May 19, 2016

BY RESS & Courier

Ms. Kirsten Walli
Board Secretary
Ontario Energy Board
Suite 2700, 2300 Yonge Street
Toronto, Ontario
M4P 1E4

Dear Ms. Walli:

Re: Union Gas Limited ("Union")
Leamington Expansion Project
Board File # EB-2016-0013

Pursuant to Procedural Order No. 4 attached please find an AC Interference Report prepared by Corrosion Service Company Limited ("CSCL").

The study was completed using power line parameters provided by Hydro One Networks Inc. ("HONI") and pipeline data from Union Gas Limited ('Union") and site surveys completed by CSCL.

The report concludes that all potential hazards associated with colocation can be mitigated to safe levels. Union is committed to implementing all identified mitigations. With respect to HONI's specific concern regarding power arcing, the report concludes the following:

> *"There is no risk of arcing along the close collocation (i.e., 4m) between the proposed pipelines and future 230 kV powerline. The actual separation distance of 4 m significantly exceeds the minimum separation distance of 1 m. Furthermore, the voltage difference under fault will not exceed 4.2kV, well below the actual voltages (i.e., 28 to 30 kV), which did not sustain arcing at the same or lower separation during the CEA testing."*

Union will be meeting with HONI in the near future to review and discuss the CSCL report.

Union requests that the Board establish a schedule for submissions on the above issue as contemplated in Procedural Order No. 4.

If you have any questions or concerns, please do not hesitate to contact the undersigned.

Sincerely,

[original signed by]

W.T. (Bill) Wachsmuth, RPF
Senior Administrator, Regulatory Projects
:sb
Attach.

cc: L. Gluck
M. Millar
All Intervenors

Union Gas Ltd.

NPS12 Leamington Expansion Phase II

Leamington, ON

AC Interference Study

15136-20

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This report was prepared exclusively for the purposes, project, and site location(s) outlined in the scope of work. The conclusions and recommendations in this report are based on data obtained and analyzed in accordance with industry practice, on the site conditions and operational status of the system at the time of the survey, and on information provided to us. Corrosion Service Company Limited waives responsibility for any decisions or actions taken as a result of our report, or for any consequential damage resulting from such decisions or actions, should the site conditions change, should the operational status change, and should the information provided to us be in error.

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Revision Table:

Status/REV	Description	Date
A0	Issued for Review	2016-05-13
C1	Issued for Use	2016-05-18

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EXECUTIVE SUMMARY

Corrosion Service Company Limited (CSCL) was retained by Union Gas Limited (UGL) to conduct an AC interference study for the collocation of the proposed UGL NPS12 Leamington Expansion Phase II (LEP2) pipeline with the proposed Hydro One 230 kV powerline (SECTR Project) in Leamington, ON.

The objectives of the AC interference study were to determine if the induced AC voltages are within safety limits under steady-state and fault conditions, to minimize the risk of AC corrosion, to avoid an arc striking between the pipeline and any grounded parts of a powerline structure, and to minimize excessive coating stress.

For the purpose of this study, the proposed LEP2 pipeline was considered electrically isolated from the stations and from the existing pipelines by installing three underground monolithic isolating fittings, as shown in Figure 3-1.

Under this configuration, any mitigation measures required to avoid AC interference on the existing UGL pipelines will not affect the results of this study.

The AC interference study was completed using Right-of-Way, software developed by Safe Engineering Services & technologies ltd. (SES). Pipeline data was obtained from UGL, and powerline parameters were obtained from HONI. A site survey, including soil resistivity measurements, was completed by CSCL personnel in April 2016.

The predicted unmitigated AC interference hazards are summarized in Table E-1.

Table E-1. Predicted Unmitigated Hazards

Condition	Hazard	Limit	Predicted Value
Steady-State	Shock to Personnel	Touch Voltage – Max. 15 V	197 V – Hazard
	AC Corrosion	AC Current Density – Max. 50 A/m^2	1,468 A/m^2 – Hazard
Fault	Shock to Personnel	Touch Voltage – Max. 356 V*	3,686 V – Hazard
		Metal-to-metal Voltage – Max. 356 V	N/A**
		Step Voltage – 356 V*	N/A**
	Power Arc	Minimum Separation Distance – 1 m	4 m – No hazard
	Coating Stress	Coating Stress Voltage – Max. 3 to 5 kV	3,686 V – Slightly exceeds lower limit

* Assuming zero soil resistivity.
** To be assessed as part of the study of AC interference on existing pipelines and UGL stations – see paragraphs 5.2.1.2 and 5.2.1.3.

The recommended mitigation measures to reduce touch potentials at above-grade appurtenances and minimize the risk of AC corrosion are summarized in Table E-2.

Table E-2. Summary of Recommended Mitigation

No.	Start Chainage (m)	End Chainage (m)	Mitigation Wire Length (m)	DC Decouplers	AC Coupons	Zinc Anodes	Description
1	0+000		-	-	1	-	Install AC coupon for monitoring.
2	0+000	1+400	1,400	4	-	22	Install one run of 1,400 m bare 2/0 copper wire and connect to pipeline via DC decouplers.
3	0+090	3+775	-	-	-	-	All test posts to be of dead-front configuration.
4	2+770		-	-	1	-	Install AC coupon for monitoring.
5	3+160		-	-	1	-	Install AC coupon for monitoring.
6	3+180	5+090	1,910	5	-	30	Install one run of 1,910 m bare 2/0 copper wire and connect to pipeline via DC decouplers.
7	5+580		-	-	1	-	Install AC coupon for monitoring.
8	7+000		-	-	1	-	Install AC coupon for monitoring.
Totals			**3,310**	**9**	**5**	**52**	

The recommended mitigation system consists of a total of 3,310 m of 2/0 bare copper mitigation wire, connected to the pipeline at nine locations. The length of wire varies with location. In order to cathodically protect the copper wire, it is recommended that 13.6 kg (30 lb.) packaged zinc anodes be connected to the copper wire at designated intervals (i.e., two anodes approximately every 150 m and at the DC decoupler junction boxes).

It is also recommended that a total of five AC coupons be installed on the LEP2 pipeline.

The primary purpose of the AC coupon is to facilitate the measurement of AC current density levels. AC coupons are fabricated of steel with a precise surface area, typically 1 cm^2, which is considered worst case for AC current density. These coupons will be monitored bi-annually during corrosion prevention surveys.

Any test stations installed on the LEP2 pipeline from Ch. 0+090 m to Ch. 3+775 m shall be of dead-front configuration.

With the proposed LEP2 pipeline electrically isolated from the stations using underground monolithic isolating fittings, there are no safety risks associated with the proposed line at UGL stations and along the two existing pipelines (i.e., NPS8 Leamington North and Leamington Expansion Phase I). The risks associated with the influence of the proposed 230 kV powerline on the UGL stations and existing lines will be assessed in a separate AC interference study.

There is no risk of arcing along the close collocation (i.e., 4 m) between the proposed pipeline and the future 230 kV powerline. The actual separation distance of 4 m significantly exceeds the minimum separation distance of 1 m. Furthermore, the voltage difference under fault will not exceed 4.2 kV, well below the actual voltages (i.e., 28 to 30 kV), which did not sustain arcing at the same or lower separation during the CEA testing. The 4 m separation distance also exceeds the literature values and the existing separation distances in other similar projects. Therefore, no mitigation is required to specifically address the hazard of power arcing.

The predicted mitigated AC interference hazards are summarized in Table E-3.

Table E-3. Predicted Mitigated Hazards

Condition	Hazard	Limit	Predicted Value
Steady-State	Shock to Personnel	Touch Voltage – Max. 15 V	12 V – No hazard
	AC Corrosion	AC Current Density – Max. 50 A/m^2	44 A/m^2 – No hazard (minimum risk)
Fault	Shock to Personnel	Touch Voltage – Max. 356 V*	1,697 V, with dead-front test stations – No Hazard
		Metal-to-metal Voltage – Max. 356 V	N/A**
		Step Voltage – 356 V*	N/A**
	Power Arc	Minimum Separation Distance – 1 m	4 m – No hazard
	Coating Stress	Coating Stress Voltage – Max. 3 to 5 kV	1,697 V – No hazard

* Assuming zero soil resistivity.
** To be assessed as part of the study of AC interference on existing pipelines and UGL stations – see paragraphs 7.3.1.2 and 7.3.1.3.

The proposed LEP2 pipeline will be electrically isolated from the existing pipeline and protected by a sacrificial cathodic protection system. Subsequently, DC interference on the tower foundations of the future 230 kV powerline is expected to be negligible due to low current outputs. However, the existing lines are protected by an impressed current installation (rectifier #193) located at Mersea Road 10. As such, it is recommended that DC interference testing be conducted once the construction of the HONI powerline is completed.

1 General

Corrosion Service Company Limited (CSCL) was retained by Union Gas Limited (UGL) to conduct an AC interference study for the collocation of the proposed UGL NPS12 Leamington Expansion Phase II (LEP2) pipeline with the proposed Hydro One Networks Inc. (HONI) 230 kV powerline (SECTR Project) in Leamington, ON.

The objectives of the AC interference study were to ensure that the induced AC voltages are within safety limits under steady-state and fault conditions, to minimize the risk of AC corrosion, to avoid an arc striking between the pipeline and any grounded parts of a powerline structure, and to minimize excessive coating stress.

For the purpose of this study, the proposed LEP2 pipeline was considered electrically isolated from the stations and from the existing pipelines by installing three underground monolithic isolating fittings, as shown in Figure 3-1.

This option is the most conservative in terms of induced voltages and arcing along the LEP2 pipeline, but would reduce the induced voltages and subsequently the risk of AC corrosion on the existing lines.

The AC interference study was completed using Right-of-Way, software developed by Safe Engineering Services & technologies ltd. (SES). Pipeline data was obtained from UGL, and powerline parameters were obtained from HONI. A site survey, including soil resistivity measurements, was completed by CSCL personnel in April 2016.

2 Reference Specifications and Standards

The AC mitigation systems for the subject pipeline will be designed in accordance with the following standards, guidelines, and specifications:

- BS EN 15280-2013: *Evaluation of a.c. corrosion likelihood of buried pipelines applicable to cathodically protected pipelines*
- CSA Z662-15: *Oil and Gas Pipeline Systems*
- CAN/CSA-C22.3 No. 6-13: *Principles and Practices of Electrical Coordination between Pipelines and Electric Supply Lines*
- CIGRE, Working Group 36.02-1995: *Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines*
- IEEE Standard 80-2013: *Guide for Safety in AC Substation Grounding*
- NACE SP0177-2014: *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems*

3 Design Data & Assumptions

3.1 Right-of-Way Configuration

Figure 3-1 depicts the pipeline/powerline right-of-way configuration.

