Final Report

AC INTERFERENCE ANALYSIS – 230 KV TRANSMISSION LINE COLLOCATED WITH OLYMPIC PIPELINES OPL16 & OPL20

Puget Sound Energy
Bellevue, Washington

Report No.: OAPUS312DKEMP (PP116591)-1, Rev. 0
Date: December 13, 2016

Project name:	AC Interference Analysis for Puget Sound Energy	Det Norske Veritas (U.S.A.), Inc.
Report title:	AC Interference Analysis – 230 kV Transmission Line Collocated with Olympic Pipelines OPL16 & OPL20	DNV GL North America Oil & Gas
Customer:	Puget Sound Energy AC Interference Analysis – 230 kV Transmission Line Collocated with Olympic Pipelines OPL16 & OPL20 355 110th Avenue NE Bellevue, Washington 98004	Pipeline Services 5777 Frantz Road 43017-1386 Dublin, OH United States Tel: +1 614 761 1214
Contact person:	Mr. Andrew Lightfoot, P.E.	
Date of issue:	December 13, 2016	
Project No.:	PP16591	
Organisation unit:	Corrosion Management	
Report No.:	OAPUS312DKEMP (PP116591)-1, Rev. 0	
Document No.:	1YZZ7NU-5	

Task and objective:

Det Norske Veritas (U.S.A), Inc. (DNV GL) was retained by Puget Sound Energy (PSE) to perform an induced AC mitigation study to investigate the possibility for AC interference effects and recommend mitigation methods as required. The HVAC induction study considered two high pressure petroleum pipelines, owned by Olympic Pipe Line Company and operated by British Petroleum, collocated with a new 17 mile long 230 kV transmission line.

Prepared by:	Verified by:	Approved by:
David Kemp, P.E. *Engineer* *Computational Modeling*	Barry Krebs *Principal Engineer* *Materials Advisory Services*	Shane Finneran, P.E. *Group Lead* *Computational Modeling*

☐ Unrestricted distribution (internal and external)
☐ Unrestricted distribution within DNV GL
☒ Limited distribution within DNV GL after 3 years
☐ No distribution (confidential)
☐ Secret

Keywords:
[Keywords]

Reference to part of this report which may lead to misinterpretation is not permissible.

Rev. No.	Date	Reason for Issue	Prepared by	Verified by	Approved by
Draft	2016-12-06	Draft for review	DK		
0	2016-12-13	Final issue	DK	BK	SF

EXECUTIVE SUMMARY

Det Norske Veritas (U.S.A.), Inc. (DNV GL) was retained by Puget Sound Energy (PSE) to perform an induced AC interference study to investigate the possibility for AC interference effects (i.e. corrosion and safety) on two nearby high pressure petroleum pipelines, owned by Olympic Pipe Line Company (Olympic) and operated by British Petroleum (BP), and recommend design considerations to minimize AC interference effects. These pipelines are currently collocated within an existing Eastside 115 kV transmission line corridor, which subsequently would be upgraded to 230 kV as part of the Energize Eastside project.

Two routes proposed in the Energize Eastside project were specifically examined: the existing transmission line corridor (commonly referred to as Willow 1), and a route that combines parts of the existing corridor with the Newport Way area (commonly referred to as Willow 2). Additionally, both operational scenarios of 230 kV/115 kV and a future 230 kV/230 kV scenario were evaluated. This report presents the results, conclusions, and recommendations of the analysis. The Oak 1 and Oak 2 routes were considered, though not explicitly modeled in this study. The Oak 1 and Oak 2 routes are similar to the Willow 2 routes, with an extended collocation length with OPL20. Thus it is expected that the AC interference levels resulting from the Oak 1 and Oak 2 routes would be higher than the Willow 2 route, which was analyzed as part of this study.

Several industry guidance documents[6,7] have presented general guidance parameters for locating transmission lines and pipelines in shared corridors, which are conservative limits used to determine when an engineering assessment, such as this one, may be required. Based upon the level of detail included in this analysis, the results are intended to serve as a detailed assessment, considering the many specific variables of this particular collocated pipeline/transmission line segment. Thus, these results, conclusions, and recommendations presented herein, may be used to satisfy a detailed engineering study, which may be used for this collocation to aid in the design and layout of the transmission line, relative to the pipeline segments.

The transmission line consists of two circuits with the proposed Richards Creek substation located approximately in the center of the collocation. The construction plan for the Energize Eastside project is to upgrade both circuits of the existing 115 kV transmission line to 230 kV standards, initially operating one circuit at 115 kV while operating the other at 230 kV. The 115 kV circuit would then be operated at 230 kV at some point in the future.

To assess the AC interference levels, field surveys were performed by DNV GL along the collocated pipeline segments to collect soil resistivity measurements to be used in the AC analysis. Additionally, PSE provided the planned operating loads for winter and summer conditions (2028) with the 230 kV/115 kV and 230 kV/230 kV configurations. The winter peak loading scenarios were evaluated for this study, as they resulted in the worst-case levels of AC interference on the collocated pipeline segments (i.e., winter peaks exceed summer peaks as the system can carry more load due to ambient cooling conditions).

Utilizing the Elsyca IRIS software program, the AC interference studies examined the following objectives for each scenario:

- Determine if steady state conditions pose a threat to personnel safety. The common industry standard is if AC potential on the pipeline exceeds 15 volts, as specified in NACE SP0177[2].
- Under fault conditions, determine if personnel safety and/or the pipeline integrity could be compromised (coating damage could occur if fault voltage exceeds the approximate coating breakdown voltage of 10,825 volts).
- Under fault conditions, determine if arcing between the pole structure grounds and the pipeline is possible; if necessary, recommend mitigation methods.
- Determine if steady state conditions are conducive to AC corrosion, thus potentially compromising the pipeline integrity and necessitating mitigation using the following threshold ranges from NACE Report 35110, "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements"[5]:
    - Low likelihood: likelihood of accelerated AC corrosion is low at current densities between 0 – 20 amps/m^2
    - Unpredictable: accelerated AC corrosion may or may not occur as it cannot be accurately predicted when the current density is between 20 and 100 amps/m^2; therefore, after the transmission lines are energized field monitoring and/or mitigation by the pipeline operator may be required.
    - High likelihood: likelihood of accelerated AC corrosion is high when the current density is greater than 100 amps/m^2

A number of sensitivity studies were performed with varying transmission line pole structures and routes in an effort to minimize the levels of AC interference on the collocated pipeline segments. These sensitivity studies were used to layout varying pole structures along the collocation for the Willow 1 and Willow 2 transmission line routes. These configurations were also assessed in this study to determine the expected levels of AC interference on the collocated pipeline segments. In addition to the AC analysis related to the upgrading of the transmission line circuits to 230 kV, the existing 115 kV transmission line route and transmission line structures were also analyzed in the same IRIS model to compare model predictions to field measured AC potentials, provided by Olympic. This was done in an effort to provide a level of validation and comparison to field measurements along the pipeline corridor for the existing configuration.

Findings

During the course of the study, three principle factors were identified to have a significant effect on the level of AC interference on the collocated pipeline segments:

- Current load unbalance between the two circuits as a result of operating at 115 kV/ 230 kV.
- Points of divergence between the transmission line and pipeline along the corridor (i.e. where the respective utilities enter and exit the shared corridor).

- Conductor geometry, where a true delta configuration provided the greatest level of field cancellation.

Based upon the results of the sensitivity studies, optimized pole configurations were designed for both the Willow 1 and Willow 2 routes for further assessment.

Considering the optimized conductor geometry, with both lines operating at 230 kV in the existing corridor (Willow 1), the induced AC potentials and theoretical AC current densities satisfied accepted industry levels:

- The maximum induced AC potentials from the optimized conductor geometry analysis were less than 15 volts, per NACE SP0177[2]
- The maximum theoretical AC current densities from the optimized conductor geometry analysis were less than 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is low[5]

For all of the other scenarios that were analyzed, the model predicted maximum theoretical AC current densities between 20 amps/m^2 and 100 amps/m^2, indicating that accelerated AC corrosion may or may not occur and is therefore unpredictable. After the transmission lines are energized, field monitoring and/or mitigation by the pipeline operator may be needed to confirm that current densities are at acceptable levels. For these same scenarios, the model also predicted induced AC potentials greater than the 15 volt industry standard, indicating field monitoring and/or mitigation by the pipeline operator may be needed to confirm AC potentials on the pipeline are at acceptable levels, after the transmission lines are energized. Table E1 below summarizes the conclusions from the various transmission line route and load configurations considered for this study and the resulting predicted levels of AC interference on the two collocated pipelines, OPL16 and OPL20.

Table E1. Conclusion Summary: Optimized Willow 1 and 2 Results

Route (Optimized Configuration)	**Load Scenario**	**Maximum Induced AC Potential (V)**		**Maximum Theoretical AC Current Density (Amps/m^2)**	
		OPL16	**OPL20**	**OPL16**	**OPL20**
Willow 1	230/230 Winter Peak	D	D	L	L
Willow 1	230/115 Winter Peak	E	D	U	L
Willow 2	230/230 Winter Peak	D	E	U	U
Willow 2	230/115 Winter Peak	E	E	U	U

Induced AC Potential: D – Does not exceed 15V NACE safety limit, E – Exceed 15V NACE safety limits.
Current Density: L – Low risk range, U – Unpredictable risk range.
Yellow: Requires additional post-construction monitoring and/or mitigation by the pipeline operator to verify that safety standards and/or thresholds are met.

DSD 003972

A fault analysis was also performed to determine the pipelines' susceptibility to damage, resulting from a fault incident. Several sensitivity studies were performed with varying pole configurations and shield wire types to aid in the design of the transmission line layout. Considering the expected fault current of 25 kA and either an Alumoweld or OPGW shield wire on the transmission lines, the predicted coating stress voltage was well below the expected coating breakdown voltage for the coal tar coated pipeline segments. Additionally, the maximum arcing distance was calculated for the collocated pipeline segments, based upon the maximum single-phase-to-ground fault current returning to ground at a single pole. The maximum arcing distance was found to be 13 feet, considering an OPGW shield wire on the transmission lines.

Due to variation in soil resistivity and lack of precision related to the pipeline location coordinates, relative to the transmission line poles, it is recommended to field verify the distance between the pipeline and transmission line pole grounds where the pole to pipeline spacing is 13 feet or less. In cases where the poles are located within 13 feet, site-specific soil resistivity tests should be conducted to determine whether mitigation by arc shielding protection is needed.

Recommendations

The following general recommendations are suggested:

- Based upon the AC interference modelling and considering certain conductor geometries, operational voltages, and routing, the AC interference effects on the collocated pipeline segments can be reduced to a level that satisfies acceptable industry thresholds for safety and accelerated AC corrosion.
- After the transmission lines are energized, field monitoring and/or mitigation may be needed (to be performed by the pipeline operator) for those loading scenarios where the AC potential is greater than 15 volts and the AC current density is greater than 20 A/m^2.
- Pipeline technicians should understand the hazards and safe practices associated with cathodic protection and AC mitigation when working with these sections of pipeline.
- It is recommended that AC pipe-to-soil potentials be recorded along with the DC pipe-to-soil potentials during the annual cathodic protection survey. This can provide information, should unexpected changes occur between the pipeline and transmission line.
- PSE should notify the pipeline operator when there are planned outages on the individual circuits, as the AC induction effects on the pipeline may be magnified when only one circuit (of the double circuit transmission lines) is energized.
- Final mitigation design, if necessary, should be based on field data collected after the system is energized. Mitigation may include installation of additional grounding such as: grounding mats, horizontal surface ribbon, and/or deep anode wells based upon a detailed mitigation study.

Table of Contents

List of Tables

List of Figures

List of Appendices

DSD 003976

1 INTRODUCTION

Det Norske Veritas (U.S.A.), Inc. (DNV GL) was retained by Puget Sound Energy (PSE) to perform an induced AC interference study to investigate the possibility for AC interference effects (i.e. corrosion and safety) on two nearby high pressure petroleum pipelines, owned by Olympic Pipe Line Company (Olympic) and operated by British Petroleum (BP), and recommend design considerations to minimize AC interference effects. These pipelines are currently collocated within a 115 kV transmission line corridor which will subsequently be upgraded to 230 kV as part of the Energize Eastside project. The high voltage alternating current (HVAC) induction study considered the existing 115 kV transmission line route and transmission line configuration as well as routes being considered for the Energize Eastside project. The existing transmission line corridor consists of two 115 kV circuits as shown below in Figure 1. The planned upgrade will accommodate both circuits operating at 230 kV in the future and may include varying pole configurations and slight variations in the transmission line route. The planned operation for the Energize Eastside project is to first operate one circuit at 115 kV while operating the other at 230 kV, then eventually operating both circuits at 230 kV. This can have an impact on the overall induction on the adjacent pipelines, while the total magnitude of current for the 115/230 kV transmission line is less than both circuits operating at 230 kV, the current unbalance between circuit can result in overall higher levels of induction on nearby pipelines.

For this study, the level of induction on the collocated pipeline segments was analyzed based upon a number of varying types of transmission line configurations and routes in an effort to identify the configuration that minimized the levels of AC interference on the pipeline segments. In total, two routes were examined, Willow 1 and Willow 2. The Willow 1 route is very similar to the existing transmission line route shown below in Figure 1, while the Willow 2 route is shown below in Figure 2. The Oak 1 and Oak 2 routes were considered, though not explicitly modeled in this study. The Oak 1 and Oak 2 routes are similar to the Willow 2 routes, with an extended collocation length with OPL20. Thus it is expected that the AC interference levels resulting from the Oak 1 and Oak 2 routes would be higher than the Willow 2 route, which was analyzed as part of this study.

