Paper No.
565

CORROSION98

AC CORROSION - CASE HISTORIES, TEST PROCEDURES, & MITIGATION

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ABSTRACT

Literature dating back to the early 1960's has shown that AC current can cause corrosion of cathodically protected steel under laboratory conditions. Until recently however, there has been little evidence to suggest that AC corrosion of cathodically protected structures may be of practical concern.

In Ontario over the past six years, the authors have investigated several corrosion anomalies occurring on pipelines exposed to induced AC interference. This paper discusses a number of such cases where AC corrosion was suspected The test procedures used to identify AC corrosion are discussed, as are some of the methods for minimizing the risk of AC corrosion.

Keywords: AC corrosion, induced AC voltage, pipeline corrosion, AC mitigation

INTRODUCTION

In 1994, the authors investigated a corrosion anomaly on a pipeline subject to induced AC interference, and concluded that the AC interference may have influenced the corrosion in some way. This pipeline is one of a number of pipelines, having separate ownership, which share a common right-of-way with a high voltage powerline across the northern part of Toronto. The Joint Pipelines Group, as it is known, also shares a common impressed current cathodic protection system, as well as the costs for

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cathodic protection maintenance and monitoring. The Joint Pipelines corrosion representatives, after reflecting on the possibility of AC influenced corrosion, were able to relate details of several of their own corrosion investigations in which induced AC interference was a common factor. Subsequently, the authors were asked to conduct a literature search on AC corrosion and report on the implication of the findings with respect to the Joint Pipelines. The results of this literature study as they apply to cathodically protected pipelines, can be summarized as follows[1]:

AC corrosion

- does not occur at AC current densities of less than 20 A/m^2
- is unpredictable at AC current densities of 20 - 100 A/m^2
- can be expected at AC current densities of greater than 100 A/m^2

AC corrosion rates

- are highest at holidays having a surface area of 1 - 3 cm^2
- increase in chloride containing or deaerated environments
- increase with decreasing AC frequency, at frequencies below 100 Hz
- decrease with increasing cathodic protection current density
- decrease with time

The most important result of this study was the identification of a threshold AC current density of approximately 100 A/m^2, above which AC corrosion can be expected to occur. By knowing the soil resistivity and the pipeline's AC voltage, and by assuming the worst-case of a 1 cm^2 holiday, the risk of AC corrosion can be determined using the following simple formula to calculate AC current density[2]:

$$i_{ac} = \frac{8V_{ac}}{\rho \pi d} \tag{1}$$

where:

i_{ac} = AC current density
V_{ac} = AC voltage of pipeline to remote earth
ρ = soil resistivity
d = diameter of a circular holiday having an area equal to that of the actual holiday

CASE HISTORIES OF AC CORROSION INVESTIGATIONS

The corrosion investigations described below were sufficiently comprehensive that causes other than AC corrosion could be reasonably ruled out. This led the authors to conclude that induced AC interference was the primary cause of corrosion in each instance. There are other corrosion anomalies of which the authors are aware, that in retrospect, are likely the result of AC corrosion, but which have not been as well documented.

Case History Nº 1

In September of 1991, after only four years of operation, a corrosion failure occurred on a 300 mm diameter high pressure gas pipeline owned by the City of Kitchener. The pipeline was coated with a double layer of extruded polyethylene, and its joints were field coated with a hot-applied coal tar tape. The pipeline was cathodically protected using 7.7 kg magnesium anodes installed at 100 m spacings, and exhibited *on* potentials in the range of -1.45 V_{cse} to -1.50 V_{cse}.

A high voltage AC power line, 14 m away from the pipeline, parallelled the pipeline's entire 4400 m length. Induced AC voltages had been mitigated by coupling the pipeline through capacitors to the station piping at each end of the pipeline, and to ground rods installed at the test stations. Voltages typically ranged from 6 V to 10 V, but often rose to 26 V when capacitors failed. In January of 1992, while the failure site was being investigated, the AC voltage was 28 V.

The leak occurred at a joint under the centre of a four-lane roadway. A 50 mm diameter pit cluster was found immediately adjacent to the weld at the 8 o'clock position, within which a pinhole perforation was found (Figure 1). Based on a nominal pipe wall thickness of 5.56 mm, the penetration rate of this pit was calculated to be 1.4 mm/year (55 mils/year). A second pit cluster discovered adjacent to the weld at the 4 o'clock position, was similar in appearance and slightly larger in size, but did not penetrate the pipe wall (Figure 2).