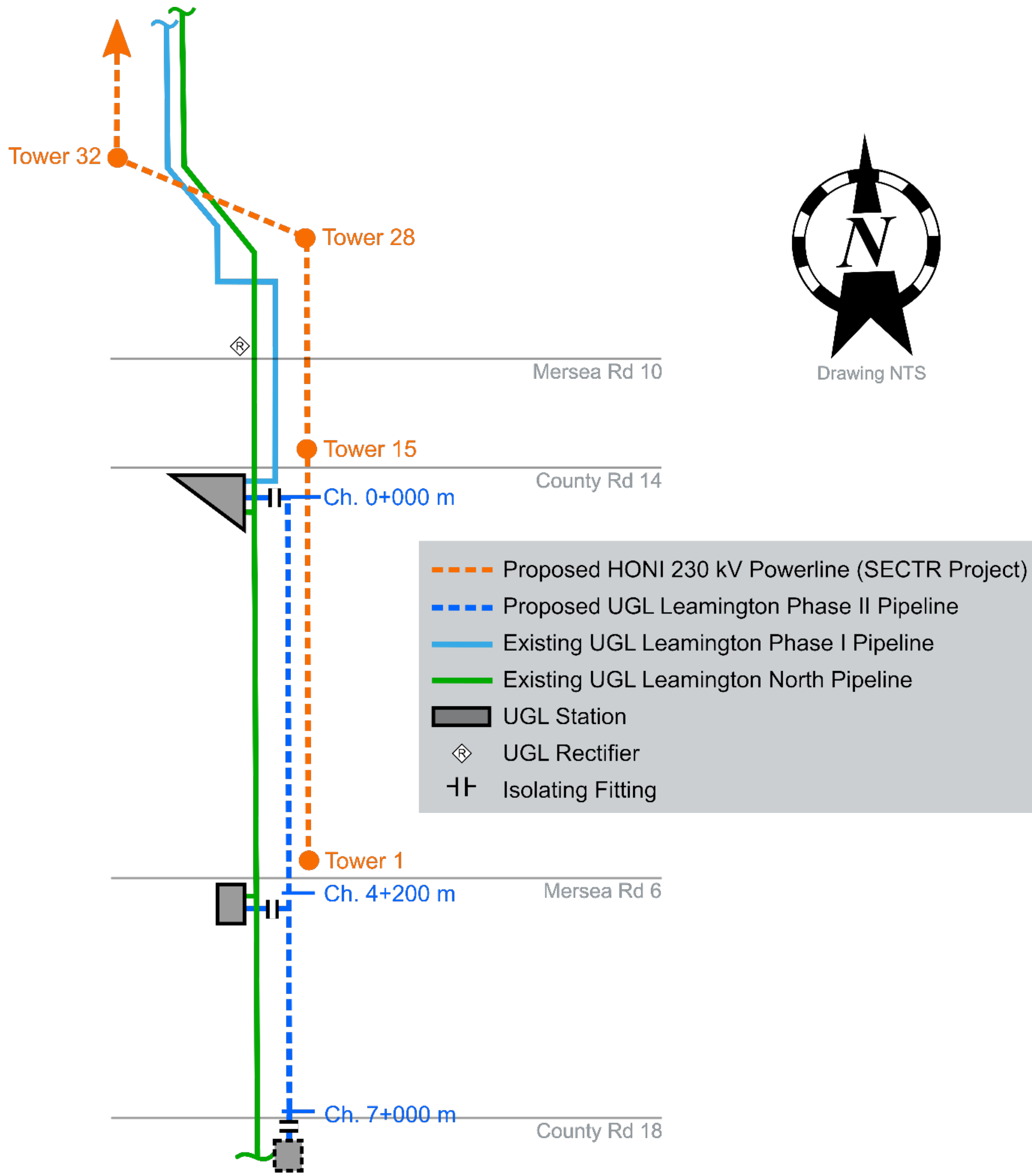

Figure 3-1. Pipeline/Powerline Right-of-Way Configuration

The proposed LEP2 pipeline is a continuation of the Leamington Phase I project (EB-2012-0431). The pipeline will extend for approximately 7 km from the UGL Transmission Station at County Road 14 to County Road 18 in Leamington, ON and will parallel the existing UGL NPS 8 Leamington North pipeline for its entire length.

The proposed pipeline will parallel the proposed HONI 230 kV powerline in close proximity (i.e., 4 m) for approximately 4 km from County Road 14 to Mersea Road 6. Three underground monolithic isolating fittings will be installed to electrically isolate the LEP2 pipeline from the stations and the other pipelines.

3.2 Pipeline Data

The new steel pipeline will be coated with 16 mils (0.4064 mm) of fusion bond epoxy, estimated to have a coating resistance of 80 kΩ-m². The parameters used to model the new and existing pipelines in the AC interference study are summarized in Table 3-1.

Table 3-1. Pipeline Parameters

Pipeline	Outer Diameter	Coating Resistance	Burial Depth
Leamington Expansion Phase I & II	323.9 mm	80 kΩ-m²	1.5 m
Leamington North	219.1 mm	20 kΩ-m²	1.5 m

The existing Leamington Expansion Phase I and Leamington North pipelines are cathodically protected by an impressed current system. The proposed LEP2 pipeline will be electrically isolated from the other two pipelines and subsequently will be protected by its own galvanic system. Table 3-2 provides the details of the cathodic protection systems.

Table 3-2. Cathodic Protection System

Pipeline	System	Location	Capacity	Output
Leamington Expansion Phase II	Galvanic Anodes	Distributed along the pipeline	<70 mA	-
Leamington North & Leamington Expansion Phase I	Impressed Current	Mersea Road 10	10 Anode Groundbed, Rectifier - 24 V, 12 A	250 mA

3.3 Powerline Data

The powerline configuration parameters, steady-state loading, and fault current contributions were provided by HONI. The powerline configuration parameters are summarized in Table 3-3.

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Table 3-3. Powerline Configuration Parameters

Parameter	Operating Details	
Circuit ID	C22J	C21J
System Voltage	230 kV	
Conductor Configuration	Double Circuit Vertical	
Horizontal Conductor Separation	8.23 m / 14.33 m / 8.23 m	
Vertical Conductor Separation	7.7 m	
Minimum Conductor Height	8 m	
Maximum Sag	10 m	
Shield Wire	2 – 7#5 Alumoweld	
Shield Wire Resistance	0.74278 Ω/km at 20^{o}C	
Tower Grounding	1 Augured Footing, 3.35 m dia. X 12 m deep	
Maximum Tower Grounding Resistance	20 Ω	
Average Span	280 m	
Phasing (top-bottom)	B-W-R	W-B-R
Primary Fault Duration	106 ms	

The steady-state loading is summarized in Table 3-4.

Table 3-4. Steady-State Loading

Steady-State Loading	Current (in 2018)	Projected
Peak	210 A	620 A
Average	150 A	470 A

The fault current contributions are summarized in Table 3-5.

Table 3-5. Fault Current Contributions

Fault Location	From North (A)	From South (A)	Total (A)
7 km from Leamington TS	7,166	326	7,492
4 km from Leamington TS	6,461	328	6,789
3.5 km from Leamington TS	6,357	329	6,686
2 km from Leamington TS	6,065	330	6,395
Outside Leamington TS	5,720	320	6,040

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3.4 Soil Resistivity

Soil resistivity measurements were taken using the Wenner 4-pin method along the proposed collocation during a site survey by CSCL personnel in April 2016. Deep measurements were taken using spacings of 1’, 2’, 5’, 10’, 15’, 20’, 30’, 50’, 75’, and 100’. Shallow measurements were taken using spacings of 1’, 2’, 5’, 10’, 15’, 20’, and 30’. Detailed resistivity measurements can be found in Appendix A. The soil stratigraphy was determined using Winsev6, software developed by W-Geosoft.

Historical soil resistivity measurements, obtained during a site survey by CSCL personnel in July 2004, were used in the area outside of the LEP2 pipeline and HONI 230 kV collocation.

Table 3-6 summarizes the soil resistivities used in the AC interference study.

Table 3-6. Soil Resistivity Data

ID	LEP2 Chainage (m)	Leamington North Chainage (m)	Closest Tower	Layer 1 Resistivity (Ω-m)	Thickness (m)	Layer 2 Resistivity (Ω-m)	Thickness (m)	Layer 3 Resistivity (Ω-m)
1	-	1+157	43	16	2.40	96	-	-
2	-	3+109	36	21	2.40	110	-	-
3	-	4+307	32	19	1.80	50	-	-
4	-	5+570	26	15	2.00	61	-	-
5	-	6+894	21	15	1.30	40	-	-
6	-	8+331	15	23	18.00	135	-	-
7	0+207	8+579	14	59	1.30	35	1.50	21
8	0+488	8+860	13	65	0.34	25	5.30	41
9	0+770	9+142	12	29	-	-	-	-
10	1+043	9+415	11	27	0.18	18	4.10	72
11	1+331	9+683	10	62	0.57	23	4.70	59
12	1+612	9+964	9	59	0.19	24	2.90	46
13	1+892	10+244	8	227	0.49	31	-	-
14	2+155	10+507	7	207	0.81	62	-	-
15	2+549	10+901	6	76	0.93	27	10.00	163
16	2+810	11+170	5	177	0.65	38		
17	3+140	11+500	4	79	0.67	34	-	-
18	3+491	11+851	3	44	0.20	27	2.50	47
19	3+782	12+142	2	45	-	-	-	-
20	4+007	12+380	1	488	0.90	48	7.60	2061
21	5+559	13+949	-	8	1.20	36	-	-
22	7+000	15+340	-	54	1.50	89	-	-
23	-	15+813	-	94	-	-	-	-

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4 Effects of AC Interference

A pipeline which runs in the proximity of a high voltage powerline is subject to voltages induced by magnetic coupling. These AC induced voltages (V_{AC}) appear both under steady-state and fault conditions and their magnitude depends on the phase current, on the length of parallelism, on the distance between pipeline and powerline, and on the pipeline-powerline configuration. The induced voltages reach maximum values at discontinuities[1] and gradually attenuate along the pipeline.

A recent NACE paper indicates that, under certain conditions, distribution powerlines (35 kV and lower) can also induce significant steady-state AC voltages on paralleling pipelines.[2] The phenomenon is attributed to the presence of 3rd harmonics of the fundamental 60 Hz frequency (i.e., 180 Hz, 360 Hz, etc.). Although these are typically a very small component of the load current, they may induce a substantial amount of AC voltage, as pipelines are hundreds of times more sensitive to AC induction of the 3rd harmonic frequency than the fundamental 60 Hz frequency.

A second type of AC interference on the pipelines, defined as “conductive coupling”, only appears under powerline fault conditions. The fault current flowing through the grounding of the high voltage structure (i.e., tower or pole) produces a potential rise in the neighboring soil defined as “ground potential rise” (GPR). Part of this rise is transferred to the pipe (V_{tr}) and would be added to the AC induced voltage.

The pipe voltage (V_{pipe}) is typically defined as the pipe voltage with respect to close ground (V_{P-CG}) and is the difference between the potential of the pipe itself (i.e., pipe metal) and the potential of the ground.

Under steady-state conditions, the AC interference could result in safety problems for people coming in contact with the metallic pipe or its appurtenances and in accelerated corrosion on the underground section of the pipe (i.e., AC corrosion).

Under fault conditions, the AC interference could result in damage to the pipe itself (i.e., electrical arc between the structure grounding and the pipe), in safety concerns for pipeline personnel and in damage to pipeline coating.

The hazards generated by AC interference are summarized in Table 4-1.

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[1] Start and end of the common ROW, phase transpositions, isolating fittings on the pipeline, etc.
[2] Boteler, D.H., Croall, S., and Nicholson, P., “Measurements of Higher Harmonics in AC Interference on Pipelines” *NACE Corrosion 2010*, Paper No. 10107.

Table 4-1. AC Interference Hazards

Condition	Hazard	Relevant Parameter	Symbol	Notes
Steady-State	Shock to Personnel	Touch Voltage	V_{touch}	Considered equal to V_{AC}.
	AC Corrosion	Current Density at Holidays	i_{AC}	Derived from the V_{AC} and soil resistivity.
Fault	Shock to Personnel	Touch Voltage	V_{touch}	Considered equal to V_{pipe} (or V_{P-CG}).
		Step Voltage	V_{step}	Dependent on the ground voltage gradient.
		Metal-to-Metal Touch Voltage	$V_{metal-metal}$	Considered equal to V_{pipe} (or V_{P-CG}).
	Power Arc	Pole/Pole Grounding Voltage	V_G	Derived from fault current, grounding electrode data, soil resistivity, etc. Cannot exceed the phase-to-ground voltage.
	Coating Stress	Coating Stress Voltage	V_{stress}	Equal to V_{pipe} (or V_{P-CG}).

5 Admissible Limits

5.1 Steady-State Conditions

5.1.1 Touch Voltage

The AC induced voltages under steady-state conditions shall not exceed 15 V at above-grade appurtenances of the pipeline in order to avoid an electrical shock to pipeline personnel or to the general public, as per NACE SP0177-2014.

5.1.2 AC Corrosion

There are no specified limits in the Canadian or NACE standards for prevention of AC corrosion on a pipeline.

European standard BS EN 15280:2013 provides criteria for evaluating the risk of AC corrosion after the mitigation system was already installed, using measured values of AC and DC current densities on coupons. It limits the AC current densities to 30 A/m^2 when the DC current density exceeds 1 A/m^2, but no upper limit is specified when the DC current density is lower or equal to 1 A/m^2.

A proposed NACE Standard under ballot is following the same approach, but it is expected to limit the AC current density to 100 A/m^2 when the DC current density is lower or equal to 1 A/m^2.

According to literature, there is no risk of AC corrosion for AC current densities less than 20 A/m^2, AC corrosion is unpredictable for AC current densities between 20-100 A/m^2, and AC corrosion is to be expected for AC current densities greater than 100 A/m^2.[3] In this same study, the highest corrosion rates were found on steel samples having a surface area in the range of 1 to 3 cm^2.

[3] Prinz, W. – "AC Induced Corrosion on Cathodically Protected Pipelines", UK Corrosion 92, Vol. 1.

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A subsequent study determined that the highest corrosion rates occurred for a holiday size of 6.45 cm^2.[4] As current densities are expected to be higher on smaller holidays, an area of 1 cm^2 was selected as the worst case value for our calculations (i.e., highest current density).

The maximum AC current density at a 1 cm^2 holiday can be calculated using the equation:

$$i_{AC} = \frac{8 \times V_{AC}}{\rho \times \pi \times d} \quad [1]$$

where

i_{AC} = AC current density (A/m^2)

V_{AC} = AC induced voltage (V)

ρ = Soil resistivity (Ω-m)

d = Diameter of holiday = 0.0113 m

The corrosion rates based on the calculated AC current density from several field investigations are summarized in Figure 5-1 and indicate that corrosion rates increase exponentially with current density.