DSD 003977

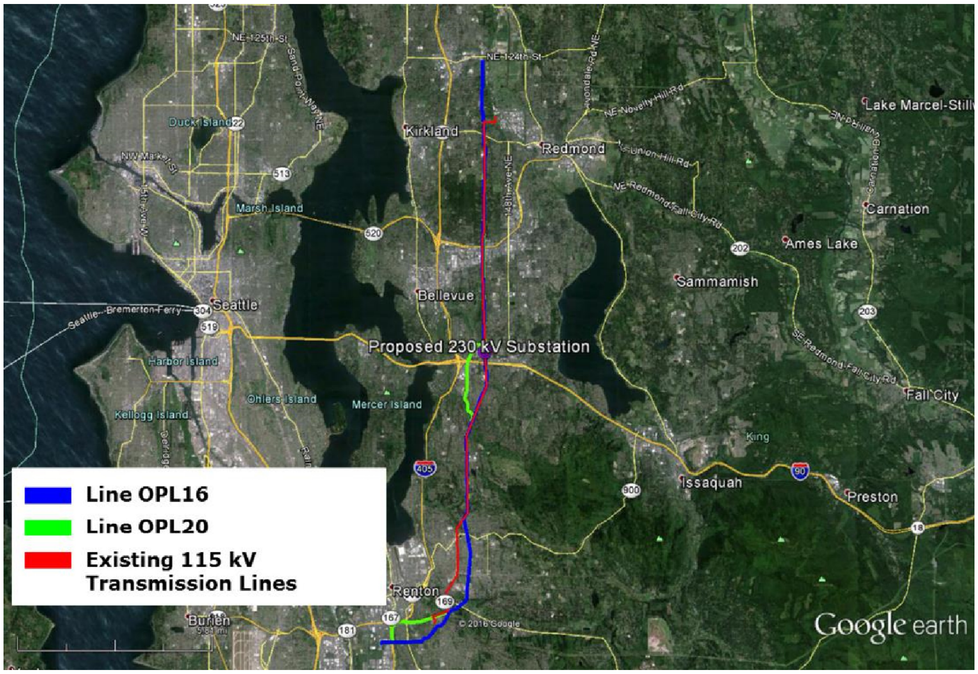

Figure 1. General Layout of Pipelines and Existing 115 kV Transmission Line

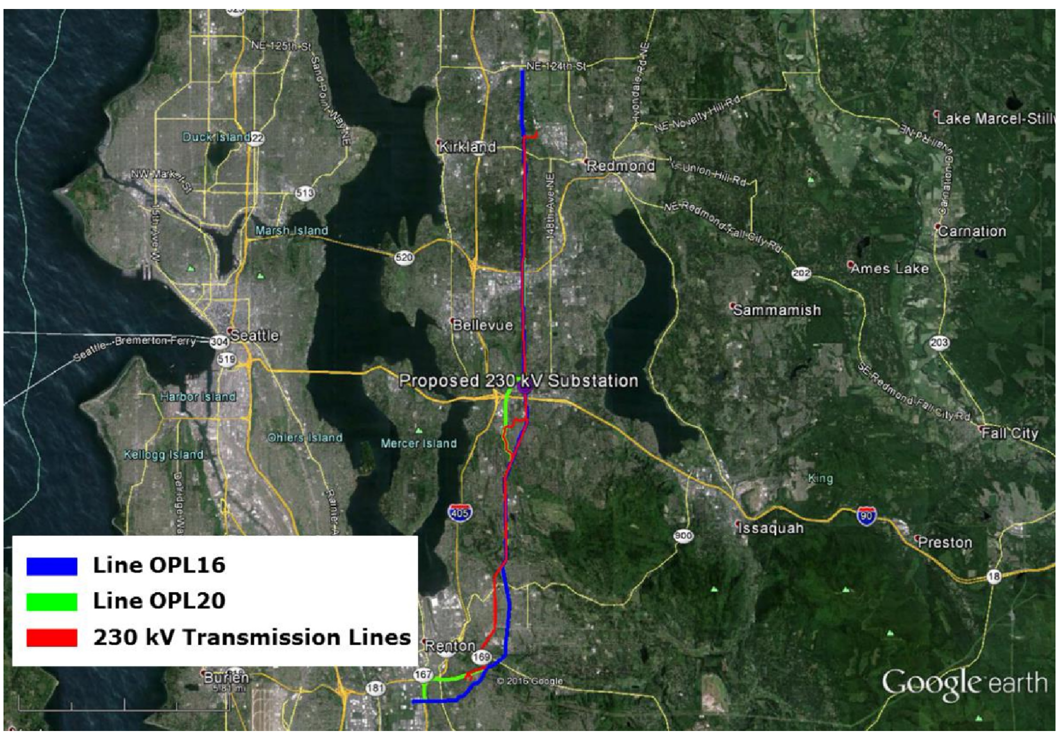

Figure 2. General Layout of Pipelines and 230 kV Transmission Line – Willow 2

In order to confirm the AC interference model predictions, AC potential data was collected at targeted locations along the corridor for both pipelines and the existing pole configurations were included in the model. The existing transmission line configuration was analyzed at known operating loads and then

DSD 003978

compared to field data collected and provided by Olympic for comparison. The results and conclusions of the AC interference sensitivity studies are presented and described in further detail in this report.

2 SCOPE OF WORK

The scope of this project was to examine the Olympic pipeline segments' susceptibility to HVAC interference and to numerically model the magnitude and location(s) of possible AC current discharge.

The scope of work was divided into a data collection phase and an AC analysis phase, completed by DNV GL as summarized in the following tasks:

2.1 Data Collection

- Task 1: Information collection and familiarization with pipeline routing.
    - Pipeline route, diameter, coating type, vintage, power line route, configurations, loads, etc.
- Task 2: Testing and measurements along the pipeline right-of-way.
    - Soil resistivity measurements and AC potential measurements.

2.2 AC Analysis

- Task 1: Development of a model of the pipeline locations for simulation purposes.
- Task 2: Assess the existing 115 kV transmission line configuration and compare model results to field data to confirm model predictions.
- Task 3: Perform detailed numerical simulations to determine the levels of AC interference which may be present on the collocated pipeline segments based upon varying pole design configurations and routes.
- Task 4: Assess two finalized route designs with varying structures, based upon lessons learned from the AC interference sensitivity studies.
- Task 5: Preparation and delivery of a final report describing the work performed.

3 HVAC TRANSMISSION LINE EFFECTS ON ADJACENT PIPELINES

Pipelines sharing, paralleling, or crossing HVAC transmission line (typically defined as 69 kV or higher) rights-of-way (ROW) may be subjected to electrical interference from capacitive interference, electromagnetic induction, and conductive effects. Electromagnetic induction is the primary effect of the HVAC transmission line on the buried pipeline during normal (steady state) operation. This form of interference is due to the magnetic field produced by AC current flowing in the conductors of the transmission line coupling with the pipeline and inducing a voltage on the pipeline as indicated in Figure 3 below.

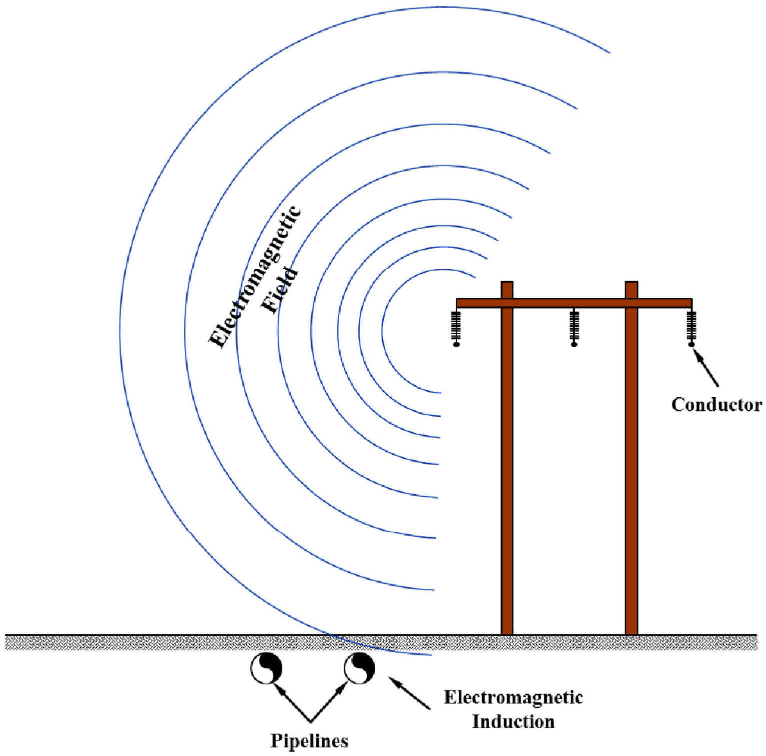

Figure 3. Steady State HVAC Interference – Electromagnetic Induction Effect

Conductive interference results from currents traveling through the soils and onto the pipeline. Conductive effects are primarily a concern when a fault occurs in an area where the pipeline is in close proximity to the transmission line and the magnitudes of the fault currents in the soil are high. The electromagnetic effects are also significant during a fault condition because the phase current of at least one conductor is very high, as indicated in Figure 4 below.

DSD 003980

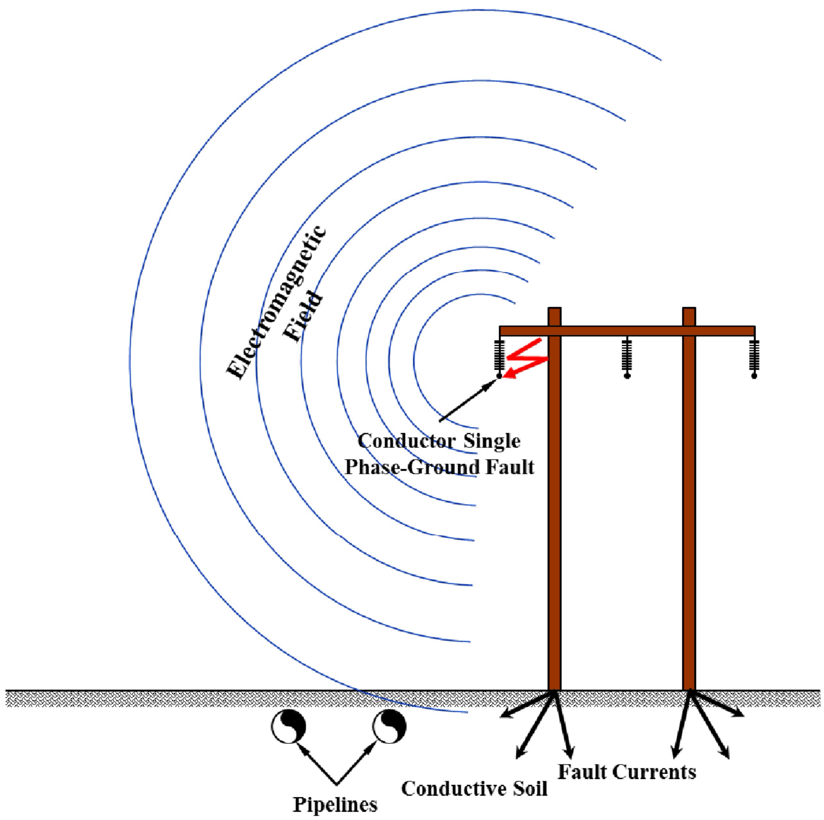

Figure 4. HVAC Fault Condition – Inductive and Conductive Interference

Electrostatic coupling or capacitive interference occurs due to the electromagnetic field produced by AC current flowing in the conductors on the transmission line induces charge on the pipeline while it is electrically isolated from the ground. The pipeline can build up charge as a capacitor with the surrounding air acting as the dielectric, which may result in a safety hazard for any personnel in contact with the pipe. Capacitive effects are primarily a concern during pipeline maintenance and construction when sections of the pipeline are isolated above ground, as indicated in Figure 5.

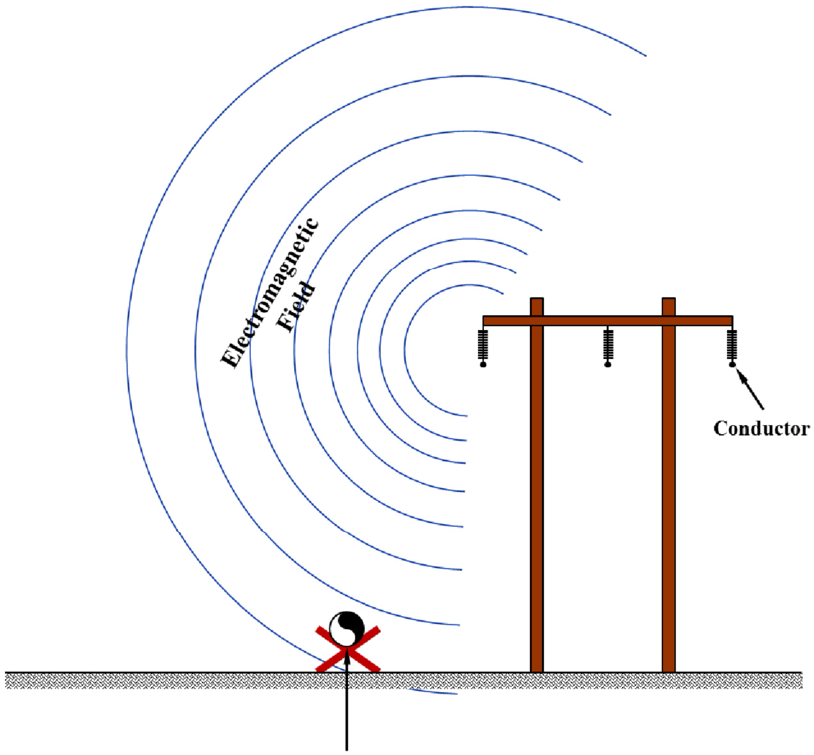

Figure 5. Capacitive Interference Effect

If these electrical effects are high enough during steady state normal operation, a possible shock hazard exists for anyone that touches an exposed part of the pipeline such as a valve, CP test station, or other aboveground appurtenance of the pipeline. During steady state normal transmission 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.

In terms of personnel safety, the concern is the voltage a person is exposed to when touching or standing near the pipeline. The "touch potential" is the voltage between an exposed feature of the pipeline such as a CP test station or valve and surrounding soil or a nearby isolated metal object such as a fence that can be touched at the same time. The "step potential" is the voltage across a person's two feet and is 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 when there are high currents and voltage gradients in the soil.

An evaluation of the possible risk to personnel safety for those working on the pipeline and possible pipeline coating damage should take place whenever a pipeline is in close proximity to an HVAC transmission line. A mitigation system can be designed for those areas where potentials are above permissible limits as specified in the Institute of Electrical and Electronics Engineers Standard IEEE-80[1]

DSD 003982

and NACE International Standard Practice SP0177-2014[2] *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems* (collectively "Standards"). These Standards indicate mitigation is necessary in those cases where step or touch potentials are in excess of 15.0 VAC.

A phase-to-ground fault on a power transmission line causes large currents in the soil at the location of the fault and large return currents on the phase conductor and ground return. Although these faults are normally of short duration (less than one second), unless appropriate mitigation measures are implemented, pipeline damage can occur from high potential breakdown of the coating, resistive conductive arcing across the coating near the fault and high-induced currents along the right of way. In the absence of mitigation measures, these high current magnitudes may result in arc damage at locations remote from the fault where a low resistance path to power ground is found. If these currents are high enough, damage to the pipe wall is possible. The high current density can cause molten pits on the pipe surface, resulting in cracks developing when the fault ceases and the pipe cools, or even burn through. The potential occurrence and consequences of such events can be significantly minimized or eliminated through appropriate design and/or mitigation measures.

Excessive conductive currents and induced voltages represent a significant localized safety hazard to personnel working on or testing the pipeline during the fault condition. AC transmission line faults are typically phase-to-ground faults and are usually caused by lightning, phase insulator failure, mechanical failure of the phase conductor, or support pole allowing the phase conductor to touch the ground and transformer failure.

