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INVESTIGATION AND MITIGATION OF AC CORROSION ON A 300 mm DIAMETER NATURAL GAS PIPELINE

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ABSTRACT

A cathodically protected natural gas pipeline experienced an external corrosion failure in its eleventh year of service. The pipeline exhibited high levels of induced AC voltage as a result of being parallelled by high-voltage powerlines, with the failure occurring at a location of peak AC voltage. An investigation uncovered additional corrosion pits, and it was concluded that these pits, as well as the failure, were caused by AC corrosion.

An AC mitigation system was designed to reduce the steady-state AC voltages to levels that would minimize the risk of subsequent AC corrosion damage, as well as reduce the electrical shock hazards faced by pipeline personnel and the general public. An investigation of fault current effects was not included as part of this project,

Keywords: induced AC voltage, AC corrosion, AC mitigation, pipeline corrosion, corrosion failure, magnesium anode consumption rates

INTRODUCTION

On January 25, 2002, a natural gas leak was discovered by Niagara Mohawk - A National Grid Company, on their Nº 58 pipeline, south of Oswego NY. The 300 mm diameter, 6.35 mm wall pipeline

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is coated with side-extruded polyethylene, and is cathodically protected by banks of 14.5 kg magnesium anodes. This 20 km long pipeline was installed in 1991.

Running parallel to Pipeline Nº 58 is a 600 mm diameter, 7.1 mm wall pipeline, designated as Niagara Mohawk Pipeline Nº 63. Pipeline Nº 63, which was installed in 1994, is similarly coated with side-extruded polyethylene and protected with magnesium anodes. The pipelines are not bonded together, and their cathodic protection systems are therefore independent of one another.

The failure occurred close to a weld, at the 7 o'clock position on the pipe. A pinhole perforation occurred near the centre of a smooth, round, dish-shaped pit that was approximately 25 mm in diameter (Figures 1 and 2). The failure was attributed to corrosion, although cathodic protection records for a test station located only a few metres from the failure site suggest that the pipeline had been well protected from the time it was constructed (potentials more electronegative than -1.3 V_{CSE} *on*). Furthermore, there was no evidence to suggest that the failure site had been shielded from receiving protective current.

The failure occurred in a rural area on the south side of a paved two-lane roadway (Hall Road) where Pipeline Nº 58 diverges from both Pipeline Nº 63 and a major electric powerline corridor (Figures 3 and 4). Pipeline Nº 58 is parallelled by four single-circuit 345 kV powerlines for 5300 m, as well as a double-circuit 115 kV power line for 9400 m (Figure 5), whereas Pipeline Nº 63 parallels the 345 kV circuits over a longer distance. These powerlines are also owned by the same company.

In 1991, the company conducted a computer analysis of the effects of AC induction on the pipeline, and concluded that where the line entered and exited the 345 kV corridor, pipe voltages could reach 300 V during periods of maximum loading. As a result of this analysis, magnesium anode beds were installed at critical locations (Sites A and B) when the pipeline was constructed, to provide both AC voltage mitigation and cathodic protection current. Despite these measures, AC voltages along the pipeline remained high, and a recent survey identified peak pipeline voltages of 50 V and 80 V at the south and north ends of the shared 345 kV corridor respectively. These locations are referred to throughout the paper as Sites A and B respectively, where Site A is also the site of the Hall Road failure.

The high AC voltages, coupled with the fact that the pipeline appeared to be cathodically protected, led the company, to speculate that AC corrosion may have caused the failure. The ensuing investigation and subsequent remedial actions are the subject of this paper. It should be noted that issues associated with Pipeline Nº 63 were not addressed in this study.

RESULTS OF FIELD INVESTIGATION

One month after the failure occurred, a site visit was made to collect additional data, and to attempt to find other corrosion sites where the corrosion mechanism might be identified. The results of this investigation follow below.

Cathodic Protection and Induced AC Measurements

An anode bed consisting of eighteen 14.5 kg high-potential magnesium anodes is located immediately adjacent to the failure site at the south side of Hall Road (Site A). At the time of the investigation however, the anode bed was found to be disconnected from the pipeline at its test station. It was later discovered that the anode bed had been disconnected two years prior to the failure, since the open-circuit potential of the anodes (-1.30 V_{CSE}) was slightly less electronegative than the pipe's *on* potential

(-1.35 V_{CSE}), and the anodes were receiving rather than contributing cathodic protection current. At the time of the investigation, it was not known why the open-circuit potential of the anodes was so much less electronegative than the value typically associated with high-potential magnesium (-1.75 V_{CSE}).

The anode bed was temporarily reconnected to the pipe, resulting in a current discharge of 9.6 AAC to ground. This lowered the AC voltage of the pipe at the test station from 33 V to 22 V, but when measured with respect to remote earth, the pipe voltage was only reduced from 53 V to 47 V.

