirectly, the accuracy of the analysis is dependent on the expertise and understanding of the analyst to assess the given variables. Similarly, the accuracy of the models can only be as good as the input data. Multiple sources are required for the collection of data, i.e. measured in field, provided by power line or pipeline operators, or based off published nominal data. For that reason, the accuracy of the results is ultimately dependent on the expertise of analyst and the reliability of the data input to ensure technically appropriate setup, despite the presence of multiple models that have been shown to be capable of providing accurate analysis when used within their applicable limitations.

4.2 Variable Analyses

Due to the number of interacting variables affecting the overall levels of AC interference, it is difficult to isolate the effects of a single variable for all collocations scenarios encountered. Consequently, it is difficult to determine distinct limits for individual variables outside of which interference becomes negligible. Considering several key interacting variables is a more viable approach. For example, reported recommendations cite a distance of 1,000 feet as considered 'far' and assumed low risk for HVAC interference. However, in cases where power line current loads are greater than 1,000 amps and in regions of low soil resistivity, elevated induced AC potentials and corresponding current density exceeding recommended thresholds have resulted at even greater distances. Therefore, separation distance alone may not provide sufficient justification to exclude a collocation from further assessment. Conversely, considering the interacting effect of the key variables identified is necessary when determining the need for detailed analysis for a collocation.

DNV GL developed a series of computer models to illustrate the influence of key variables affecting induced AC on pipelines from nearby HVAC power lines. The software used is a graphical simulation platform developed to predict the steady state interference and resistive fault effects of HVAC power lines on buried pipelines in shared right-of-ways (ROWs). Using a TLM and appropriate input data, the software calculated the LEF, which then calculated the magnitude of induced AC potential, and current along the modeled collocated pipelines.

The models created for these studies are simplistic in terms of geometry and serve as a demonstration of the variables' influence on AC induction on adjacent pipelines. Based upon the number of variables and their interactions with respect to AC interference on pipelines, these studies determine the relevancy of the various parameters. The studies offer guidance demonstrating the trends associated with each parameter on the overall level of interference, and were used along with existing industry guidance and literature findings to develop the recommended guidelines presented in Section 6.

The primary variables analyzed as part of this study are as follows:

- HVAC Power Line Current
- Soil Resistivity
- Separation Distance Between Pipeline and Power Line
- Collocation Length of Pipeline and Transmission Line
- Angle Between Pipeline and Transmission Line
- Coating Resistance
- Pipeline Diameter and Depth of Cover

The results of these studies are presented and summarized in the following sub-sections.

4.2.1 HVAC Power Line Current

A primary variable influencing the magnitude of induced AC potential on a pipeline collocated with HVAC power lines is the magnitude of the phase conductor current. The current load of the nearby power lines has a direct influence on the LEF generated by the HVAC power line circuit(s). The intensity of the LEF varies with the current loads affecting both magnitude of induced AC potential on the nearby pipeline, as well as the area of influence. The area of influence affects the separation distance at which a collocated pipeline experiences significant interference and is further discussed in Section 4.2.3.1.

To demonstrate the sensitivity of power line current on pipeline interference, DNV GL created a computer model simulating a single circuit vertical transmission line, parallel to a 10-inch diameter pipeline for 5,000 feet at a horizontal separation distance of 100 feet. The pipeline approaches the transmission line at a 90-degree angle and parallels the transmission line for 5,000 feet before receding from the transmission line at a 90-degree angle, as depicted in Figure 7. The HVAC load current was varied while all other model inputs remained constant, to analyze the influence of current alone. A uniform soil resistivity of 10,000 ohm-cm was applied and constant throughout the analyses. The transmission line current loads analyzed were 250, 500, 1,000, 2,500, and 5,000 amps based on ranges of operating and emergency loading conditions reported in literature and previously provided from power transmission operator's design conditions. Figure 8 shows the maximum induced AC potential as a function of transmission line current load.

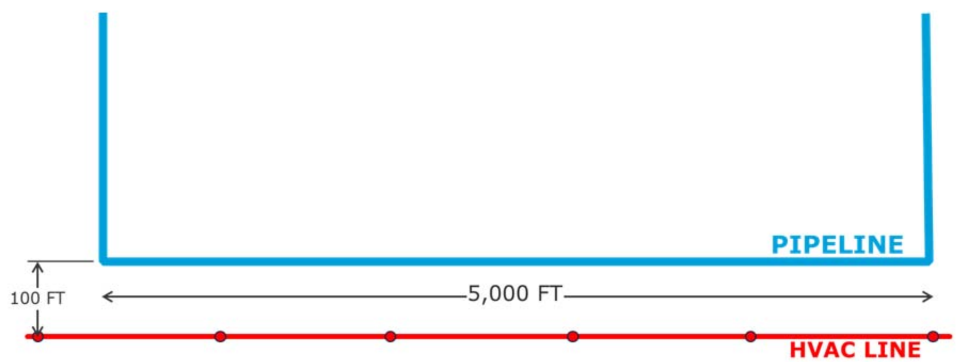

Figure 7. Simplified ROW Model Geometry

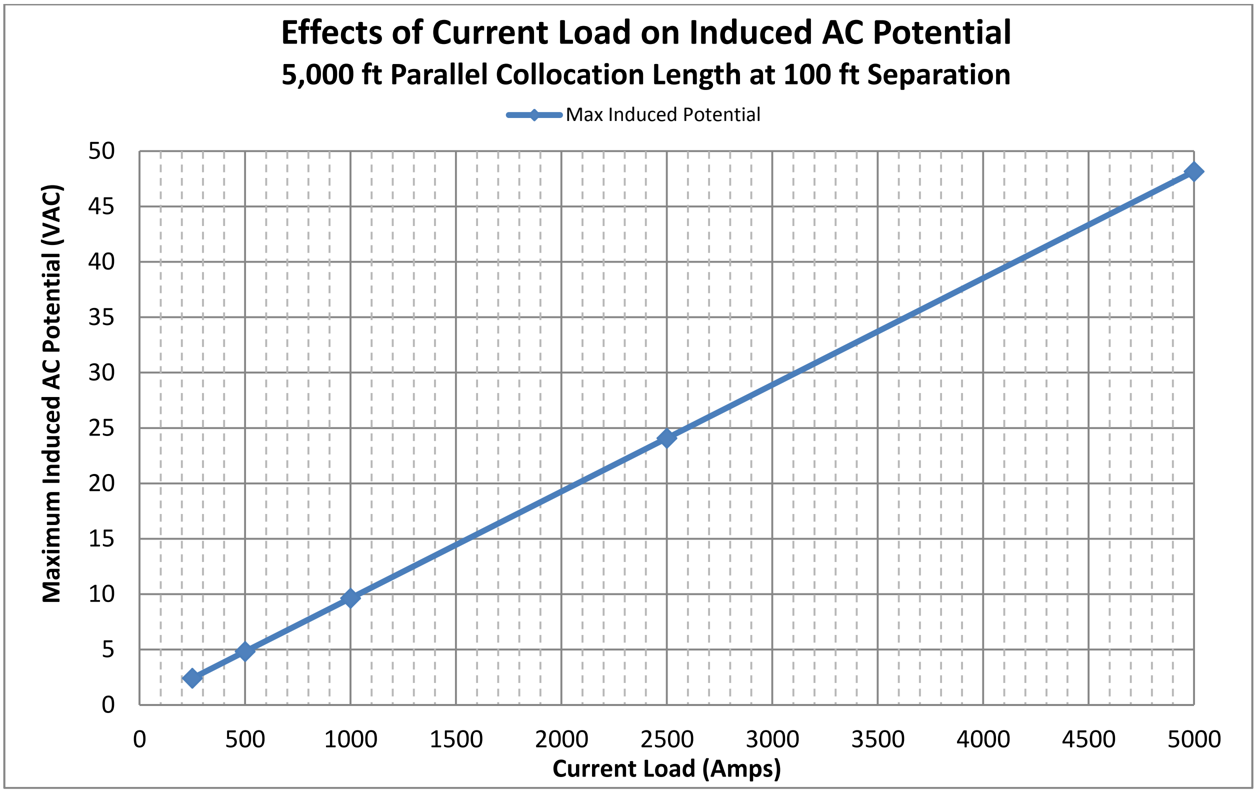

Figure 8. Maximum Induced AC Potential as a Function of HVAC Transmission Line Current

The results of this analysis show that the relationship between transmission line current and maximum induced AC potential on the pipeline is linear for a parallel collocation, considering a single interfering power line. When all other variables remain constant, the HVAC operating current load has a direct linear effect on the magnitude of the induced AC potential. This relationship allows for estimating influence of elevated current loads based on field measured AC pipe-to-soil potentials. For the specific case, with a pipeline collocated with a single HVAC circuit, if sufficient measurements of AC pipe-to-soil potential are taken, and corresponding transmission line current loads are provided for the specific time of measurement, the values can be scaled linearly to estimate the induced AC potential likely at the correspondingly scaled transmission current. This may be applicable, for example, for estimating the effects associated with a power line upgrade with a new current load. However, this method of approximation is only applicable for pipelines collocated with a single transmission line where sufficient data is available. As the number of transmission line circuits increases, the multiple interference sources and interaction the complexity of the interference increases such that the simply linear relationship is no longer valid. As the number of influencing HVAC circuits and pipelines within the area of influence are increased, the complexity of the interaction necessitates analysis that is more detailed.

It is known that while the higher current loads presented represent the high end of typical reported design loads, recent trends in the power transmission industry have shown development and installation of higher capacity HVAC transmission systems capable of carrying significantly greater current loads. For example, previous references indicate a typical load for 345kV to 500kV systems to be approximately 500 to 1,000 amps per circuit.3[24] Recent research indicates increased capacity for 345kV lines carrying up to 5,000 amps per circuit, and over 6,000 amps for 500kV systems.[2,24] While these magnitudes are not considered typical, numerous projects have developed recently that require mitigation for circuits operating at these elevated loads, indicating a need to consider actual current ratings for certain collocations. For this reason, loads are presented in terms of current rather than line voltage rating, as current is the driving load to control the level of EMI. It is noted that line ratings are typically given in terms of voltage ratings such as 138 kV, 345 kV, etc. however, the current load is the more relevant variable when determining the level of HVAC interference. Voltage rating alone can be misleading as the associated loads can be significantly higher or lower than the 'typical' current loads for that kV rating. For this reason, it is recommended to obtain current load data from the power utility company when assessing risk of interference.

4.2.2 Soil Resistivity

The soil resistivity along the collocation affects the magnitude of induced AC potential distribution as well as the theoretical AC current density along a given pipeline. It is necessary to consider both the bulk and specific layer resistivity when assessing likelihood and severity of interference. The bulk resistivity to the pipeline depth is one of the controlling factors in the analysis of induced AC potential. The bulk resistivity is the average soil resistivity measured in a half-hemisphere to the depth of the pipe, as shown in Figure 9 below. However, the specific resistivity of the soil layer directly next to the pipe surface, shown as Layer 2 in Figure 9, is a primary factor affecting the corrosion activity at a coating holiday, considering both conventional galvanic and AC assisted corrosion. The bulk soil resistivity combined with the coating resistance of the pipeline affect the level of induced AC potential expected along the pipeline.

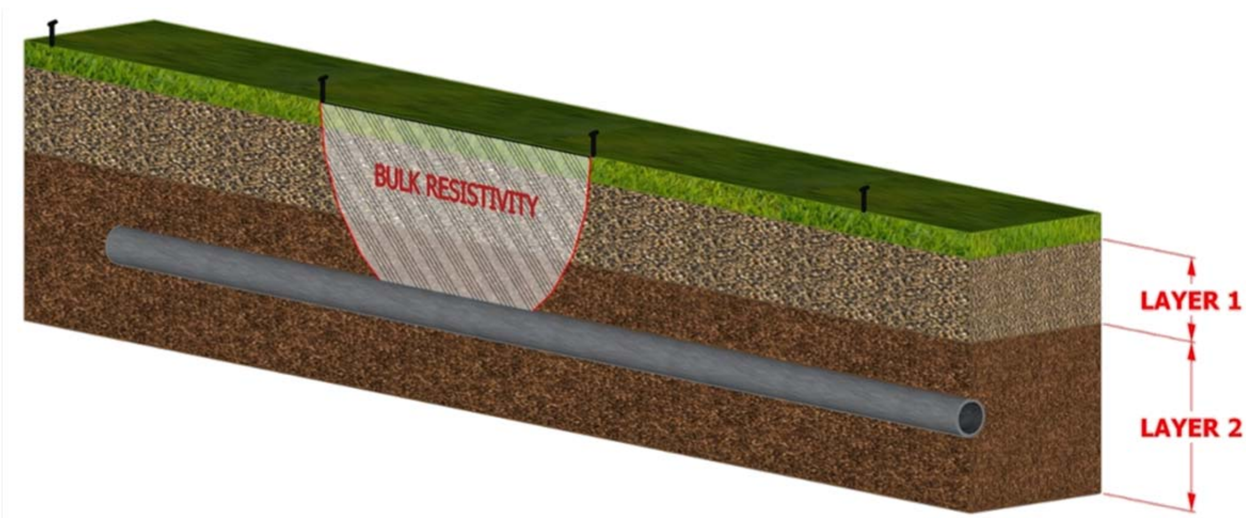

Figure 9. Graphical representation of soil resistivity measurements, showing bulk and layer zones

To demonstrate the sensitivity of soil resistivity on pipeline interference and current density, DNV GL created a computer model simulating a single circuit vertical transmission line, parallel to a 10-inch diameter pipeline with a configuration similar to the model setup described in Section 4.2.1. The soil resistivity was varied along the pipeline while all other model inputs remained constant, to analyze the influence of resistivity alone. The soil resistivity was uniform along the entire modeled collocation, considering 100, 1,000, 10,000, and 100,000 ohm-cm. Figure 10 shows the maximum induced AC potential corresponding to varying current loads.