Pipeline corrosion control considerations involving AC transmission lines include coating damage during faults and accelerated corrosion (even in the presence of cathodically protected DC potentials) due to high AC current density at coating holidays. Fault current conditions that produce excess voltages across the coating are of concern for dielectric coatings. The dielectric strength of the coating is dependent upon a number of factors ranging from coating type and thickness to fault duration. Guidance on allowable coating stress voltage varies across references. NACE SP0177-2014[2] indicates thresholds for coating stress voltages varying from 2 kV for tape wrap and coal tar enamel coatings to 3 to 5 kV for FBE and polyethylene coatings, considering a short-duration fault. However, multiple industry references have shown higher tolerable limits, especially for thicker coatings such as coal tar enamel. For reference NACE SP0188-2006[3] recommends the following equation for calculating allowable test voltages for holiday detection:

$$TV = 1{,}250\sqrt{t} \tag{1}$$

Where:

TV = Test Voltage (V)

t= Average coating thickness in mils

This results in a test voltage of 10,825 volts for a pipeline coated with a 75 mil coal tar coating. For thicker coatings, the Test Voltage can be approximated from Equation 1. While NACE SP0188-2006 specifically relates to holiday testing, it is referenced for calculating a voltage that will damage various pipeline coatings as a function of coating thickness.

It should be noted that the steady state 15 VAC threshold (in the standards listed above) was established with personnel safety in mind and not with consideration of corrosion influences. Recent research and experience has shown that AC accelerated corrosion can occur in low resistivity soils at AC voltages well below this threshold. The effects of the power transmission line on an adjacent pipeline are a function of geometry, soil resistivity, coating resistance, and the transmission line operating parameters. The geometry characteristics include separation, depth of cover (DOC), pipe diameter, angle between pipeline and transmission line, pole footing design, and phase conductor spacing and average distance above the ground. These remain constant over the life of the installation. The coating resistance, power system ground resistance and soil resistivity may change slightly with the seasonal variations and as the installation ages but remain reasonably constant. The operating parameters of the transmission line such as phase conductor load, phase balance, voltage, and available fault current and clearing time also have significant influence on the effects of AC accelerated corrosion. The individual conductor current load and balance is dynamic and changes significantly with load requirements and switching surges.

Individual phase conductor currents can vary up to 5% during typical transmission line operation. In addition to the changes in load during the 24 hour period, there is typically 5%+/- ripple in the measured AC pipe-to-soil voltage. This ripple has a period cycle much longer than the 60 hertz base and can be seen with a typical digital multi-meter with a screen update rate of 4 per second.

4 DESCRIPTION OF FACILITIES

4.1 General Pipeline Routing

The analysis considered approximately 105,500 feet (20 miles) of Line OPL20 and 102,900 feet (19.5 miles) of Line OPL16. Both pipelines are collocated for approximately 12 miles with the proposed 230 kV transmission line. A summary of the pipelines involved in this analysis is shown in Table 1. The coating resistance and coating thickness were both provided by Olympic.

Table 1. Pipeline Model Summary

Pipeline Name	Outer Diameter (in.)	Burial Depth (ft.)	Coating Type	Average Coating Resistance (kohm-ft^2)	Approximate Coating Thickness (mils)
OPL16	16	4	Coal Tar	22.5	75
OPL20	20	4	Coal Tar	22.5	75

4.2 HVAC Power Transmission Line

The AC analysis considered approximately 12 miles of the proposed double circuit transmission line operated by PSE (operated at 115/230 kV and eventually 230/230 kV). The proposed transmission line will have a new substation (Richards Creek) located just north of Interstate 90, which is located at the approximate midpoint the overall length of the transmission line considered for the analysis. All pertinent load and transmission line design information was provided by PSE for the analysis. The transmission line design considered for all structures north of the proposed substation was a double circuit vertical pole (C1), constructed on a single pole, based upon drawings provided by PSE.

For the two circuits south of the Richards Creek substation, the transmission line circuits would be mounted on separate structures. Depending on the ROW, varying structure configurations were able to be used along the corridor. Thus, in an effort to minimize the level of AC interference on the collocated pipeline segments, several sensitivity studies were conducted to aid in the design and layout of the transmission line. These sensitivity studies considered the same structure for the entire corridor (north and south of the substation). In total four (4) sensitivity studies were conducted for both the Willow 1 and Willow 2 routes considering all C2 structures, all C3 structures, all C16 structures, and all C13 structures. For each sensitivity study, the Winter Peak loads at 230 kV/115 kV and 230 kV/230 kV ratings were evaluated for the maximum induction and current density on the pipelines. The varying structure types are shown below Figure 6 while the varying load scenarios are shown in Table 2 for the projected worst case loading for the year 2028 with the 115/230 kV configuration while the projected worst case loading for the year 2032 with the 230/230 kV configuration is shown in Table 3.

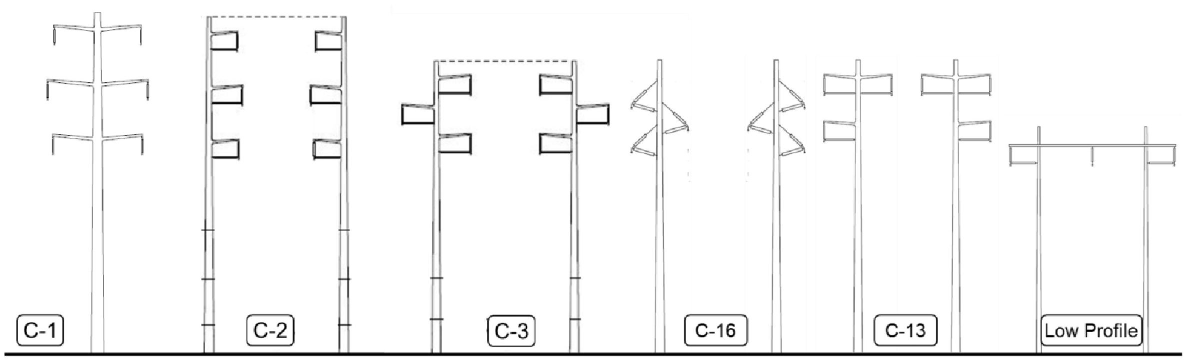

Figure 6. Pole Configurations Considered in the AC Analysis

Table 2. Transmission Line Load Summary - 2028

Circuit Voltage (kV)	Loading Scenario	North of Substation		South of Substation	
		West Circuit (Amps)	East Circuit (Amps)	West Circuit (Amps)	East Circuit (Amps)
115/230	Winter 75%	452	74	503	921
115/230	Winter Peak	646	106	718	1315

Table 3. Transmission Line Load Summary - 2033

Circuit Voltage (kV)	Loading Scenario	North of Substation		South of Substation	
		West Circuit (Amps)	East Circuit (Amps)	West Circuit (Amps)	East Circuit (Amps)
230/230	Winter 75%	449	407	758	676
230/230	Winter Peak	641	581	1083	966

DSD 003985

The loading scenarios presented above represent the worst case loading scenarios for the 115 kV and 230 kV configuration and the eventual 230/230 kV loading scenario. The Winter Peak loading scenarios represent the maximum current loading scenarios the transmission lines are expected to experience, which is expected to be limited to a week or less per year. The Winter 75% loading configurations represent the current loads the transmission lines are expected to operate at for the majority of the time.

5 FIELD TESTING DATA

5.1 Soil Resistivity

Soil resistivity measurements were collected by DNV GL using the Wenner four-electrode method (ASTM G57) at selected locations along the right-of-way. This test measures the bulk electrical resistivity of the soil in half hemispheres at a depth equal to the pin spacing. Pin spacings of 2.5, 5, 7.5, and 10 feet were used. The average bulk resistivity to the pipeline depth is one of the controlling factors in the analysis of HVAC interference. However, the specific resistivity of the soil layer directly next to the pipe surface is the factor of concern in the corrosion activity (conventional galvanic and AC assisted). Table 4 below shows the range of the bulk soil resistivity values taken at 32 locations along the collocation at the average pipe depth. The complete set of soil resistivity measurements is tabulated and provided in Appendix B.

Table 4. Bulk Soil Resistivity Data Summary

Pipeline Name	Minimum Resistivity (ohm-cm)	Maximum Resistivity (ohm-cm)	Average Resistivity (ohm-cm)	Average Pipe Burial Depth (ft.)	Bulk Resistivity Depth (ft.)
OPL16	6,607	402,174	101,251	4	5
OPL20	6,607	402,174	100,564	4	5

6 THEORETICAL AC CURRENT DENSITY

In January of 2010, NACE International prepared and published a report entitled "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements"[5], 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 cathodic protection 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 may or may not occur (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)."

The AC current density is related to the soil resistivity, the induced voltage and the size of a holiday in the coating. Additionally, research has indicated the highest corrosion rates occur at holidays with

DSD 003986

surface areas of one to three square centimeters. Holiday testing during installation of the pipeline should catch all holidays of this magnitude, but in general smaller holidays could be missed; so the smallest, or one square centimeter, is considered in calculation of AC current density.

After the pipeline was modeled, a theoretical AC current density at each node was calculated utilizing the following equation provided in the aforementioned NACE state of the art publication in conjunction with the data contained in Appendix B.

$$i_{ac} = (8xV_{ac}) / (\rho \times \pi \times d)$$

Where:

i_{ac}	=	ac current density (A/m^2)
V_{ac}	=	pipe ac voltage to remote earth (V)
ρ	=	soil resistivity (ohm-m)
π	=	3.1416
d	=	diameter of a circular holiday having a one square centimeter surface area (0.0113 meter)

It should be noted that this analysis is strictly based on the identified parameters and field conditions can vary significantly. The theoretical AC current density is inversely proportional to the specific soil resistivity values at the depth of the pipe, as shown in the equation above. As previously mentioned, theoretical AC current density values less than 20 amps/m^2 indicate the likelihood of AC corrosion is low, while current densities between 20 amps/m^2 and 100 amps/m^2 indicate that AC corrosion may or may not occur and is therefore, unpredictable. Current densities greater than 100 amps/m^2 indicate the likelihood of AC corrosion is high.

7 ELSYCA IRIS MODELING

The Elsyca Inductive and Resistive Interference Simulator (IRIS) software is a graphical simulation platform developed to predict the steady state interference and resistive fault effects of HVAC transmission lines on buried pipelines in shared ROWs. IRIS uses a transmission line model (TLM) to calculate longitudinal electrical field (LEF) based on established fundamental Maxwell equations. This LEF is then utilized to calculate the magnitude of induced AC potential, and current along the collocated pipelines. Resistive coupling during single or three phase-to-ground fault conditions are analyzed using a layered boundary element method (BEM) approach, which calculates the ground potential rise (GPR) and voltage across the coating, as well as touch and step potentials and arcing distance throughout the collocation.

The geometry and routing of the complete pipeline and transmission line network can be incorporated in the model without restriction on number of pipelines, transmission lines, or poles. Data is entered individually for each pipeline and transmission line at discrete nodes with each node's spacing generally defining specific HVAC poles, routing changes, pipeline stations, or other points of interest. Model parameters such as specific pipeline geometry, depth, soil resistivity, pole geometry, pole-to-earth resistance, conductor sag, and phasing can be input for each node individually and varied throughout the model. Additionally, all direct or resistive bonds, insulators, and mitigation grounds are input at the specific nodes. Model refinement is defined by the number of elements connecting each node. Analysis outputs are calculated at the individual elements between the model nodes allowing for data significantly more refined than the node spacing. For these reasons, IRIS is considered appropriate for analyzing large pipeline network models, complex with regard to both collocation geometry and the overall number of interacting transmission lines and pipelines.

7.1 Model Setup

Parameters for the AC interference study are described in section 4.1 and 4.2 and detailed in appendices A and B. The steady state and fault analyses were performed considering the provided pole locations, configurations, phasing, and loading conditions. The GPS coordinates of the pipeline were obtained from As-Built drawings provided by Olympic, while the coordinates for the HVAC transmission line poles were provided by PSE. This data was used to develop the IRIS model geometry to enable accurate predictions of induced AC voltage and current levels. As the pipeline and transmission lines are modeled individually, the geometry layout varies for each pipeline. The total pipeline network was constructed with appropriate node and element distribution to accurately assess the induced potential along the collocation.

However, details of the existing cathodic protection system, such as grounding resistance of anode beds, were not included in the assessment to provide an added level of conservatism. The node and element layout for the pipelines was identical between the model for the existing 115 kV transmission lines and the 230 kV upgraded transmission line model.

7.2 Steady State Induced AC Results

7.2.1 Existing Transmission Line Comparison

In an effort to compare the model results to the levels of AC interference on the collocated pipeline segments at present, the existing transmission line route and configuration was modeled. The existing 115 kV transmission line route is the same corridor that is proposed for the Willow 1 route discussed previously and is comprised of two single circuit horizontal structures, as shown in Figure 7 below. The model results were then compared to field measured AC potentials, collected by Olympic via data loggers along with the date and time at which the measurements were recorded. The locations where AC potentials were measured were requested by DNV GL based upon expected regions of elevated AC potentials. PSE then provided the operating currents of the transmission lines for the times at which the AC potentials were measured in order to provide a direct comparison to the model. In total, 11 sets of AC potential measurements were provided by Olympic: six (6) for OPL16 and five (5) for OPL20 as indicated below in Figure 7.

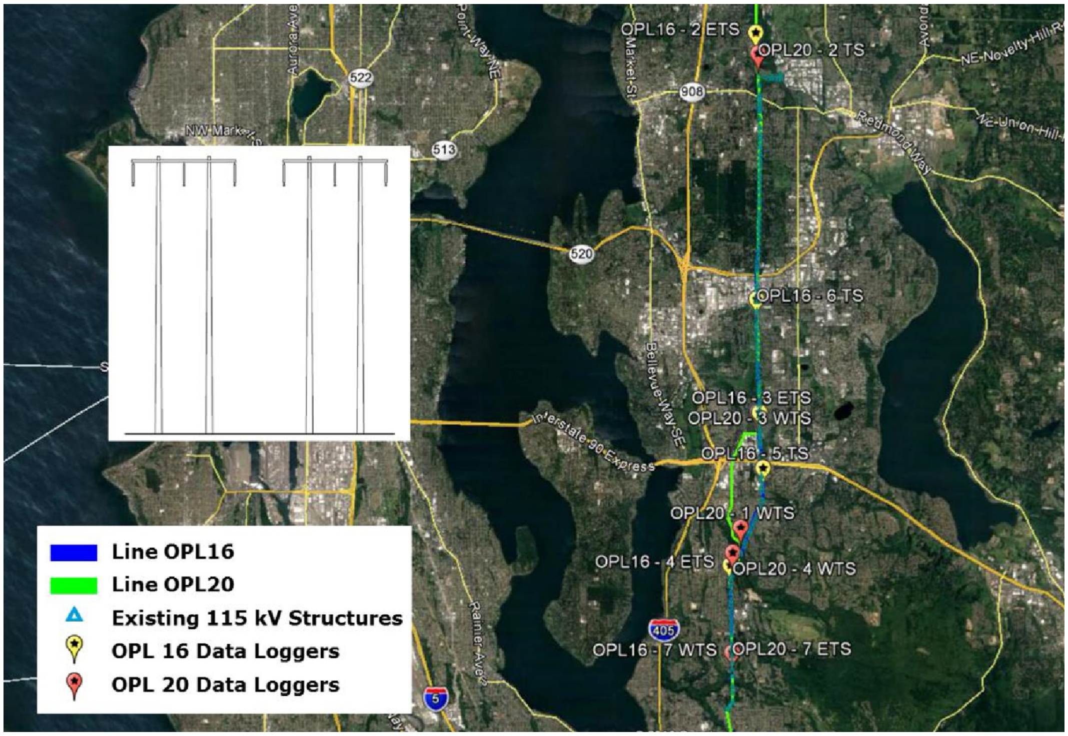

Figure 7. Existing 115 KV Transmission Line Route and Data Logger Locations

A summary of the field measured AC potentials is shown below in Table 5 and Table 6 for OPL16 and OPL20, respectively. The AC potential measurements were recorded between 8/24/2016 and 8/26/2016 at approximately 5 minute intervals. In general, the measured AC potentials were fairly low, with a maximum of 5.6 volts recorded on line OPL20. The average potentials during the time the data was collected were generally between 1 and 3 volts for all locations where data was collected.