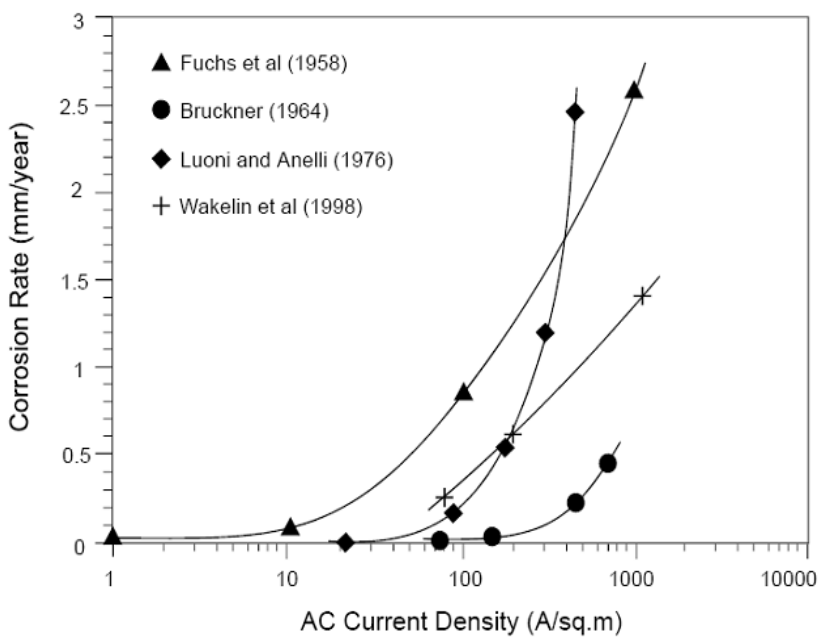

Figure 5-1. Corrosion Rate vs AC Current Density

The LEP2 pipeline will be protected using a galvanic system, therefore the DC current density is expected to be well below 1 A/m^2 at a 1 cm^2 holiday.

[4] Goidanich, S., Lazzari, L., Ormellese, M., and Pedeferri, M.P. – "Influence of AC on Carbon Steel Corrosion in Simulated Soil Conditions", 16th ICC, Paper 04-03, held September 19-24, Beijing, China, 2005.

Previous UGL projects used an AC current density of 50 A/m^2 at a 1 cm^2 holiday as the allowable limit to minimize the risk of AC corrosion.

With the proposed NACE Standard not yet officially issued and based on literature and the European Standard, the same 50 A/m^2 limit will be used for the LEP2 pipeline.

5.2 Fault Conditions

5.2.1 Hazardous Voltages

The recommended safety limits for AC voltage under fault conditions were calculated using the methodology specified in IEEE Standard 80 *Guide for Safety in AC Substation Grounding*.

5.2.1.1 Touch Voltage

For a person with a 50 kg body weight in uniform soil

$$V_{touch} = \frac{116 + 0.17 \times \rho}{\sqrt{t_f}} \qquad [2]$$

For a person with a 50 kg body weight standing on a 0.1 m stone layer[5]

$$V_{touch} = (1000 + 1.5 \times \rho_s \times C_s) \times \frac{0.116}{\sqrt{t_f}} \qquad [3]$$

where

V_{touch}	=	Touch voltage (V)
t_f	=	Duration of fault = 0.106 s
ρ	=	Soil resistivity, varies with location. A minimum of 0 Ω-m would be considered as the worst case for safety limit calculations.
ρ_s	=	Resistivity of the ¾" washed round stone layer = 3,000 Ω-m
C_s	=	Corrective factor, calculated as:

$$C_s = 1 - \frac{0.09 \times \left(1 - \frac{\rho}{\rho_s}\right)}{2 \times h_s + 0.09}$$

h_s	=	Thickness of the stone layer = 0.1 m

After calculations, the touch voltage limit in open field is 356 V, increasing to 1,462 V when using a 0.1 m layer of stone.

[5] An isolating layer of stone inside the station significantly reduces the current through the body in the event of contact with an above-grade appurtenance, when the pipeline voltage rises due to a fault on the high voltage powerline.

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5.2.1.2 Metal-to-Metal Touch Voltage

$$V_{metal-metal} = \frac{116}{\sqrt{t_f}} \qquad [4]$$

where

$V_{metal\text{-}metal}$ = Metal-to-metal voltage (V)

t_f = Duration of fault = 0.106 s

After calculations, the metal-to-metal voltage limit is 356 V. Note that since the voltage is developed across the body, the presence of a layer of stone does not affect the safety limit.

5.2.1.3 Step Voltage

For a person with a 50 kg body weight in uniform soil

$$V_{step} = \frac{116 + 0.696 \times \rho}{\sqrt{t_f}} \qquad [5]$$

For a person with a 50 kg body weight standing on a 0.1 m stone layer[6]

$$V_{step} = (1000 + 6 \times \rho_s \times C_s) \times \frac{0.116}{\sqrt{t_f}} \qquad [6]$$

where

V_{step} = Step Voltage (V)

t_f = Duration of fault = 0.106 s

ρ = Soil resistivity, varies with location. A minimum of 0 Ω-m would be considered as the worst case for safety limit calculations.

ρ_s = Resistivity of the ¾" washed round stone layer = 3,000 Ω-m

C_s = Corrective factor, calculated as:

$$C_s = 1 - \frac{0.09 \times \left(1 - \frac{\rho}{\rho_s}\right)}{2 \times h_s + 0.09}$$

h_s = Thickness of the stone layer = 0.1 m

After calculations, the step voltage limit in open field is 356 V, increasing to 4,779 V when using a 0.1 m layer of stone.

[6] An isolating layer of stone inside the station significantly reduces the current through the body in the event of contact with an above-grade appurtenance, when the pipeline voltage rises due to a fault on the high voltage powerline.

5.2.2 Risk of Arcing

There is no specified limit in the standards for the safe separation distance to prevent a power arc from damaging a pipeline.

Canadian Standard CAN/CSA-C-22.3 No. 6-13[7] states that "It is difficult to quantify the safe distance between the pipeline and the fault current discharging facilities. Historically, a distance of 10 m between the pipeline and the tower footings of power lines with shield wires has appeared to be a conservative value". The standard further clarifies that "The 10 m separation distance was established as a reasonable physical clearance during construction and maintenance activities".

When the powerline is not equipped with a shield wire, the standard indicates that "a 10 m separation is not as effective in reducing the probability of damage to the pipeline, and agreement between the pipeline and power line companies is advisable".

NACE SP0177-2014[8] also requires that a "minimum separation distance shall be maintained between powerline structure grounds and buried structures in order to ensure an arc initiated by lightning cannot be sustained by the fault current", but no numeric value is specified. However, the standard refers to CEA report 239 T-817[9] to indicate that "Testing has been performed up to tower-ground-to-pipeline voltages of approximately 45 kV and power arcs were found to be sustained up to distances of up to 5.5 m (18 ft) at this voltage".

The European guide[10] on the influence of high voltage powerlines on pipelines indicates that in low and medium soil resistivity areas, a power arc initiated by lightning would be unlikely, since "lightning can cause soil ionization only at a short distance (i.e., a few tens of cm) from a tower grounding electrode". The guide also states that "However this phenomenon is not well understood. In areas of high earth resistivity and lightning activity, a larger separation (i.e., a few meters) is recommended between a pipeline and a tower".

The CEA report 239 T 817 referenced in the NACE standard describes the tests that were conducted to determine the voltages required to sustain an arc to a pipeline through various soil types over a range of distances. The test results were used to develop regression formulas giving the critical voltage to sustain an arc as a function of the separation distance.

A particular "worst case scenario" was considered by the study authors to generate sets of safe distances, without having to calculate the actual voltage difference between the faulted tower and the pipeline. It noted that the voltage rise of the tower cannot exceed the phase-to-ground voltage of the powerline, used this value in the regression formulas, and proposed the values shown in Table 5-1.

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[7] CAN/CSA-C22.3 No. 6-13 – Principles and Practices of Electrical Coordination between Pipelines and Electric Supply Lines. Approved June 2014.
[8] NACE SP0177-2014 – Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems, Houston, 2014.
[9] Canadian Electricity Association (CEA) report 239 T 817 – Powerline Ground Fault Effects on Pipelines, Surrey, BC, December 1994.
[10] CIGRE, Working Group 36.02 - Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines, Paris, France, 2000, page 56.

Table 5-1. Safe Separation Distance (Worst Case Scenario)

System Voltage (kV)	Predicted Maximum Sustained Arc Length (m)
138	11
230	18
500	40

CSCL technical approach is to use the "worst case scenario" safe distances as a primary filter to estimate if there is any risk of arcing and to conduct detailed calculations to determine the actual voltage rise of the tower, when the separation distance is below the values indicated in Table 5-1.

A complete description of the arcing phenomena and CSCL calculation methodology is included in paragraph 6.2.2.1 of this report.

5.2.3 Coating Stress

When a fault occurs at a power generation station and the potential difference between the pipe and the ground exceeds the dielectric strength of the coating, the subsequent current transfer between the pipe and ground could damage the coating.

NACE SP0177-2014 *Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems* specifies threshold values of 2 kV for coal tar enamels and tape wraps, and 3-5 kV for fusion bond epoxy (FBE), polyethylene (PE) coatings, and high performance composite coatings.

5.3 Summary

The calculated safety limits are summarized in Table 5-2.

Table 5-2. Safety Limits

Condition	Hazard	Relevant Parameter	Safety Limit
Steady-State	Shock to Personnel	Touch Voltage	15 V
	AC Corrosion	Current Density at Holidays	50 A/m^2
Fault	Shock to Personnel	Touch Voltage	356 V*
		Touch Voltage with Stone Layer	1462 V
		Metal-to-Metal Touch Voltage	356 V
		Step Voltage	356 V*
		Step Voltage with Stone Layer	4,779 V
	Power Arc	Minimum Separation Distance	1 m – see paragraph 6.2.2
	Coating Stress	Coating Stress Voltage	3,000 to 5,000 V**

* A minimum soil resistivity of 0 Ω-m was considered as the worst case for safety limit calculations.

** Recommended range.

6 Predicted Unmitigated AC Interference

The hazards predicted along the LEP2 pipeline under steady-state and phase-to-ground fault conditions on the powerline were evaluated using Right-of-Way, software developed by SES.

6.1 Steady-State Conditions

6.1.1 Touch Voltage

Unmitigated touch voltages predicted along the LEP2 pipeline, under peak steady-state powerline operating conditions, are shown in Figure 6-1.

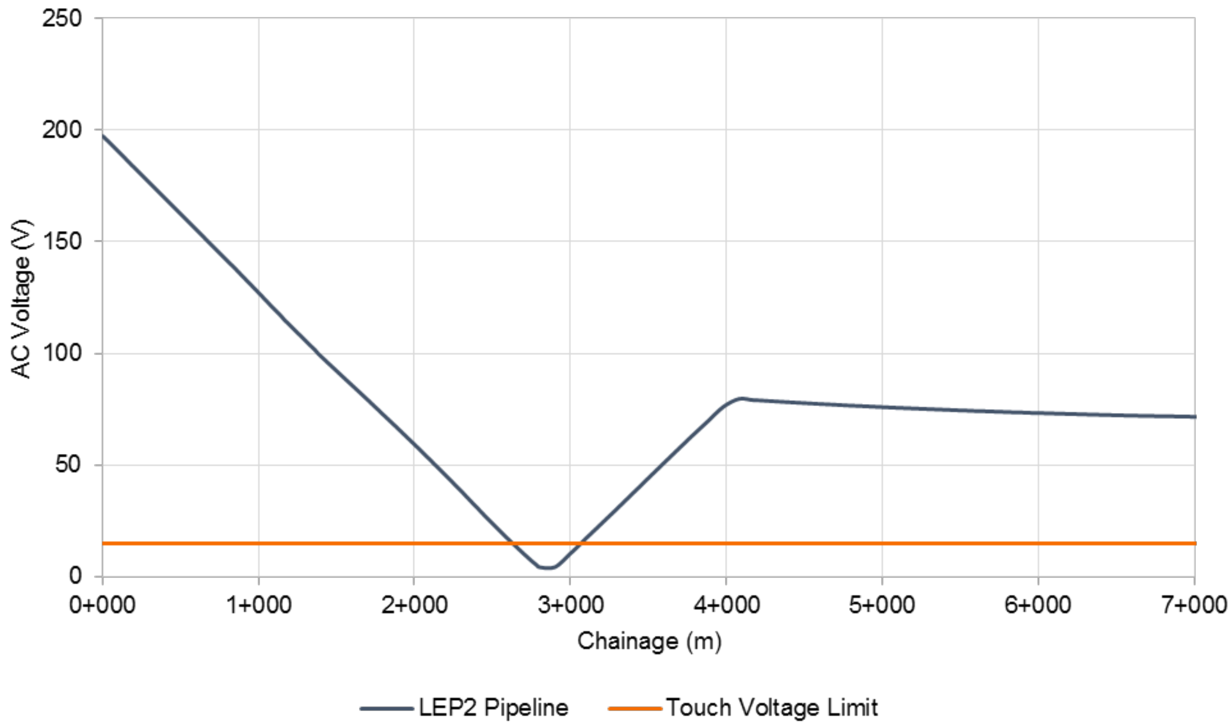

Figure 6-1. Predicted Unmitigated Touch Voltages under Steady-State Conditions

As shown, the unmitigated touch voltages predicted along the LEP2 pipeline exceed the 15 V safety limit from Ch. 0+000 m to Ch. 2+603 m and Ch. 3+079 m to Ch. 7+020 m. The maximum unmitigated touch voltage is 197 V at Ch. 0+000 m. As such, mitigation is required.