At the north end of the collocation between the pipeline and the 345 kV powerlines (Site B), the AC pipe voltage was 46 V, although 80 V had been recorded during a recent CP survey. A large anode bed consisting of twenty 14.5 kg magnesium anodes was installed at this location when the pipeline was constructed, but was found to have no AC or DC current output at the time of this investigation.

Temporary ground electrodes were connected to the pipeline at Sites A and B, to determine what effect they would have on lowering the AC voltages. At Site A, the pipe was connected to a 400 mm diameter by 90 m long abandoned casing underneath a muck field. At Site B, approximately 75 m of AWG Nº 8 solid copper wire was placed along the wet ground and connected to the pipe. The effect of these temporary ground electrodes is shown in Table 1.

The company personnel conducted soil resistivity measurements in the vicinity of Sites A and B, so that the resistance of permanent ground electrodes could be calculated. This data is provided in Table 2.

Excavation of Pipeline

It was considered unlikely that additional corrosion damage, similar to that which had resulted in the failure, could be found by conducting random excavations of the pipeline. Nevertheless, pipeline Nº 58 was excavated on the south side of the Hall Road crossing, immediately adjacent to where the failure had occurred, with the hope of finding and investigating additional corrosion sites. Since the failure had occurred at a joint, it was expected that the inspection of other joints would have the greatest chance of success.

The first joint west of the failure site was found, and was carefully excavated. A small nodule, measuring approximately 20 mm in diameter by 20 mm in height, was found on the top of the pipe beneath a 10 mm diameter break in the coating (Figure 6).

Immediately after uncovering this anomaly (Anomaly Nº 1), the potential of the pipe was measured by placing a copper sulfate reference electrode directly on top of the coating holiday. The pipe potential was found to be -1080 mV_{CSE}.

The pH inside the nodule was measured using a combination pH/reference micro-electrode and a high impedance meter, and was found to be 17.0. Since the pH meter was calibrated using buffer solutions of pH 4.0, 7.0, and 10.0, it is expected that this unrealistically high pH value was the result of not using a high pH buffer solution during calibration. The pH of the nodule was later measured in the lab and found to be 13.1.

The coating was removed from the vicinity of the anomaly, and the nodule was removed for analy-

sis. A corrosion pit was found immediately beneath where the nodule and coating holiday had been (Figure 7). The pit was round, smooth, and dish-shaped, and measured 30 mm in diameter by 1.35 mm deep.

Upon further investigation, a second nodule was found on top of the pipe (Anomaly Nº 2), nearly identical in appearance to the first, approximately 600 mm to the west of Anomaly Nº 1 (Figure 8). In this case, the nodule was protruding through the pipe's factory applied polyethylene coating. Once again, measurements were taken within the break in the coating. The pipe potential was found to be -1170 mV_{CSE}, and the pH inside the nodule was 12.2.

After removing the coating, the nodule of corrosion products was retrieved, and the pipe surface was cleaned, revealing another round, dish-shaped corrosion pit, 40 mm in diameter by 2.3 mm deep (Figure 9).

The corrosion products from the two pits, as well as those obtained from the failure site, were analyzed for chloride ion content and pH. Two soil samples were also retrieved from the excavation close to the sites of the two anomalies, and were analyzed for the characteristics which are typically considered to influence corrosivity. The results are provided in Tables 3 and 4 respectively.

Aside from the two coating holidays at which the corrosion pits were found, both the factory applied and the field applied coatings were found to be in good condition, and exhibited excellent adhesion to the pipe.

A portion of the anode bed was also excavated. The intent was to remove one anode for analysis, to determine the cause of the low open-circuit potential of the magnesium. An anode was located and was removed from the excavation. Upon closer examination however, no magnesium was found to remain. All that was left of the 14.5 kg anode was its steel strap core, a small block of white magnesium oxide, and the select backfill from the anode package.

DISCUSSION OF RESULTS

It is often difficult to determine the cause of a pipeline corrosion failure, since the repair of the pipeline understandably takes precedence over the careful collection of evidence. In this case, it was fortunate that a random excavation resulted in the discovery of two additional anomalies which were similar in appearance to that of the failure, and in all likelihood, were caused by the same corrosion mechanism.

The cathodic protection potentials measured directly on top of the two anomalies (-1080 mV_{CSE} and -1170 mV_{CSE}) indicate that the pipe surface exposed at the coating holidays was well protected. This was further verified by the high pH values of the nodules as measured both in the field, and afterwards in the lab.

There was no evidence that the pipe was ever shielded from receiving cathodic protection current, either by disbonded coating or by rocks in the soil. Furthermore, there was no evidence that DC stray current interference problems had ever affected the pipeline, and a recent close-interval potential survey indicated that no such problems exist at this time.

Bacterial corrosion was also be ruled out as a possible cause, since cathodic protection potentials

more negative than -950 mV_{CSE} should be sufficient to prevent bacterial corrosion.