Table 5. Summary of AC Potential Measurements – OPL16

OPL16							
Label	Measured AC Potential (V)			Date		Date for Comparison	AC at Date for Comparison (V)
	Min	Max	Average	Start	Stop		
2 ETS	0.79	3.16	1.69	8/25/2016 14:07	8/26/2016 14:23	8/25/2016 14:00	2.42
3 ETS	1.45	1.45	1.45	8/25/2016 12:50	8/26/2016 13:05	8/25/2016 14:00	1.45
4 ETS	1.52	1.85	1.58	8/25/2016 11:23	8/26/2016 11:53	8/25/2016 14:00	1.68
5 TS	1.49	2.85	2.28	8/24/2016 11:43	8/25/2016 11:55	8/24/2016 16:30	2.56
6 TS	1.60	4.08	2.74	8/24/2016 12:26	8/25/2016 13:23	8/24/2016 16:30	3.75
7 WTS	0.52	0.94	0.73	8/25/2016 9:39	8/26/2016 11:19	8/25/2016 14:00	0.78

Table 6. Summary of AC Potential Measurements – OPL20

OPL20							
Label	Measured AC Potential (V)			Date		Date for Comparison	AC at Date for Comparison (V)
	Min	Max	Average	Start	Stop		
1 WTS	1.44	1.61	1.59	8/25/2016 10:37	8/26/2016 12:22	8/25/2016 14:00	1.61
2 TS	1.48	5.63	3.44	8/25/2016 13:55	8/26/2016 14:10	8/25/2016 14:00	4.02
3 WTS	1.58	2.92	2.18	8/25/2016 13:01	8/26/2016 13:13	8/25/2016 14:00	2.41
4 WTS	1.31	2.52	1.73	8/25/2016 11:04	8/26/2016 11:41	8/25/2016 14:00	2.02
7 ETS	0.52	1.08	0.79	8/24/2016 9:16	8/25/2016 9:21	8/24/2016 16:30	1.07

When comparing the model results to field measured AC potentials, it is important to understand the variables which affect AC induction on pipelines. As explained above, the effects of the power transmission line on an adjacent pipeline are a function of geometry, soil resistivity, coating resistance, and the transmission line operating parameters. The geometry characteristics include separation distance, depth of cover (DOC), pipe diameter, angle between the pipeline and transmission line, phase conductor spacing and distance above ground. These geometry characteristics remain reasonably constant over time, with the exception being the construction of new transmission lines or modifications of existing transmission lines in the corridor. The coating resistance and soil resistivity may change with the seasonal variations and as the installation ages, providing another source of variability. The operating parameters of the transmission line such as phase conductor load and phase balance (i.e. the current load between the phases of each circuit) have a significant influence on the induced AC potentials on the collocated pipeline segments. The individual current load and balance is dynamic and changes significantly with load requirements and switching surges with the power system.

There was not a single date/time where potentials were available at all data logger locations, thus the model was analyzed at two different loads corresponding to 8/25/2016 at 14:00 (blue highlighted cells above) and 8/24/2016 at 16:30 (magenta highlighted cells above). The far right column, labeled AC at Date for Comparison (V), in Table 5 and Table 6 above was the AC potential measurement corresponding to the date and times previously mentioned. This was the field measurement used when comparing the Induced AC model results at the corresponding transmission line loads.

The model results along with the field measured AC potentials are shown below in Figure 8 and Figure 9. All figures are plotted with respect to the model number on the horizontal axis. The pipelines were modeled starting at the north end, thus the pipeline nodes are ascending in a north to south direction. Further, the location of the Richards Creek substation along the collocation is marked with vertical lines on all plots to provide a further sense of location along the corridor. The blue curve corresponds to the model results from the transmission line operating loads from 8/25/2016 at 14:00 while the magenta curve corresponds to the model results at the operating loads from 8/24/2016 at 16:30. The field measured AC potential symbols are colored accordingly based upon the proper AC model results for comparison.

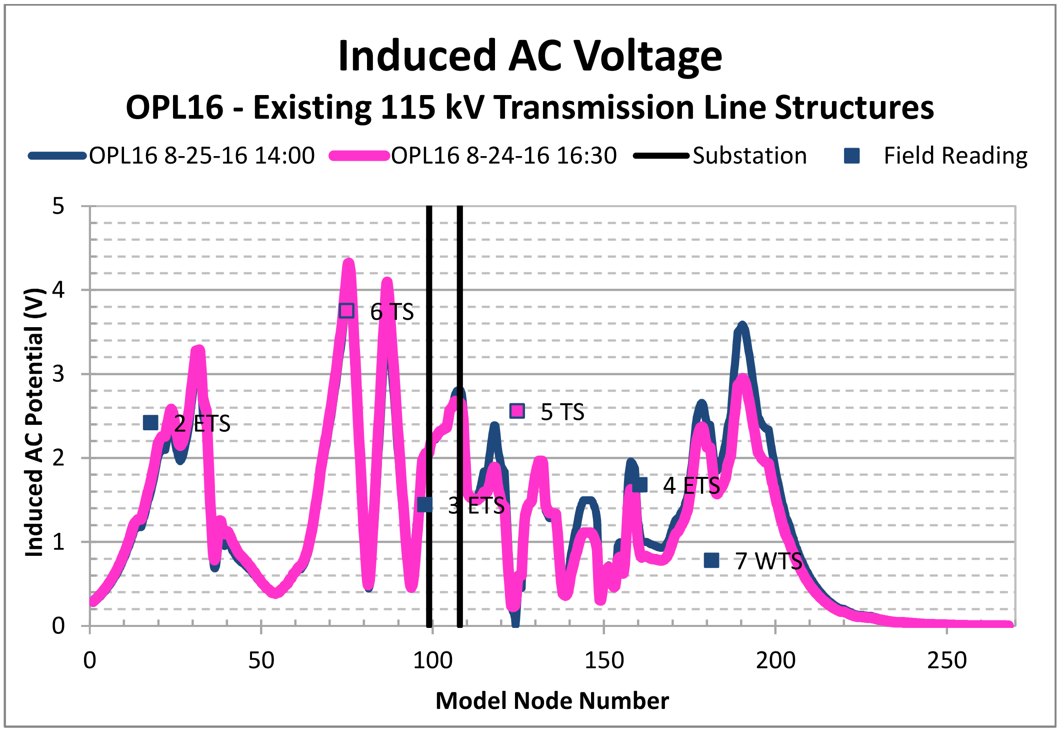

Figure 8. Model Results Compared to Field Measured AC Potentials – OPL16

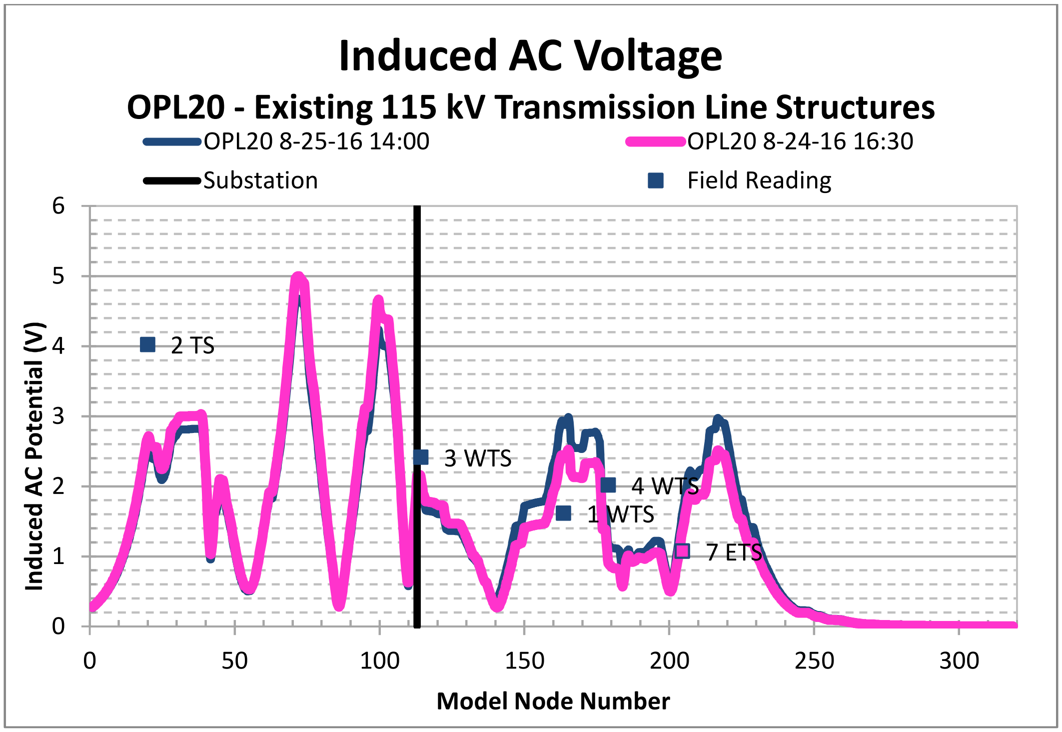

Figure 9. Model Results Compared to Field Measured AC Potentials – OPL20

Based upon the variables discussed above, the model results show generally very good agreement with the field measured AC potentials for both lines OPL16 and OPL20 with similar trends in AC potential trends along the collocation as well as overall magnitude. This indicates the model is predicting AC interference levels similar to those measured in the field along the corridor.

7.2.2 Sensitivity Studies

The steady state model was analyzed considering various loading scenarios, pole configurations, and transmission line routes, as discussed previously. For the majority of the sensitivity studies, a single pole configuration was applied along the entire transmission line route for each circuit in the model. The maximum induced AC potential and AC current density results were then recorded for several regions along the pipeline, corresponding to specific transmission line segments along the corridor. The segment names and the corresponding location along the transmission line route are shown below in Figure 10.

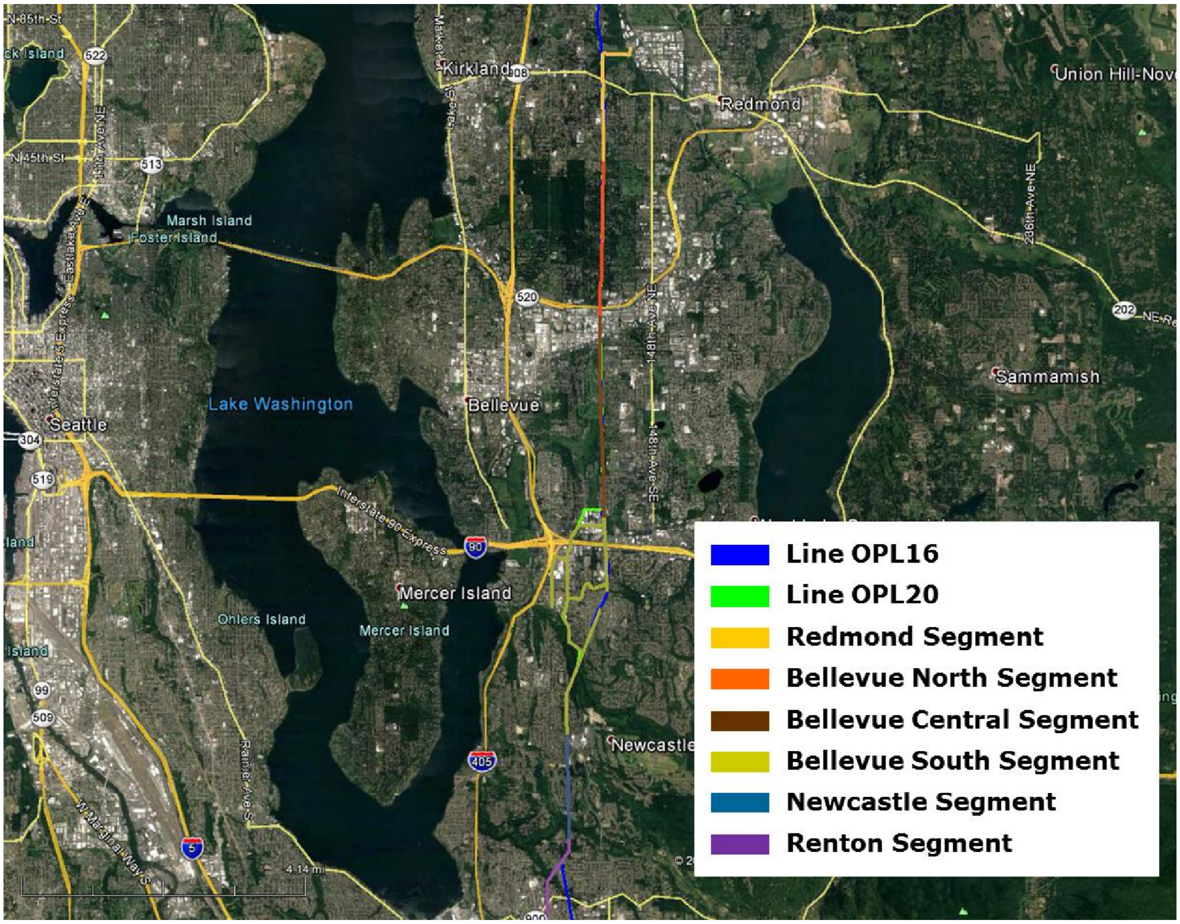

Figure 10. Map of Transmission Line Segments for Presentation of AC Model Sensitivity Study Results

A summary of the results for the various sensitivity studies are shown below in Table 7 with the Load Scenario corresponding to the operating current magnitudes listed in Table 2. The pole configuration corresponds to those shown in Figure 6. For each sensitivity study, these poles were used for the entire corridor which was being studied (i.e. Willow 1 or Willow 2). The pole structure location corresponds to the segments displayed in Figure 10 above. All sensitivity studies were performed for either the Willow 1 or Willow 2 route as noted in the transmission line route column. The Oak 1 and Oak 2 routes were considered, though not explicitly modeled in this study. The Oak 1 and Oak 2 routes are similar to the Willow 2 routes, with an extended collocation length with OPL20. Thus it is expected that the AC interference levels resulting from the Oak 1 and Oak 2 routes would be higher than the Willow 2 route, which was analyzed as part of this study. The Low Profile poles were not assessed for the entire collocation as part of these sensitivity studies, as the design intent for these poles was only for a short segment of the Willow 2 route. Additionally, based upon the configuration and lower height of the conductors, relative to the other pole configurations, it was expected that the low profile pole configuration would result in higher levels of AC interference on the pipelines, and thus their use along the collocation was minimized. The results shown below for the Low Profile poles were obtained from the optimized Willow 2 route, discussed below in Section 7.2.4.