The section of pipeline crossing the roadway had been fabricated from two lengths of pipe that were welded together above grade. The joint was coated before the pipe was installed through an open cut in the road. Although the crew which repaired the leak had noted that the coating was intact except at the leak site itself, the location and symmetrical appearance of the two pit clusters suggests that the coating had indeed been damaged during installation, perhaps by the pipeline boom grip used to lower the pipe into the trench.

The soil at the failure site was a dark brown sandy clay having a pH of 8.8, an electrical resistivity of 130 Ω-cm, and a chloride ion concentration of 3600 ppm. Since the pipeline crosses the roadway on a hill, the high chloride ion concentration was no doubt due to the frequent application of de-icing salts. The soil on either side of the roadway exhibited lower chloride ion concentrations (50 ppm to 500 ppm) and correspondingly higher resistivities (1000 Ω-cm to 4800 Ω-cm). An inspection of the pipe joints at each side of the roadway found no evidence of corrosion damage, even though the joint coating had been poorly applied, resulting in the ingress of moisture between the pipe and coating.

The cause of the corrosion could not be identified, since the failure site had been disturbed by the emergency repair crew prior to the investigation. It was originally speculated that the failure could have been the result of an occluded cell, because of the high chloride ion concentrations in the soil, or that bacterial corrosion could have been responsible, since sulphides were found in the corrosion products. In retrospect, it is more likely that the corrosion was AC induced, due to the extremely high AC current density calculated for the pit site. Using Equation (1), the AC current density at the pit was calculated to be 1100 A/m2, based on a voltage of 28 V, a soil resistivity of 130 Ω-cm, and an assumed holiday diameter equal to the pit diameter of 50 mm. This current density is well in excess of the 100 A/m^2 threshold above which AC corrosion is expected to occur.

Case History Nº 2

In 1976, a 250 mm diameter oil products pipeline operated by Trans-Northern Pipelines Inc. was rerouted around the future site of an electrical transformer station at Leslie Street in Toronto. The new piping was coated with extruded polyethylene, and was cathodically protected by a jointly operated impressed current system serving a number of pipelines that shared the power line corridor across the north end of Toronto.

A magnetic flux internal inspection tool was passed through the piping in 1986, which identified a minor anomaly (much less than 25% wall penetration) in this rerouted section. A subsequent internal inspection in 1994, using an ultrasonic tool, indicated a significant anomaly at this same location. Upon excavating and examining the pipeline, a crater-like corrosion pit was found. The pit was 50 mm long by 45 mm wide by 6.9 mm deep, and penetrated through 88% of the pipe's 7.8 mm thick wall. Assuming that the pit grew from 25% to 88% penetration over the eight years between internal inspections, this translates to an average corrosion rate of 0.61 mm/year (24 mils/year).

Pipe-to-soil potentials more electronegative than -1.27 V_{cse} *on* had been recorded in the vicinity of this corrosion site during previous surveys, thus indicating a satisfactory level of protection. Moreover, the potential with the reference electrode located at the pit was -1.18 V_{cse} compared to -1.47 V_{cse} *on* with the electrode located at grade level. The soil adjacent to the pit exhibited an electrical resistivity of 300 Ω-cm, a chloride ion concentration of 1920 ppm, and tested negative for sulphides. The high chloride concentration was attributed to the application of de-icing salts, since this corrosion anomaly was located under the edge of the roadway. The reddish brown corrosion product tested negative for sulphate reducing bacteria, and had a pH of 10.7, compared to a pH of 8.0 for the bulk soil.

The induced AC voltage at this location was 15 V at the time of this investigation, and was 12 V during the previous year's cathodic protection survey. Using Equation (1), the AC current density was calculated to be 200 A/m^2 at 12 V, which is well above the 100 A/m^2 threshold value. Except for the possibility that this was an occluded corrosion cell, the cause of corrosion was concluded to be induced AC current.

Case History Nº 3

A 500 mm diameter coal tar coated high pressure natural gas pipeline was installed in 1972 by Union Gas. Approximately 40 km of this 74 km long pipeline were parallelled by a high voltage AC power line. In 1995, an internal inspection using an ultrasonic inspection tool identified a number of anomalies, all of which were located along the power line right-of-way. Defects estimated to have a corrosion depth of greater than 40% of the 7.1 mm wall thickness were concentrated along two discrete pipe sections, from 7.55 to 8.14 km and from 18.1 to 19.5 km. Two anomalies located at 7.59 km and 18.53 km, were estimated to penetrate 80% and 63% of the pipe wall respectively.