6.1.2 AC Corrosion

Unmitigated AC current densities predicted along the LEP2 pipeline, under average steady-state powerline operating conditions, are shown in Figure 6-2.

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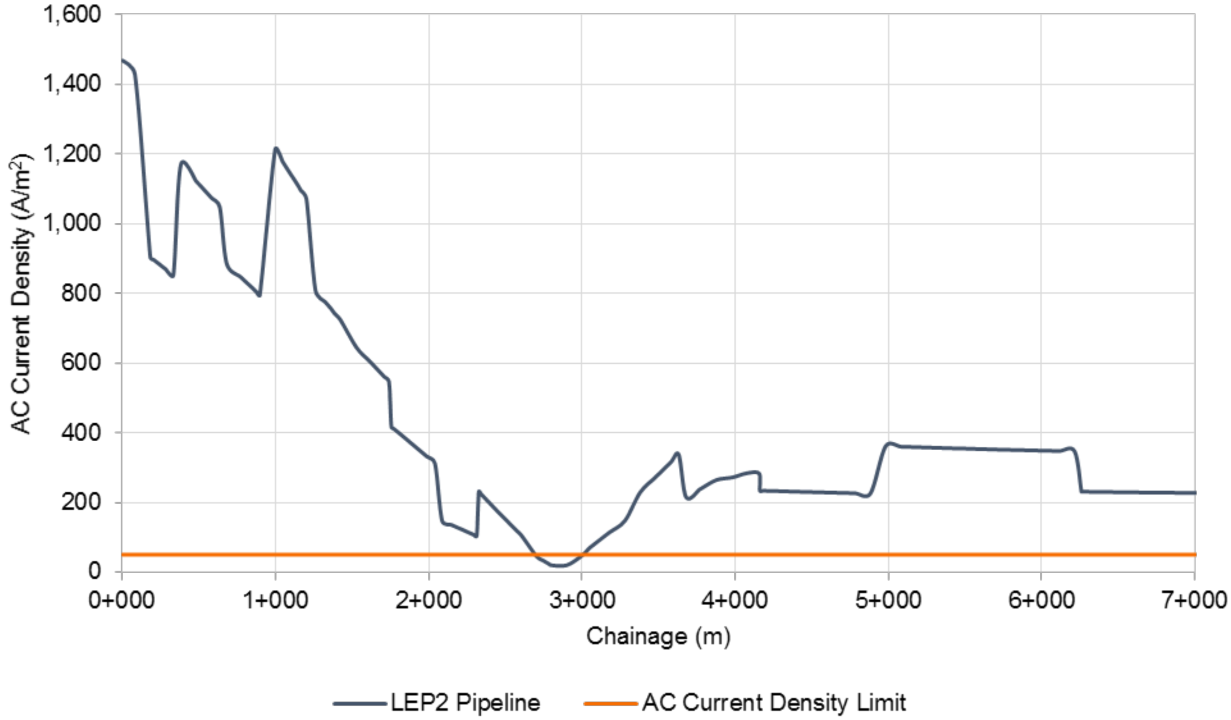

Figure 6-2. Predicted Unmitigated AC Current Densities under Average Steady-State Conditions

As shown, the unmitigated AC current densities predicted along the LEP2 pipeline exceed the 50 A/m^2 limit from Ch. 0+000 m to Ch. 2+603 m and Ch. 3+046 m to Ch. 7+020 m. The maximum unmitigated AC current density is 1,468 A/m^2. As such, there is an elevated risk of AC corrosion and mitigation is required.

6.2 Fault Conditions

6.2.1 Hazardous Voltages

6.2.1.1 Touch Voltage

Unmitigated touch voltages predicted along the LEP2 pipeline, under phase-to-ground fault conditions on the powerline, are shown in Figure 6-3.

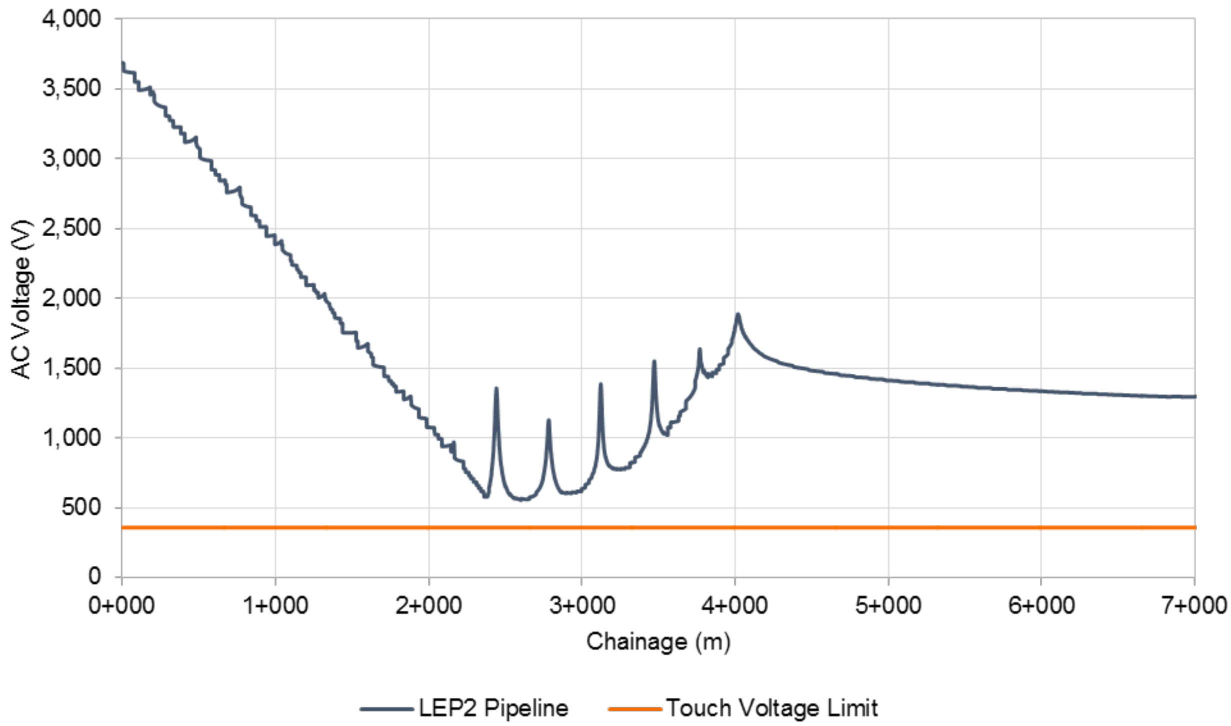

Figure 6-3. Predicted Unmitigated Touch Voltages under Fault Conditions

As shown, the unmitigated touch voltages predicted along the LEP2 exceed the 356 V open field safety limit the entire length of the pipeline. The maximum unmitigated touch voltage is 3,686 V. As such, mitigation is required.

6.2.1.2 Metal-to-Metal Touch Voltage

The installation of underground monolithic isolating fittings to electrically isolate the LEP2 pipeline from the stations and other existing UGL pipelines will prevent the transfer of hazardous induced voltages from the LEP2 pipeline to the UGL stations. As such, there are no metal-to-metal touch hazards at above-grade appurtenances within the UGL stations due to the installation of the proposed LEP2 pipeline.

However, hazardous induced voltages may be transferred inside the station by the existing pipelines and subsequently this safety risk will be assessed as part of the future study dealing with AC interference on the existing pipelines.

6.2.1.3 Step Voltage

With the LEP2 pipeline electrically isolated, the step voltage safety hazard at the UGL stations will not be affected by the installation of the new line and subsequently will also be assessed as part of the future study dealing with AC interference on the existing pipelines.

6.2.2 Risk of Arcing

6.2.2.1 Technical Background

When lightning hits a powerline tower or the shield wire, the lightning current is discharged to ground via the tower foundations and via any additional grounding electrodes. The duration of the lightning discharge is extremely short (microseconds), but the current and the voltages are very high. These voltages can ionize the soil around the foundations, especially in high resistivity soil, increasing the apparent radius of the foundation acting as a grounding electrode and subsequently reducing its impulse resistance. The radius of the ionized area depends on the soil resistivity, the crest value of the lightning current, and the ionization gradient of the soil. The discharge of lightning current via the tower foundation creates a radial voltage gradient, which may be distorted by the presence of an electrically long pipeline.

From the edge of the ionized area, streamers can extend in various directions until the average gradient equals the breakdown gradient of the soil. If the pipeline is close enough to the tower that a streamer reaches the pipe, an ionized channel would be established between the tower foundation and the pipeline.

The total reach of the lightning arc as measured from the edge of the tower foundation may be calculating using equations developed by E. D. Sunde[11]:

In low resistivity soils (i.e., $\rho \leq 100$ Ω-m)

$$r = 0.08\sqrt{J \times \rho} \quad [7]$$

In high resistivity soils (i.e., $\rho \geq 1{,}000$ Ω-m)

$$r = 0.046\sqrt{J \times \rho} \quad [8]$$

where

- r = Maximum distance at which a lightning arc can develop (m)
- J = Lightning crest current (kA)
- ρ = Soil resistivity at pipe depth (Ω-m)

For reference, based on the typical low soil resistivities measured along the shared right-of-way (i.e., around 30 Ω-m), only streamers originating from lightning currents exceeding 80 kA would reach a pipeline located 4 m away.

Furthermore, due to the very low energy carried by such a “lightning arc”, the damage to the pipe would be negligible.

However, although a lightning arc would not damage the pipe, the ionized channel in soil may be “used” by a lightning initiated fault current (i.e., a power arc) to hit the pipe. In this case, the damage could be significant, with risk of pipeline rupture or explosion.

If the phase-to-ground fault is not initiated by lightning or if the distance between the powerline and pipeline is higher than the reach of the lightning arc, then an ionized channel would not be

[11] Sunde, E. D., 1949, Earth Conduction Effects in Transmission Systems, D. van Nostrand Co., Inc.

established through the soil, and the fault current itself would have to initiate the arc. The safe distance required to avoid initiating a power arc is defined as “flashover safe distance” and is significantly smaller than the safe distance required to avoid “sustaining” an arc initiated by lightning.

It is industry practice to assume the worst case scenario (i.e., that an ionized channel was already initiated by lightning) and to calculate the safe distance to sustain an arc. For reference, Rule 5.3 of CAN/CSA C22.3 No. 6-13 Standard states “The probability of a power line fault current causing serious damage to a pipeline increases when the fault current arc in the soil is sustained until the fault is automatically cleared by the powerline’s protection”. NACE Standard SP0177-2014 also states in paragraph 4.14 that “A minimum separation distance shall be maintained between powerline structure grounds and buried structures in order to ensure an arc initiated by lightning cannot be sustained by the fault current”.

Rule 5.3 of CAN/CSA C22.32 No. 6-13 Standard further clarifies that “The probability of the fault current arc being sustained depends on factors such as distance, pipeline coating characteristics, and the potential difference between the fault current discharge facility and the pipeline”. Paragraph 4.14.2 of NACE Standard SP0177-2014 is even more specific, stating that “The sustainable arc length is a function of the GPR of the faulted powerline structure and of the soil resistivity”. It also references CEA Report 239 T 817, mentioning in the same paragraph that “Testing has been performed up to tower-ground-to-pipeline voltages of approximately 45 kV and power arcs were found to be sustained up to distances of up to 5.5 m (18 ft) at this voltage”.

Based on our knowledge, the referenced CEA study is the only source to provide regression formulas to calculate the safe separation as a function of the difference in potential between the faulted tower and the pipeline in various resistivity soils, as well as to disclose the actual test results.