Table 7. Sensitivity Study Description and Results Summary

Structure	Load Scenario	Pole Structure Location	Maximum Induced AC Potential (V)		Maximum Theoretical AC Current Density (Amps/m²)	
			OPL16	OPL20	OPL16	OPL20
C2	230/115 Winter Peak	Renton Segment	9	14	3	27
C2	230/230 Winter Peak	Renton Segment	6	3	2	1
C2	230/115 Winter Peak	Bellevue South Segment – Willow 1 Option	19	10	26	17
C2	230/230 Winter Peak	Bellevue South Segment – Willow 1 Option	4	4	13	10
C13	230/115 Winter Peak	Renton Segment	17	18	5	6
C13	230/230 Winter Peak	Renton Segment	18	18	6	5
C13	230/115 Winter Peak	Bellevue South – Willow 1 Option & Newcastle Segment	13	16	18	31
C13	230/230 Winter Peak	Bellevue South – Willow 1 Option & Newcastle Segment	12	17	22	34
C16	230/115 Winter Peak	Renton Segment	7	9	2	3
C16	230/230 Winter Peak	Renton Segment	5	6	1	2
C16	230/115 Winter Peak	Bellevue South – Willow 1 Option, Newcastle & Renton Segments	9	9	11	10
C16	230/230 Winter Peak	Bellevue South – Willow 1 Option, Newcastle & Renton Segments	6	6	14	7
Low Profile*	230/115 Winter Peak	Bellevue South Segment – Willow 2 Option	10	-	47	-
Low Profile*	230/230 Winter Peak	Bellevue South Segment – Willow 2 Option	11	-	52	-
C2	230/115 Winter Peak	Bellevue South Segment – Willow 2 Option	22	24	74	47
C2	230/230 Winter Peak	Bellevue South Segment – Willow 2 Option	18	18	83	71

*Results for the Low Profile Structures were obtained from the Optimized Willow 2 Route Configurations

For both the Willow 1 and Willow 2 routes, due to complexities along the ROW and construction limitations, the same pole configuration cannot be used along the entire corridor. Considering these limitations, the results of the sensitivity studies were used to design pole configurations along the Willow 1 and Willow 2 corridors, which would result in an optimized, reduced level of AC interference on the collocated pipeline segments. Based upon the outcomes of the sensitivity studies discussed above, two additional simulations were performed using an optimized pole configuration along the Willow 1 and Willow 2 routes. In each case, the structures vary along the collocation, in an effort to minimize induced AC potentials and theoretical AC current density. The details of these analyses are discussed in further detail below.

7.2.3 Willow 1 Optimized Pole Configurations

The Willow 1 route for this study was comprised of C1 and C16 structures as shown below in Figure 11. All structures north of the proposed Richards Creek substation are a double circuit vertical pole configuration (C1), as indicated below and detailed in Figure 6 above. A combination of C1 and C16 structures were used south of the proposed substation.

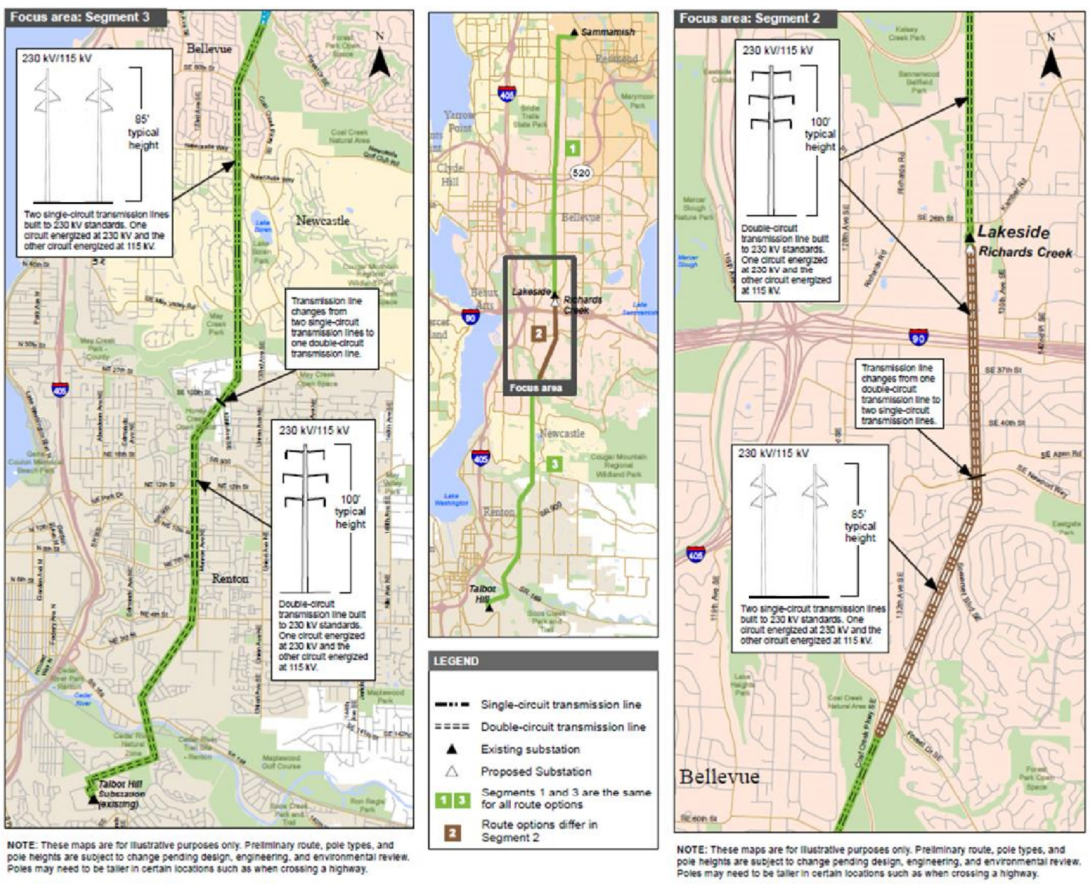

Figure 11. Willow 1 Transmission Line Route with C1 and C16 Structures

The transmission line route and corresponding structures, as noted above, were included in the model and the analysis was performed considering the same 230 kV/115 kV and 230 kV/230 kV Winter Peak

DSD 003995

loads discussed previously. The model results are displayed in a similar fashion to those for the existing transmission line structures above. The NACE 15 volt threshold is indicated with a red dashed line while the goal AC potential to satisfy a theoretical AC current density of 20 amps/m^2 or less is shown in orange. The model results corresponding to the 230 kV/115 kV Winter Peak loads are represented by the blue curve, while the 230 kV/230 kV model results are represented by the pink curve. The model results for the optimized Willow 1 Route structures are shown below in the following sections for OPL16 and OPL20.

Line OPL16 Model Results

The model results for Induced AC potential and theoretical AC current density are shown below in Figure 12 and Figure 13.

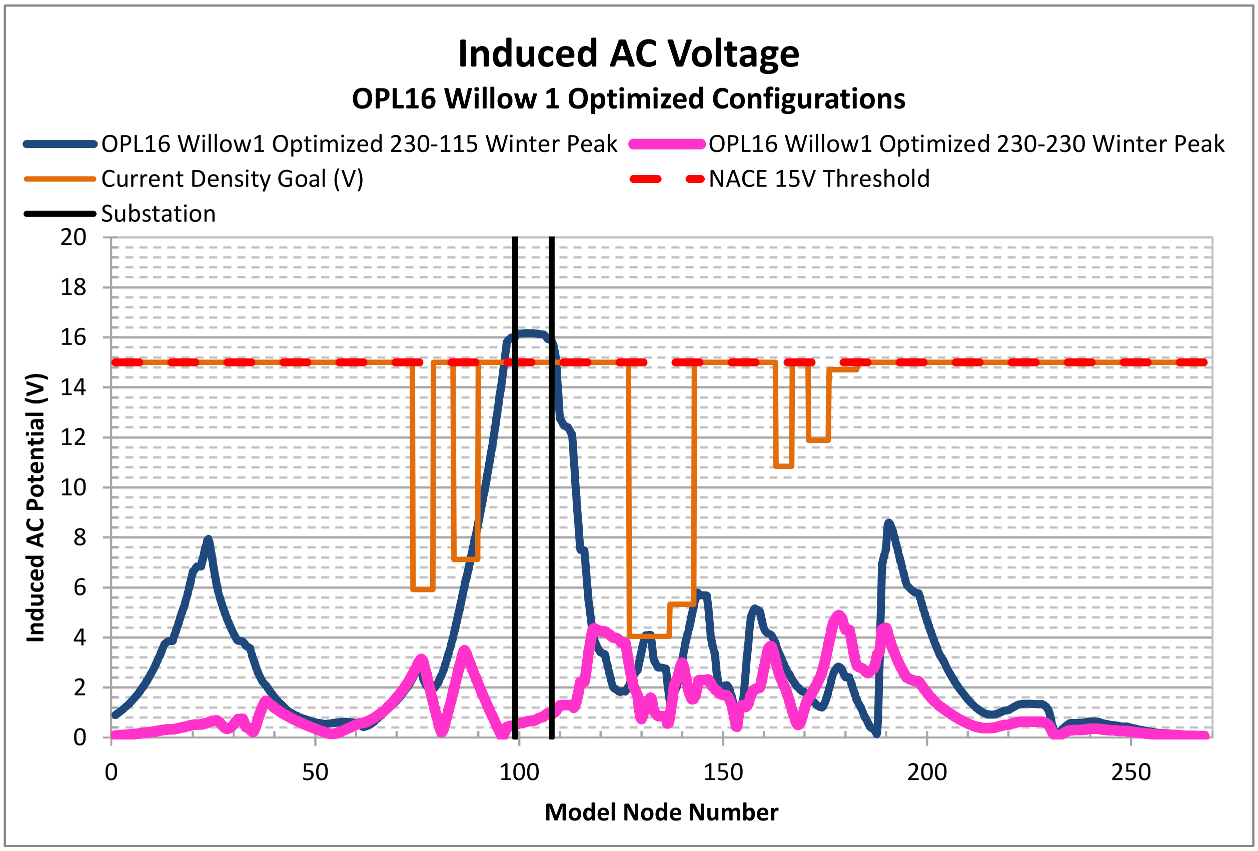

Figure 12. OPL16 Induced AC Potential Model Results for Willow 1 Route with Optimized Configurations

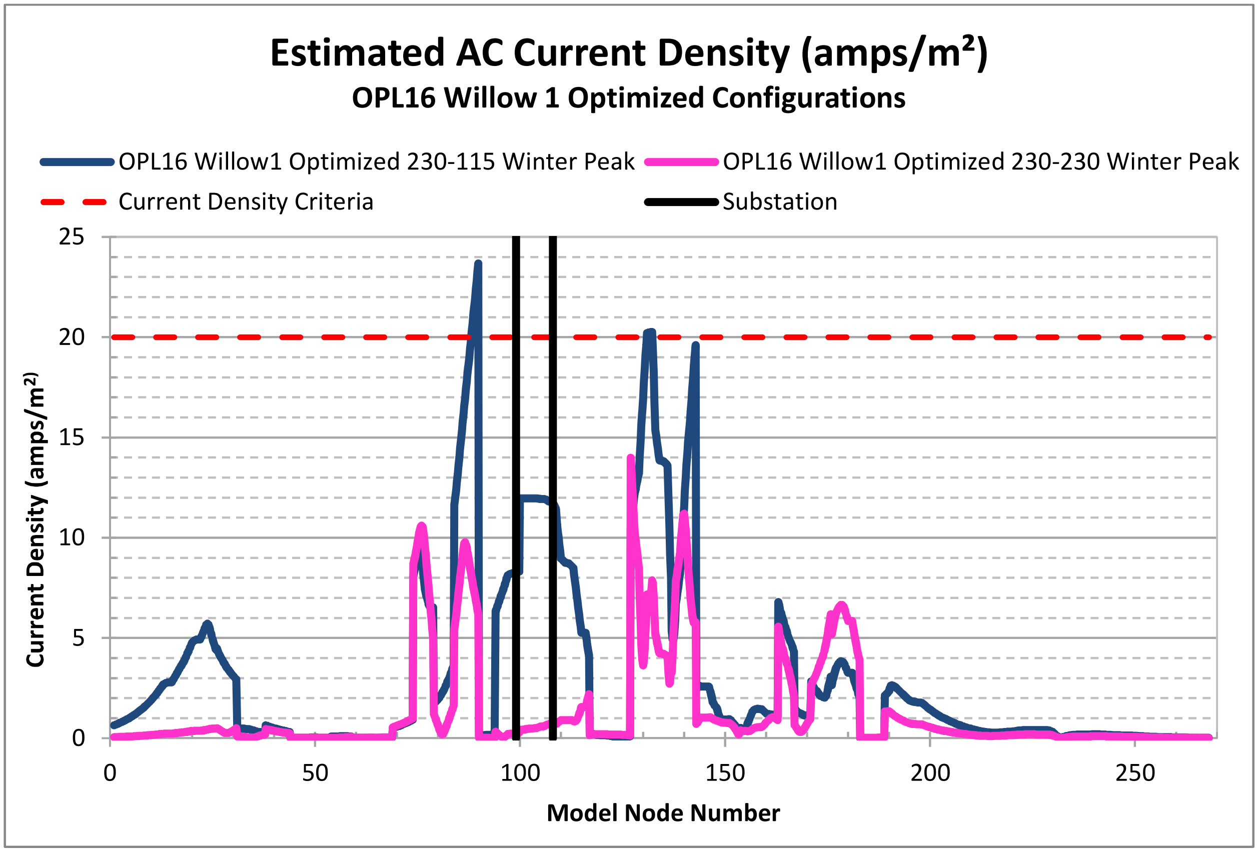

Figure 13. OPL16 Theoretical AC Current Density Results for Willow 1 Route with Optimized Configurations

Considering the 230 kV/115 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was 16 volts, which is greater than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 24 amps/m^2. This is greater than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is unpredictable. As discussed previously, the Winter Peak loading scenario was the worst case loading scenario for the proposed transmission line configuration which the lines will operate at for a limited time throughout the year.

Considering the 230 kV/230 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 5 volts, which is less than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 14 amps/m^2. This is less than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is low. The balanced loading of the 230/230 kV configuration is the principal factor that reduces the AC potential and theoretical AC current density when compared to the 115/230 kV loading scenario. Additionally, following the Willow 1 route, using the optimized pole configurations with the 230/230 kV loading scenario resulted in the least induced AC potential and theoretical AC current density for OPL16.

Line OPL20 Model Results

The model results for Induced AC potential and theoretical AC current density are shown below in Figure 14 and Figure 15.