With all other possible causes eliminated, the possibility of AC corrosion was considered. AC corrosion can occur on a cathodically protected pipeline when the AC current density discharging from the pipe's surface at a coating holiday exceeds 100 A/m^2.[1,2] This current density is simply a function of the holiday diameter d, the soil resistivity ρ, and the pipe voltage to remote earth V_{ac}, and can be calculated using Equation Nº 1.

$$i_{ac} = \frac{8V_{ac}}{\pi\rho d} \qquad ...(1)$$

At both Anomalies Nº 1 and Nº 2, the opening in the coating was approximately 10 mm, and the pipe voltage was approximately 50 V, although a peak of 60 V was recorded during the site visit. The soil resistivity in the excavation varied from 12.5 Ω-m to 16.0 Ω-m. Using the more conservative values of 50 V and 16 Ω-m for the calculation, the AC current density at the anomalies is found to be 800 A/m^2, which is well above the threshold value of 100 A/m^2 at which AC corrosion can occur on a cathodically protected pipeline.

It should be noted that the soil resistivities measured in the excavation were significantly lower than the bulk resistivities measured along the pipeline route using the Wenner Four-Pin Method (92 Ω-m to 206 Ω-m, 160 Ω-m average - Table 2). It is attributed to the moderately high chloride ion content of the soil at Hall Road (190 ppm to 215 ppm), presumably due to the application of de-icing salts to the roadway during the winter months.

As is generally found to be the case, the chloride ion contents were even higher in the corrosion products than in the surrounding soil, ranging from 275 ppm to 470 ppm. This may be because the negatively charged chloride ions are attracted to the corrosion site by the surplus of positively charged iron ions, or the chloride ions may become trapped in the corrosion product matrix, and accumulate during subsequent wetting and drying of the corrosion products, similar to what occurs in the cement mortar of buried concrete piping. The highest chloride ion content was found in the corrosion products taken from the failure site, which is consistent with this site having a higher corrosion rate than either of the two anomalies.

In addition to causing AC corrosion, the high induced AC pipeline voltages also pose an electrical safety hazard to both the comapny personnel and the general public. Various standards give 15 V as the maximum steady-state AC voltage that should be permitted on a pipeline, where this voltage is accessible to touch.[3,4] If steady-state AC pipeline voltages were permitted to exceed 15 V continuously, the pipeline would need to be treated as a live conductor, meaning that pipe contact work would have to be conducted while working from temporary gradient control mats, and that all test station locations would require permanent gradient control mats to mitigate shock hazards.

From the potentials and currents measured at the two primary anode beds on pipeline Nº 58 (sites A and B), and from the examination of one magnesium anode, these anode beds appeared to have been totally consumed. Typically, a 14.5 kg anode installed on a well-coated pipeline in moderately high resistivity soil, should have a life in excess of 20 years, however at high AC current densities, the life of an anode can be significantly reduced. Considering that the Hall Road anode bank was disconnected two years before the failure occurred, the life of this anode bed was only eight years or less.

MITIGATION

As has already been stated, the critical AC current density at which AC corrosion of cathodically protected steel can be expected is 100 A/m^2. The literature also suggests that AC corrosion is unlikely to occur at AC current densities of less than 20 A/m^2, and that for the range between 20 and 100 A/m^2, AC corrosion is unpredictable.[5] Furthermore, Equation 1 indicates that AC current density increases as the diameter of the holiday decreases, although the literature suggests that AC corrosion is generally not found at pinholes or at coating holidays much smaller than 1 cm^2 in area.[6] Therefore, for this project, a maximum AC current density of 50 A/m^2 was chosen as a goal for the mitigation system, based on an assumed worst-case 1 cm^2 holiday size.

The most effective method of mitigating AC corrosion is to lower the pipeline voltages to acceptable levels. In the moderately high resistivity soil (i.e. 150 Ω-m) which exists along the majority of the pipeline route, 30 V would be required to produce AC current densities of 50 A/m^2. Where chloride contamination of the soil exists however, pipeline voltages must be reduced to much lower values.

The practical difficulties in mitigating the voltages on this pipeline were illustrated when the large abandoned casing was used as a temporary grounding electrode. While this casing was able to drain 26.6 A from the pipeline, it only reduced the pipeline voltage from 60 V to 42 V with respect to remote earth. Clearly, much larger ground electrodes would be required to reduce pipeline voltages to acceptable levels.

In order to determine the requirements for the AC mitigation system, the pipeline-powerline corridor was modelled using software developed as a research project by the Pipeline Research Council International (PRCI)[†].

Data Gathering

Prior to conducting the modelling, a detailed survey of soil resistivities was conducted, in order to identify pockets of low resistivity soil that might be AC corrosion hot-spots. The soil survey was conducted using an electromagnetic soil conductivity meter[††] capable of measuring average soil conductivities (which can then be converted to resistivities) to depths of 3 m and 6 m (Figure 10).