The report describes the tests that were conducted to determine the voltages required to sustain an arc initiated by lightning through various soil types over a range of distances. The test results were used to develop two regression formulas giving the critical voltage to sustain an arc (*V*) in kV as a function of the separation distance (*D*) in cm:

In native soil (soil resistivity of 15,000 Ω-cm wet and 55,000 Ω-cm dry)

Linear regression formula:

$$V = 5.801 + 0.0703D \quad [9]$$

Geometric regression formula:

$$V = 0.6375D^{0.6659} \quad [10]$$

In sand (soil resistivity of 45,000 Ω-cm wet and 75,000 Ω-cm dry)

Linear regression formula:

$$V = 0.3564 + 0.0845D \quad [11]$$

Geometric regression formula:

$$V = 0.1272D^{0.9318} \quad [12]$$

In top soil (soil resistivity of 6,500 Ω-cm wet and dry)

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<u>Tests at 8 kA</u>

Linear regression formula:

$$V = 0.1296 + 0.09450D \quad [13]$$

Geometric regression formula:

$$V = 0.05097D^{1.106} \quad [14]$$

<u>Tests at 4 kA</u>

Linear regression formula:

$$V = 9.137 + 0.0557D \quad [15]$$

Geometric regression formula:

$$V = 7.821D^{0.2315} \quad [16]$$

The report mentions that "a general trend was noted which indicated that it was easier to sustain the arc at lower arc currents i.e. for higher source impedances". This behavior was attributed to the transient recovery voltage characteristics of the Powertech High Power Laboratory test circuits.

A "worst case scenario" was considered by the study authors to generate "absolute" safe separation distance, by assuming the highest possible voltage rise of a tower (i.e., the phase-to-ground voltage of the powerline). The safe distance calculated under this worst case scenario are shown in Table 5-1.

For example, the phase-ground-voltage of a 230 kV line is:

$$\frac{230}{\sqrt{3}} = 132.8\ kV$$

Introducing this value in the linear regression equation for native soil, the worst case safe distance would be:

$$D = \frac{132.8 - 5.801}{0.0703} = 1806.5\ cm = 18\ m$$

This matches the value in Table 5-1.

The actual voltage rise of the tower for lines equipped with shield wires, rarely exceeds 25 to 30 kV, therefore a safe distance of 10 m is considered conservative by CAN/CSA C22.3 No. 6-13 Standard. The Standard also clarifies that "The 10 m separation distance was established as a reasonable physical clearance during construction and maintenance activities".

CSCL has used the "worst case scenario" safe distances as a first approach to estimate if there is any risk of arcing and has conducted detailed calculations to determine the actual voltage rise of the tower, when the separation distance was below the values indicated in Table 5-1.

This methodology has been successfully used in more than 1,000 projects, including situations of close proximity that are similar or even more severe than those found in this project.

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6.2.2.2 Methodology & Calculations

Step 1 – Check if the separation distance at each tower exceeds the “worst case scenario” safe distance indicated in Table 5-1.

The separation distance (i.e., 4 m) is less than the value indicated in Table 5-1 (i.e., 18 m), therefore detailed calculations must be conducted.

Step 2 – Calculate the distribution of the fault current and the voltage rise of the tower for each tower of the close collocation.

The calculations were conducted using Right-of-way, software developed by SES. Powerline details and operating parameters were provided by HONI – see paragraph 3.3. Site data including soil resistivity measurements, were collected by CSCL in April 2016. The soil resistivity stratigraphy (i.e., resistivities per layer) was calculated from the apparent resistivities using Winsev6, software developed by W-Geosoft – see paragraph 3.4.

The calculations were conducted initially using the maximum tower grounding resistance provided by HONI (i.e., 20 Ω), representing the “worst case scenario” in terms of voltage rise of the tower. A second set of calculations was then conducted based on tower foundation geometry and measured soil resistivities at each tower location, to determine the actual current distribution.

The calculation results, assuming maximum grounding resistance, are summarized in Table 6-1 and the results for the calculated ground resistance are summarized in Table 6-2.

Table 6-1. Current Distribution and Voltage Rise of the Towers Assuming a Maximum Tower Resistance of 20 Ω

Tower	Total Fault Current (A)	Tower Resistance (Ω)	Tower Fault Current** (A)	Tower Voltage Rise (V)
1	6,040*	20	87	1,748
2	6,082	20	106	2,129
3	6,132	20	131	2,615
4	6,190	20	157	3,134
5	6,247	20	178	3,555
6	6,303	20	195	3,891
7	6,350	20	206	4,112
8	6,395*	20	215	4,295
9	6,454	20	223	4,452
10	6,513	20	229	4,582
11	6,570	20	234	4,687
12	6,627	20	239	4,773
13	6,686*	20	242	4,843
14	6,741	20	245	4,897
15	6,789*	20	247	4,940

* Values provided by HONI. All other values were estimated using linear interpolation.
** Defined as the part of the total fault current discharged via the grounding of the faulted tower.

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Table 6-2. Current Distribution and Voltage Rise of the Towers Using the Calculated Tower Resistance Based on Measured Soil Resistivities at Each Tower

Tower	Total Fault Current (A)	Tower Resistance (Ω)	Tower Fault Current** (A)	Tower Voltage Rise (V)
1	6,040*	5.82	325	1,624
2	6,082	1.87	363	1,817
3	6,132	1.74	412	2,059
4	6,190	1.44	454	2,268
5	6,247	1.63	478	2,389
6	6,303	1.81	491	2,457
7	6,350	2.66	499	2,493
8	6395*	1.32	501	2,506
9	6,454	1.63	503	2,513
10	6,513	1.68	504	2,518
11	6,570	1.72	504	2,518
12	6,627	1.21	502	2,508
13	6,686*	1.40	497	2,484
14	6,741	0.95	489	2,445
15	6,789*	1.22	483	2,417

* Values provided by HONI. All other values were estimated using linear interpolation.
** Defined as the part of the total fault current discharged via the grounding of the faulted tower.

Step 3 – Calculate the vectorial voltage difference between the faulted tower and the pipeline using the induced voltages under fault and the voltage rise of the towers, conservatively assuming they are 180^0 out of phase.

Note: The mitigated induced voltages on the pipeline are typically less than 1 kV and subsequently were considered negligible compared to the phase-to-ground voltages used in Table 5-1 under the “worst case scenario” (i.e., 132.8 kV for a 230 kV powerline).

The unmitigated induced voltages under fault were calculated using Right-of-way, software developed by SES.

The calculated voltage differences between the faulted towers and the pipeline assuming maximum grounding resistance are summarized in Table 6-3 and for the calculated grounding resistance are summarized in Table 6-4.

Table 6-3. Voltage Difference between Faulted Tower and Pipeline Assuming a Maximum Tower Resistance of 20 Ω

Tower	Tower Voltage Rise (V)	Pipeline Induced Voltage* (V)	Voltage Difference (V)
1	1,748	1,562	3,309
2	2,129	1,282	3,411
3	2,615	952	3,567
4	3,134	654	3,788
5	3,555	454	4,009
6	3,891	384	4,275
7	4,112	417	4,529
8	4,295	500	4,795
9	4,452	580	5,032
10	4,582	664	5,246
11	4,687	730	5,416
12	4,773	801	5,573
13	4,843	847	5,691
14	4,897	897	5,794
15	4,940	858	5,798

* Includes transferred voltage to the pipe.

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Table 6-4. Voltage Difference between Faulted Tower and Pipeline Using the Calculated Tower Resistance Based on Measured Soil Resistivities at Each Tower

Tower	Tower Voltage Rise (V)	Pipeline Induced Voltage* (V)	Voltage Difference (V)
1	1,503	1,459	2,962
2	1,734	1,169	2,903
3	1,995	911	2,906
4	2,231	696	2,927
5	2,374	552	2,926
6	2,457	553	3,010
7	2,493	427	2,920
8	2,506	424	2,930
9	2,513	447	2,960
10	2,518	480	2,998
11	2,518	509	3,027
12	2,508	467	2,975
13	2,484	489	2,973
14	2,445	475	2,920
15	2,417	506	2,922

* Includes transferred voltage to the pipe.

Step 3 – Calculate the safe separation distance between the pipeline and the closest grounded part of the tower (i.e., foundation edge) using CEA regression formulas.

The calculated safe separation distances assuming maximum grounding resistance are summarized in Table 6-5 and for the calculated grounding resistance are summarized in Table 6-6.

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Table 6-5. Minimum Calculated Safe Separation Distances Assuming a Maximum Tower Resistance of 20 Ω

Tower	Voltage Difference (V)	Minimum Safe Distance* (cm)							
		Native Soil		Sand		Top Soil			
						8 kA		4 kA	
		Lin**	Geo***	Lin*	Geo***	Lin**	Geo***	Lin**	Geo***
1	3,309	N/A	11.86	34.95	33.03	33.65	43.52	N/A	0.02
2	3,411	N/A	12.41	36.15	34.11	34.72	44.73	N/A	0.03
3	3,567	N/A	13.28	38.00	35.79	36.38	46.58	N/A	0.03
4	3,788	N/A	14.53	40.61	38.18	38.71	49.18	N/A	0.04
5	4,009	N/A	15.82	43.22	40.57	41.05	51.76	N/A	0.06
6	4,275	N/A	17.42	46.37	43.47	43.87	54.86	N/A	0.07
7	4,529	N/A	19.00	49.38	46.25	46.56	57.80	N/A	0.09
8	4,795	N/A	20.70	52.52	49.16	49.37	60.86	N/A	0.12
9	5,032	N/A	22.26	55.34	51.78	51.88	63.58	N/A	0.15
10	5,246	N/A	23.69	57.86	54.15	54.14	66.01	N/A	0.18
11	5,416	N/A	24.86	59.88	56.04	55.94	67.95	N/A	0.20
12	5,573	N/A	25.95	61.74	57.78	57.61	69.73	N/A	0.23
13	5,691	N/A	26.77	63.13	59.09	58.85	71.05	N/A	0.25
14	5,794	N/A	27.50	64.35	60.24	59.94	72.22	N/A	0.27
15	5,798	N/A	27.53	64.40	60.29	59.98	72.26	N/A	0.27

* N/A is used where the voltage difference is too low to sustain an arc.
** Linear regression.
*** Geometric regression.

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Table 6-6. Minimum Calculated Safe Separation Distances Using the Calculated Tower Resistance Based on Measured Soil Resistivities at Each Tower

Tower	Voltage Difference (V)	Minimum Safe Distance* (cm)							
		Native Soil		Sand		Top Soil			
						8 kA		4 kA	
		Lin**	Geo***	Lin*	Geo***	Lin**	Geo***	Lin**	Geo***
1	2,962	N/A	10.04	30.83	29.32	29.97	39.37	N/A	0.02
2	2,903	N/A	9.74	30.14	28.69	29.35	38.66	N/A	0.01
3	2,906	N/A	9.76	30.17	28.72	29.38	38.69	N/A	0.01
4	2,927	N/A	9.86	30.42	28.94	29.60	38.95	N/A	0.01
5	2,926	N/A	9.86	30.41	28.94	29.59	38.94	N/A	0.01
6	3,010	N/A	10.28	31.40	29.82	30.48	39.94	N/A	0.02
7	2,920	N/A	9.83	30.33	28.87	29.52	38.86	N/A	0.01
8	2,930	N/A	9.88	30.45	28.98	29.63	38.98	N/A	0.01
9	2,960	N/A	10.03	30.81	29.30	29.95	39.35	N/A	0.02
10	2,998	N/A	10.23	31.26	29.70	30.35	39.81	N/A	0.02
11	3,027	N/A	10.38	31.61	30.01	30.66	40.15	N/A	0.02
12	2,975	N/A	10.11	30.99	29.46	30.11	39.53	N/A	0.02
13	2,973	N/A	10.10	30.97	29.44	30.09	39.50	N/A	0.02
14	2,920	N/A	9.83	30.34	28.87	29.53	38.87	N/A	0.01
15	2,922	N/A	9.84	30.36	28.90	29.55	38.89	N/A	0.01

* N/A is used where the voltage difference is too low to sustain an arc.
** Linear regression.
*** Geometric regression.

The required safe separation distance is less than 1 m, therefore there is no risk of arcing with an actual separation distance of 4 m.

Step 5 – Validate that there is no risk of arcing at the actual separation distance of 4 m by comparing the calculated voltage difference between the faulted towers and the pipeline with the test voltage which did not sustain an arc at a similar distance, as recorded during the CEA testing.

A plot of the CEA test data in native soil is shown in Figure 6-4 (Figure 3.4 in the CEA study).