A review of pipe-to-soil potential data collected during test station surveys and close interval surveys since 1972, indicated no evidence of subcriterion potentials along this pipeline. Rectifier data for the influencing impressed current systems indicated that there were only 10 days of downtime since 1983, all occurring in 1994 while an AC mitigation system consisting of banked magnesium anodes was being installed.

At the first dig site, three corrosion anomalies were investigated. Anomaly Nº 1 was a smooth and generally round corrosion pit, having a diameter of 5 cm, and a maximum depth of 6.1 mm (86% of the wall thickness). The adjacent soil was moist clay having a resistivity of 2000 ohm-cm. A hard tightly adhering tubercle, which protruded 5 cm above the pipe's surface, covered the pit. The coating around the pit was disbonded over a 20 cm radius. A pH test using litmus paper indicated that the pH was greater than 8.5 at this pit, as well as at two smaller pits examined in the vicinity. Furthermore, there was no evidence of bacterial induced corrosion, and the local cathodic protection potential was -1.56 V_{cse} *on*. Accordingly, there was no apparent cause for the observed corrosion. The AC current density at this site was calculated to be 84 A/m^2 at 33 V, which was the average induced AC voltage prior to the installation of the AC mitigation system in 1994.

At the second dig site, three additional anomalies were investigated. The deepest of these (Anomaly N° 4) was found at the 2 o'clock position beneath a large hemispherical shell of extremely hard soil, approximately 15 cm thick (Figure 3). The pit was 56 mm in diameter by 6.34 mm in depth (89.3% penetration), and was smooth and dish-shaped. A 25 mm diameter steel pipe was found to be wedged against the pipe at the pit (Figure 4). The pH of the soil immediately adjacent to the pit was 8.2, the soil resistivity of the moist clay soil was 1350 ohm-cm, and only trace amounts of chlorides and sulphides were found. The pipe-to-soil potential with the reference electrode located on top of the corrosion product was -1.050 V_{cse} compared to -1.490 V_{cse} *on* with the reference at grade.

Although the small steel pipe, if in contact with the pipeline steel, would electronically shield the pit from receiving cathodic protection current, it is likely that the electrical contact was broken as corrosion progressed, thereby eliminating any shielding effect. In such a case however, the small pipe would serve to focus both cathodic protection current and AC current at the pit location because of its low resistivity compared to that of the surrounding soil. The pipe-to-soil potential suggests that the pit did not lack for cathodic protection current. Furthermore, the possibility of bacterial induced corrosion was dismissed because the cathodic protection level was more electronegative than the -0.95 V_{cse} criterion generally considered sufficient to prevent corrosion due to sulphate reducing bacteria.

The other two anomalies investigated at the second dig site were both similar in appearance to Anomaly N° 4. Both were smooth, round, and dish shaped, and both were initially covered in hemispherical shell of hardened soil. Anomaly N° 5, which is shown in Figures 5 and 6, was the deepest of the two (3.8 mm), and actually consisted of two pits located immediately beside one another.

Before the distributed AC mitigation system was installed on this pipeline in 1994, the AC voltage at the second dig site was approximately 25 V, resulting in a calculated AC current density of 84 A/m^2 at Anomaly N° 4 This is identical to the AC current density calculated for Anomaly N° 1, and coincidentally, the corrosion rates were nearly identical (0.27 and 0.29 mm/year). Accordingly, it was concluded that the observed corrosion at both dig sites was AC induced.

Other Cases

In addition to the investigation described in Case History N° 1, two earlier investigations of corrosion anomalies were conducted for TNPI during 1993 and 1994. In each case, the anomalies were found immediately beneath roadways where soil resistivities were low and chloride ion concentrations were high.

At Pineway Avenue, 400 m west of the Leslie Street site discussed in Case N°1, three pits were found along the top of a coal tar coated pipe, within 300 mm of one another. All pits were smooth, round, dish-shaped, and approximately 25 mm in diameter, ranging in depth from 2.3 mm to 5.1 mm. The low soil resistivity of 340 Ω-cm was attributed to the high chloride ion concentration of 700 ppm. The pipe potential measured at grade was -1.35 V_{cse} *on* compared to -1.15 V_{cse} measured above the pit. A cathodic protection monitoring coupon installed during the investigation measured a cathodic protection current density of 0.5 A/m^2. Assuming an AC voltage equivalent to that at Leslie Street, the AC current density was calculated to be 360 A/m^2 at each pit.