The results of the soil survey are summarized in Figure 11. Soil resistivities generally tended to be higher at the 3 m depth than at the 6 m depth. For the purposes of modelling the pipeline, calculating the voltages, and determining the effects of mitigation, average resistivities to a 6 m depth were used. For the purpose of calculating AC current densities at holidays and assessing AC corrosion risks, average resistivities to a 3 m depth were used.

The company engineering supplied the powerline information (current loads, phasing, tower configurations) and pipeline information (route maps, coating information, cathodic protection system information) as required by the software. Actual current loads for the four 345 kV circuits were provided for the first two months of 2002 (Figure 12). Over this same period, peak loads for the 115 kV circuits was stated to be 175 A. To approximate the annual peak loads for all circuits, all of these values were increased by 30% (Table 5).

[†] *AC Mitigation*, Technical Toolboxes Inc.

[††] *EM-31* Earth Conductivity Meter, Geonics Inc.

Computer Modelling

The pipeline-powerline system was modelled in 47 sections, each section ranging from 100 m to 500 m in length. Pipe sections were chosen based on the locations where the characteristics of either the electromagnetic field or the pipeline changed significantly. Other pipe sections were chosen simply as convenient points for the software to calculate voltages.

The induced AC voltages for the pipeline were first calculated assuming that no mitigation equipment (DC decouplers, sacrificial anodes, or other ground electrodes) has been installed. In this case, voltage peaks of approximately 200 V were predicted where the pipeline enters and leaves the 345 kV powerline corridor (Figure 13).

The 115 kV lines which parallel the pipeline from the 10.5 km to the 20.0 km mark, were found to contribute very little to the induced AC voltages. This is not only due to the fact that their loads are small in comparison to the 345 kV lines, but more importantly, because the phase arrangement used on the double-circuit tower (full-roll arrangement) is conducive to cancellation effects that minimize the magnetic field seen by the pipeline.

AC voltages are most effectively mitigated by locating ground electrodes at major electrical discontinuities along the pipeline-powerline corridor, since this is where the peak voltages are generated. In the first case of mitigation which was investigated, groundbeds having a resistance of 0.5 ohms each were located where the pipeline enters and leaves the 345 kV powerline corridor. This mitigation scheme would lower the voltages at both of the peak locations from 200 V to 65 V, representing a 68% reduction in voltages.

If these voltage peaks were to be further reduced to 15 V for electrical safety reasons, the ground electrodes installed at the two critical locations would each need to have a resistance of 0.1 ohms. Given the local soil conditions, it was not expected that such low resistance groundbeds could be realistically achieved.

As an alternative to using discrete ground electrodes, the software permits the use of a mitigation wire (i.e. a long wire running parallel to the pipe). Figure 14 shows the effects that various lengths of mitigation wire would have on the induced AC voltage profile. A 400 m long wire installed at both of the critical locations would have an effect similar to that of a 0.5 ohm groundbed. Increasing the lengths of each of these wires to 800 m in length further reduces the peak voltages to 28 V, but a subsequent increase in wire length to 1200 m results in no further voltage reduction. Therefore, under maximum load conditions, pipeline voltages at the two critical conditions cannot be reduced to less than 28 VAC, regardless of the length of mitigation wire. Increasing the length of mitigation wire does, however, serve to shorten the length of pipe that experiences the high voltages.

The effects of adding additional grounds at the ends of the pipeline were also investigated (Figure 14). These grounds could be grounding electrodes, but in this case, it was assumed that DC decouplers would be installed across the insulators at each end of the line, and that this would have the same effect as installing 0.5 ohm ground electrodes. The decouplers were found to lower the voltages at the ends of the line, but had no effect on the peak voltages at the two major discontinuities.

It should be noted that the AC voltage profiles shown in Figures 13 and 14 are the pipeline voltages to remote earth. In the case where the pipe is adjacent to the mitigation wire, pipeline voltages to

local earth (i.e. the voltage to which a person working on the pipe would be exposed) would be significantly lower than the predicted voltages, and should in fact be less than 15 V. This is because the mitigation wire also serves as a gradient control mat, similar to a substation ground mat, raising the potential of local earth close to that of the pipeline. Therefore, in the case of the 1200 m long mitigation wires, voltages to which a person could be realistically exposed would be less than 15 V along the entire length of pipeline.

Prediction and Mitigation of AC Corrosion Risks

Using equation Nº 1 and the close-interval soil resistivity data (Figure 15), the AC voltage profiles required to produce AC current densities of 100 A/m^2, as well as more conservative current densities of 50 A/m^2, are plotted in Figure 15. These calculations assume the worst case of a 1 cm^2 holiday. Note that detailed soil resistivity data is only available between the chainages of 4 km and 10.5 km.

The effects of the various possible mitigation systems on AC current densities are shown in Figure 16. As was the case with the induced AC voltages, the most effective mitigation of AC current densities, and hence AC corrosion, is achieved with an 800 m long mitigation wire installed at both of the critical locations. A 800 m long wire reduces all current densities to less than 100 A/m^2, and the vast majority of current densities to less than 50 A/m^2. A 400 m long wire continues to allow current densities to exceed 100 A/m^2, while the 1200 m long wire does not significantly reduce the current densities much below that of the 800 m long wire.