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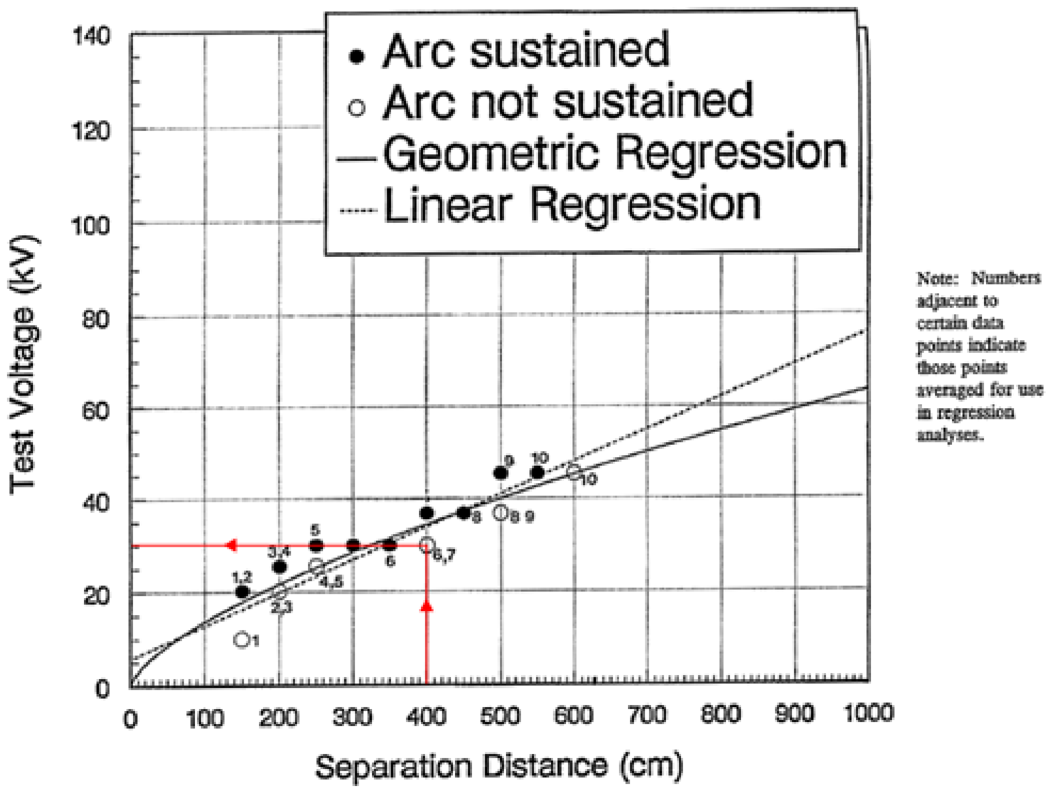

Figure 6-4. CEA Test Data in Native Soil

Tests conducted at 4 m separation indicated that arcs for an average test voltage of 30 kV were not sustained. With the maximum voltage between a faulted tower and the pipeline of less than 5.8 kV under maximum tower grounding resistance of 20 Ω and less than 3.1 kV using the calculated tower resistance, there is no risk of a power arc damaging the pipeline in native soil.

A plot of the CEA test data in sand is shown in Figure 6-5 (Figure 3.5 in the CEA Study).

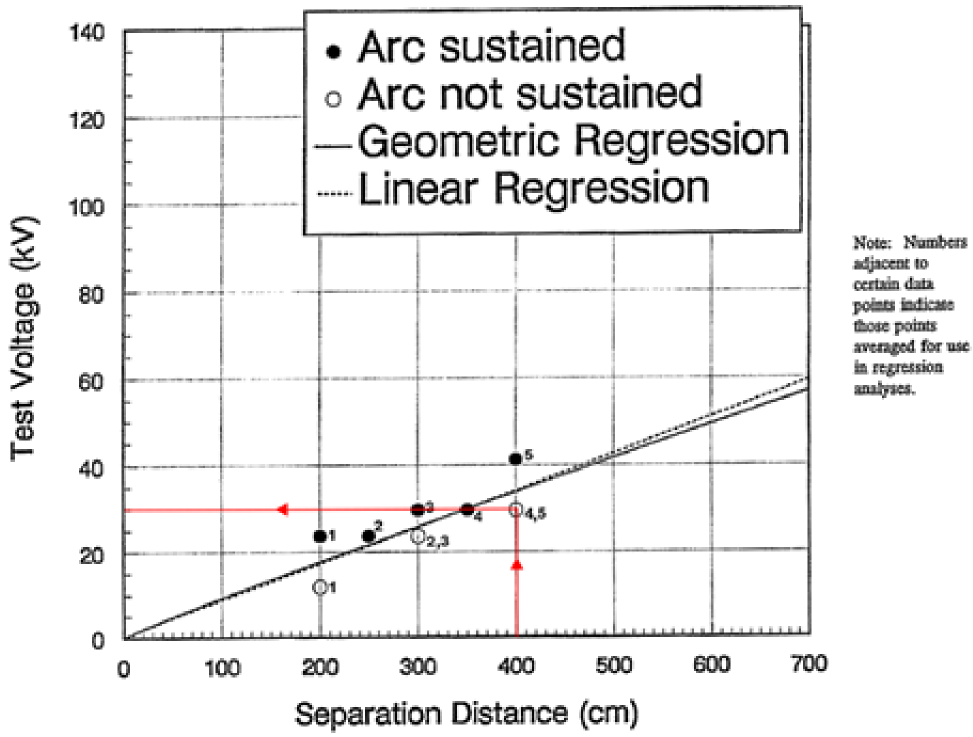

Figure 6-5. CEA Test Data in Sand

Tests conducted at 4 m separation indicated that arcs for an average test voltage of 30 kV were not sustained. With the maximum voltage between a faulted tower and the pipeline of less than 5.8 kV under maximum tower grounding resistance of 20 Ω and less than 3.1 kV using the calculated tower resistance, there is no risk of a power arc damaging the pipeline in sand.

Plots of the CEA test data in top soil are shown in Figure 6-6 and Figure 6-7 for currents of 8 kA rms and 4 kA rms, respectively (Figures 3.6 and 3.7 in the CEA study).

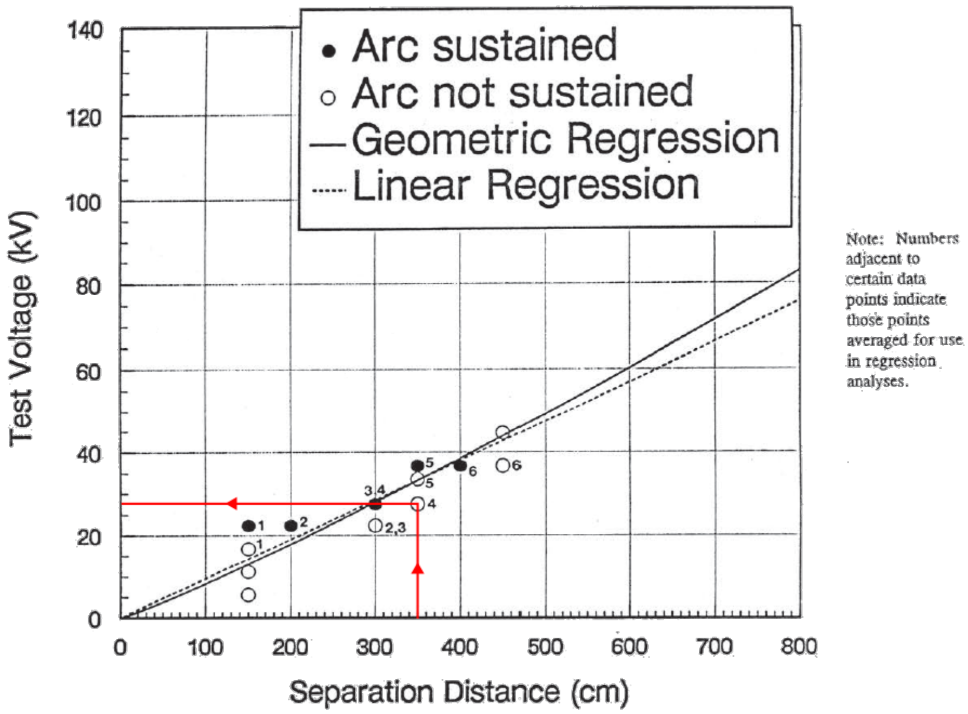

Figure 6-6. CEA Test Data in Top Soil (8 kA)

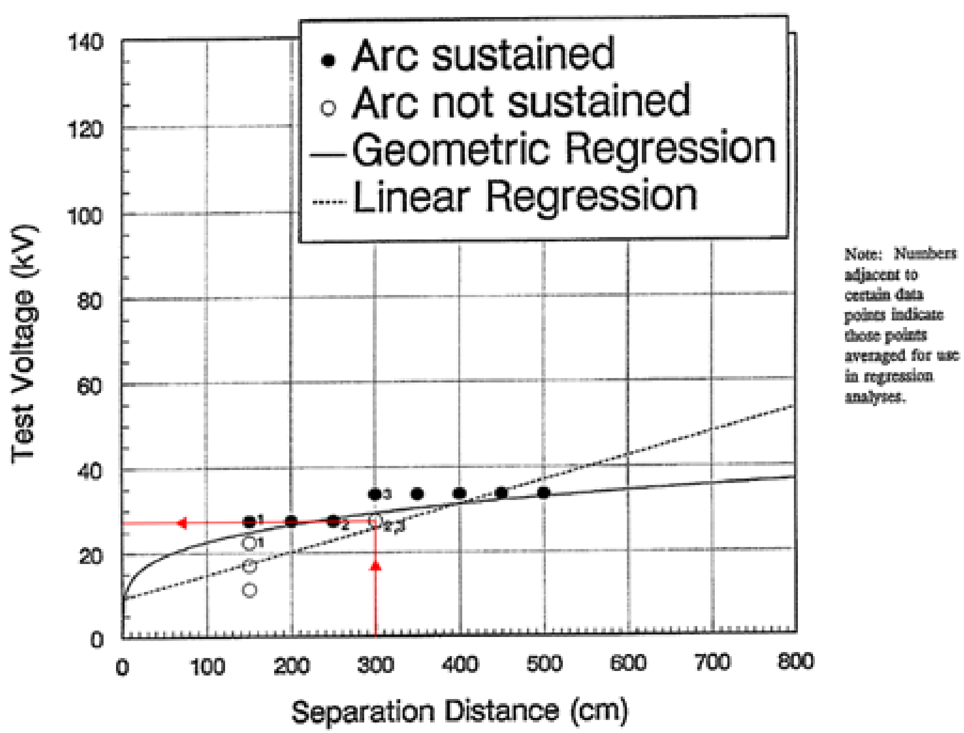

Figure 6-7. CEA Test Data in Top Soil (4 kA)

Tests conducted at 3.5 m separation at 8 kA and 3 m separation at 4 kA indicated that arcs for average test voltages of 28 kV, for both cases, were not sustained. With the maximum voltage between a faulted tower and the pipeline of less than 5.8 kV under maximum tower grounding resistance of 20 Ω and less than 3.1 kV using the calculated tower resistance, there is no risk of a power arc damaging the pipeline in top soil.

Step 6 – Compare the minimum safe separation distance with the recommended safe distances in literature and in previous similar projects.

The European Guide[12] on the influence of high voltage powerlines on pipelines addresses the question if "a power-frequency discharge could be observed for large pipeline-to-tower separations when the discharge was initiated by a lightning stroke to the tower" by stating that "this event appears rather unlikely to occur because:

- In low and medium earth resistivity areas, lightning can cause soil ionization only at a short distance (i.e., few tens of cm) from a tower grounding electrode.
- The soil discharge resulting from lightning would probably have been dissipated by the time the power frequency fault current be established.

However, this phenomenon is not well understood. In areas of high earth resistivity and lightning activity, a larger separation (i.e., a few meters) is recommended between a pipeline and a tower".

The collocation area in the Leamington utility corridor displays low soil resistivities preventing even the lightning arc reaching the pipe and opening an ionized channel, but even in areas of high soil resistivity, the 4 m separation distance satisfies the "a few meters" recommendation.

NACE Standard SP0177-2015, paragraph 4.14.2 refers to the CEA study (reference 27) by stating that "Testing has been performed up to tower-ground-to-pipeline voltages of approximately 45 kV and power arcs were found to be sustained up to distances of up to 5.5 m (18 ft) at this voltage". As indicated in step 5, a 4 m separation distance is very conservative for a voltage difference of 3.1 kV.

The pipelines known as the Joint Pipelines[13] (JPL), share a common right-of-way with HONI high voltage AC powerlines for more than 50 years across the northern boundary of Toronto (Finch corridor). The separation distances are minimal (i.e., 2.6 m between Sun-Canadian Pipeline Co. line and the high voltage tower foundation at Dufferin Street crossing). No arcing damage has ever been reported.