At Alness Street, 7 km west of Leslie Street, fourteen pits were found ranging from 5 mm to 25 mm in diameter, and from 0.5 mm to 3.0 mm in depth. The pits were generally round and smooth, and most were found to be covered with a hard tubercle. The soil was a green-grey clay, having an electrical resistivity of between 230 Ω-cm and 500 Ω-cm, and a chloride ion concentration of between 960 ppm and 1700 ppm. Pipe potentials were typically between -1.0 V_{cse} and -1.2 V_{cse}, although short-duration excursions in the electropositive direction occurred as the result of interference from the city's DC rail transit system. Induced AC voltages in this area varied between 1 V and 10 V, however even 1 V would be sufficient to produce a current density of 100 A/m^2 at a 1cm^2 holiday in such low resistivity soil.

METHODS OF IDENTIFYING AC CORROSION

At present, there is no specific test for the identification of AC corrosion, other than to calculate the AC current density at the pit site, and to systematically eliminate all other possible causes. From the authors' experience with the case histories discussed above, corrosion investigations conducted on pipelines subject to AC interference must be conducted carefully, using the procedure outlined below. Note that most of these steps would be conducted in the course of any corrosion investigation, whether or not AC corrosion was suspected.

1) Carefully excavate the anomaly, being careful not to disturb the soil immediately adjacent to the anomaly, or the corrosion products.

2) Measure DC and AC potentials at several stages of the excavation.

3) Obtain soil samples from adjacent to the anomaly and from the side of the excavation at pipe depth, and determine:

   a) Soil resistivity, both as-found and then saturated with distilled water
   b) Moisture content
   c) pH
   d) Chloride ion concentration
   e) Sulphide ion concentration. A quantitative test can be conducted by mixing the corrosion products with iodine and 3% sodium azide solution, and checking for the evolution of nitrogen gas[3].
   f) Soil type, colour, and any other special characteristics.

4) Photograph the anomaly after first exposing it.

5) Examine the condition of the coating, and determine if the anomaly may have been shielded from receiving cathodic protection current.

6) Measure the potential at the anomaly by placing a reference electrode immediately on top of any corrosion products.

7) Using a combination pH/reference micro-electrode and a compatible meter, measure the pH and potential at the bottom of the pit (See Figure N° 7).

8) Remove the corrosion products from the pit, and conduct tests to determine:

   a) pH
   b) Chloride ion concentration.
   c) Sulphide ion concentration.
   d) Sulphate reducing bacteria concentration. This can be determined using a kit such as Conoco's *RapidChek II SRB Detection System.*

9) Photograph the pit after cleaning it, and measure its dimensions.

10) Conduct 24 hour recordings of AC and DC pipe potentials, and review the history of these potentials over the life of the pipeline.

After gathering the above data, the following analysis should be conducted to determine if AC corrosion was the primary cause of the pit.

1) Determine if the pit site was cathodically protected, by considering the pH and potential measurements taken in the soil, on the corrosion products, and at the bottom of the pit. If measurements taken adjacent to the pit indicate protection, but those taken within the pit do not, determine if the pit could have been electrically shielded by either the coating, the corrosion products, or by something in the soil. Consider the cathodic protection history of the pipeline, and determine if some prior cathodic protection deficiency or stray current interference problem could have caused the pit.

2) Determine if the pit could have been caused by bacterial corrosion, by considering the pipe potential (less negative than -950 mV), the presence of sulphides, the degree of soil aeration (anaerobic), and the count of sulphate reducing bacteria measured within the pit.

3) If the pit site appears to have received adequate cathodic protection over the life of the pipeline, and if bacterial corrosion can be ruled out, investigate the possibility of AC corrosion. Using the soil resistivity and the surface area of the coating holiday (or if not known, the area of the pit), calculate the AC current density, considering any variations in AC voltage which may have occurred over time. Consider the appearance of the pit site compared to the appearance of the sites discussed in the case histories (i.e. hard hemisphere of soil surrounding the pit site, smooth round dish-shaped pits having a minimum diameter of 1 cm, hard tubercles covering the pit, etc.).