It is important to note that the mitigation wire also provides a secondary benefit in the mitigation of AC corrosion, just as it does in the mitigation of AC voltages. For a coating holiday located in the vicinity of the mitigation wire, the effective resistance of the holiday is increased due to the mutual resistance between the holiday and mitigation wire, thereby reducing the AC current density at the holiday to a value less than that predicted by Equation 1. The resistance of a 1 cm^2 circular holiday can no longer be calculated using the equation for the resistance of a circular disk, since its resistance is now closer to that of a 1 cm^2 area on the surface of the mitigation wire. This mutual resistance effect can be thought of in terms of anode interference effects, where the installation of one anode close to another effectively raises the individual resistances of both anodes. In view of this, it is quite likely that the use of two 800 m long mitigation wires would reduce AC current densities at all locations along the pipe to 50 A/m^2 or less.

Recommendations

A mitigation wire typically consists of a ribbon of sacrificial anode material installed parallel to the pipeline, and connected directly to the pipeline. In the case of zinc ribbon, the ribbon must be installed in select sacrificial anode backfill, to ensure that the anode material does not passivate, and that it maintains a low resistance to earth. Alternatively, bare copper wire may be used, provided that it is connected to the pipeline through a DC decoupling device to prevent if from draining CP current away from the pipeline. For large ground electrodes, the cost of this device is easily offset by the lower material costs for copper wire versus zinc ribbon in backfill. Furthermore, the copper wire is easier to install than the zinc, since it can be installed using a cable plough rather than a ditching machine, and again, since it does not need to be installed in special backfill.

On this project, the owner decided to use AC-coupled copper wire rather than direct-connected zinc ribbon. It was recommended that 800 m of AWG 2/0 copper cable be installed at the two critical

locations (sites A and B). At site B, it was recommended that the wire be centre-connected to the pipe (through a DC decoupler) in order to reduce the effects of attenuation along the wire. At Hall Road (site A), it was recommended that the mitigation wire be split into two 400 m lengths, one for each side of the road, with each wire being centre-connected to the pipe through a DC decoupler.

It must be emphasized that when using copper wire as a ground electrode, maintaining the DC isolation of the copper wire from the pipe is critical, and requires a commitment to regular monitoring. Even though the particular DC decoupling device† used is reported to have a very low failure rate, should it fail, it would do so in short-circuit mode. From an electrical safety viewpoint, this is considered the fail-safe mode, but from a corrosion viewpoint, the direct connection of a long length of bare copper wire to a well-coated pipeline protected only with sacrificial anodes would have serious consequences if undetected over a significant period of time. It was therefore recommended that these installations be checked once a month, or preferably on a continuous basis using remote monitoring.

Finally it was recommended that DC decouplers be installed across the flanges at each end of the pipeline, to provide additional drain points for both induced AC currents and fault currents, and to provide protection to the insulating flanges.

Final Results

At this time, the company has completed the installation of the two 800 m long mitigation wires. These have each been centre-connected to the pipeline using a DC decoupling device. DC decouplers have not been installed across the insulating flanges at each end of the pipeline, and no AC mitigation work has yet been initiated on Pipeline Nº 63.

Although a thorough survey of AC voltages has not been conducted along the pipeline, measurements have been made at the two critical locations. AC voltages measured at the test stations nearest to Sites A and B were found to be 5 V and 3 V respectively, whereas they had previously ranged from 50 V to 80 V. It is important to note that these voltages were measured with the earth connection made in close proximity to the AC ground electrode, and therefore cannot be compared to the voltages to remote earth predicted by the software. AC voltage measurements were subsequently conducted while moving the earth connection more and more remote from both the pipeline and the ground electrode. This data (Figure 17) suggests that the voltage to remote earth at both sites is approximately 20 V, which is less than the values of 30 V and 25 V predicted for Sites A and B respectively (Figure 14). In order to more accurately assess the performance of the mitigation system, AC voltage and current recordings should be recorded versus time and be compared to current loading information for the powerlines.

SYNOPSIS

An external corrosion failure occurred on a well-coated cathodically protected pipeline after approximately 10.5 years. Assuming that corrosion initiated at the time the pipeline was installed, this corresponds to a corrosion rate of 0.6 mm/a (24 mpy). Other corrosion pits discovered near the failure site exhibited both a high pH and a cathodic protection potential more electronegative than -1.0 V_{CSE}, suggesting that these sites, and probably the failure site, were receiving adequate cathodic protection current. It was concluded that the high induced AC voltage at this location, coupled with low soil resis-

† *Dairyland* PCR

tivities due to the application of de-icing salts to the roadway, resulted in AC current densities at the holidays of approximately 800 A/m^2, which is sufficient to cause AC corrosion of cathodically protected steel.