Pacific Gas and Electric Company (PG&E) is one of the largest combination gas and electric utilities in the US. In 2012, the utility implemented a proactive program to investigate and mitigate the risks to its existing pipeline infrastructure from AC interference, with special emphasis on the risk of arcing.[14] 7,041 sites were initially identified where the separation distance was less than 25

[12] CIGRE, Working Group 36.02 - Guide on the Influence of High Voltage AC Power Systems on Metallic Pipelines, Paris, France, 2000, page 56.
[13] The JPL group consists of Enbridge Pipelines Inc, Sarnia Products Pipeline Co. Ltd., Sun-Canadian Pipe Line Co. Ltd. And Trans-Northern Pipelines Inc.
[14] W. Fieltsch, B. Winget – Mitigation of Arcing Risks to Pipelines Due to Phase-to-ground Faults at Adjacent Transmission Powerline Structures, Paper 4389, NACE Conference 2014, San Antonio, TX.

ft (7.6 m). CSCL calculations were conducted using Sunde equations and then CEA regression formulas were used to calculate the safe separation distance. The collocations where the minimum separation distance was not satisfied were then prioritized for remedial work. Note that although the probability of lightning in California is low, the majority of PG&E powerlines have no shield wires, resulting in high tower voltage rises. Arcing damage has never been reported.

Another combination gas and electric utility in Texas installed a new pipeline in 2008 in parallel with an existing 138 kV powerline. Due to right-of-way restrictions, the separation distance was less than 3 m. The phase-to-ground fault current exceeded 30 kA, which is significantly higher than the 7.5 kA on the proposed HONI 230 KV SECTR line. The voltage rise of the towers varied between 8.28 kV and 26 kV, with mitigated induced voltages on the pipeline of less than 1 kV. Arcing damage has never been reported.

6.2.2.3 Conclusions

Due to low fault current (i.e., 7.5 kA), low shield wire impedances (i.e., 0.7 Ω/km) and connection of the shield wires to a nearby substation, the maximum fault current discharged at a tower does not exceed 510 A. The voltage rise of the tower does not exceed 2.5 kV and the total voltage difference between the tower grounding and the pipe is less than 3.1 kV.

The safe separation distance calculated using CEA study regression formulas for this very low voltage difference is less than 1 m.

However, to avoid any possible inaccuracies resulting from CEA test data interpolation, the calculated voltage difference between the faulted tower and pipeline was compared with the critical voltage, which did not sustain an arc during the CEA tests in various soils at the same or smaller separation distance (i.e., less or equal to 4 m).

In all cases, the actual voltage difference was well below the critical voltage.

Finally, the 4 m separation distance exceeds the calculated safe separation distances, the literature values and the existing separation distances in other similar projects.

6.2.3 Coating Stress

As shown in Figure 6-3, the maximum unmitigated coating stress (i.e., 3,686 V) slightly exceeds the lower limit of the 3-5 kV coating stress range, as recommended by NACE SP0177-2014 for FBE and PE coatings.

6.3 Summary

The predicted unmitigated AC interference hazards are summarized in Table 6-7.

Table 6-7. Predicted Unmitigated Hazards

Condition	Hazard	Limit	Predicted Value
Steady-State	Shock to Personnel	Touch Voltage – Max. 15 V	197 V – Hazard
	AC Corrosion	AC Current Density – Max. 50 A/m^2	1,468 A/m^2 – Hazard
Fault	Shock to Personnel	Touch Voltage – Max. 356 V*	3,686 V – Hazard
		Metal-to-metal Voltage – Max. 356 V	N/A**
		Step Voltage – 356 V*	N/A**
	Power Arc	Minimum Separation Distance – 1 m	4 m – No hazard
	Coating Stress	Coating Stress Voltage – Max. 3 to 5 kV	3,686 V – Slightly exceeds lower limit

* Assuming zero soil resistivity.
** To be assessed as part of the study of AC interference on existing pipelines and UGL stations – see paragraphs 5.2.1.2 and 5.2.1.3.

7 Mitigation of AC Interference

7.1 Proposed AC Mitigation

The recommended mitigation measures to reduce touch potentials at above-grade appurtenances and minimize the risk of AC corrosion are summarized in Table 7-1.

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Table 7-1. Summary of Recommended Mitigation

No.	Start Chainage (m)	End Chainage (m)	Mitigation Wire Length (m)	DC Decouplers	AC Coupons	Zinc Anodes	Description
1	0+000		-	-	1	-	Install AC coupon for monitoring.
2	0+000	1+400	1,400	4	-	22	Install one run of 1,400 m bare 2/0 copper wire and connect to pipeline via DC decouplers.
3	0+090	3+775	-	-	-	-	All test posts to be of dead-front configuration.
4	2+770		-	-	1	-	Install AC coupon for monitoring.
5	3+160		-	-	1	-	Install AC coupon for monitoring.
6	3+180	5+090	1,910	5	-	30	Install one run of 1,910 m bare 2/0 copper wire and connect to pipeline via DC decouplers.
7	5+580		-	-	1	-	Install AC coupon for monitoring.
8	7+000		-	-	1	-	Install AC coupon for monitoring.
Totals			**3,310**	**9**	**5**	**52**	

The recommended mitigation system consists of a total of 3,310 m of 2/0 bare copper mitigation wire, connected to the pipeline at nine locations. The length of wire varies with location. In order to cathodically protect the copper wire, it is recommended that 13.6 kg (30 lb.) packaged zinc anodes be connected to the copper wire at designated intervals (i.e., two anodes approximately every 150 m and at the DC decoupler junction boxes).

It is also recommended that a total of five AC coupons be installed on the LEP2 pipeline.

The primary purpose of the AC coupon is to facilitate the measurement of AC current density levels. AC coupons are fabricated of steel with a precise surface area, typically 1 cm^2, which is considered worst case for AC current density. These coupons will be monitored bi-annually during corrosion prevention surveys.

Any test stations installed on the LEP2 pipeline from Ch. 0+090 m to Ch. 3+775 m shall be of dead-front configuration.

7.2 Mitigated Steady-State Conditions

7.2.1 Touch Voltage

Mitigated touch voltages predicted along the LEP2 pipeline, under peak steady-state powerline operating conditions, are shown in Figure 7-1.

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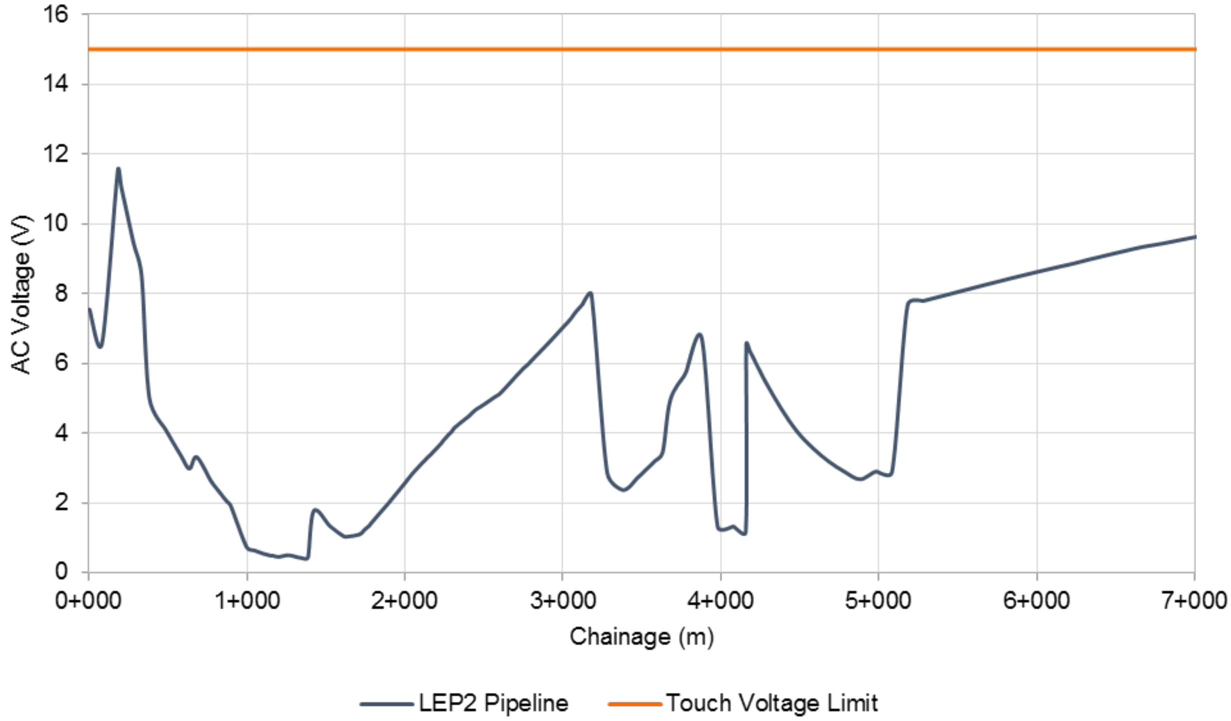

Figure 7-1. Predicted Mitigated Touch Voltages under Steady-State Conditions

As shown, the mitigated touch voltages predicted along the LEP2 pipeline do not exceed the 15 V safety limit. The maximum mitigated touch voltage is 12 V at Ch. 0+182 m.

7.2.2 AC Corrosion

Mitigated AC current densities predicted along the LEP2 pipeline, under average steady-state powerline operating, conditions are shown in Figure 7-2.

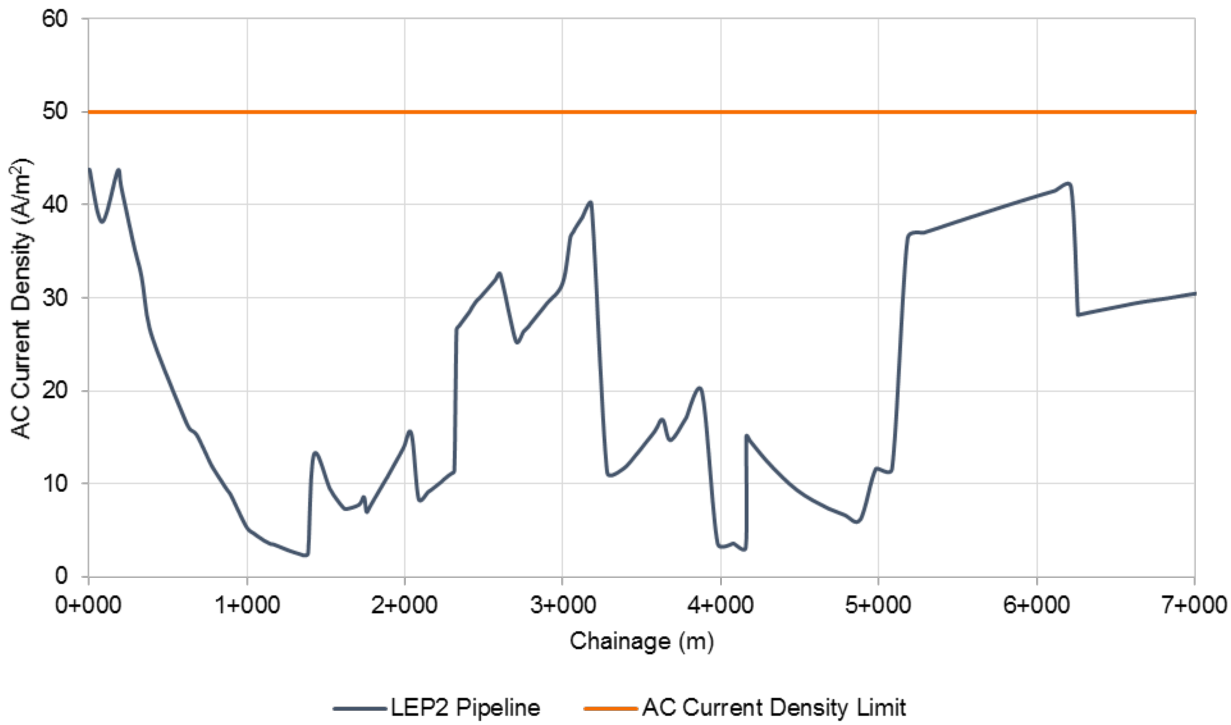

Figure 7-2. Predicted Mitigated AC Current Densities under Average Steady-State Conditions

As shown, the mitigated AC current densities predicted along the LEP2 pipeline do not exceed the 50 A/m^2 safety limit. The maximum mitigated AC current density is 44 A/m^2 at Ch. 0+000 m. As such, there is a minimum risk of AC corrosion.

7.3 Mitigated Fault Conditions

7.3.1 Hazardous Voltages

7.3.1.1 Touch Voltage

Mitigated touch voltages predicted along the LEP2 pipeline, under phase-to-ground fault conditions on the powerline, are shown in Figure 7-3.