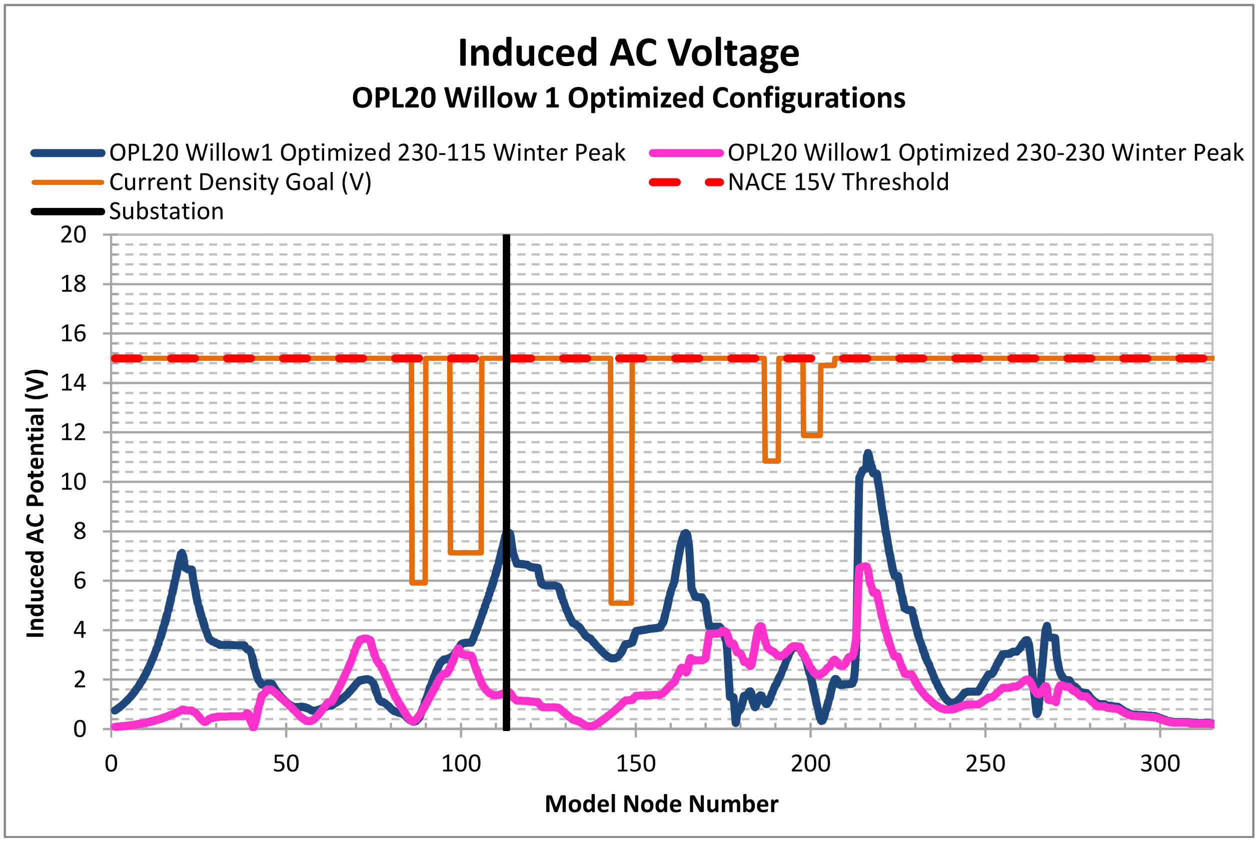

Figure 14. OPL20 Induced AC Potential Model Results for Willow 1 Route with Optimized Configurations

DSD 003998

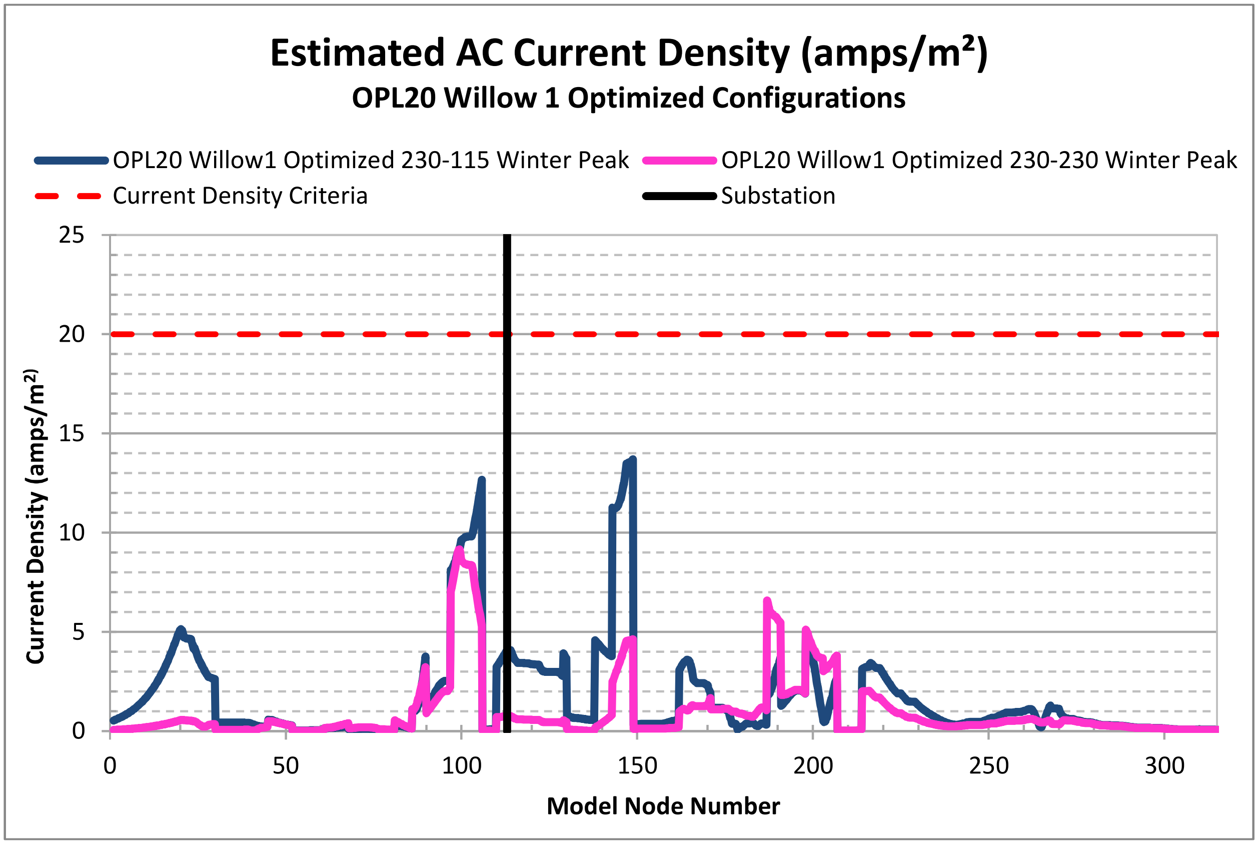

Figure 15. OPL20 Theoretical AC Current Density Results for Willow 1 Route with Optimized Configurations

Considering the 230 kV/115 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 11 volts, which is less than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 14 amps/m^2. This is less than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is low. As discussed previously, the Winter Peak loading scenario was the worst case loading scenario for the proposed transmission line configuration which the lines will operate at for a limited time throughout the year

Considering the 230 kV/230 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 7 volts, which is less than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 9 amps/m^2. This is less than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is low. The balanced loading of the 230/230 kV configuration is the principal factor that reduces the AC potential and theoretical AC current density when compared to the 115/230 kV loading scenario. Additionally, following the Willow 1 route, using the optimized pole configurations with the 230/230 kV loading scenario resulted in the least induced AC potential and theoretical AC current density for OPL20.

DSD 003999

7.2.4 Willow 2 Optimized Pole Configurations

The Willow 2 route for this study was similar to the Willow 1 route presented above with the primary difference being the transmission line route near the proposed 230 kV substation (Richards Creek). This region is comprised of varying C1, C2, Low Profile, and C16 structures as shown below in Figure 16. The structures north and south of this region are the same as the Willow 1 route discussed in section 7.2.3.

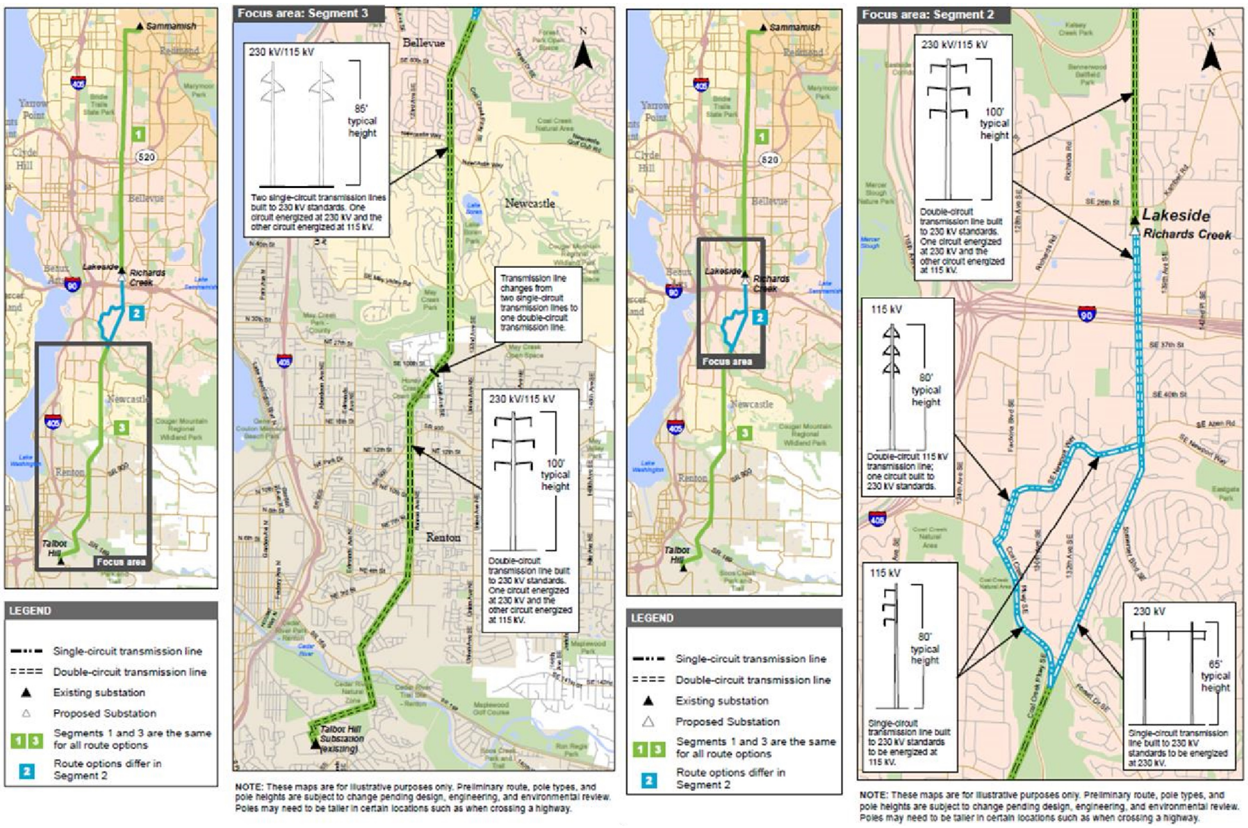

Figure 16. Willow 2 Transmission Line Route with C1, C2, Low Profile, and C16 Structures

The transmission line route and corresponding structures, as noted above, were included in the model and the analysis was performed considering the same 230 kV/115 kV and 230 kV/230 kV Winter Peak loads discussed previously. The model results are displayed in a similar fashion to those presented for the Willow 1 optimized pole configuration study. The model results for the revised Willow 2 Route structures are shown below in the following sections for OPL16 and OPL20.

Line OPL16 Model Results

The model results for Induced AC potential and theoretical AC current density are shown below in Figure 17 and Figure 18.

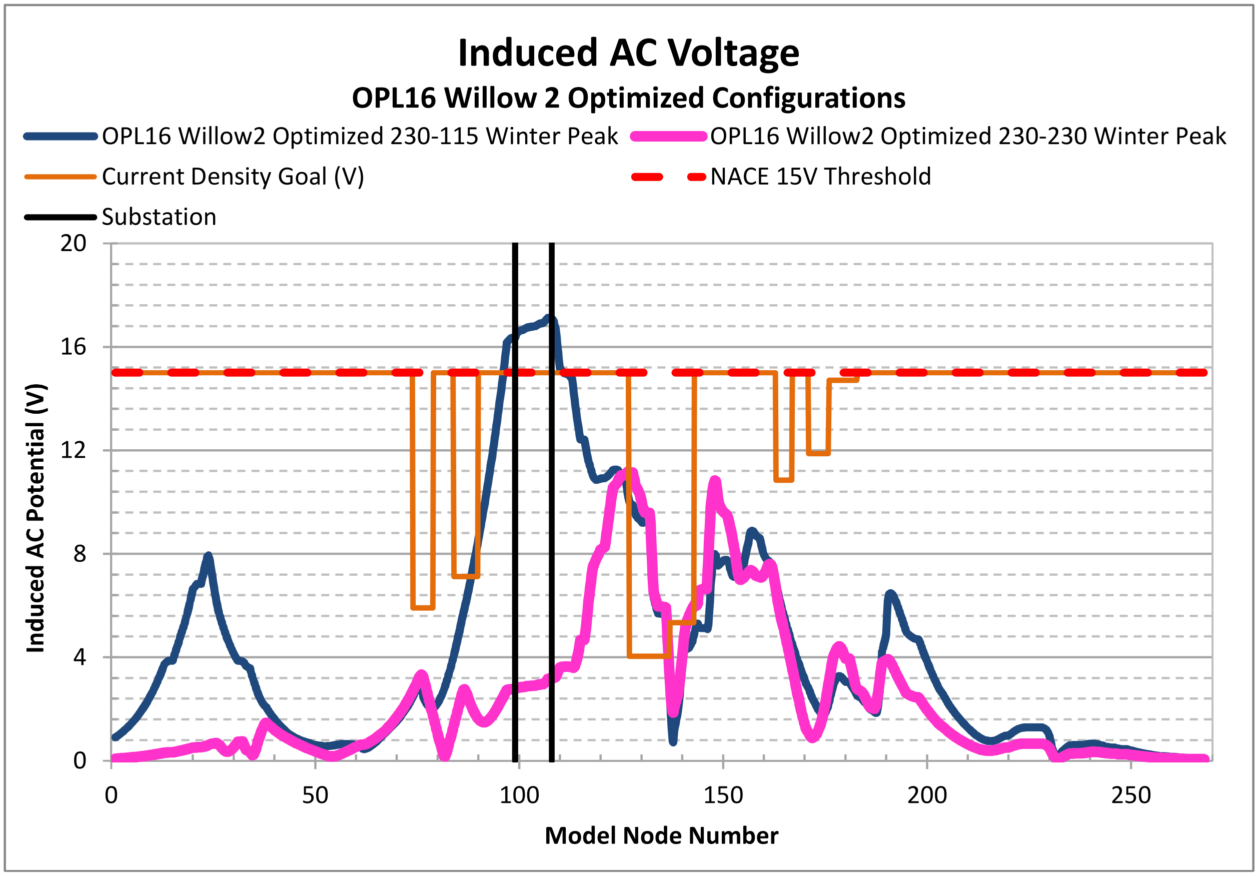

Figure 17. OPL16 Induced AC Potential Model Results for Willow 2 Route with Optimized Configurations