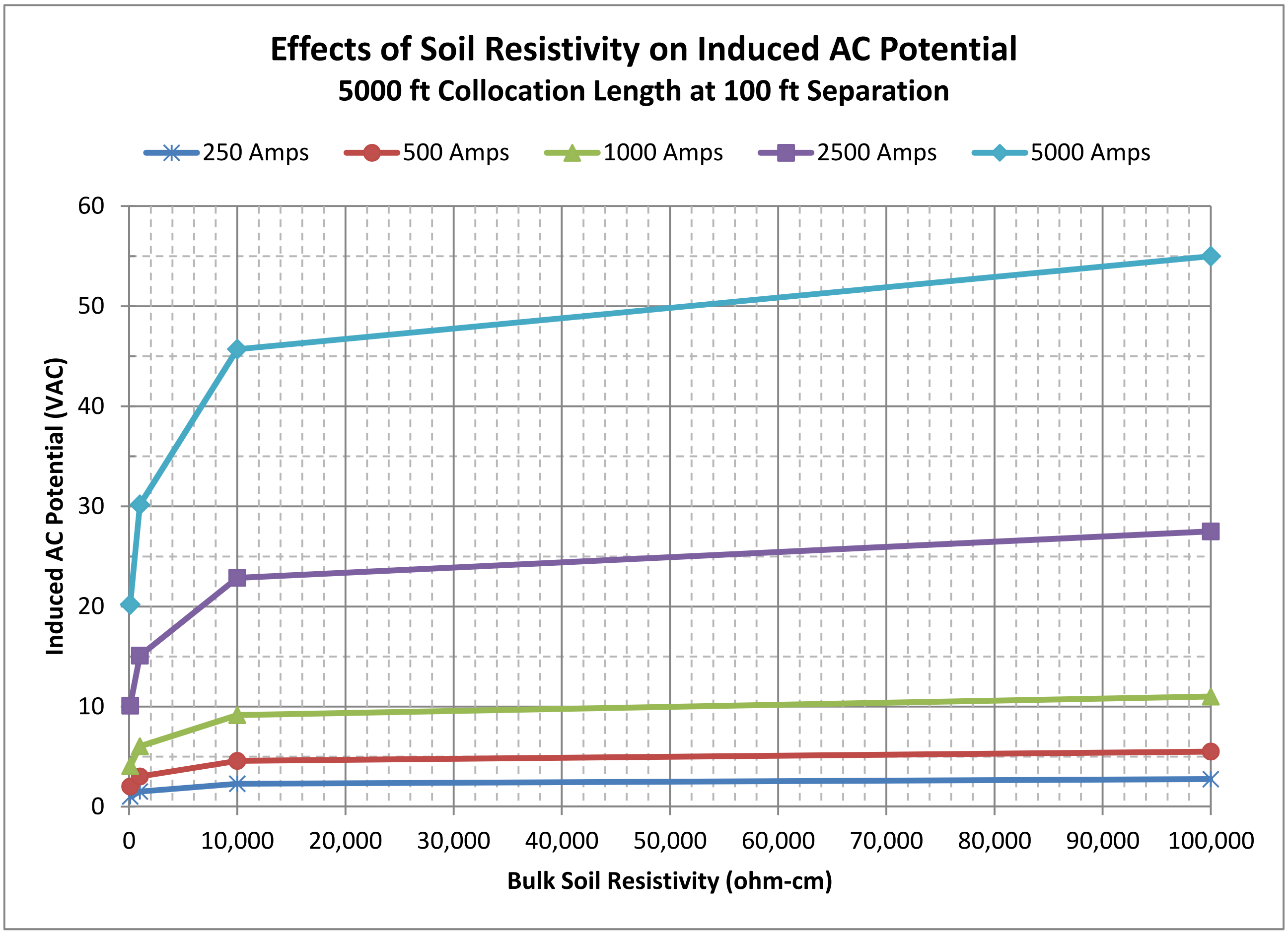

Figure 10. Maximum Induced AC Potential as a Function of Soil Resistivity

The results of the analyses show that the induced AC potential increases logarithmically with increasing soil resistivity. This increase in induced AC potential changes significantly between 100 and 10,000 ohm-cm but approaches asymptotical limit at soil resistivity values greater than 10,000 ohm-cm.

The effects of soil resistivity have greater influence however on the current density. While an increase in soil resistivity can result in a slight increase in the magnitude of induced AC voltage for a given collocation, the theoretical current density and associated risk of AC corrosion decreases linearly with the increased resistivity. The layer resistivity of the soil directly next to the pipe surface is a primary factor in the corrosion activity at a coating holiday. The specific resistivity near the pipe at a holiday is inversely related to theoretical AC current density, as shown by the calculation for theoretical AC current density in Equation 1. Thus, an increase in soil resistivity results in a decrease in theoretical AC current density.

Considering the 250 amp current load case from Figure 10, the theoretical current density was calculated from the induced AC potential for each magnitude of soil resistivity, considering a 1 cm^2 holiday, shown in Figure 11 and Table 2. While the soil resistivity values increase several orders of magnitude across the range, the theoretical current density decreases on similar order, with minimal change in the overall induced AC potential, as shown in Figure 11 and 0 Table 2. The red dashed line represents the lower bound 20 amps/m^2 threshold for current density as discussed in Section 3.3.1.1. It can be seen that based on the calculations provided by Equation 1, a very high theoretical AC current density is possible for relatively low AC potential, if soil resistivity values are below 10,000 ohm-cm. This results in elevated risk for AC corrosion for soil resistivity ranges below 10,000 ohm-cm.

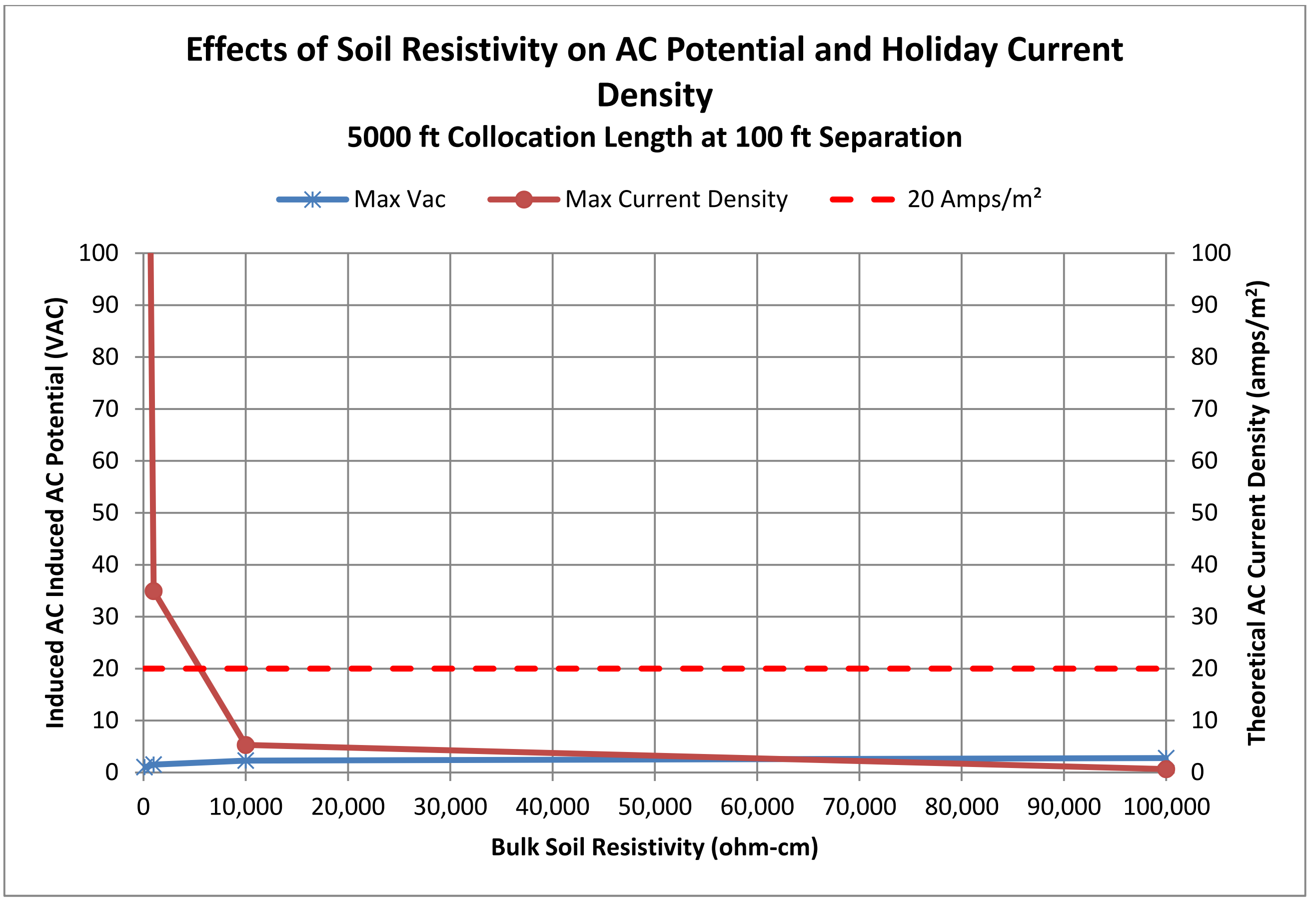

Figure 11. Effects of Soil Resistivity on Induced AC Potential and Corresponding Holiday Current Density. Current density presented for a theoretical 1cm^2 holiday

Table 2-Calculated current density and induced AC potential

ρ (ohm-cm)	Calculated Current Density (A/m^2)	Induced Potential (V_{ac})
100	234	1.0
1,000	35	1.5
10,000	5	2.3
100,000	0.6	2.8
Based on 5,000ft parallel collocation with a power line operating at 250 A load, 100-ft separation distance		

4.2.3 Collocation Geometry

The geometry of the pipeline relative to the transmission line is critical in determining the magnitude and distribution of induced AC potential along the pipeline. The level of AC interference for a given collocation or crossing, with respect to collocation geometry, is dependent on the relative distance between the phase conductors and pipeline, the locations of convergence or divergence, and angle of approach or crossing. Each of these variables affects the overall level of induction or susceptibility to fault hazards, and their influence is dependent on all other configuration variables. When assessing susceptibility to AC interference all of these variables are considered. However, for the sake of this assessment, the following studies analyzed each independently in order to provide a simplified assessment of the influence of each parameter.

The figures presented in Section 4.2.3.1 to 4.2.3.3 incorporate a dashed line similar to the current density threshold indicator in Figure 11. The limit lines provide reference to the AC potential limit that may result in a theoretical AC current density of 20 amps/m^2 for a hypothetical 1 cm^2 holiday, at soil resistivity of 1,000 and 10,000 ohm-cm. The limit lines are included to provide guidance illustrating the levels that may pose an elevated risk of AC corrosion at potentials below the NACE specified 15 volt limit for personnel safety.

4.2.3.1 Separation Distance Between Pipeline and Power Line

The separation distance between the pipeline and transmission line is a significant variable controlling the level of induced AC potential influencing a given pipeline. The proximity of the pipeline to the phase wires limits the strength of the LEF to which the pipeline is exposed.

To demonstrate the sensitivity of separation distance on pipeline interference, DNV GL created a computer model simulating a single 10-inch pipeline, and single circuit vertical transmission line, with similar configuration as described in Section 4.2.1. The separation distance was varied between the models while all other model inputs remained constant, to analyze the influence of separation alone. Induced AC potential results are plotted for separation distances of 50, 100, 500, 1,000, and 2,500 feet in Figure 12. The results indicate that for the higher load currents, the 20 A/m^2 recommended current density threshold is exceeded for separation distances greater than 500 feet is exceeded.