MITIGATION OF AC CORROSION

Although the literature suggests that AC corrosion rates can be reduced by increasing the cathodic protection current density, the corrosion rates may still be significant, even at relatively high cathodic protection current densities[4]. The most effective means of controlling AC corrosion is therefore to mitigate the induced AC voltages to acceptable values.

AC voltages can be mitigated by lowering the pipeline's resistance to earth. This can be achieved a number of ways as discussed in the literature[5,6,7]. Sacrificial anodes can be directly connected to the pipeline, and can either be evenly distributed, grouped, or installed as a continuous ribbon anode along the entire pipeline trench. Auxiliary grounds such as pipeline casings, electrically isolated piping, and grounding electrodes can also be exploited, providing that they are coupled to the pipe through either capacitors, polarization cells, or solid-state isolation/surge protectors, to maintain DC isolation of the pipeline.

Pipeline companies having facilities located along electrical power corridors are required to maintain induced AC pipeline voltages below a certain limit, usually 15 V[8]. However, as was demonstrated by the case histories, high AC current densities resulting from low soil resistivities can occur at voltages significantly less than the limits specified for electrical safety.

Case History Nº 4

In 1997, Nova Gas Transmission Ltd. of Calgary, Alberta, recognized the need to address the possibility of AC corrosion, as well as the safety aspects of induced AC voltages, in the design of their 1200 mm diameter Mainline Loop N° 4 on the Eastern Alberta System. The pipeline was to parallel a double circuit 240 kV transmission line for 14.3 km, at separations ranging from 40 m to 170 m.

Using the graphical calculation methods outlined in the EPRI Report[9], induced AC voltages were calculated for the pipeline. Without any mitigation, it was determined that pipeline voltages would exceed 20 V, as shown in Figure 8. A detailed soil resistivity survey was conducted along the route of the pipeline, and this data, when used in conjunction with the AC voltage calculations, produced a profile of AC current densities (for the worst case assumption of a 1 cm^2 holiday area), as shown in Figure 9. This plot indicated that approximately half of the pipeline could experience AC current densities of 100 A/m^2 or more, with some locations exceeding 400 A/m^2.

The possible criteria for mitigation were considered. It was mandatory that AC current densities be reduced to less than the 100 A/m^2 threshold value where AC corrosion is expected to occur, but current densities could not practically be lowered at all locations to less than the 20 A/m^2 level where AC corrosion does not occur. As a compromise, it was decided that the voltages be mitigated to levels which would limit the AC current density at a 1 cm^2 holiday to 50 A/m^2 or less, as shown in Figures 8 and 9.

By installing a total of 1125 m of zinc ribbon at key locations along the pipeline, and by utilizing bonds to other existing pipelines, the induced AC voltages and resulting AC current densities could be reduced to the levels shown in Figures 8 and 9 respectively.

Other AC Mitigation Considerations

The use of anodes or ground electrodes to reduce the induced AC voltage on a pipeline also has a secondary benefit not accounted for in the design discussed above; that being, it further reduces AC current densities by increasing the effective resistance of the holidays. In the same way that a cathodic protection anode's resistance increases when it is in close proximity to other anodes, the mutual resistance between the holiday and a ground electrode raises the effective resistance of the holiday with respect to earth.

Consider the case of a pipeline grounded by a continuous zinc ribbon. The AC current density at a holiday located immediately adjacent to the ribbon will be essentially the same as that on the surface of the ribbon. As the distance between the ribbon and the holiday increases, the mutual resistance between the two decreases. When the two become far enough apart that they are electrically remote from one another, the mutual resistance between them is zero, and the AC current density at the holiday is that calculated by Equation (1).

<u>Example N° 1.</u> Consider the case of a 1 cm^2 holiday in 1000 Ω-cm soil, where the induced AC voltage on the pipeline is 10 V. Using Equation (1), the AC current density at the holiday is found to be 225 A/m^2. Now consider that as an AC mitigation measure, a 20 mm diameter by 50 m long zinc ribbon has been installed along the pipeline at a depth of 1.5 m. The resistance of the zinc R_Z is calculated as[10]:

$$R_Z = \frac{\rho}{2\pi L} \ln \frac{L^2}{tD} \tag{2}$$

the surface area A_Z of the zinc ribbon is:

$$A_Z = \pi DL \tag{3}$$

and the current density i_{ac} on the surface of the zinc ribbon is (ignoring end effect):

$$i_{ac} = \frac{V_{ac}}{R_Z \cdot A_Z} \tag{4}$$

where:

ρ = soil resistivity
L = length of ribbon
t = depth of ribbon
D = diameter of ribbon

The current density at the zinc ribbon is then calculated to be:

$$i_{ac} = \frac{10}{\frac{10}{2\pi 50} \ln\left(\frac{50^2}{0.02 \cdot 1.5}\right) \times \pi \cdot 0.02 \cdot 50}$$

$$= 8.8 \text{ A/m}^2$$

Therefore, the installation of the zinc ribbon has reduced the current density at the holiday from 225 A/m^2 to 8.8 A/m^2, simply by raising the effective resistance of the holiday, ignoring any effect the zinc ribbon would also have in lowering the pipe voltage.