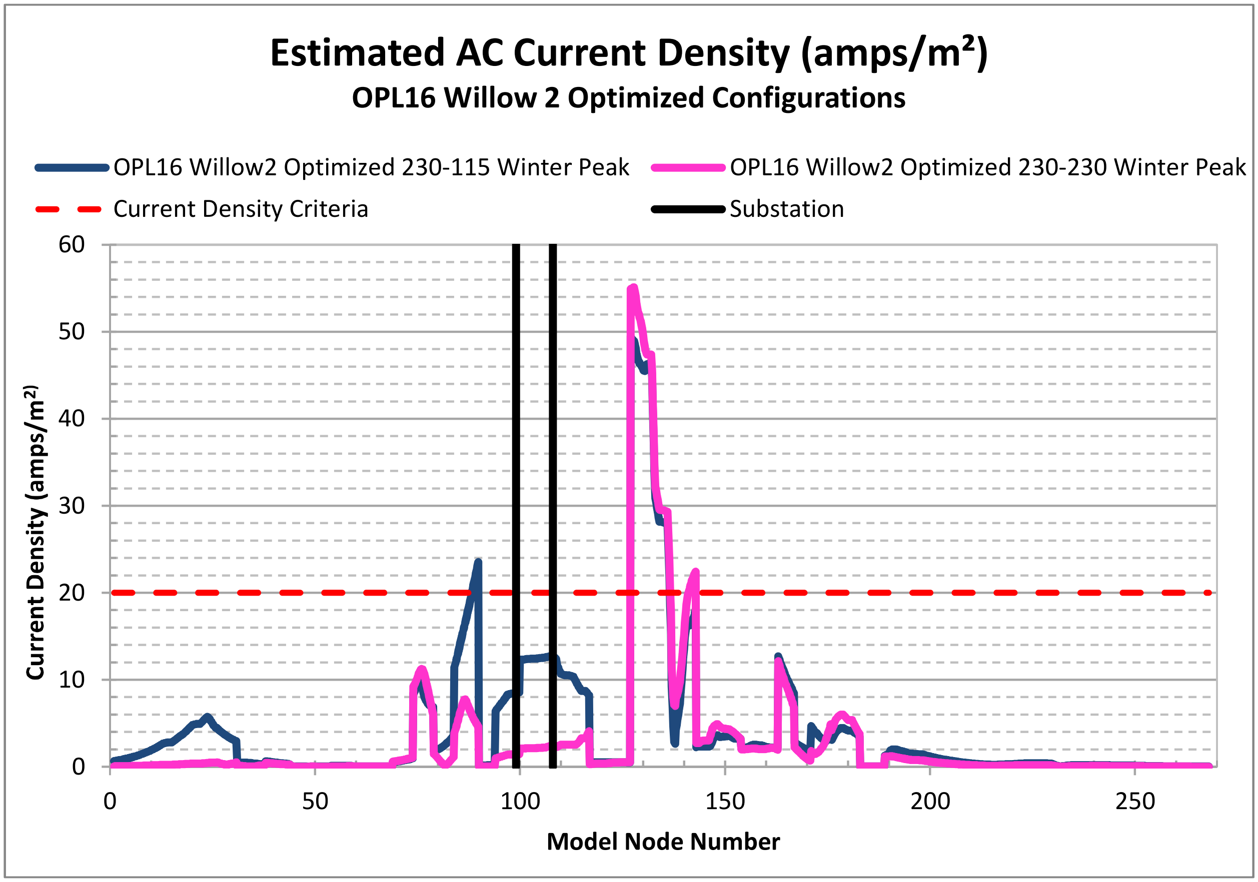

Figure 18. OPL16 Theoretical AC Current Density Results for Willow 2 Route with Optimized Configurations

Considering the 230 kV/115 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 17 volts, which is greater than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 50 amps/m^2. This is greater than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is unpredictable. As discussed previously, the Winter Peak loading scenario was the worst case loading scenario for the proposed transmission line configuration which the lines will operate at for a limited time throughout the year.

Considering the 230 kV/230 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 11 volts, which is less than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 55 amps/m^2. This is greater than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is unpredictable.

Line OPL20 Model Results

The model results for Induced AC potential and theoretical AC current density are shown below in Figure 19 and Figure 20.

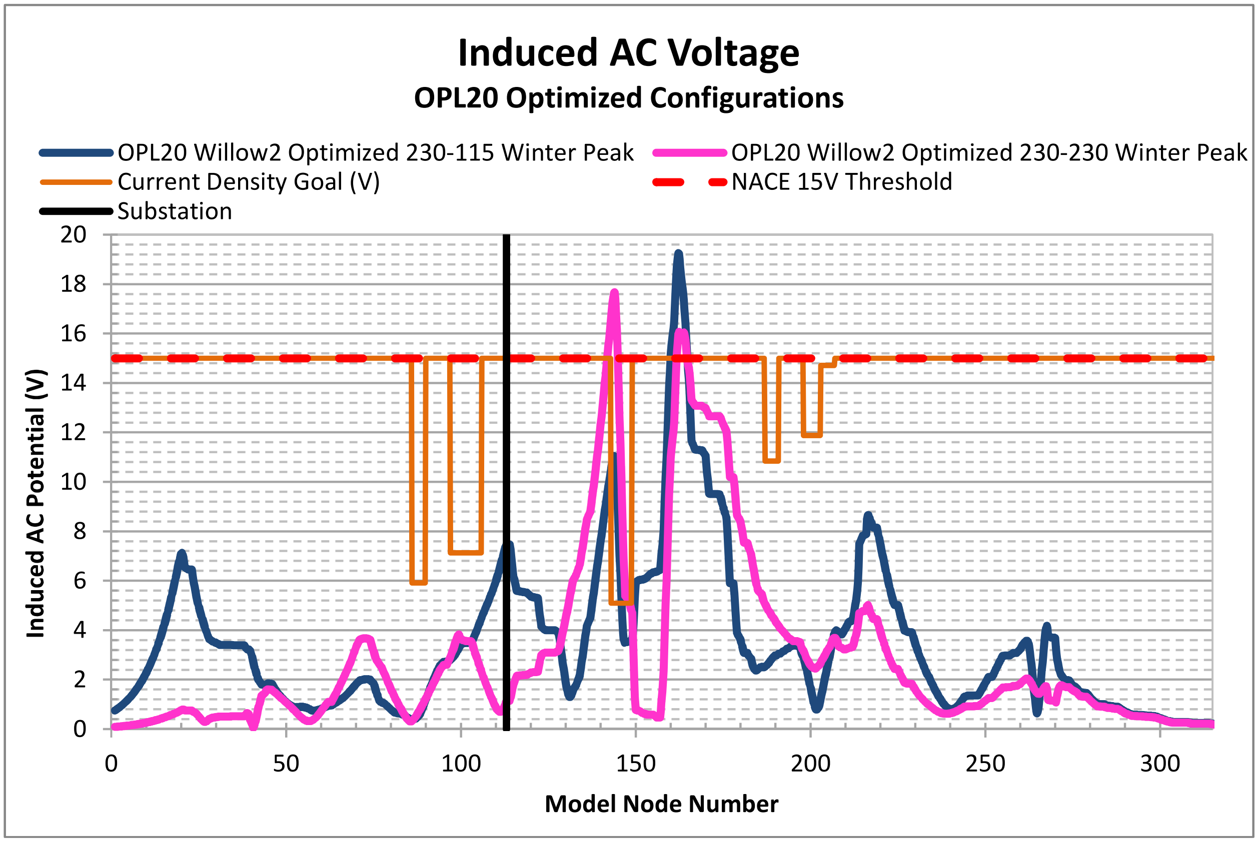

Figure 19. OPL20 Induced AC Potential Model Results for Willow 2 Route with Optimized Configurations

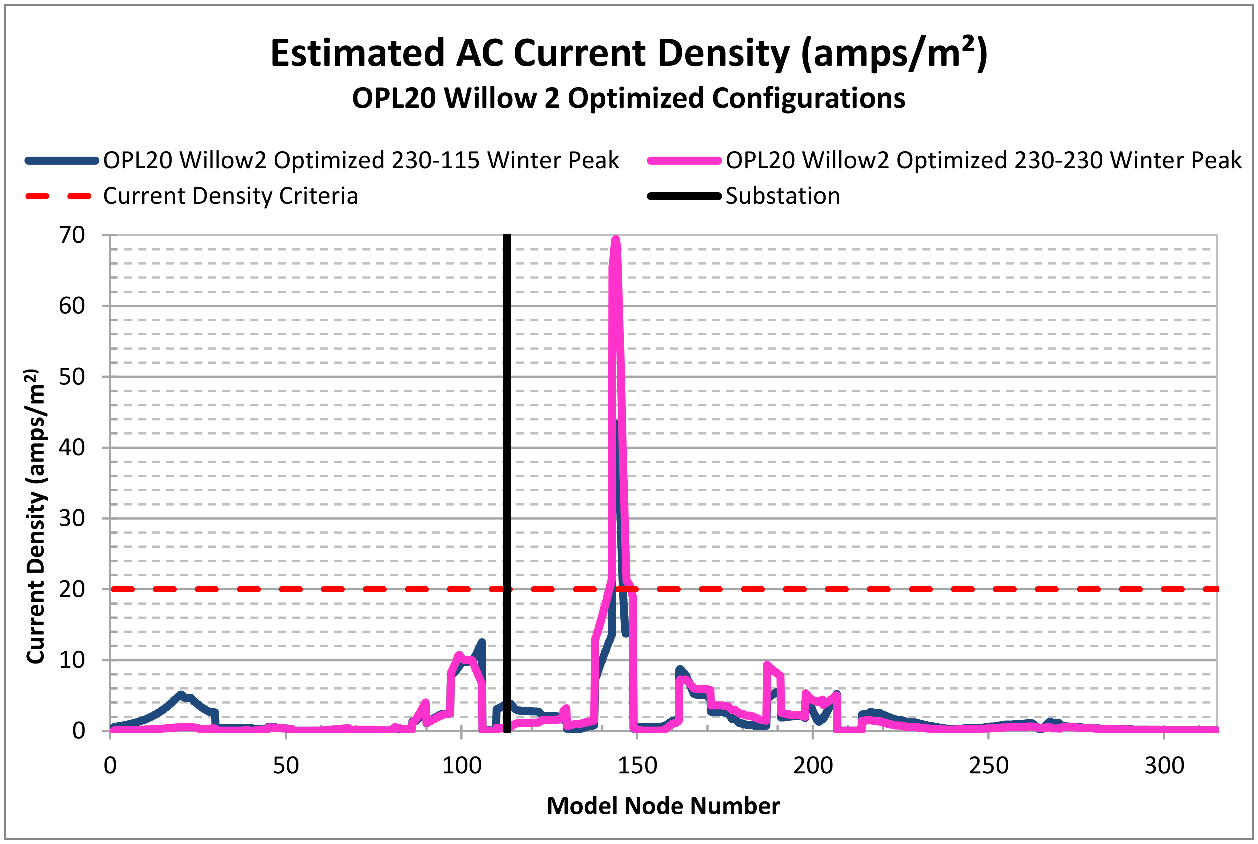

Figure 20. OPL20 Theoretical AC Current Density Results for Willow 2 Route with Optimized Configurations

Considering the 230 kV/115 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 19 volts, which is greater than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 43 amps/m^2. This is greater than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is unknown. As discussed previously, the Winter Peak loading scenario was the worst case loading scenario for the proposed transmission line configuration which the lines will operate at for a limited time throughout the year.

Considering the 230 kV/230 kV Winter Peak operating loads, the maximum induced AC potential along the collocation was approximately 18 volts, which is greater than the NACE 15 volt safety threshold. Under the same loading conditions, the maximum theoretical AC current density along the collocation was approximately 69 amps/m^2. This is greater than the current density threshold of 20 amps/m^2, indicating the likelihood of accelerated AC corrosion is unpredictable.

8 FAULT VOLTAGE AND CURRENT RESULTS

In addition to the sensitivity studies related to induced AC analysis presented above, several sensitivity studies were performed with regards to the fault analysis whereby the effects of fault currents, shield wire configurations, and pole configurations were evaluated to determine the pipelines' susceptibility to damage, resulting from a fault incident. For each fault sensitivity study, a single line-to-ground fault was considered at multiple locations south along the collocation. The resulting coating stress voltage (voltage across the coating) on the pipeline was compared for the C1, C2, C3, and Low Profile pole configurations, which showed for the same magnitude of fault current, the C2 and C3 pole configurations resulted in the same coating stress voltages. Thus for the resistive fault simulation, as the C2 and C3 poles were both single pole configurations, the coating stress voltage was the same in each case. Based upon these results, a separate fault sensitivity study was not performed for the C16 structures, as the coating stress voltages were expected to be similar to the C2 and C3 structures. For the Low profile structures, as they are comprised of two poles, the resulting coating stress voltage is different, considering the same fault current.

A fault current value of 25 kA was used in this study, which is based on the maximum transmission system fault current that could be experienced in the portions of the corridor where the pipelines are co-located. The scenarios that were analyzed to arrive at 25 kA include a bus fault at the Sammamish, the proposed Richards Creek, and Talbot Hill substations. The Olympic Pipelines first enter the PSE transmission corridor approximately 3 miles north of the Talbot Hill substation, which was accounted for in the calculation of fault current present at that location. Using a fault current of 25 kA the sensitivity studies were analyzed with no shield wire, an Alumoweld shield wire, and an Optical Ground Wire (OPGW). The same four poles were considered for the C1, C2, and C3 studies where the two closest poles north and south of the substation were faulted in the analysis. For each case, the maximum coating stress voltage and maximum arcing distance were calculated. A summary of the fault model sensitivity studies is presented below in Table 8.

Table 8. Coating Stress Voltage Summary

			Coating Stress Voltage (Volts) Resulting from 25 kA Fault Current		
Fault Scenario	**Pole Number**	**Pole Configuration**	**No Shield Wire**	**Alumoweld**	**OPGW**
FC1	16	C1	18,840	3,219	2,833
FC2	48	C1	55,170	7,902	5,970
FC3	179	C2/C3	44,850	6,297	3,447
FC4	46	C2/C3	20,010	2,826	1,517
FC5	100	Low Profile	-	2,595	1,637
FC6	106	Low Profile	-	1,931	2,097
FC7	108	Low Profile	-	2,560	2,428

Information provided by Olympic indicated lines OPL16 and OPL20 are both primarily coated with Coal Tar Enamel, which Olympic indicated an approximate coating thickness of 75 mils. This equates to an approximate coating breakdown voltage of 10,825 volts (per Equation 1 in section 3). The coating stress voltages decrease dramatically when a shield wire is used, as the primary function of the shield wire is to provide a low resistance path to carry the majority of the fault current to ground. In the absence of a shield wire, the total fault current (in this case 25 kA) returns to ground at a single location. The OPGW resulted in the lowest overall coating stress voltage while the faulted poles with the low profile pole configuration showed an overall lower coating stress voltage than the worst case faulted poles considering the C1, C2, or C3 pole configurations.