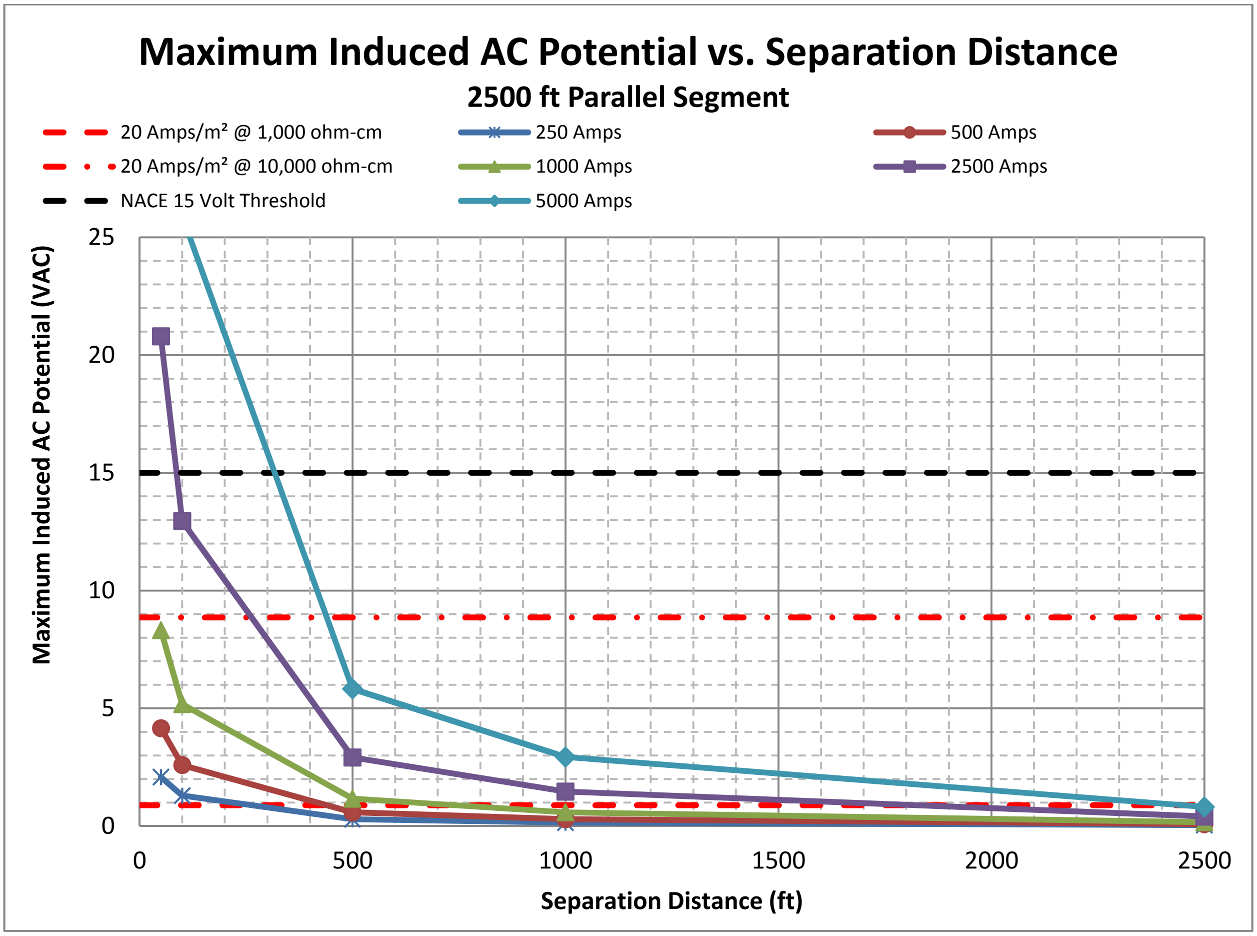

Figure 12. Effects of separation distance on induced AC potential. Current density limits presented for a theoretical 1cm^2 holiday.

As the distance between the pipeline and transmission line increases, the induction on the pipeline decreases. This is expected as where the distance between the pipeline and phase conductors increase the distance from the LEF origin increases, decreasing the coupling effects. The results of this study as presented in Figure 12 illustrate an important effect of the load current as well. The area of influence or separation distance at which a collocated pipeline experiences significant interference increases accordingly.

The figure also depicts potential levels corresponding to a 20 amp/m^2 current density for both 1,000 and 10,000 ohm-cm soil resistivity for reference. For the given parameters analyzed, a current load of 250 amps results in an induced potential of approximately 2 volts at a 50 foot separation distance which quickly decreases to less than 0.5 volts at a distance of 500 feet. However, a load of 2,500 amps results in an induced AC potential of approximately 21 volts at a separation distance of 50 feet, and approximately 1.5 volts at a separation distance of 1,000 feet. This is important when determining which pipeline collocations require detailed analysis, as there is variation among industry guidance documents for the limiting distance. A limiting distance of 1,000 feet is common practice, however, for HVAC current loads greater than 1,000 amps, significant interference might be possible at distances exceeding 1,000 feet. While the induced AC potentials magnitudes may appear relatively low in Figure 12, for separation greater than 2,000 feet, it should be noted this example is considering a single HVAC circuit, and only an approximately 0.5 mile collocation length. In practice additional interfering circuits collocated for longer distances would result in higher induced AC potentials. Further, as discussed in Section 4.2.2, it is possible to have an elevated AC current density under relatively low soil resistivity conditions, such that AC corrosion is a concern at relatively low induced potential.

It is necessary to consider separation distance in conjunction with the other factors to exclude a collocation from further analysis for separation distances within 2,500 feet. At a minimum, operating current, or an estimate of it, is also necessary when determining if further analysis is required.

4.2.3.2 Collocation Length of Pipeline and Transmission Line

Just as separation distance affects the magnitude and distribution of induced AC potential along the pipeline, so does the length of collocation. The collocation length is the distance along the ROW that a pipeline parallels or crosses the transmission line within a separation distance and angle that allow for inductive coupling. The collocation length affects the magnitude of induced AC potential that accumulates on the pipeline as it defines the length of the pipeline exposed to the LEF of the phase wires.

To demonstrate the sensitivity of collocation length on pipeline interference, DNV GL created a computer model simulating a single 10-inch pipeline, parallel to a single circuit vertical transmission line at a 50 foot offset. The collocation length was varied between the models while all other model inputs remained constant, to analyze the influence of collocation length alone. Collocation lengths of 500, 1,000, 2,500, 5,000, and 10,000 feet of the pipeline and transmission line compare the maximum induced AC potential in Figure 13.

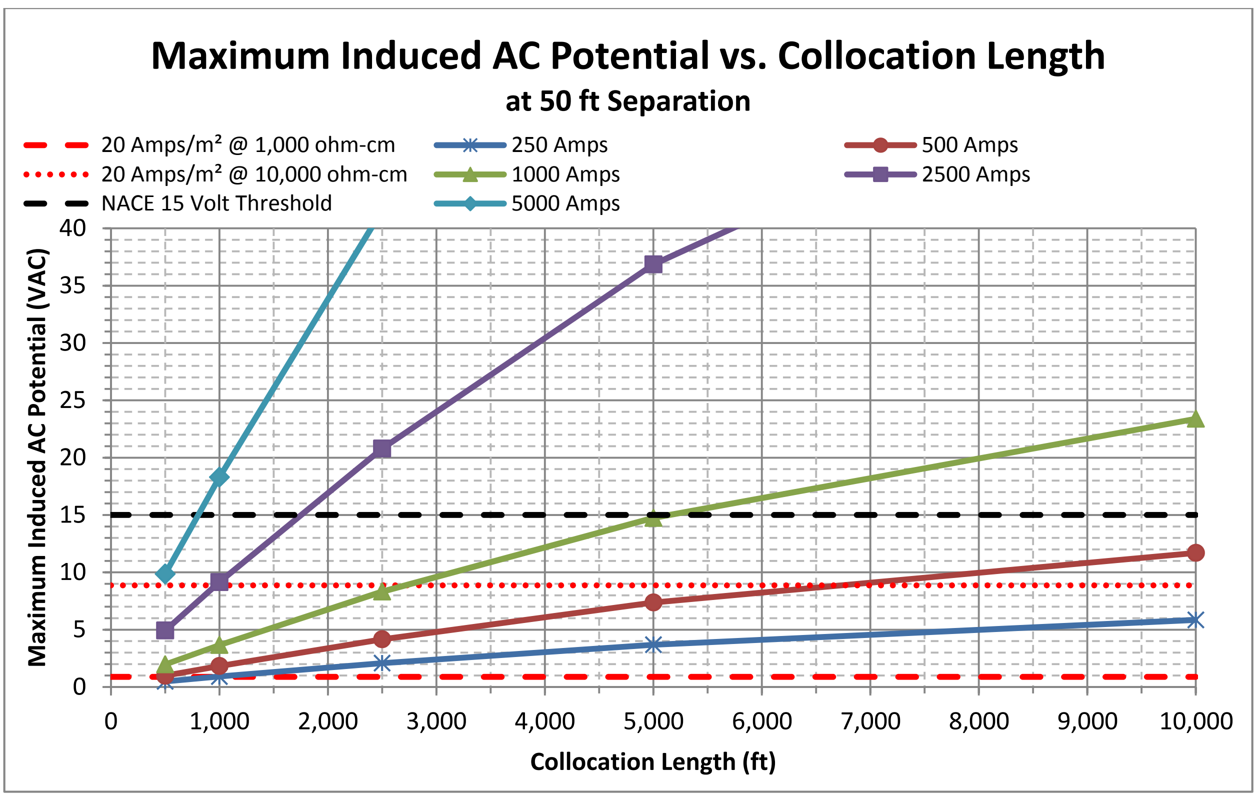

Figure 13. Maximum Induced AC Potential as a Function of Collocation Length

As the collocation length increases, the magnitude of induced AC potential on the pipeline increases, as the length of pipeline exposed to the LEF is increased. Collocation lengths as short as 500 feet are capable of inducing 2 – 10 VAC or greater considering a single collocated power line operating at 1,000 amps or greater.

The potential levels corresponding to a 20 amp/m^2 current density for both 1,000 and 10,000 ohm-cm soil resistivity have been included for reference. Considering a relatively low soil resistivity of 1,000 ohm-cm, the 20 amps/m^2 current density criteria is exceeded at a 2,500 foot collocation length for all load currents analyzed.

The results of the collocation length study also accentuate the sensitivity to HVAC load current as previously discussed in Section 4.2.1. The collocation length required prior to exceeding the 15 volt safety threshold for the 2,500 and 5,000 amp load conditions is approximately 1,750 and 800 feet respectively. These conditions are further increased in complex collocations where multiple lines exist.

It is necessary to consider collocation length in conjunction with the other factors to exclude a collocation from further analysis for separation distances within 2,500 feet. At a minimum, operating current, or an estimate of it, is also necessary when determining if further analysis is necessary.

4.2.3.3 Angle Between Pipeline and Transmission Line

The angle at which the pipeline and HVAC transmission line cross has an effect on the magnitude of induction on the pipeline at the crossing. As the angle increases between the pipeline and transmission line, the magnitude of the induction decreases as the component of the pipeline exposed to induction decreases. For a perpendicular crossing, with the pipeline crossing at or near 90° to the power line, the induction on the pipeline is minimized as the effective parallel length is minimized. The magnitude of the current on the transmission line also has a significant impact on the induced AC potential at crossing locations. Previous ‘rule-of-thumb’ practices throughout industry may have indicated crossings greater than 60° resulted in negligible induction on adjacent pipelines.[2] However, recent studies have resulted in HVAC installations with significantly greater current capacity, which acts to increase the corresponding interference resulting in cases with induced AC voltage at relatively high angle crossings.

To demonstrate the sensitivity of collocation angle on pipeline interference, DNV GL created a computer model simulating a single 10-inch pipeline, and single circuit vertical transmission line, with similar configuration as described in Section 4.2.1. The pipeline was approximately 2 miles long and the angle between the pipeline and transmission line varied between models while all other model inputs remained constant, in order to analyze the influence of crossing angle alone. Figure 14 shows the results of an analysis of crossing angles between 15 and 90 degrees and the calculated maximum induced AC potential for each case.