AC corrosion rates determined from a variety of investigations is compared in Figure 18, where the data collected by Wakelin is for cathodically protected pipelines, and the data collected by others is for unprotected steel in laboratory experiments. All investigators have found corrosion rates to increase with increasing AC current density. Assuming a 10.5 year pit growth period for the company corrosion failure, the corrosion rate associated with this failure seems relatively low considering the high AC current density.

The corrosion failure occurred immediately adjacent to a large magnesium anode bed. In this paper it was argued that a large groundbed in the vicinity of a coating holiday effectively raises the holiday's resistance to earth, thereby decreasing its AC current density. However, the prematurely consumed anode bed had been disconnected from the pipeline approximately 2 years before the failure occurred. Even though the anode bed was not contributing cathodic protection current, and its effectiveness as an AC ground electrode was reduced, it should still have been effective in limiting the magnitude of the AC current density at nearby holidays. It is therefore suggested that the majority, if not all of the pit growth, may have actually occurred over a 2 year period rather than a 10.5 year period, and that the AC corrosion rate may have been as high as 3.2 mm/a (125 mils/yr).

An AC mitigation system designed and installed on the pipeline appears to be effective in mitigating AC voltages to acceptable levels, however as of this time, a thorough evaluation has not been conducted.

ACKNOWLEDGEMENT

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5. Gummow, p.9.

6. Gummow, pp. 6-7.

TABLE 1 - Effects of Temporary Grounding

Parameter	Site A	Site B
AC Voltage (before grounding)	60 V	46 V
AC Voltage (local - after grounding)	17 V	26 V
AC Voltage (remote - after grounding)	42 V	Unknown
AC Current	26.6 A	15 A
Ground Electrode Resistance	1.6 Ω	1.7 Ω (approx.)

TABLE 2 - Soil Resistivity Data (Wenner 4-Pin Method)

Location Nº	Soil Resistivity (Ω-m) vs. Pin Spacing			
	1.5 m	3 m	7.5 m	15 m
1	148	163	176	146
2	192	181	187	161
3	131	151	166	108
4	206	176	172	92

TABLE 3 - Analysis of Corrosion Products

Characteristic	Pit 1	Pit 2	Failure Site
Chloride Ion Content (ppm)	335	275	470
pH	13.1	12.3	10.7

TABLE 4 - Corrosivity Analysis of Soil Samples

Characteristic	Sample 1	Sample 2
Description	Wet, brown clayey silt or loam	
Resistivity - as found (Ω-m)	16	12.5
Resistivity - saturated (Ω-m)	16	12.5
Chloride Ion Content (ppm)	190	215
pH	7.4	8.8
Water content	22%	24%

TABLE 5 - Estimated Annual Peak Line Currents

Circuit	Peak Current (A)	Estimated Annual Peak Current (A)
345 kV - Circuit 1	1650	2145
345 kV - Circuit 2	1280	1665
345 kV - Circuit 3	925	1200
345 kV - Circuit 4	1190	1550
115 kV - Circuit 1	175	230
115 kV - Circuit 2	175	230

FIGURE 1 - Corrosion Failure (as found)

FIGURE 2 - Corrosion Failure Following Removal of Temporary Repair Clamp

FIGURE 3 - Mutual Right-Of-Way (looking north from Site A - Hall Road)

FIGURE 4 - Failure Site (south side of Hall Road)

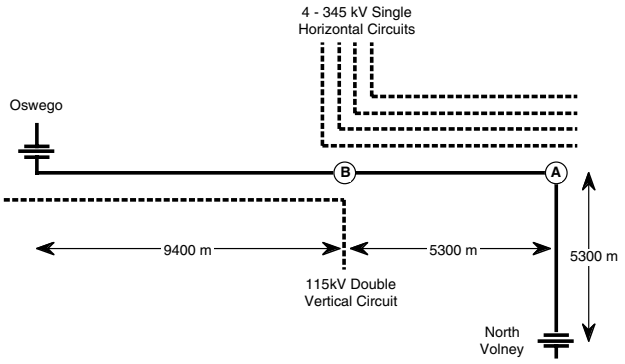

FIGURE 5 - Pipeline-Powerline Routes Showing Locations of Sites A and B on Pipeline Nº 58 (Schematic Representation Only)

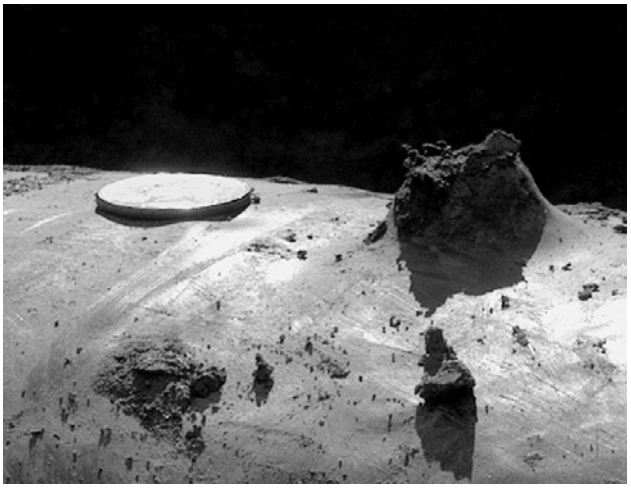

FIGURE 6 - Anomaly Nº 1 - As Found (25¢ Piece Shown to Illustrate Size)