To determine what effect the zinc ribbon would have on reducing the current density at a more remote holiday, the mutual resistance R_M between the holiday and a zinc ribbon located at a distance of X metres away, can be determined using the following equation, as long as X is not significantly less than L[11]:

$$R_M = \frac{\rho}{2\pi X} \tag{5}$$

From Equation (1), the holiday resistance R_H is:

$$R_H = \frac{\rho}{2d} \tag{6}$$

The total resistance R_T of the holiday and zinc ribbon in parallel is then[12]:

$$R_T = \frac{R_H R_Z + R_M^2}{R_H + R_Z - 2R_M} \tag{7}$$

Now, assuming that the resistance of zinc ribbon is relatively unaffected by the presence of the holiday, due to their respective sizes, then only the effective resistance of the holiday R'_H is dependent upon the mutual resistance between the two. The total resistance of the holiday and the zinc ribbon can therefore be considered as the parallel combination of two resistances, R'_H and R_Z.

$$R_T = \frac{R'_H R_Z}{R'_H + R_Z} \tag{8}$$

Therefore

$$R'_H = \frac{R_Z R_T}{R_Z - R_T} \tag{9}$$

Using Equation (9), the AC current densities at the holiday in Example N° 1 are plotted in Figure 10 at various distances from the zinc ribbon, for a number of different zinc ribbon lengths. Note that the current densities at a distance of 0 m have been calculated as being equal to the zinc ribbon current density, and that the current densities between 0 m and the distance at which Equation (5) becomes applicable have been interpolated.

The dramatic effect that grounding has in reducing the AC current density at nearby holidays illustrates why pipeline casings can also be so useful for this purpose. In northern climates where de-icing salts are applied to roadways, the greatest risk of AC corrosion occurs at major road crossings, and since such crossings are often cased, the casings can be used as an electrical ground to reduce the AC current density where it is most needed.

SUMMARY

The case histories of corrosion investigations described herein suggest that AC current can indeed cause the corrosion of cathodically protected steel structures. In each of these cases, a high AC current density of approximately 100 A/m^2 or more was found to correspond to a corrosion anomaly, where the DC potential measured at the anomaly indicated that corrosion should not have occurred. The maximum corrosion rates calculated for the three case histories were found to increase with AC current density, and this relationship is consistent with the findings of previous studies on unprotected steel samples[13], as shown in Figure 11.

With the exception of AC current density, there were no other common denominators which linked all of the case histories together. There were, however, a number of factors which may be important indicators of AC corrosion activity, as follows:

- In all cases, except for those on the Union Gas pipeline (Case History N° 3), the anomalies were found at road crossings, where chloride ion concentrations are typically highest (and soil resistivities are lowest) due to the application of de-icing salts.

- The locations of three anomalies (Case History N° 3) were indicated by the presence of a hemispherical shell of hard soil surrounding the anomaly, perhaps resulting from the localized heating of the soil by the AC current.

- With the exception of Case History N° 1, pits were generally smooth, round, and dish-shaped (i.e. not steep-sided), and were often covered by a hard tubercle of corrosion products.

It is obvious that more data must be collected and shared from corrosion investigations occurring on pipelines exposed to induced AC interference, in order to more accurately identify instances of AC corrosion, and to understand the factors which affect AC corrosion rates. In the meantime, it would be prudent for pipeline operators to mitigate AC voltages below the levels shown in Figure 12[14], to ensure that the risk of AC corrosion is minimized.

ACKNOWLEDGEMENT

The authors wish to acknowledge the support and encouragement of the Joint Pipeline Group (Interprovincial Pipe Line Inc., Trans-Northern Pipelines Inc., Sun-Canadian Pipe Line Co. Ltd. and Sarnia Products Pipeline Co. Ltd.) and their corrosion representatives, in preparation of this paper. We would also like to thank Ken Currier of the City of Kitchener, Rod Reid of Union Gas, and Cliff Mitchell of Nova Gas Transmission for their cooperation with regards to Case Histories N° 1, N° 3 and N° 4 respectively.