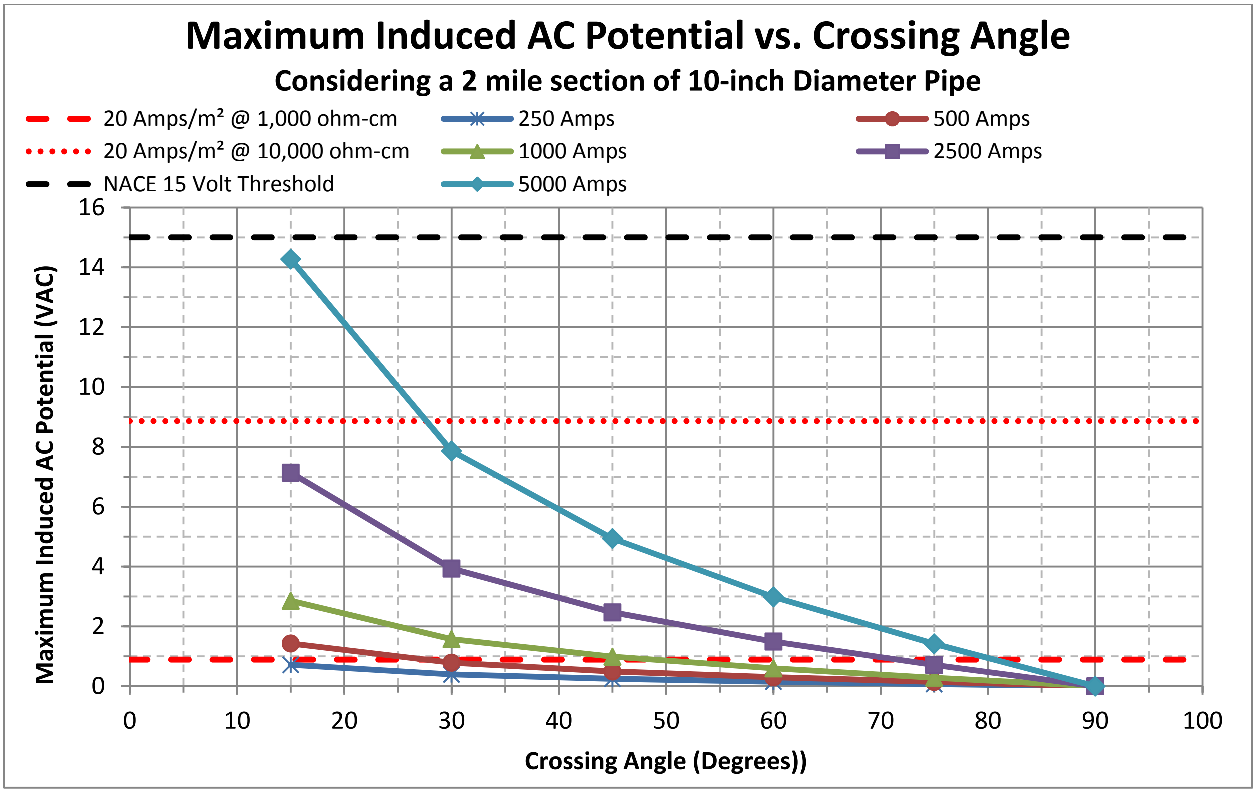

Figure 14. Maximum calculated induced voltage at various HVAC line crossing angles

Considering a typical 345kV circuit, and current loads of up to 1,000 amps, a crossing angle of greater than 45° degrees resulted in an induced potential of less than two (2) VAC for the study presented. A crossing angle of greater than 60° induces minimal potential such that the corresponding current density is less than 20 amps/m^2 even in a relatively low soil resistivity at 1,000 ohm-cm. Previous industry experience and general guidance practices across industry appear consistent with this understanding that crossings of greater than 60° are typically low-severity with respect to induction.

However, as the transmission line load increases to greater than 1,000 amps, it can be shown that crossing angles up to 60° may induce potentials such that corresponding current density exceeds 100 amps/m^2, in low resistivity soil conditions. Depending on target limits for current density, models show that crossing angles of 80° can cause high current density in relatively low soil resistivity locations.

The crossing angles discussed above are with respect to induced AC interference specifically. Assessment for susceptibility to faults, and coating breakdown due to fault voltage, is required for all crossings where pipelines pass in close proximity to a tower ground.

4.2.4 Coating Resistance

The resistance of the pipeline coating to ground is a significant factor controlling the level of induced potential that may build up on a pipeline. However, in practice the coating resistance is typically not known with great certainty and is generally inconsistent along the pipeline length. The coating resistance to ground is a function of the coating type, condition, thickness, and local soil resistivity, all of which may vary along a typical collocation length.

In general, a poorly coated pipeline, or deteriorated coating with low resistance to ground allows multiple paths to ground for AC potential to dissipate. This reduces the buildup of induction, resulting in lower AC potential and lower current density discharge at any individual holiday. Conversely, considering a well coated line with high dielectric strength and excellent coating condition, the resistance to earth along the length of the pipeline is relatively high allowing for greater induction build up over longer distances. For example, this case may exist with a newly FBE coated pipeline, with minimal holidays, in proximity to a collocated HVAC power line. Due to the high resistance to ground, and relatively few ground paths, the induced AC potential can build along the collocation length. This can generate elevated AC potentials, which may be hazardous from a safety standpoint, but also create a possible corrosion risk, as the AC current can discharge from a relatively few holidays after a physical or electromagnetic discontinuity, such as the pipeline diverging from the collocation.

Relative estimates of coating resistance are provided by Dabkoski in the report for Pipeline Research Council International (PRCI) and Parker[24,25], and summarized in Appendix B for reference, to be utilized in detailed modeling analysis based on coating quality, and soil resistivity, however specific guidance is not provided for a relative risk associated with the various coating resistance values.

4.2.5 Pipeline Diameter and Depth of Cover

The diameter of the pipeline collocated with or crossing an HVAC power line affects the level of induced AC potential on the pipeline. However, historical experience has indicated that the effect is relatively minor compared with the influence of other variables.

To demonstrate the sensitivity of pipe diameter on pipeline interference, DNV GL created a computer model simulating a single pipeline, parallel to a single circuit vertical transmission line for 5,000 feet at a horizontal separation distance of 100 feet. The pipeline approaches the transmission line at a 90-degree angle and parallels the transmission line for 5,000 feet before receding from the transmission line at a 90-degree angle. The pipeline model considered diameters of 6, 10, 18, 24, 36, and 48 inches, while all other model inputs remained constant, to analyze the influence of diameter alone. The model used a uniform soil resistivity of 10,000 ohms-cm. The results of this study indicate that the magnitude of induced AC potential decreases with an increase in pipeline diameter, as shown in Figure 15.

As the diameter of the pipeline decreases, the surface area exposed to the LEF also decreases. However, the magnitude of LEF generated by the transmission line remains unchanged. For a smaller diameter pipeline, the LEF influences a smaller surface area resulting in greater induced AC potential compared to a larger diameter line, considering all other variables equal. Further, the pipeline characteristic impedance varies inversely with pipeline diameter, as presented in previous work by PRCI3[24]. Considering all other parameters equal, a larger diameter pipeline will have a generally lower effective resistance to ground, and therefore a lower tendency of HVAC interference. For relative comparison, an increase in diameter from 6 to 48 inches resulted in a 20% decrease in induced AC potential on the pipeline, regardless of the interfering current level.

In the previous analysis, the models used 10-inch diameter pipeline, which will provide a conservative estimate relative to typical larger diameter transmission lines. This was chosen to clearly demonstrate the effects of the individual variables.

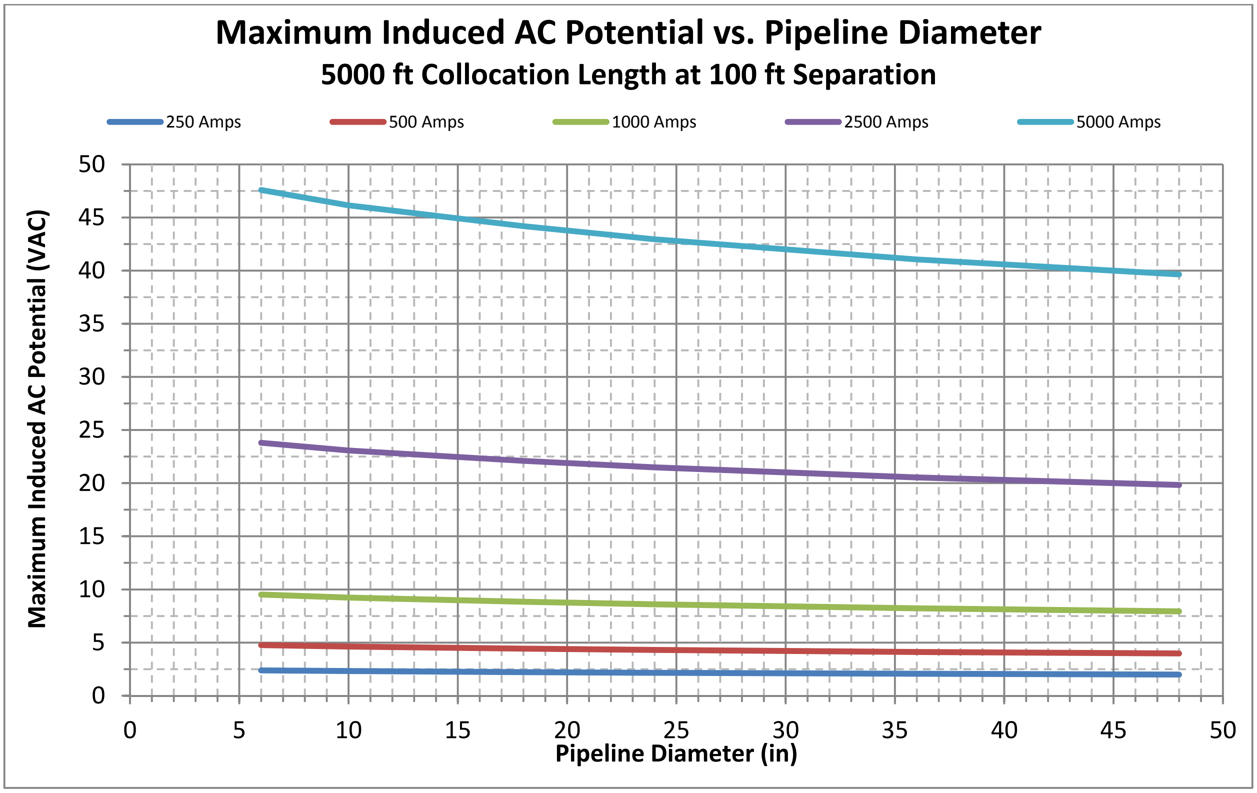

Figure 15. Maximum Induced AC Potential as a Function of Pipeline Diameter

Similar to pipeline diameter, the pipeline depth of cover has a relatively minor influence on the induced AC potential on the pipeline. In general, the level of AC interference decreases with increasing depth of cover as the distance from the individual phase conductors and total resistance to the LEF is increased, though the effect is relatively minor for typical burial depths. A fixed depth of cover of approximately 5 feet was used in the sensitivity studies above.

5 MITIGATION

NACE International Standard Practice SP0177-2014 requires a mitigation system designed for pipelines where HVAC interference is present.[10] Mitigation system design varies across the industry, but in general all involve a low resistance grounding system to pass interfering AC to ground. Typical mitigation system designs can be either surface or deep grounding designs. Both designs have benefits and detriments considering performance, cost, and constructability.

Liquid and gas transmission pipelines are regulated under the Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) Regulations §49 CFR Part 195 Subpart H Corrosion Control (195.551 – 195.589)[26] and §49 CFR Part 192 Subpart I Requirements for Corrosion Control (192.451 – 192.491)[27], respectively. The regulations have various requirements for corrosion control of which CP and electrical isolation are major factors in compliance. CP systems apply a DC to the pipeline, and electrical isolation quantifies the surface area or limits of the system. CP systems designed for transmission pipelines must meet federally regulated criteria.

5.1.1 DC Decouplers

When designing mitigation systems for induced AC and faults on transmission pipelines, detrimental effects to the CP system must be considered. It is essential to ensure they do not compromise the operation of the CP systems. Additional structures such as grounding and shield wires used in mitigating induced AC attached directly to the pipeline change the operating characteristics of the CP system, changing the surface area intended for the CP compromising its effectiveness. Direct current decouplers (DCD) alleviate this situation. However, there are some cases where the design of CP accounts for the mitigation. The decouplers, designed into the circuit, allow AC current to pass to ground, while blocking the DC CP current, maintaining the pipeline surface area. There are various types, sizes and ratings of decouplers used depending on the predicted faults or induced AC and mitigation design. DCDs are also used to block DC current at grounded above grade appurtenances, such as block valves, metering stations, and launcher/receiver stations.

Decouplers installed across electrical isolation flanges (IF) prevent "burn over" which can occur when an AC fault current or lightening surge is large enough in magnitude to arc over the gap between flange faces or exceeds the rating of the IF.

5.2 Surface Grounding

Surface grounding generally refers to one of several types of mitigation grounding installed at or near the surface or pipe depth. Typical designs may consist of bare copper cable, zinc ribbon, or engineered systems buried generally parallel to the pipe path and connected to the pipeline through a DCD. During new construction, surface grounding can be installed directly in the pipe trench, or laid parallel to the pipe in an adjacent trench or bore. This approach allows for cost-effective installation of a significant length of mitigation at a lower cost relative to alternative forms of mitigation, but is dependent on construction access along the ROW.[16]

If necessary, connecting additional mitigation ribbon in parallel and even adding shallow vertical anodes to the circuit will further reduce grounding resistance up to a certain extent. Installing this type of mitigation system at distributed, targeted locations, optimized from the interference model, reduces the induction along the pipeline. Additionally, when laid parallel to the pipeline in regions where transmission line towers are in close proximity, the mitigation ribbon also acts to protect and shield the pipeline from damage resulting from fault and arcing scenarios.

Analysis of the reduction in ground resistance possible with various installation approaches included a calculation of the resistance of 1,000 foot long mitigation ribbon in varying soil resistivity, using the modified Dwight's Equation for multiple anodes installed horizontally[28]. Figure 16 illustrates how this calculated grounding resistance varies with the number of ribbons connected in parallel at multiple levels of soil resistivity. While numerous sizes of ribbon cables exist, the length is a much more significant factor in determining total resistance than diameter, when considering typical ribbon diameters, therefore this analysis considers a constant diameter ribbon.