FIGURE 7 - Anomaly Nº 1 - After Removal of Coating and Corrosion Products

FIGURE 8 - Anomaly Nº 2 - As Found

FIGURE 9 - Anomaly Nº 2 - After Removal of Coating and Corrosion Products

FIGURE 10 - Soil Resistivity Survey Using Electromagnetic Soil Conductivity Meter

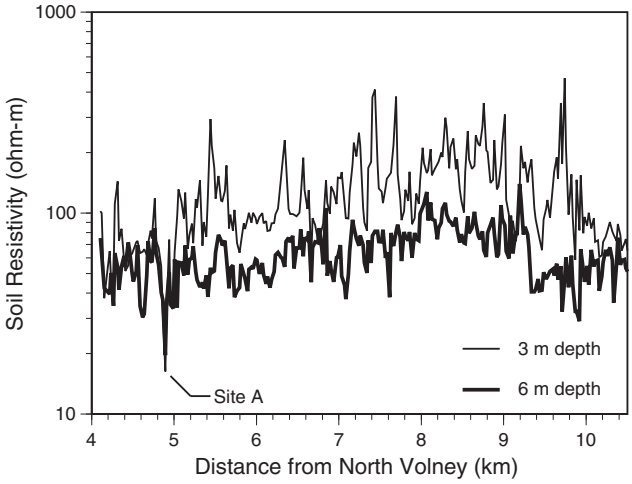

FIGURE 11 - Soil Resitivity Data

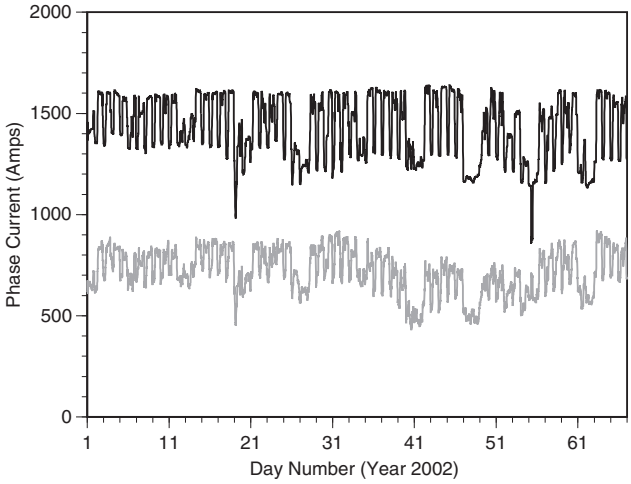

FIGURE 12 - Loading for 345 kV Circuits (Circuits with highest and lowest loads shown)

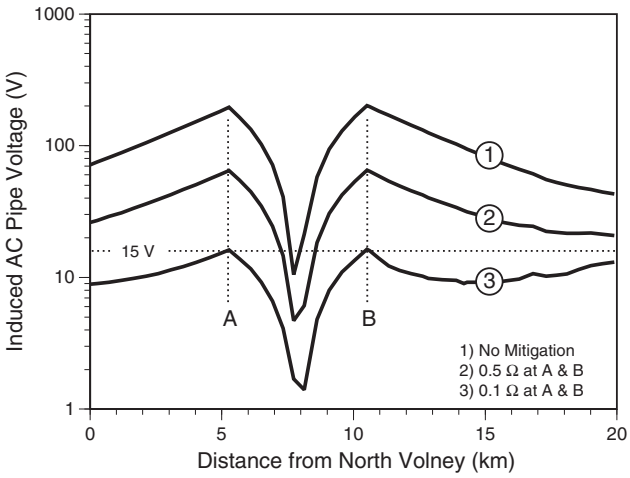

FIGURE 13 - Mitigation of AC Voltages Using Groundbeds

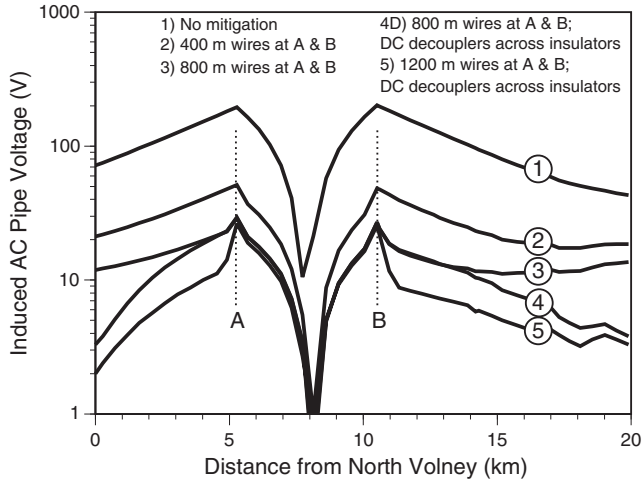

FIGURE 14 - Mitigation of AC Voltages Using Wires and DC Decouplers at Insulators