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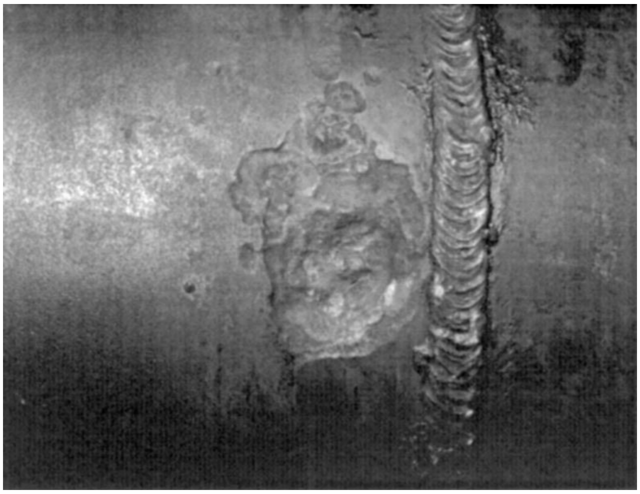

FIGURE 1 - Pit Cluster and Pinhole Failure at 8 O'Clock Position (Case History Nº 1)

FIGURE 2 - Pit Cluster at 4 O'Clock Position (Case History Nº 1)

FIGURE 3 - Hemispherical Shell of Hardened Soil Surrounding Anomaly Nº 4 (Case History Nº 3)

FIGURE 4 - Corrosion Anomaly Nº 4 Adjacent to Scrap Steel Pipe (Case History Nº 3)

FIGURE 5 - Hemispherical Shell of Hardened Soil Surrounding Anomaly Nº 5 (Case History Nº 3)

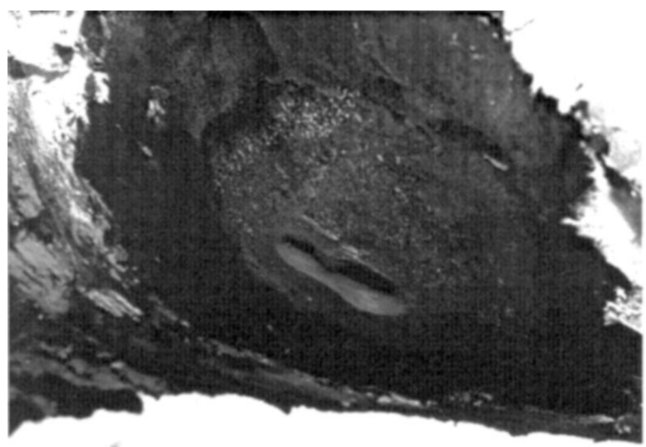

FIGURE 6 - Corrosion Anomaly Nº 5 (Case History Nº 3)

FIGURE 7 - Measurement of pH and Potential Within Pit using a Micro-Electrode

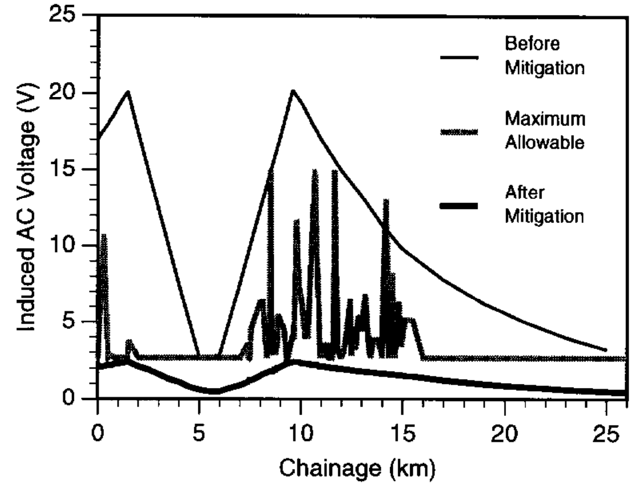

FIGURE 8 - Induced AC Voltages on Pipeline Before and After Mitigation (Case History Nº 4)