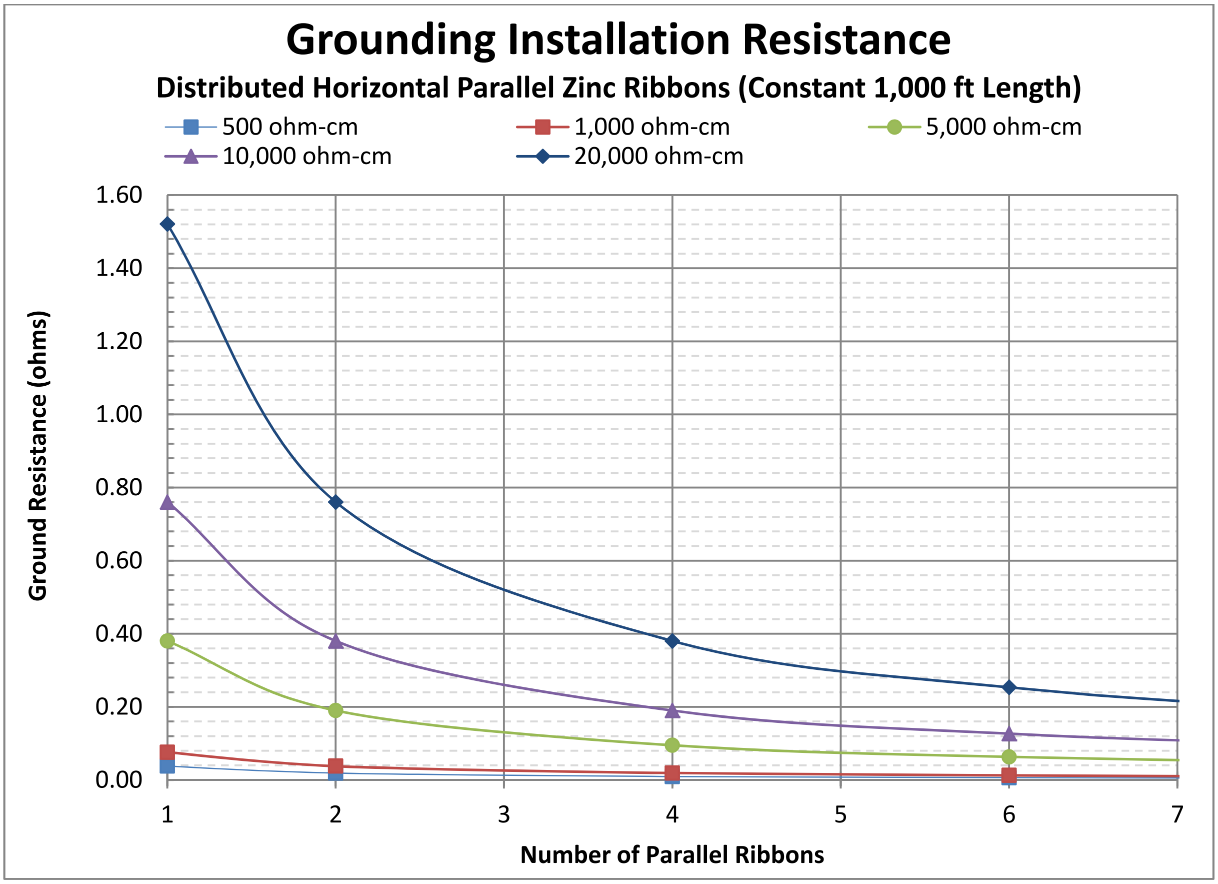

Figure 16. **Grounding Resistance of Horizontal Parallel Zinc Ribbons at Varying Soil Resistivities**

As shown in Figure 17, at low soil resistivities, very low grounding resistance results with a single, relatively short ribbon length. As the soil resistivity increases, so does the achievable grounding resistance. The data is presented considering multiple parallel mitigation ribbons to demonstrate that further reduction in ground resistance is possible by adding additional grounding at a particular installation. However, diminishing returns exist such that further increasing the extent of grounding at a specific site, beyond a certain threshold, results in minimal additional reduction, as shown in Figure 16.

The length of vertical grounding installations requires review of economics, construction, and practical design considerations. Multiple shorter grounding rods can be incorporated to achieve a low resistance to ground without requiring deep drilling, where parallel surface grounding does not sufficiently reduce the ground resistance. Vertical ground rods should be separated horizontally by the length of the ground rods at minimum for optimum efficiency.[23]

For locations of high surface resistivity, one drawback for horizontal surface grounding is the length of mitigation ribbon wire required to achieve a low resistance. Where multiple parallel ribbons are required to achieve sufficient grounding resistance significant ROW access may be required. As discussed, the shared utility ROW may limit construction access for mitigation parallel to a collocated pipeline. Additionally, as pipelines cross physical obstructions, such as roadways, railroads, access may limit the extent of parallel mitigation systems. However, surface grounding still continues to be the preferred mitigation technique and can efficiently provide adequate mitigation grounding for a majority of collocations.

5.3 Deep Grounding

Deep drilled ground wells (deep wells) offer another form of mitigation grounding, and may be considered for select applications. Deep wells generally consist of one or more anodes drilled vertically into the ground in order to achieve low ground resistance. Actual deep well depths can vary based on needs, but they generally range greater than 100 feet in depth.

In general, construction costs are generally higher for deep well grounding than for comparable surface mitigation. However, deep well grounding can be a viable option in specific applications where one or both of the following criteria are satisfied.

1 The soil resistivity at the surface is significantly greater than (>20 x) the soil resistivity at lower depths.

2 Horizontal surface grounding is not feasible due to construction obstacles (roads, railways, right-of-way access, etc.)

For typical mitigation systems, where parallel ribbon and deep grounding are both options, parallel ribbon proves to be more efficient and economical because it can achieve a lower resistance to ground for lower overall cost. For comparison, ground resistance calculations were analyzed to determine the approximate equivalency in effective ground resistance between parallel zinc ribbon, and an individual deep well anode.

Figure 17 below shows a comparison of parallel horizontal grounding configurations compared to a single 6-inch diameter deep well anode approximately 200 feet deep. The soil resistivity ratio, plotted on the x-axis, is the ratio between the bulk soil resistivity to a depth of 10 feet for surface ribbon and the bulk soil resistivity to a 200 foot depth for a deep well. Along the y-axis is the equivalent length of horizontal surface grounding required to meet the same level of grounding resistance as the deep well anode. The two curves in the figure below display this trend for single and double surface ribbon installations.

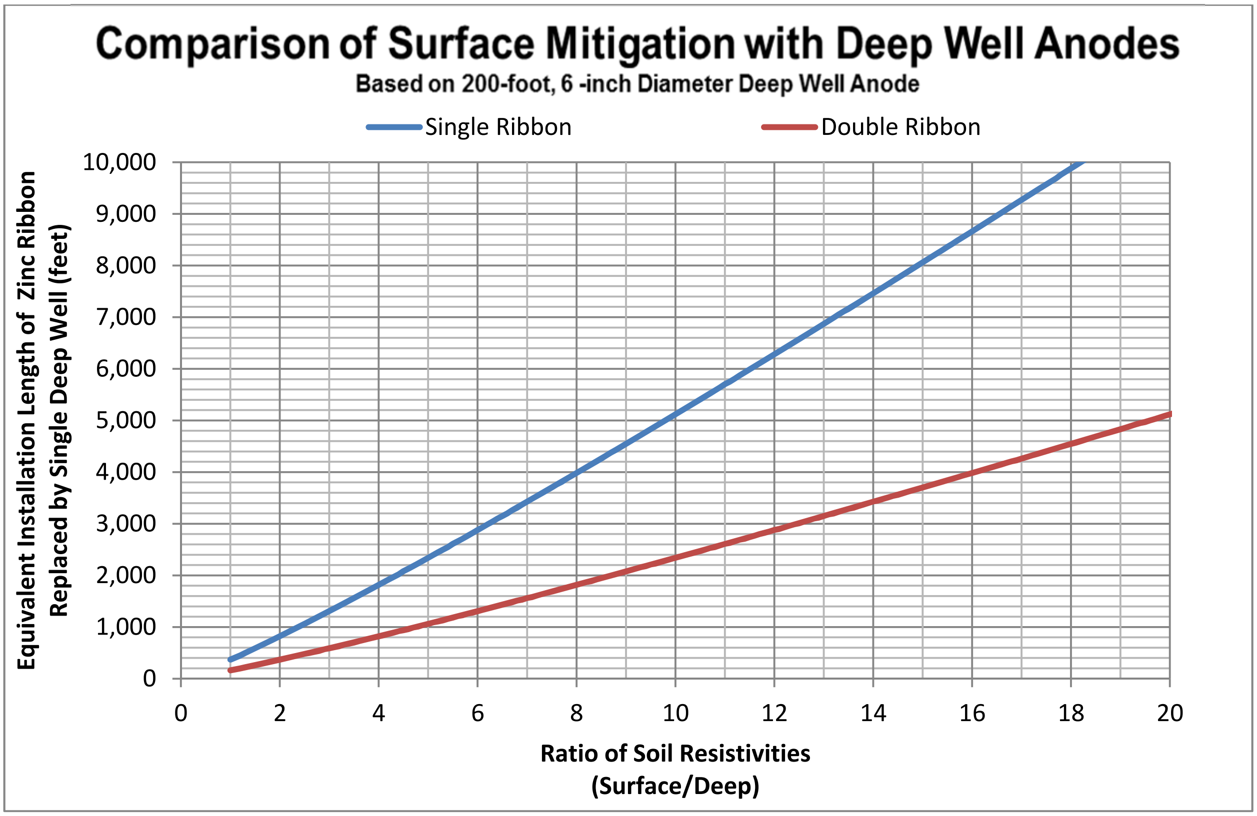

Figure 17. Comparison of Surface Mitigation to Deep Well Anodes

Considering a typical scenario where deep soil resistivity values are of similar order to the surface resistivity, a single deep well grounding installation would be necessary for approximately every 1,000 to 2,000 feet of individual parallel ribbon. However, considering a hypothetical location where the deep soil resistivity is an order of magnitude lower than at the surface (soil ratio of 10), it can be shown that a single deep well installation could provide a similar ground resistance as approximately 5,000 feet of individual parallel ribbon. Under certain scenarios, where the ratio between the surface and deep soil resistivity is high, deep well anodes may become a viable solution to obtain a low grounding resistance. Previous case studies and project experience have rarely shown soil resistivity ratios of this magnitude, such that deep well grounding was a preferred option. However, where construction access is limited, not allowing for installing longer lengths of surface grounding to achieve the required mitigation deep well grounding may be beneficial. In scenarios where grounding is only necessary at a single specific location on the pipeline, deep well grounding may be an option.

5.4 Mitigation Comparison

Deep well anodes may provide a viable mitigation option under specific circumstances, but industry practice, historical assessments, and construction practice have generally shown that surface mitigation provides more economical and efficient mitigation for the majority of collocations. In cases where arc shielding protection is required to guard against fault scenarios, deep well anodes do not provide such protection, thus necessitating the installation of surface ribbon in addition to primary mitigation. Surface mitigation can also serve as fault shielding, protecting against damage to the pipeline and its coating when properly placed between the pipeline and power transmission ground.

A primary benefit for surface mitigation is ease of installation and a lower associated cost. Mitigation installed in the same trench beside the pipe during pipeline construction further reduces installation costs. Typical industry construction estimates indicate that the cost of a single drilled deep well anode installation may be ten times the cost of a 1,000-foot surface installation, if installed during pipe construction. This would indicate that each deep well anode would need to replace approximately 10,000 feet of surface mitigation before it is economically viable from a ground resistance standpoint alone. That said, the decision between surface and deep grounding installation methods most often comes down to a number of other considerations, including construction access, grounding distribution, and contractor preference in addition to cost alone. [Appendix C contains a simplified summary, presents the pros and cons for various mitigation materials and methods for reference.] The comparison information provides guidance and demonstrates the comparative benefits of each approach based on various soil resistivity layers.

5.5 Additional Mitigation Methodologies

The AC mitigation techniques discussed utilize low-resistance grounding to transmit induced AC voltage to ground. While grounding can be an effective mitigation technique for many interference cases, recent industry experience has identified collocations where induced potentials or current density reduction to adequate levels cannot be achieved by grounding alone. This is generally due to a combination of elevated transmission currents and unfavorable soil resistivity conditions. Trends in the power transmission industry have led to increased power capacity and corresponding operating currents, for some long distance transmission systems as shown. This increase in operating current has a direct effect on the level of EMI. In many cases, this has presented a significant challenge for achieving adequate mitigation on pipelines crossing or collocated with the power transmission lines. In these cases, additional mitigation techniques should be considered.

In terms of risk reduction or prevention, the approach to AC interference mitigation can be categorized on a primary, secondary, or tertiary level. Primary prevention targets controlling or reducing the source of the risk, through elimination or control. Secondary prevention targets reducing exposure to a risk factor, and tertiary prevention targets treating the response or consequences of the risk factor, generally after exposure to the risk. By these terms, a standard practice of mitigating AC induction by grounding alone is considered a tertiary form of mitigation. That is to say, the treatment targets only the consequence of the interference by reducing the detrimental AC effects at the pipeline level, after allowing the pipeline to be exposed to the interference risks. While not currently in widespread application, further research of primary and secondary risk controls should be considered in future development, to reduce overall interference and risks associated with AC interference, especially considering cases that cannot be effectively mitigated by traditional means. While the concepts presented may not be readily employed by pipeline operators without further research, they are presented to address the need for continued research and development of more robust high voltage interference mitigation methodologies, and pursue improved collaboration between the power line and pipeline operators.