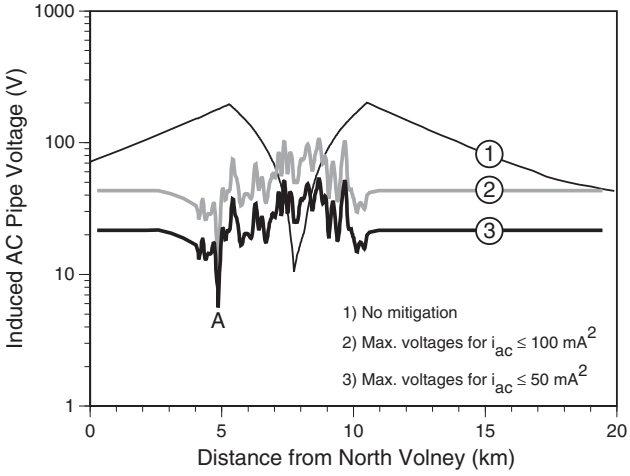

FIGURE 15 - AC Pipe Voltages Required to Produce Current Densities of 50 and 100 A/m²

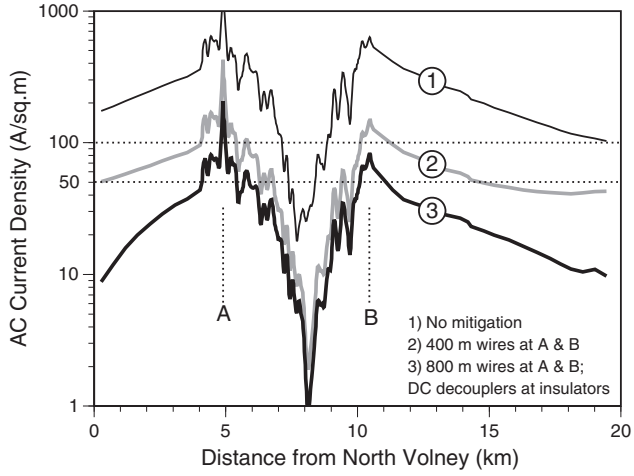

FIGURE 16 - Mitigation of AC Current Densities

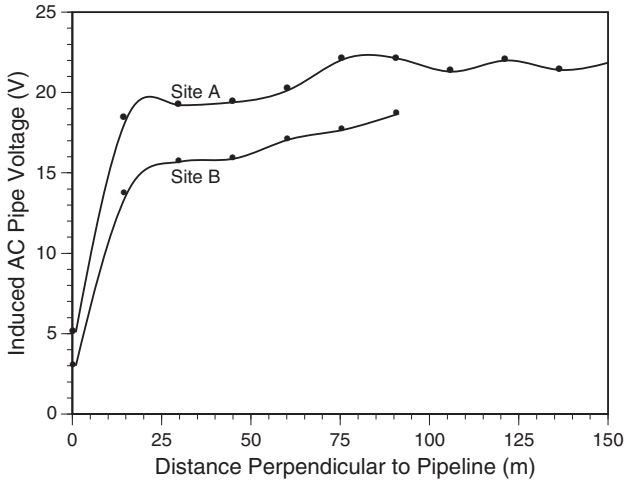

FIGURE 17 - Actual AC Pipe Voltages at Sites A and B After Mitigation

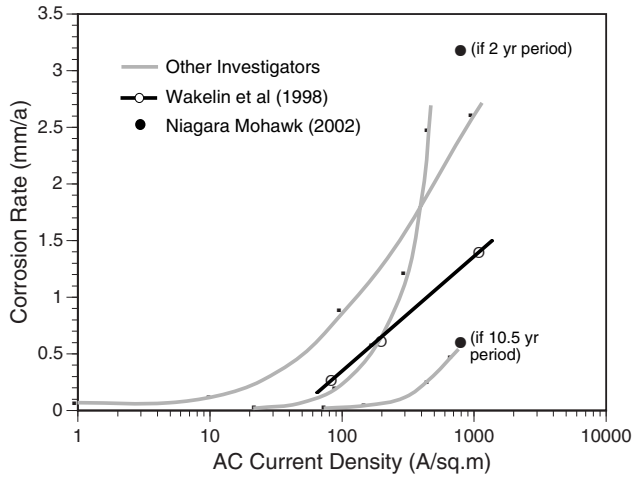

FIGURE 18 - AC Corrosion Rates vs. AC Current Density