Based upon the data provided, the coating stress voltage for both pipelines is expected to be less than the coating breakdown voltage as long as an Alumoweld or OPGW shield wire is used on the transmission line poles. As discussed previously, the resulting coating stress voltages for the C16 pole configuration are expected to be similar to the C2 and C3 results as poles are similar.

The maximum arcing distance for each region was obtained using the maximum soil resistivity and the maximum fault current for each region.

Table 9. Arcing Distance Summary

Pole Configuration	Scenario	Fault Current (kA)	Maximum Return Current to Ground (Amps)	Maximum Soil Resistivity (Ohm-m)	Maximum Arcing Distance (ft)
C1 and C2/C3	No Shield Wire	25	25,000	4021.74	42
C1 and C2/C3	Alumoweld	25	3,805	4021.74	17
C1 and C2/C3	OPGW	25	2,207	4021.74	13
Low Profile	Alumoweld	25	1,109	4021.74	10
Low Profile	OPGW	25	602	4021.74	7

Due to the close proximity of the pipeline and transmission line poles along the collocation, there are several poles which are within the maximum arcing distance. With a fault current level of 25 kA, PSE will include a shield wire using OPGW on the pole structures. The initial screening for the arcing distance was based upon the maximum soil resistivity for the collocation, which would result in the maximum arcing distance. Considering the poles within the maximum arcing distance of 13 feet (considering a fault current of 25 kA and an OPGW shield wire) the local soil resistivity ranged from 66 ohm-m to 3,256 ohm-m. Considering the local soil resistivity along the collocation, the resulting arcing distances range from 4 ft to 13 ft at these pole locations. Due to variation in soil resistivity, and lack of precision related to the pipeline location relative to the proposed transmission line poles, in those areas where the transmission poles are proposed within 13 feet of the pipeline, the following is recommended:

- Distances between the pipeline and transmission line pole grounds should be field verified by the transmission line and pipeline operators.
- If the transmission line pole grounds are found to be within 13 feet of the pipeline, Arc shielding protection should be installed, consisting of a single zinc ribbon extending a minimum of 25 feet past the transmission line pole grounds in both directions. The zinc ribbon should be connected to the pipeline through a single direct-current decoupler (DCD).

9 CONCLUSIONS AND RECOMMENDATIONS

During the course of the study, three principle factors were identified to have a significant effect on the level of AC interference on the collocated pipeline segments:

- Current load unbalance between the two circuits as a result of operating at 115 kV/ 230 kV.
- Points of divergence between the transmission line and pipeline along the corridor (i.e. where the respective utilities enter and exit the shared corridor).
- Conductor geometry, where a true delta configuration provided the greatest level of field cancellation.

The following conclusions and recommendations are provided based on the Elsyca Iris software, NACE standards, and other common industry practices.

➢ The model results for the steady state induced AC analysis indicated the following and are summarized in Table 10. For both loading scenarios and optimized route configurations, the maximum theoretical AC current density was less than 100 amps/m^2, indicating that the likelihood for accelerated AC corrosion is in the low or unpredictable range (0-20 amps/m^2 and 20-100 amps/m^2, respectively.

Table 10. Conclusion Summary: Optimized Willow 1 and 2 Route Results

Route (Optimized Configuration)	Load Scenario	Maximum Induced AC Potential (V)		Maximum Theoretical AC Current Density (Amps/m^2)	
		OPL16	OPL20	OPL16	OPL20
Willow 1	230/230 Winter Peak	D	D	L	L
Willow 1	230/115 Winter Peak	E	D	U	L
Willow 2	230/230 Winter Peak	D	E	U	U
Willow 2	230/115 Winter Peak	E	E	U	U

Induced AC Potential: D – Does not exceed 15V safety limit, E – Exceed 15V safety limits

Current Density: L – Low risk range, U – Unpredictable risk range

Yellow: Requires additional post-construction monitoring and/or mitigation by the pipeline operator to verify that safety standards and/or thresholds are met.

- The Optimized Willow 1 route presented in section 7.2.3 indicated maximum induced AC potentials and theoretical AC current densities are less than 15 volts and the 20 amps/m^2 level (low likelihood of AC corrosion) for the 230 kV/230 kV Winter Peak Loads for both lines OPL16 and OPL20. This configuration resulted in the lowest induced AC potentials and theoretical AC current densities of the scenarios which were studied.

    - Considering the 230 kV/115 kV loading scenario, the maximum induced AC potential for OPL16 was approximately 16 volts, which is greater than the NACE 15 volt safety threshold. Based upon the model results, after the transmission lines are energized, field monitoring and/or mitigation by the pipeline operator may be needed to confirm these AC potentials are less than the 15 volt safety threshold.
    - Considering the 230 kV/115 kV loading scenario, the maximum theoretical AC current density was approximately 24 amps/m^2 on line OPL16, which is greater than the 20 amps/m^2 current density threshold, indicating the likelihood of accelerated AC corrosion is unpredictable. After the transmission lines are energized, field monitoring and/or mitigation by the pipeline operation may be needed to confirm these current density levels are at acceptable levels.

- The Optimized Willow 2 route presented in section 7.2.4 indicated:
    - Maximum induced AC potentials did not exceed the 15 volt safety threshold for the 230 kV/230 kV Winter Peak Loads for line OPL16. The maximum theoretical AC current density was between 20 amps/m^2 and 100 amps/m^2, indicating the likelihood of accelerated AC corrosion is unpredictable.
    - Considering the 230 kV/230 kV Winter Peak loading scenario, the maximum induced AC potential for OPL20 was approximately 18 volts, which is greater than the NACE 15 volt safety threshold. Based upon the model results, after the transmission lines are energized, field monitoring and/or mitigation by the pipeline operator may be needed to confirm these AC potentials are less than the 15 volt safety threshold.
        - Under the same loading scenario, the theoretical AC current densities were approximately 55 amps/m^2 and 70 amps/m^2 for OPL16 and OPL20, respectively. This is greater than the 20 amps/m^2 current density threshold, indicating the likelihood of AC corrosion is unpredictable. After the transmission lines are energized, field monitoring and/or mitigation by the pipeline operator may be needed to confirm these current density levels are at acceptable levels.
    - Considering the 230 kV/115 kV loading scenario, the maximum induced AC potential for OPL16 and OPL20 was approximately 17 volts and 19 volts, respectively, which is greater than the NACE 15 volt safety threshold. Based upon the model results, after the transmission lines are energized field monitoring and/or mitigation by the pipeline operator may be needed to confirm these AC potentials are less than the 15 volt safety threshold.

        - Under the same loading scenario, the theoretical AC current densities were approximately 50 amps/m^2 and 43 amps/m^2 for OPL16 and OPL20, respectively. This is greater than the 20 amps/m^2 current density threshold, indicating the likelihood of AC corrosion is unpredictable. After the transmission lines are energized, field monitoring and/or mitigation by the pipeline operator may be needed to confirm these current density levels are at acceptable levels.

- The results of the fault analysis sensitivity studies are summarized in Table 8.
    - Considering the expected fault current of 25 kA, the maximum coating stress voltage for the Alumoweld and OPGW shield wire types were less than the expected coating breakdown voltage for Coal Tar coating on both pipelines, indicating the risk of fault damage from a fault incident is low.
    - For the studies where no shield wire was included, the coating stress voltage far exceeded the expected coating stress voltage, indicating the likelihood of damage resulting from a fault incident is high.
- Using the results of the fault analysis, the results of the corresponding arcing distance studies are summarized in Table 9.
    - For cases where the pipeline(s) are found to be located within 13 feet of the transmission line pole grounds, arc shielding protection may be needed to reduce the risk of damage from a fault incident. Arc shielding mitigation typically consists of a single zinc ribbon, extending at a minimum of 25 feet past the transmission line pole grounds in both directions, connected to the pipeline through a single DCD.

9.1 General Recommendations

The following general recommendations are suggested:

- Based upon the AC interference modelling and considering certain conductor geometries, operational voltages, and routing, the AC interference effects on the collocated pipeline segments can be reduced to a level that satisfies acceptable industry thresholds for safety and accelerated AC corrosion.
- After the transmission lines are energized, field monitoring and/or mitigation may be need (to be performed by the pipeline operator) for those loading scenarios where the AC potential is greater than 15 volts and the AC current density is greater than 20 A/m^2.
- Pipeline technicians should understand the hazards and safe practices associated with cathodic protection and AC mitigation when working with these sections of pipeline.
- It is recommended that AC pipe-to-soil potentials be recorded along with the DC pipe-to-soil potentials during the annual cathodic protection survey. This can provide information, should unexpected changes occur between the pipeline and transmission line.

DSD 004009

- PSE should notify the pipeline operator when there are planned outages on the individual circuits, as the AC induction effects on the pipeline may be magnified when only one circuit (of the double circuit transmission lines) is energized.
- Final mitigation design, if necessary, should be based on field data collected after the system is energized. Mitigation may include installation of additional grounding installation such as: grounding mats, horizontal surface ribbon, and/or deep anode wells based upon a detailed mitigation study.

10 GLOSSARY OF TERMS

- Appurtenance – an item associated with the pipeline(s), such as a valve
- Bond – an electrical connection intended to provide electrical continuity between two metallic objects
- Coating Breakdown Voltage – the rated voltage of the coating which, if exceeded, results in the destruction of the coating
- Coating Stress Voltage – voltage difference across the coating isolating the pipe from the ground (i.e. potential difference between the pipe and the soil in contact with the coating)
- Direct Current Decoupler (DCD) – an isolation device used to allow DC current to pass while blocking AC current
- Fault Current – the current flowing from a single conductor to ground or to another conductor as a result of an abnormal operating conditions such as a failed connection, electrical arc, or a lightning strike (see fault scenario)
- Fault Scenario – an abnormal operating condition in the power system, usually results in elevated currents for a very short duration of time
- Grounding Mat – a system of bare conductors connected to the energized structure and placed at or below grade, usually at above grade appurtenances or stations, intended to provide localized reduction in touch and step potentials
- Shield Wire – a conductor or system of conductors suspended above the phase wires in the power system which is intended to protect the phase wires from lightning strikes and dissipate elevated currents in the power system

11 REFERENCES

1. IEEE Std 80-2000 “Guide for Safety in AC Substation Grounding,” 2000
2. NACE SP0177-2014 “Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems,” 2014
3. NACE SP0188-2006 “Discontinuity (Holiday) Testing of New Protective Coatings”
4. “AC Predictive and Mitigation Techniques – Final Report”, for Corrosion Supervisory Committee PRC International, 1999.
5. NACE TG 327, “AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements”, NACE Report 35110, 2010
6. R. Gummow, S. Segall, “AC Interference Guidelines,” CEPA 2014
7. S. Finneran, B. Krebs, “Criteria for Pipelines Co-Existing with Electric Power Lines,” The INGAA Foundation 2015-04

APPENDIX A: SOIL RESISTIVITY DATA

Table A1. Soil Resistivity Data

ID #	Latitude	Longitude	Northing	Easting	Bulk Resistivity (Ω-cm)				Barnes Layer Res	
					2.5' SR	5' SR	7.5' SR	10' SR	0-2.5ft	2.5-5ft
1	47.683982	-122.158787	5281520.034	563132.766	22,024	25,854	25,854	24,896	22,024	31,297
2	47.678368	-122.158656	5280896.209	563149.373	49,314	37,345	33,036	38,302	49,314	30,051
3	47.671523	-122.158160	5280135.871	563194.865	292,055	220,238	143,634	112,992	292,055	176,770
4	47.664768	-122.158404	5279384.933	563184.702	62,241	67,029	71,817	59,369	62,241	72,615
5	47.656433	-122.158344	5278458.646	563199.265	148,421	248,965	330,357	402,174	148,421	771,791
6	47.650902	-122.158612	5277843.723	563185.814	119,695	181,936	201,087	248,965	119,695	379,033
7	47.643848	-122.158780	5277059.619	563181.704	129,270	134,058	143,634	1,378,883	129,270	139,214
8	47.637067	-122.158959	5276305.848	563176.435	306,418	354,296	402,174	268,116	306,418	419,907
9	47.630028	-122.159100	5275523.435	563174.327	306,418	402,174	430,901	497,930	306,418	584,981
10	47.622973	-122.159034	5274739.414	563187.788	44,048	49,793	57,453	61,284	44,048	57,262
11	47.616958	-122.159205	5274070.783	563182.187	15,800	9,384	6,464	5,362	15,800	6,674
12	47.609960	-122.159045	5273293.175	563202.642	16,757	20,109	17,236	18,385	16,757	25,136
13	47.602400	-122.158712	5272453.250	563236.781	20,109	11,491	9,623	8,618	20,109	8,043
14	47.594124	-122.158553	5271533.610	563258.707	52,666	101,501	147,943	157,039	52,666	1,395,640
15	47.589045	-122.158323	5270969.334	563282.121	52,666	47,878	35,908	26,812	52,666	43,888
15a	47.584699	-122.158223	5270486.415	563294.879	17,236	22,024	22,981	26,812	17,236	30,495
16	47.582174	-122.157924	5270206.039	563320.406	47,399	38,302	33,036	24,896	47,399	32,135
17	47.574487	-122.157421	5269352.143	563367.504	244,177	325,570	258,541	229,814	244,177	488,354
18	47.568057	-122.157877	5268637.163	563340.964	11,969	6,607	3,447	2,873	11,969	4,563
19	47.561888	-122.161718	5267948.435	563059.465	10,533	7,660	7,900	6,703	10,533	6,019
20	47.555240	-122.165852	5267206.250	562756.427	47,878	48,835	37,345	28,727	47,878	49,832
21	47.548630	-122.169677	5266468.555	562476.514	157,997	105,331	87,617	74,689	157,997	78,998
22	47.541416	-122.169851	5265666.680	562471.993	35,430	18,194	9,623	4,979	35,430	12,239

DSD 004014

ID #	Latitude	Longitude	Northing		Easting	Bulk Resistivity (Ω-cm)				Barnes Layer Res		
						2.5' SR	5' SR	7.5' SR	10' SR	0-2.5ft	2.5-5ft	
23	47.536463	-122.169402	5265116.585		562511.669	52,666	43,090	33,036	22,981	52,666	36,461	
24	47.529893	-122.169165	5264386.614		562537.317	10,054	11,491	12,783	10,533	10,054	13,406	
25	47.522802	-122.169186	5263598.535		562544.165	37,345	22,981	18,672	14,938	37,345	16,598	
26	47.517809	-122.169061	5263043.736		562559.511	95,756	181,936	215,450	229,814	95,756	1,819,359	
27	47.511271	-122.173335	5262313.698		562245.465	119,695	90,968	83,307	57,453	119,695	73,361	
28	47.581572	-122.168860	5270130.266		562498.789	210,663	172,360	122,089	80,435	210,663	145,843	
29	47.574156	-122.169784	5269305.333		562438.125	21,545	19,151	20,109	19,151	21,545	17,236	
30	47.567900	-122.169122	5268610.597		562495.354	28,727	9,576	5,171	2,681	28,727	5,745	
31	47.560610	-122.169414	5267800.178		562482.060	143,634	181,936	186,724	65,114	143,634	248,094	

DSD 004015

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.