5.5.1 Primary Threat Control of AC Interference

Although mitigation grounding is a common industry practice, cases exist where grounding alone is insufficient to reduce interference levels on collocated pipelines. For such cases, additional techniques should be considered. From an engineering risk basis, with respect to overall risk reduction, a preferred approach is to reduce the source of interference. Specifically, this means reducing the interference prior to it reaching the pipeline, generally through design controls during the development phase prior to construction, where modifications to the pipeline or transmission line are possible. The level of interference experienced at the pipeline is dependent on the magnitude of EMI generated at the source, and the collocation parameters that limit the EMI levels reaching the pipeline. Specifically, revising collocation routing, and tower and circuit configuration modifications can reduce or optimize the level of EMI produced. Conductor arrangements can be designed to balance individual phases producing the lowest levels of EMI for a given circuit configuration.

For a given circuit configuration (single circuit horizontal/vertical, double circuit horizontal/vertical/delta, etc.) there exists an ideal phase sequence which minimizes the LEF at the pipeline location and thus results in lower magnitudes of AC interference. Dabkowski studied the magnitudes of the LEF for varying circuit types and phase sequence. The results demonstrated that for a single horizontal circuit a reduction of up to 9 percent of the LEF may be achieved, by choosing the proper phase sequence.[24] With the single circuit vertical case, the LEF at the pipeline location could be reduced by as much as 15% with the proper phase sequence.

The double circuit vertical tower configuration presents a unique scenario for phase sequencing. There are 36 possible phase sequences, classified into five sets of phase combinations: center point symmetric, full roll, partial roll upper, partial roll lower, and center line symmetric. The LEF magnitude between the various phasing configurations can vary significantly.[29] Generally, the ideal phase sequence for a double vertical circuit is the center point symmetric phase configuration, which generates an LEF approximately 65% to 90% less than the center line symmetric phase configuration.[29] This is significant when considering this is simply the result of the physical interaction between conductors, and primary mitigation reduction at the source reduces the interference levels that ever reach the collocated pipeline. Additionally, optimization of the phase configuration does not require unconventional installation methods to obtain this reduction in LEF magnitude.[29] It is recognized that for existing installations, pipeline operators generally may not be able to influence HVAC power design; however, for new construction and power system expansions where interference is a concern, communication between pipeline operators and transmission owners of possible effects is recommended in order to review possible interference hazards prior to construction. Where possible, pipeline and HVAC power line design controls can limit EMI and interference on adjacent pipelines.

The addition of phase transpositions along a given collocation can also act to reduce the overall EMI influencing a collocated pipeline. However, phase transpositions should only considered as part of a detailed analysis, as the discontinuity presented by a phase transposition can create a localized point of elevated interference, and may have further impact on the power transmission design.[24] However, where appropriate, phase transpositions can create discontinuities and effectively break up long line interference built up on long collocations. Further, in areas where construction access may be limited, phase transpositions can be located strategically to reduce interference at the source.

5.5.2 Secondary Threat Control of AC Interference

With respect to overall threat reduction, a secondary control works by means of isolating a threat from a structure. In the case of AC interference, this specifically means intercepting and grounding the EMI prior to reaching the pipeline.

One proposed example is overhead shielding, which is used to mitigate AC interference in other industries including rail transport systems, but is notably less common in mitigating AC interference on pipelines. An overhead shielding technique works by placing a conductor, grounded at regular intervals, within a targeted region between the pipeline and the adjacent transmission line. This shielding conductor, located in the same LEF generated by the conductor circuit, induces a current and an accompanying LEF 180 degrees out of phase with the field generated by the transmission line. In so doing the conductor acts to cancel part of the LEF generated by the transmission line, resulting in lower levels of induction on the pipeline. Dabkowski studied the effectiveness of this technique for the same tower configurations discussed in Section 5.5.1.[29] The results indicated a substantial reduction in the induced potential on the pipeline was possible; however, the mitigating effectiveness was highly sensitive to loading conditions, and the precise location of the shielding conductor. For the single circuit horizontal circuit, an auxiliary overhead ground wire resulted in a reduction of approximately 25% in the LEF, and thus the corresponding induction on the pipeline. The ideal placement of this overhead auxiliary shield wire was approximately the same height as the phase wires, which for single circuit horizontal circuits may make this solution impractical. For the single circuit vertical tower configuration, Dabkowski found a maximum LEF reduction of approximately 60% to 75% by mounting the overhead shield wire at an optimum height on the tower centerline. Reductions in the LEF generated by the double circuit vertical configuration were found to be range from 50%-95%. However, when examining slight imbalances of +/-5 to 15% between phase wires, the benefits realized by this auxiliary shield wire quickly diminished to 20% or less when compared to uniform current across all phase wires of the circuit.29[23] While this is generally not a common practice in mitigation of pipeline interference, overhead shielding has been considered and studied in the past, and is used within other industries. Specific overhead shielding installations require detailed design, and precise locating but this approach may present an alternative means of mitigation where ineffective through more traditional means. Further research and testing is required on a case-specific basis to determine if this is a viable technique.

Fault and arc shielding, which are used to reduce the risk of damage to the pipeline and the coating near tower grounds during fault conditions are another form of secondary risk control. Fault protection typically takes the form of a parallel shield wire, similar to mitigation ribbon discussed in Section 5.2. However, the primary function of fault and arc shielding protection acts to intercept transmission line fault current and transfer to ground prior to reaching the pipeline. For this reason, the location and placement of the arc shielding mitigation is far more critical when protecting against conductive (fault) interference than for inductive interference.

5.5.3 Tertiary Threat Control of AC Interference

With respect to overall risk reduction, tertiary controls rely on reducing the consequences of the threat after exposure to the structure. Per this definition, typical grounding mitigation can be considered a tertiary control. Mitigation grounding works by transmitting the AC potential to ground, only after it has already reached the pipeline. While grounding has proven to be an effective means of mitigation for many historical installations, and installation is generally within the capabilities and access of the pipeline operators, scenarios occur where grounding alone is not sufficient to reduce interference to acceptable levels.

Ideally, a combination of primary, secondary, and tertiary mitigation techniques would provide the highest level of threat reduction and protection for the pipeline. However, addressing a threat at the lowest level possible will provide reduction in severity, increasing the likelihood that mitigation will be effective. That is to say, reducing AC interference at its source or shielding EMI from reaching an adjacent pipeline can provide greater risk reduction than simply allowing the interference to pass to the structure and dissipating to ground via tertiary mitigation methods. In practice however, it may not always be possible or practical to address interference at a primary or even secondary level. Tertiary mitigation through low resistance grounding techniques may provide adequate risk reduction for a majority of interference collocations. However, further research and continued development into additional mitigation techniques would benefit the industry.

5.6 MONITORING

As mentioned previously, the measurement or calculation of AC current density has been the primary indicator to determine the likelihood of AC corrosion across industry in North America. It is possible to measure AC current density on a representative holiday through the installation and use of metallic coupons or ER probes. A test wire connected to the coupon, routed to the surface and connected to the pipeline through a test station is an example of a simple installation. By inserting an ammeter into the circuit, an AC and DC current can be measured which when can be used to calculate the current density at that location. In many cases, test stations with coupons also include additional instrumentation such as ER probes and reference electrodes. The ER probes provide a time based corrosion rate while the reference electrodes provide both and AC and DC pipe-to-soil potentials for comparison.

Using coupon test stations (CTS), and ER probes, real-time monitoring can provide a better understanding of the interference effects acting on a collocated pipeline. However, as previously discussed, the magnitude of interference depends on the magnitude of current loads on the associated power lines. Correlation of the CTS and ER probe data with power line loads provides a thorough understanding of the system performance. While it has historically been difficult to obtain this information from power line operators, there is a recognized need to have good understanding of the operating power line loads to determine relevance of coupon test station or ER probe data. Additionally, best practices dictate obtaining data over a representative period (days or weeks as relevant) in order to assess the interference response during high load conditions. A measurement for AC potential or AC current density at a single point in time with unknown operating current loads may not be representative of the actual risk for interference on the pipeline.

6 GUIDELINES FOR INTERFERENCE ANALYSIS

The following steps are provided as best practice procedures for determining where detailed analysis is recommended based on the results of this study, industry standards, historical technical publications, and previous industry experience.

Pipeline operators are faced with many existing and new construction pipelines collocated and crossing power line ROW. Little guidance exists to assist in selecting and prioritizing collocations for detailed analysis and modeling. Under certain conditions, it may be possible to justify the low likelihood of AC interference, and exclude specific locations from further detailed modeling with detailed monitoring, or justification that the risk due to interference is low.

It is recommended to collect the following information, where possible, to determine if a detailed AC analysis is required. Appendix D is a sample of data to collect from the powerline company. Use the corresponding severity limits in Sections 6.1.1 through 6.1.5 to assist with this methodology:

- Peak and Emergency load rating (amps) for collocated power lines
- Line rating (kV) for collocated power lines
- Soil resistivity along the collocation at multiple depths
- Collocation and / or crossing routing geometry for the pipeline and power line
- AC pipe-to-soil (P/S) measurements (for existing pipelines)
- AC Current density using coupons or probes where previously installed
- Maximum fault potential and fault clearing time

Detailed “analysis” in the context of this document refers either to data collection using detailed monitoring or to specific application of numerical calculation of interference magnitudes. This analysis is done using detailed computer modeling or similar application of interference calculation methods.

6.1 Severity Ranking Guidelines

This section provides general guidance with respect to the relative severity ranking for the identified variables with respect to their impact on the severity of AC interference.

6.1.1 Separation Distance

Separation distance and load current are key factors in determining whether a collocation will experience significant AC interference. Generally, the separation distance is readily available or easily determined, so it is often a primary screening variable. However, it has been shown that significant interference is possible for distances greater than 1,000 feet when considering collocations with load capacity greater than 1,000 amps.[2] It is therefore recommended to consider collocations within 2,500 feet, and the decision for further analysis should also incorporate estimate of the power line current.

Severity ranking for separation distance is provided in Table 3.The following generalized rankings have been determined through review of industry data, parametric studies, and historical experience.

Table 3-Severity Ranking of Separation Distance

Separation Distance - D (Feet)	Severity Ranking of HVAC Interference
$D < 100$	High
$100 < D < 500$	Medium
$500 < D < 1{,}000$	Low
$1{,}000 < D \leq 2{,}500$	Very Low

6.1.2 HVAC Power Line Current

The magnitude of transmission line currents is one of the most influential parameters determining the likelihood and severity of AC interference. However, there is often debate as to which load rating to consider for interference analysis and mitigation design. HVAC power lines generally have multiple ratings that specify the operating loads allowable during normal operation and peak or emergency load ratings allowable during short duration scenarios. Ultimately, the load rating considered should be a risk-based decision made by the pipeline operator, considering the frequency of occurrence for the load level, typical duration throughout operation, and the consequence associated.

From a personnel safety standpoint, it is recommended to consider the maximum load that a power line can carry for any duration. The terminology for this varies among transmission operators, but it is commonly referred to as "Emergency Load", defined as the maximum load a transmission circuit is capable of carrying for a short duration such as during an emergency or maintenance condition. Considering personnel safety, elevated step or touch potential could pose an instantaneous threat as a shocking hazard, regardless of duration of the elevated power line current. As the pipeline operator is generally unaware of an emergency load condition on the power line, it may not be feasible to reduce or prevent exposure during even a short-duration elevated current load. It is therefore generally best practice to consider the maximum capacity or emergency loading conditions when assessing the risk of personnel safety threats such as shocking, unless other provisions can be made to prevent exposure.

However, AC corrosion is a time-dependent threat. The magnitude of AC current density possible on a pipeline under AC interference will be sensitive to the current load on the adjacent HVAC conductor. While emergency loads, or other spikes in power line current may cause an elevated current density, the associated corrosion damage may be low as the duration is limited.

The power line current is often the most controlling parameter influencing the magnitude of AC interference. For this reason, we recommend obtaining the power line load limits from the relevant power transmission operator when assessing the risk of AC interference on a given pipeline. These limits should include the various operating ratings (generally 'Normal', 'Peak', and 'Emergency'), the allowable duration for each, and expected frequency of occurrence.

Transmission operating parameters are not always readily available to pipeline operators, and this information may be difficult to obtain. However, the power line current is a primary factor, and the relevance and accuracy of an AC analysis may vary greatly with the accuracy of the operating current. Where actual load data is unavailable, published reference currents for various HVAC power line ratings are available in literature[24]. However, these guidelines are for reference only, and may provide over or under conservative results. In practice, there are cases where the operating currents provided for a specific power line significantly exceeded these estimates. Additionally, as discussed in Section 4.2.1, increase load capacity on new and upgraded systems may result in load ratings above the provided reference levels.

Severity rankings associated with HVAC load current for a collocated power line is provided in Table 4.

The following generalized rankings have been determined through review of published technical literature, industry data, parametric studies, and historical experience.

Section 5.2.1 contains further background and detailed information for effects of power line phase current.