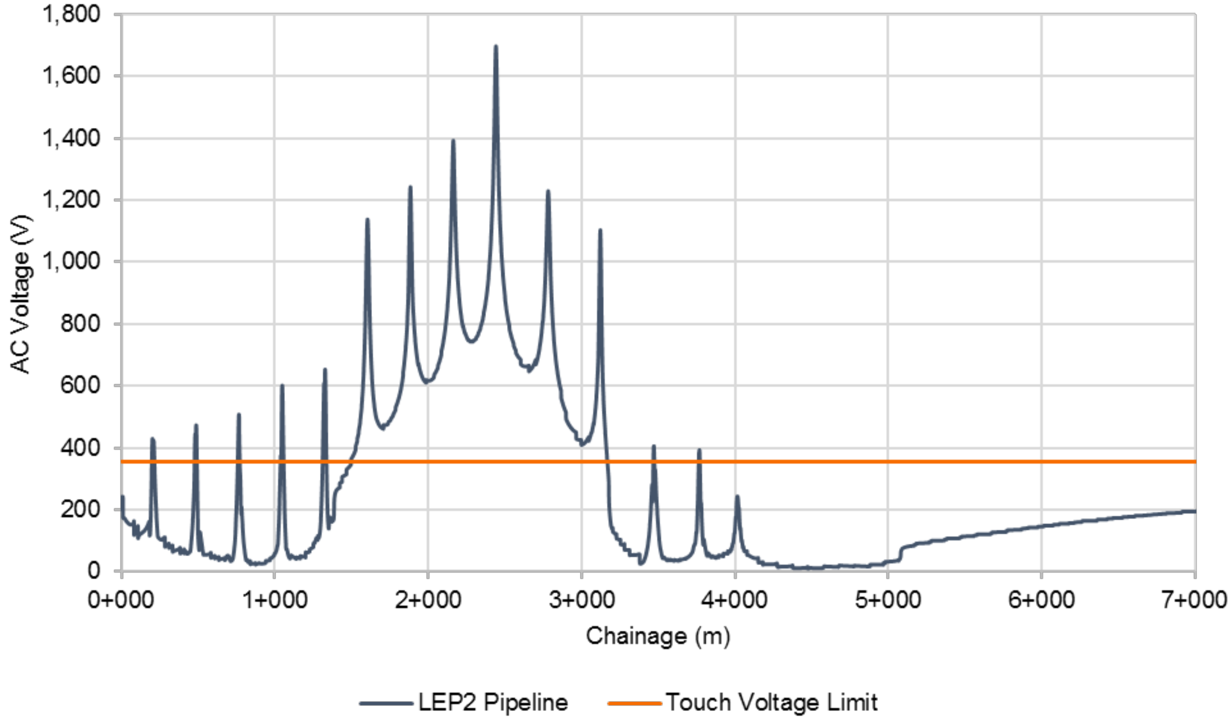

Figure 7-3. Predicted Mitigated Touch Voltages under Fault Conditions

As shown, the mitigated touch voltages predicted along the LEP2 pipeline under a fault on the powerline exceed the 356 V open field safety limit from Ch. 0+090 m to Ch. 3+775 m. The maximum mitigated touch voltage is 1,697 V at Ch. 2+442 m. With no above grade appurtenances along the pipeline and with dead-front test stations along the high touch voltage section, there are no touch voltage risks for pipeline personnel and the general public.

7.3.1.2 Metal-to-Metal Touch Voltage

The metal-to-metal touch voltages at the UGL stations will be assessed as part of the AC interference on existing pipelines study – see paragraph 5.2.1.2.

7.3.1.3 Step Voltage

The step voltages at the UGL stations will be assessed as part of the AC interference on existing pipelines study – see paragraph 5.2.1.3.

7.3.2 Risk of Arcing

With the induced voltages under fault further reduced due to mitigation, the maximum voltage difference between the faulted tower and the pipeline is below 4.2 kV and the minimum separation distance remains below 1 m. There is no risk of arcing under mitigated or unmitigated conditions.

7.3.3 Coating Stress

As shown in Figure 7-3, the 3-5 kV coating stress limit, as recommended by NACE SP0177-2014 for fusion bond epoxy coatings, was not exceeded at any location along the UGL Leamington Expansion Phase II pipeline. As such, there is a negligible risk of coating damage to the LEP2 pipeline under mitigated fault conditions.

7.4 Summary

The predicted mitigated AC interference hazards are summarized in Table 7-2.

Table 7-2. Predicted Mitigated Hazards

Condition	Hazard	Limit	Predicted Value
Steady-State	Shock to Personnel	Touch Voltage – Max. 15 V	12 V – No hazard
	AC Corrosion	AC Current Density – Max. 50 A/m^2	44 A/m^2 – No hazard (minimum risk)
Fault	Shock to Personnel	Touch Voltage – Max. 356 V*	1,697 V, with dead-front test stations – No Hazard
		Metal-to-metal Voltage – Max. 356 V	N/A**
		Step Voltage – 356 V*	N/A**
	Power Arc	Minimum Separation Distance – 1 m	4 m – No hazard
	Coating Stress	Coating Stress Voltage – Max. 3 to 5 kV	1,697 V – No hazard

* Assuming zero soil resistivity.
** To be assessed as part of the study of AC interference on existing pipelines and UGL stations – see paragraphs 7.3.1.2 and 7.3.1.3.

8 Risk of DC Interference

When a powerline tower is located close to the groundbed of a cathodic protection system, part of the current discharged by the groundbed could be picked up by the grounding rods, tower foundations, or the guy wire anchors near the groundbed. This stray current could travel through the shield wire along the powerline and be discharged back to the pipeline via the grounding rods, tower foundations, or the guy wires of other towers, resulting in accelerated corrosion at the discharge location (DC interference).

For pipelines with sacrificial cathodic protection systems, such as the proposed LEP2, DC interference is expected to be negligible due to low current outputs. However, the existing lines are protected by an impressed current installation (rectifier #193) located at Mersea Road 10. As such, it is recommended that DC interference testing be conducted once the construction of the HONI powerline is completed.

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9 Conclusions

Following mitigation, the calculated AC induced voltage under steady-state conditions will be below the 15 V safety limit along the entire proposed LEP2 pipeline.

Following mitigation, the calculated AC current densities will be below the 50 A/m^2 AC corrosion limit along the entire proposed LEP2 line.

Following mitigation, including use of dead-front test stations, there are no safety risks at above-grade appurtenances for pipeline personnel and the general public along the entire proposed LEP2 line under fault conditions.

With the proposed LEP2 pipeline electrically isolated from the stations using underground monolithic isolating fittings, there are no safety risks associated with the proposed line at UGL stations and along the two existing pipelines (i.e., NPS8 Leamington North and Leamington Expansion Phase I). The risks associated with the influence of the proposed 230 kV powerline on the UGL stations and existing lines will be assessed in a separate AC interference study.

There is no risk of arcing along the close collocation (i.e., 4 m) between the proposed pipeline and the future 230 kV powerline. The actual separation distance of 4 m significantly exceeds the minimum separation distance of 1 m. Furthermore, the voltage difference under fault will not exceed 4.2 kV, well below the actual voltages (i.e., 28 to 30 kV), which did not sustain arcing at the same or lower separation during the CEA testing.

Following mitigation, the calculated coating stress under fault conditions will be below the 3 to 5 kV limit along the entire proposed LEP2 pipeline.

There is no risk of DC interference on the tower foundations associated with the proposed LEP2 pipeline, since it is protected by a sacrificial cathodic protection system. However, the existing lines are protected by an impressed current installation (rectifier #193) and subsequently it is recommended that DC interference testing be conducted once the construction of the HONI powerline is completed .

Appendix A

Soil Resistivity Measurements

Table A-1. Soil Resistivity Measurements from Site Survey

ID	LEP2 Chainage (m)	Closest Tower	Spacing (ft)	Spacing (m)	Resistance (Ω)	Resistivity (Ω-m)
6	-	15	1	0.30	11.00	21.06
			2	0.61	7.20	27.56
			5	1.52	2.70	25.84
			10	3.05	1.30	24.88
			15	4.57	0.76	21.82
			20	6.10	0.59	22.59
			30	9.14	0.39	22.40
			50	15.24	0.29	27.76
			75	22.86	0.21	30.15
			100	30.48	0.23	44.03
7	0+207	14	1	0.30	32.00	61.25
			2	0.61	16.00	61.25
			5	1.52	3.80	36.37
			10	3.05	2.60	49.77
			15	4.57	1.00	28.71
			20	6.10	0.65	24.88
			30	9.14	0.42	24.12
8	0+488	13	1	0.30	31.00	59.34
			2	0.61	10.00	38.28
			5	1.52	3.20	30.63
			10	3.05	1.60	30.63
			15	4.57	0.80	22.97
			20	6.10	0.67	25.65
			30	9.14	0.56	32.16
9	0+770	12	1	0.30	17.00	32.54
			2	0.61	7.70	29.48
			5	1.52	3.10	29.67
			10	3.05	1.40	26.80
			15	4.57	0.92	26.42
			20	6.10	0.66	25.27
			30	9.14	0.48	27.56

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Table A-1. Soil Resistivity Measurements from Site Survey Continued

ID	LEP2 Chainage (m)	Closest Tower	Spacing (ft)	Spacing (m)	Resistance (Ω)	Resistivity (Ω-m)
10	1+043	11	1	0.30	12.00	22.97
			2	0.61	5.00	19.14
			5	1.52	2.00	19.14
			10	3.05	1.20	22.97
			15	4.57	0.74	21.25
			20	6.10	0.72	27.56
			30	9.14	0.55	31.58
			50	15.24	0.50	47.85
			75	22.86	0.39	55.99
			100	30.48	0.29	55.51
11	1+331	10	1	0.30	30.00	57.42
			2	0.61	15.00	57.42
			5	1.52	3.20	30.63
			10	3.05	1.30	24.88
			15	4.57	0.99	28.43
			20	6.10	0.84	32.16
			30	9.14	0.59	33.88
12	1+612	9	1	0.30	22.00	42.11
			2	0.61	7.60	29.09
			5	1.52	2.70	25.84
			10	3.05	1.50	28.71
			15	4.57	1.05	30.15
			20	6.10	0.89	34.07
			30	9.14	0.65	37.33
13	1+892	8	1	0.30	110.00	210.56
			2	0.61	38.00	145.47
			5	1.52	5.48	52.45
			10	3.05	1.80	34.45
			15	4.57	1.20	34.45
			20	6.10	0.65	24.88
			30	9.14	0.58	33.31

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Table A-1. Soil Resistivity Measurements from Site Survey Continued

ID	LEP2 Chainage (m)	Closest Tower	Spacing (ft)	Spacing (m)	Resistance (Ω)	Resistivity (Ω-m)
14	2+155	7	1	0.30	101.20	193.71
			2	0.61	55.00	210.56
			5	1.52	12.00	114.85
			10	3.05	3.70	70.82
			15	4.57	2.50	71.78
			20	6.10	1.70	65.08
			30	9.14	1.05	60.30
15	2+549	6	1	0.30	41.00	78.48
			2	0.61	18.00	68.91
			5	1.52	4.90	46.90
			10	3.05	1.80	34.45
			15	4.57	1.20	34.45
			20	6.10	0.85	32.54
			30	9.14	0.50	28.71
			50	15.24	0.46	44.03
			75	22.86	0.41	58.86
			100	30.48	0.38	72.74
16	2+810	5	1	0.30	88.50	169.40
			2	0.61	38.30	146.62
			5	1.52	7.54	72.16
			10	3.05	2.15	41.15
			15	4.57	1.28	36.69
			20	6.10	0.98	37.33
			30	9.14	0.71	40.48
17	3+140	4	1	0.30	39.80	76.18
			2	0.61	19.04	72.89
			5	1.52	5.09	48.71
			10	3.05	1.77	33.88
			15	4.57	1.15	32.88
			20	6.10	0.90	34.57
			30	9.14	0.65	37.04

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Table A-1. Soil Resistivity Measurements from Site Survey Continued

ID	LEP2 Chainage (m)	Closest Tower	Spacing (ft)	Spacing (m)	Resistance (Ω)	Resistivity (Ω-m)
18	3+491	3	1	0.30	19.55	37.42
			2	0.61	7.54	28.87
			5	1.52	3.11	29.76
			10	3.05	1.65	31.49
			15	4.57	1.18	33.94
			20	6.10	0.98	37.33
			30	9.14	0.71	40.60
19	3+782	2	1	0.30	25.80	49.38
			2	0.61	10.56	40.43
			6	1.83	4.58	52.60
			10	3.05	2.22	42.49
			15	4.57	1.47	42.09
			20	6.10	1.10	42.00
			30	9.14	0.72	41.12
20	4+007	1	1	0.30	236.00	451.74
			2	0.61	128.30	491.17
			6	1.83	13.80	158.49
			10	3.05	4.20	80.39
			15	4.57	2.26	64.89
			20	6.10	1.56	59.72
			30	9.14	1.45	83.27
			50	15.24	1.15	110.06
			75	22.86	1.24	178.02
			100	30.48	1.32	252.67

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