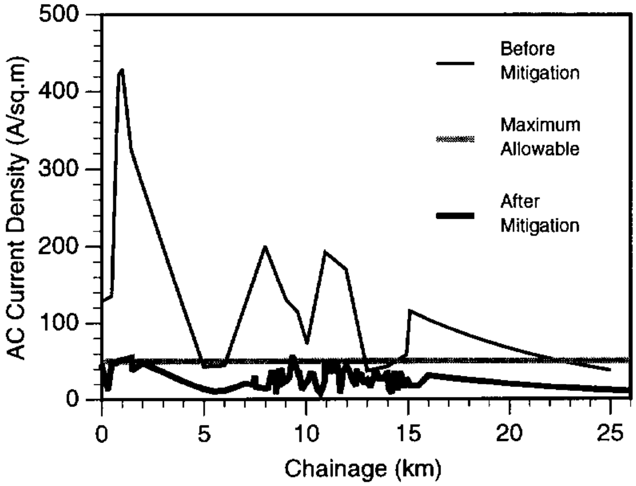

FIGURE 9 - Induced AC Current Densities on Pipeline Before and After Mitigation (Case History Nº 4)

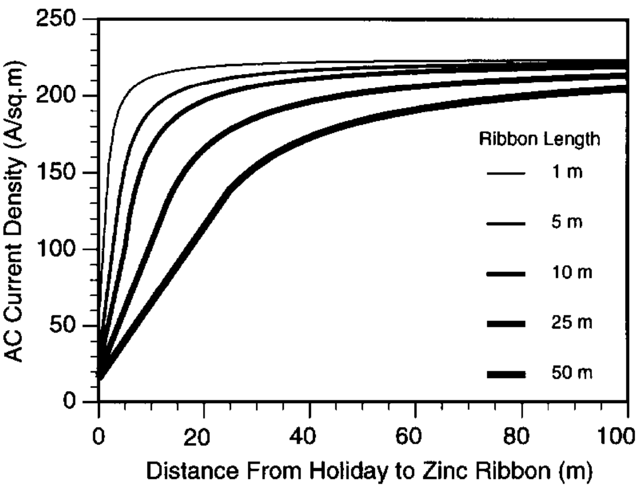

FIGURE 10 - Effect of Zinc Ribbon on AC Current Density (Example Nº 1)

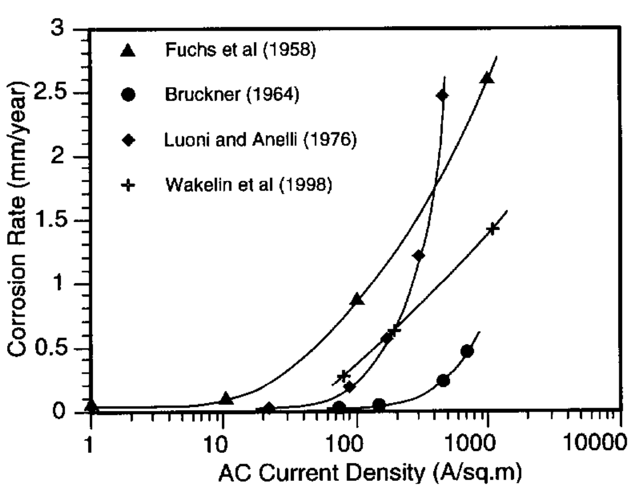

FIGURE 11 - Corrosion Rate Versus AC Current Density

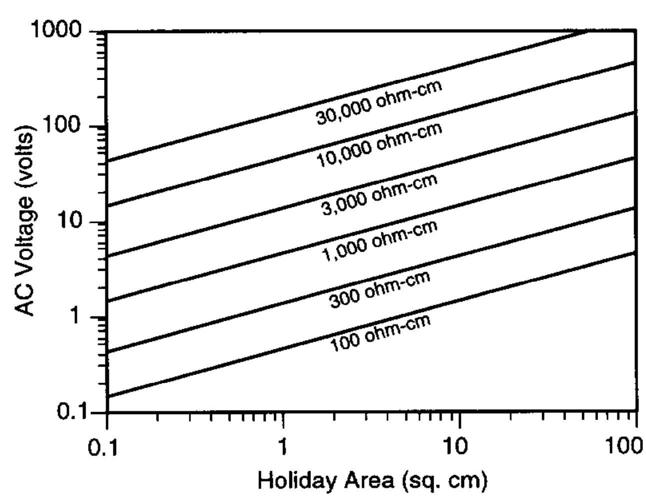

FIGURE 12 - AC Voltage Required to Produce an AC Current Density of 100 A/m²