Table 4-Relative Ranking of HVAC Phase Current

HVAC Current - I (amps)	Relative Severity of HVAC Interference
$I \geq 1,000$	Very High
$500 < I > 1,000$	High
$250 < I < 500$	Med-High
$100 < I < 250$	Medium
$I < 100$	Low

6.1.3 Soil Resistivity

Soil resistivity affects both the magnitude of induced AC and the susceptibility to AC corrosion. The AC corrosion process, as presented in Section 3.3.1 is a function of the AC current density at a coating holiday, which in turn is dependent on the level of AC voltage on the pipeline and the local spread resistance. The bulk soil resistivity is a primary factor controlling overall level of induction, while the local soil resistivity near a holiday is a primary factor in the corrosion activity, as discussed in Section 4.2.2. The following generalized severity rankings have been determined based on industry experience and guidance provided in EN 15280:2013, with respect to AC corrosion.[15]

Table 5-Relative Ranking of Soil Resistivity

Soil Resistivity - ρ (ohm-cm)	Relative Severity of HVAC Corrosion
$\rho < 2{,}500$	Very High
$2{,}500 < \rho < 10{,}000$	High
$10{,}000 < \rho < 30{,}000$	Medium
$\rho > 30{,}000$	Low

6.1.4 Collocation Length

The collocation length of the pipeline and transmission line affects the magnitude of induced AC potential accumulating on the pipeline as it defines the length of the pipeline exposed to the LEF of the phase wires. The following generalized rankings have been determined through parametric studies, and historical experience.

Table 6-Relative Ranking of Collocation Length

Collocation Length: L (feet)	Relative Severity
$L > 5{,}000$	High
$1{,}000 < L < 5{,}000$	Medium
$L < 1{,}000$	Low

6.1.5 Collocation / Crossing Angle

The angle of collocation or crossing of the pipeline and power line limits the influence of induction. The following generalized rankings have been determined through parametric studies, and historical experience.

Table 7-Relative Ranking of Crossing Angle

Collocation/Crossing Angle - θ (°)	Relative Severity
$\theta < 30$	High
$30 < \theta < 60$	Med
$\theta > 60$	Low

6.2 Recommendations for Detailed Analysis

The guidance parameters presented are based on industry literature and standards where available. Where guidance has not previously been provided, qualitative classifications have been provided to aid in severity ranking and prioritization. The qualitative guidance parameters have been determined based on published industry guidance, numerical modeling parametric studies, previous analytical experience, laboratory studies, and failure investigations for AC corrosion related damage. The intention is not to replace or remove detailed analysis from the design decisions, but rather to aid in severity ranking and prioritization when determining where additional detailed analysis and mitigation design is required.

The guidelines within should be used by the operators as part of an overall risk-based decision. The details within this report and this section can only provide guidance regarding the severity of HVAC interference or AC corrosion. When determining whether to perform further detailed analysis, add location specific monitoring, or where no further action is required, possible consequences must be a part of the decision process and reviewed on a case-specific basis.

As discussed in Section 4.2, collocations with power lines operating at greater than 1,000 amps are subject to interference under conditions where likelihood would otherwise be low. Special consideration required for collocations where the power line loads are greater than or equal to 1,000 amps. For this reason, an understanding of the power line load current is necessary for evaluating the need for further analysis. The two cases below provide an assessment of collocations and crossings encountered, based on:

Case 1 – Current Load greater than or equal to 1,000 amps, pipeline crossing or collocated within 2,500 feet

Case 2 – Current Load less than 1,000 amps, pipeline crossing or collocated within 1,000 feet

6.2.1 Case 1

For scenarios where power line current is known or can be estimated to operate at or above 1,000 amps, and a steel pipeline is crossing or collocated within 2,500 feet of the power line, a detailed analysis is recommended when one or more of the following conditions are met:

- Collocation Length severity is characterized as “High”
- Soil resistivity severity is characterized as “High” or worse
- Three or more of the variables identified in Section 6.1 are categorized as “Medium” or worse

6.2.2 Case 2

For scenarios where power line current is known or estimated to operate below 1,000 amps, and a steel pipeline is crossing or collocated within 1,000 feet of the power line, a detailed analysis is recommended when one or more of the following conditions are met:

- Phase current severity is characterized as “High” or worse
- Collocation length severity is characterized as “High”
- Soil resistivity severity is characterized as “High” or worse
- Three or more of the variables of severity rankings identified in Section 6.1 are categorized as “Medium” or worse

High angle crossings, with crossing angles of greater than 60°, while considered low-risk for inductive interference, are susceptible to fault or lightning arcing, as well as coating breakdown due to fault voltage. Crossings with an angle greater than 60° may still be susceptible to inductive interference if subject to very high current load, or multiple HVAC power lines.

6.2.3 Faults

As fault conditions are generally infrequent and of short duration, it is not practical to obtain measurements of AC potential during a fault condition. Analysis of fault voltages generally requires numerical modeling. Fault current levels or estimates of possible magnitudes, are generally obtained by HVAC power line operators and can vary significantly depending on tower design, power capacity, and location relative to substation and generation source.

Whenever a pipeline crosses or is collocated in close proximity within 500 feet an HVAC tower, it is susceptible to faults. Detailed calculations or modeling is required to determine the possibility of fault arcing and possible coating damage due to GPR.

6.2.4 Fault Arcing Distance

When a pipeline crosses or is collocated in close proximity to an HVAC tower ground, a theoretical fault arcing radius can be calculated. The fault arcing radius is the distance from a HVAC tower ground that a sustained lighting or fault arc may reach an adjacent metallic structure. The arcing radius is primarily a function of the fault or lightning current and the local soil resistivity magnitude, and is estimated using equations 2 and 3 based on Sunde's equations for lightning arc distance.[30] The equations presented were developed to predict a safe separation distance considering an elevated current due to lightning strike, and can be utilized to provide an estimate of possible fault arcing distance from a faulted high voltage tower ground as well.

$$r_a = 0.08\sqrt{I_{ac}x\frac{\rho}{100}} \qquad \text{If } \rho \leq 100{,}000\ \Omega\cdot\text{cm} \qquad (2)$$

$$r_a = 0.047\sqrt{I_{ac}x\frac{\rho}{100}} \qquad \text{if } \rho > 100{,}000\ \Omega\cdot\text{cm} \qquad (3)$$

Where: r_a = arc distance in m

ρ = soil resistivity in Ω·cm

I_{ac} = the fault current in kA

6.3 Data and Documentation Requirements

Where the Severity Rankings Guidelines criteria indicated a more detailed analysis is necessary, collect the following information where possible, to facilitate development of an AC interference model. Appendix D contains a sample data log provided for reference:

Pipeline Parameters:

- Routing geometry
- Depth of cover
- Diameter
- Coating details
- Coating resistance
- Existing CP installations
- Location of bonds
- Soil resistivity at multiple depths and locations along the ROW
- Location of insulating joints

Power line Parameters:

- Routing geometry
- Number of circuits
- Conductor configuration (dimensions, orientation, phasing)
- Conductor loading (Peak and Emergency current)

- Tower ground resistance
- Maximum fault voltage
- Fault clearing time
- Shield wire configuration

6.4 General Recommendations

As the operating current is a controlling parameter influencing AC interference, it is recommended to obtain the power line load current from the relevant electrical utility operator when assessing a collocation for the threat of AC interference. Historically, lack of collaboration between pipeline and power line operators has led to projects being assessed without accurate understanding of the power line data. This can lead to either an overly conservative and costly design or an under-designed system not adequately reducing the interference. Collaboration between the respective pipeline and power line operators is critical to accurate assessment and efficient mitigation of any possible interference effects.

In addition to the assessment described in previous sections, the following general recommendations apply for collocations and crossings where AC interference is a concern:

- Install coupon test stations or ER probes to monitor AC Current density, a coupon surface area of 1.0 cm^2 is recommended.
- During pipeline construction near HVAC transmission lines, confirm that the contractor safety program complies with the recommended 15 VAC limit for shock hazards, and applicable OSHA construction standards as referenced in Section 3.2.2.
- Record AC pipe-to-soil potentials along with the DC pipe-to-soil potentials during the annual cathodic protection survey on sections where AC interference threats may exist. This can provide information, should the power transmission company change its operating parameters, or unexpected changes occur between the pipeline and transmission line.
- Request power line loads corresponding to the time of AC pipe-to-soil potential measurement to provide thorough understanding of the interference measurements
- Measure soil resistivity at locations where AC interference threats may exist. This data can be used with the measured AC potentials to estimate theoretical AC current density for specific locations in the absence of coupons or ER probes.
- Operating personnel should be trained in the hazards and safe practices associated with working on pipelines subject to HVAC interference
- Suspend work (when possible) along the collocated or crossing section of pipeline during weather conditions that may lead to a transmission line fault.

Safety precautions are required when making electrical measurements:

- Only knowledgeable and qualified personnel trained in electrical safety precautions install, adjust, repair, remove, or test impressed current cathodic protection and AC mitigation equipment.
- Properly insulated test lead clips and terminals should be used to prevent direct contact with the high voltage source.
- Attach test clips one at a time using a single-hand technique for each connection when possible.

- Extended test leads require caution near overhead HVAC power lines, which can induce hazardous voltages onto the test leads, or present a source of data error.

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APPENDIX A LITERATURE REVIEW

Where published, historically identified corrosion defects and pipeline failures associated with AC corrosion degradation were reviewed and are presented to demonstrate the magnitudes and variability in corrosion rates possible with AC accelerated corrosion. The general findings, discussion, technical details, and results are utilized and summarized throughout this document.

This lack of industry consensus on the subject of AC corrosion guidelines has led to varied practices among pipeline operators in regards to mitigating AC interference on pipelines. As part of this study, The INGAA Foundation requested a review of industry practices and procedures related to AC interference. The INGAA Foundation provided DNV GL with the procedures related to AC interference or mitigation for 10 pipeline operators who are members of the Foundation. The primary finding from this review is that there is significant variation in company procedures with respect to AC interference. Based upon this review, all of the procedures provided address a safety concern and define a maximum allowable AC pipe-to-soil potential limit for above grade appurtenances. Faults were included as a concern/risk for pipelines in close proximity to HVAC power lines in almost all of the procedures. However, few addressed coating stress limit above which mitigation is required. For current density criteria, several procedures had clearly defined limits, while others addressed it as a concern for AC corrosion but did not specify a targeted limit of AC current density or define limits for mitigation.

Case Studies

Numerous studies, both laboratory and field based, have been performed that attempt to determine magnitudes of corrosion rates associated with AC interference. However, reviewing available technical literature confirms a wide range of experimental rates, and a scarcity of controlled field measured rates.

Where published, historically identified corrosion defects and pipeline failures associated with AC corrosion degradation have been reviewed and are presented to demonstrate the magnitudes and variability in corrosion rates possible with AC accelerated corrosion.

Field investigations reported by Ragault[31] considering a coated cathodically protected pipeline, identified corrosion rates between 12 and 54 mpy (0.3 and 1.4 mm/yr), for AC current densities ranging between 84 and 1,100 A/m^2.

Wakelin, Gummow, et al[32] provided three case studies where field inspections identified defects as AC corrosion-related degradation. Based on inspection intervals and corrosion degradation, corrosion rates were identified ranging from 17 to 54 mpy (0.4 to 1.4 mm/yr) for AC current densities between 75 and 200 A/m^2.

A German field coupon study, published by Prinz, and Shoneich,[7] indicated general AC corrosion rates between 2 to 4 mpy (0.015 to 0.1 mm/yr) for a current density of 100 A/m^2, and 12 mpy (0.3 mm/yr) at 400 A/m^2. However, pitting rates were considerably greater and showed a wider range between 8 and 56 mpy (0.2 to 1.4 mm/yr), with considerably less dependence on AC density.[6]

A doctoral thesis study by Goidanich presents similar findings concluding that AC current density as low as 10 A/m^2 may be considered hazardous as the experimental studies showed it nearly doubled the free corrosion rate of the experimental samples in simulated soil tests.[33]

A 1998 report by Wakelin, Gummow, et al published by NACE reviewed several case studies dating back to the 1960's where AC corrosion was identified or suspected to be the primary mechanism of degradation. The report summarized recorded details on multiple case studies with specific focus on comparison of corrosion rates and AC current density where known. In 1991, a failure investigated on a 12-inch diameter pipeline concluded AC accelerated corrosion after only four (4) years of service. Induced AC potentials measured as high as 28 volts. Based on the nominal wall thickness and time to leak, an average pitting rate for the through wall pit was estimated to be greater than 55 mpy. Two other case studies indicated the average AC induced corrosion rates for the identified sites between 11 and 24 mpy.

A 2004 paper by Hanson and Smart, published by NACE, presents a case study for a gas pipeline installed in the summer of 2000.[8] The pipeline was collocated in a shared ROW with a 230 kV transmission line for approximately 9 miles, and then entered a shared power corridor with six power transmission lines, two of which were rated at 500 kV, all within sufficient proximity of the pipeline to cause interference. A leak occurred within 5 months of installation, before the line was in operation. Several other leaks were identified shortly after, with four leaks within close proximity. Induced AC potential measurements found AC voltages as high as 90 volts on the pipeline. The failure assessment indicated the corrosion was due to induced AC corrosion, and estimated rates in excess of 400 mpy.

The majority of literature reviewed indicates AC corrosion rates in the range of 5 to 60 mpy.[3, 9, 10] However, cases have been identified with localized corrosion rates significantly greater, in excess of 400 mpy. There is general agreement that higher AC current density leads to greater risk of AC corrosion. While higher current density may lead to accelerated corrosion rates, the correlation is not simple or direct.

International Standards

Review and comparison of multiple international standards identified the consistencies and variations across accepted industry standards.

Recent laboratory and field work has focused on the interaction between AC and DC current density in determining overall risk of AC corrosion, and the latest European standards reflect this as discussed in Section 3.3.1.1.[15] However, there is no generally accepted method of correlating current density or any other measurable indicator to an expected corrosion rate. A direct method of approximating the AC corrosion rate using a buried coupon or probe would provide accurate information.

The Canadian Standards Association (CSA), NACE International (NACE), and the European Committee for Standardization (CEN) have developed published standards addressing HVAC interference issues, as below:

- CAN/CSA-C22.3 No. 6-13 "Principles and Practices of Electrical Coordination Between Pipelines and Electric Supply Lines
- NACE SP0177-2014 "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems
- CEN EN 50443:2012 "Effects of Electromagnetic Interference on Pipelines Caused by High Voltage AC Electric Traction Systems and/or High Voltage AC Power Supply Systems"
- CEN EN 15280:2013 "Evaluation of AC Corrosion likelihood of buried pipelines applicable to cathodically protected pipelines"

Of these standards, the first three primarily discuss safety issues, interference effects, and mitigation systems but do not explicitly address criteria for AC corrosion control. The European Standard EN15280:2013 deals specifically with corrosion due to AC interference, and establishing criteria or tolerable limits for interference effects, as presented in Section 3.3.1.1.

NACE Standard Practice SP0177-2014, *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems*, addresses problems caused primarily by the proximity of metallic structures to AC power transmission systems. In this standard practice document, SP0177-2014 defines a steady state touch voltage of 15 volts or more with respect to local earth at above-grade or exposed sections and appurtenances to constitute a shock hazard. Findings presented in the standard indicate the average hand-to-hand or hand-to-foot resistance for adult male ranges from 600 ohms to 10,000 ohms. NACE uses "a reasonable safe value" of 1,500 ohms (hand-to-hand or hand-to-foot) for estimating body currents. Based upon work by C.F. Dalziel regarding muscular contraction, SP0177-2014 indicates the inability to release contact occurs between 6 mA and 20 mA for adult males.[10] Ten milliamps (hand-to-hand or hand-to-foot) is recognized as the maximum safe let-go current. This 15-volt safety threshold is therefore determined based upon 1,500 ohms hand-to-hand or hand-to-foot resistance and an absolute maximum let-go current of 10 mA. However, under certain circumstances, an even lower value is required. One such circumstance specifically identified where a lower touch potential safety threshold should be considered is "areas (such as urban residential zones or school zones) in which a high probability exists that children (who are more sensitive to shock hazard than are adults) can come in contact with a structure under the influence of induced AC voltage."[10] This standard practice document requires remedial measures to reduce the touch potential on the pipeline where shock hazards exist.

During construction of metallic structures in regions of AC interference, SP0177-2014 requires minimum protective requirements of the following:

- "On long metallic structures paralleling AC power systems, temporary electrical grounds shall be used at intervals not greater than 300 m (1,000 feet), with the first ground installed at the beginning of the section. Under certain conditions, a ground may be required on individual structure joints or sections before handling."
- "All temporary grounding connections shall be left in place until immediately prior to backfilling. Sufficient temporary grounds shall be maintained on each portion of the structure until adequate permanent grounding connections have been made."

The intent of the temporary grounds is to reduce AC potentials on the structure, and thus the shock hazard to personnel during construction. SP0177-2014 advises against direct connections to the electrical utility's grounding system during construction as this could actually increase the probability of a shock hazard to personnel.

Regarding AC corrosion, there are no established criteria for AC corrosion control provided in SP0177-2014. Further, this standard states that the subject of AC corrosion is "not quite fully understood, nor is there an industry consensus on this subject. There are reported incidents of AC corrosion on buried pipelines under specific conditions, and there are also many case histories of pipelines operating under the influence of induced AC for many years without any reports of AC corrosion."

While not a Standard Practice document, NACE published "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements"[1] in 2010, providing guidance for evaluating AC current density, and providing recommended limits as discussed in Section 3.3.1.1.

The State-of-the-Art report also cites European Standard CEN/TS 15280:2006[15], which previously offered the following guidelines related to the likelihood of AC corrosion:

> *"The pipeline is considered protected from AC corrosion if the root mean square (RMS) AC density is lower than 30 A/m^2 (2.8 A/ft^2).*

In practice, the evaluation of AC corrosion likelihood is done on a broader basis:

- *Current density lower than 30 A/m^2 (2.8 A/ft^2): no or low likelihood;*
- *Current density between 30 and 100 A/m^2 (2.8 and 9.3 A/ft^2): medium likelihood; and*
- *Current density higher than 100 A/m^2 (9.3 A/ft^2): very high likelihood"*

EN 15280:2013

The latest revision of EN 15280:2013 was revised to present criteria based upon the AC interference and DC current due to CP. EN 15280:2013 presents using the cathodic protection system of the pipeline to ensure the levels of induced AC potential do not cause AC corrosion under the following conditions:

1. AC voltage on the pipeline should be decreased to a target value, which should be less than 15 V (measured over a representative time period, i.e. 24 hr)
2. Effective AC corrosion mitigation can be achieved while maintaining cathodic protection criteria as defined in EN 12954:2001
3. One of the following conditions is satisfied in addition to items 1 and 2:
    - Maintain AC current density (RMS) over a representative period of time (i.e. 24 hr) less than 30 A/m^2 (2.8 A/ft^2) on a 1cm^2 coupon or probe
    - If AC current density is greater than 30 A/m^2 (2.8 A/ft^2), maintain the average cathodic (DC) current density over a representative period of time (i.e. 24 hr) less than 1 A/m^2 on a 1cm^2 coupon or probe
    - Maintain a ratio between AC current density and DC current density (J_{AC}/J_{DC}) less than 5 over a representative period of time (i.e. 24 hr)

The NACE State-of-the-Art report also references experimental studies by Yunovich and Thompson that concluded

> *"AC density discharge on the order of 20 A/m^2 (1.9 A/ft^2) can produce significantly enhanced corrosion (higher rates of penetration and general attack without applied CP). Further, the authors stated that there likely was not a theoretical 'safe' AC density (i.e., a threshold below which AC does not enhance corrosion); however, a practical one for which the increase in corrosion because AC is not appreciably greater than the free-corrosion rate for a particular soil condition may exist."*[1]

APPENDIX B COATING RESISTANCE ESTIMATES

Pipe Coating Conductance/Resistance

Pipe Line Corrosion and Cathodic Protection, Marshall E. Parker & Edward G. Peattie

No.	Coating Quality	Soil Resistivity	Conductance Range		Resistance Range					
			µmhos/ft2		ohm-m^2		ohm-ft^2		Kohm-ft^2	
1	Excellent	High	1	10	92,903	9,290	1,000,000	100,000	1,000	100
2	Good	High	10	50	9,290	1,858	100,000	20,000	100	20
3	Excellent	Low	50	100	1,858	929	20,000	10,000	20	10
4	Good	Low	100	250	929	372	10,000	4,000	10	4
5	Average	Low	250	500	372	186	4,000	2,000	4	2
6	Poor	Low	500	1,000	186	93	2,000	1,000	2	1

PRCI

No.	Coating Quality	Soil Resistivity (ohm-m)	Coating Resistance (Kohm-ft2)		
1	Excellent	25	Multiply Soil Resistivity (ohm-m) by 5	5	125
	Excellent	50	Multiply Soil Resistivity (ohm-m) by 5	5	250
	Excellent	200	Multiply Soil Resistivity (ohm-m) by 5	5	1,000
	Excellent	600	Multiply Soil Resistivity (ohm-m) by 5	5	3,000
2	Good	25	Multiply Soil Resistivity (ohm-m) by 2	2	50
	Good	50	Multiply Soil Resistivity (ohm-m) by 2	2	100
	Good	200	Multiply Soil Resistivity (ohm-m) by 2	2	400
	Good	600	Multiply Soil Resistivity (ohm-m) by 2	2	1,200
3	Fair	25	Multiply Soil Resistivity (ohm-m) by 0.5	0.5	13
	Fair	50	Multiply Soil Resistivity (ohm-m) by 0.5	0.5	25
	Fair	200	Multiply Soil Resistivity (ohm-m) by 0.5	0.5	100
	Fair	600	Multiply Soil Resistivity (ohm-m) by 0.5	0.5	300

APPENDIX C MITIGATION COMPARISON SUMMARY

Zinc Ribbon

Advantages
- Can typically be installed during pipeline construction minimizing installation costs
- Cost of raw material is typically one third the cost of copper
- Can be trenched or plowed in relatively inexpensively after pipeline installation
- Typically results in very low resistances
- Historically has performed as intended
- Surface mitigation ribbon can double as shielding for fault mitigation

Disadvantages
- Zinc clad ribbon is more difficult to work with compared to copper
- Life expectancy is generally less than comparable copper installation

Copper Cable

Advantages
- Can typically be installed during pipeline construction minimizing installation costs
- Can be trenched or plowed in relatively inexpensively after pipeline installation
- Typically results in very low resistances
- Historically has performed as intended
- Surface mitigation cable can double as shielding for fault mitigation
- Depending on the size cable the material cost of a copper installation can be lower than a zinc installation

Disadvantages
- Cost of raw material is typically higher than the cost of zinc
- Risk of having a more noble metal (cathodic) near or connected to pipeline even if through a decoupler

Deep Grounding (anodes used as the ground)

Advantages
- May be advantageous when surface resistivity is extremely high

Disadvantages
- Typically high cost for both installation and materials
- Generally not suitable for mitigating ground potential rises (GPR) or arcing issues associated with faults

Shallow Grounding (driven ground rods or bored ribbon or cable)

Advantages
- Can be used to supplement horizontal ribbon or cable installation if required
- Magnitude of the surface resistivity affects the resistance

Disadvantages
- Generally not suitable for mitigating ground potential rises (GPR) or arcing issues associated with faults

Engineered mitigation and / or Additives (no specific product identified)

Advantages
- Could increase design life

Disadvantages
- Typically increases the material costs

Notes:
1) These are typical statements and there are instances where they do not apply.
2) All mitigation installations are considered connected through a decoupling device such that there is no direct passage of DC current to or from the mitigation.

APPENDIX D DATA REQUEST TEMPLATE

Company: ____
Project: ____
Project Number: _____________________________________

High Voltage Alternating Current (HVAC) Power Transmission Parameters

No.	Information Requested	T-Line 1	T-Line 2	T-Line 3
	General			
1	Owner:			
2	Power transmission voltage (kV):			
3	Average Tower Span (feet)			
4	Substation ground grid impedance (ohms):			
	Phase Wires			
5	No. of circuits:			
6	Circuit type:			
	Conductors:			
7	No. 1 average height (ft):			
8	No. 1 average horizontal distance (ft):			
9	No. 1 phasing (degrees):			
10	No. 2 average height (ft):			
11	No. 2 average horizontal distance. (ft):			
12	No. 2 phasing (degrees):			
13	No. 3 average height (ft):			
14	No. 3 average horizontal distance (ft):			
15	No. 3 phasing (degrees):			
16	Other: Cable Sag, Lowest point (feet):			
	Circuit Loading			
17	Peak loading (amps):			
18	Emergency loading (amps):			
19	Emergency loading time (hours):			
	Shield Wires			
20	No. of conductors:			
21	No. 1 type:			
22	No. 1 conductor GMR (ft):			
23	No. 1 conductor resistance (ohms/mil):			
24	No. 1 average height (ft):			
25	No. 1 average horizontal distance (ft):			
26	No.2 type:			
27	No. 2 conductor GMR (ft):			
28	No. 2 conductor resistance (ohms/mil):			
29	No. 2 average height (ft):			
30	No. 2 average horizontal distance (ft):			
	Fault Current Parameters			
31	Fault clearing time (cycles):			
32	Average tower resistance (ohms):			
33	Beginning of Collocation: Total______from left substation ___________ from right substation			
34	Middle of Collocation: Total______from left substation ___________ from right substation			
35	End of Collocation: Total______from left substation ___________ from right substation			

Company: ____
Project: ____
Project Number: ______________________________________

Pipeline Parameters

No.	Information Requested	Pipeline 1	Pipeline 2	Pipeline 3
	General			
1	Pipeline number:			
2	Pipeline owner:			
3	Pipeline name:			
4	Product transported:			
5	Diameter (in.):			
6	Burial depth (ft.):			
7	Wall Thickness (inch):			
8	Length of Collocation (feet/miles):			
_	**Coatings**			
9	Coating type (majority):			
10	Coating resistance (kohm-ft2):			
11	Coating thickness (mils):			
_	**Cathodic Protection**			
12	Location of cathodic protection:			
13	Resistance of cathodic protection groundbed(s):			
14	Bonding to foreign pipelines? (Y/N):			
15	Existing AC mitigation measures? (Y/N):			
16	Describe existing AC mitigation:			