AC CORROSION – A NEW THREAT TO PIPELINE INTEGRITY?

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ABSTRACT

Corrosion of steel by alternating current was investigated as far back as the early 1900’s. These early studies and others in the 1950-60’s indicated that AC corrosion of steel was only a fraction of an equivalent amount of direct current (i.e. less than 1% of a like amount of DC) and in addition was controlled to negligible levels with cathodic protection applied to industry standards. In 1986 however, an investigation into a corrosion failure on a high pressure gas pipeline in Germany indicated that the sole cause of the failure was AC corrosion. This corrosion failure on an otherwise well protected pipeline resulted in several laboratory and field studies which indicated, that above a certain minimum AC current density, standard levels of cathodic protection will not control AC corrosion and AC mitigation is required to prevent further corrosion. Several other corrosion anomalies were discovered at coating holidays during the follow-up investigations in Germany. The authors have investigated several corrosion occurrences on pipelines in Ontario during the last 2-3 years which appear to be caused by AC corrosion. This presentation traces the literature record on AC electrolysis from the past to the present and discusses the key parameters which determine the likelihood of corrosion attack. Several case histories of suspected AC corrosion will be discussed and guidelines on how to assess whether or not a pipeline is susceptible to AC corrosion will be offered.

INTRODUCTION

In 1994, the authors investigated a corrosion anomaly on a pipeline subject to induced AC and concluded that AC may have influenced the corrosion in some way. This pipeline was one of a number of pipelines, having separate ownership, which shared a common right-of-way with a high voltage powerline across the northern part of Toronto. This group of pipelines (called the Joint Pipelines) also shared common impressed current cathodic protection facilities, as well as the cathodic protection maintenance and monitoring costs. The Joint Pipelines corrosion representatives, after reflecting on the possibility of AC influenced corrosion, were able to relate details of several of their own investigations into corrosion anomalies in which induced AC 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. This paper is a result of that literature study and includes details of three corrosion investigations in Southern Ontario conducted by the authors over the last four years that indicate AC as the fundamental cause of corrosion.

AC CORROSION OF STEEL IN THE ABSENCE OF CATHODIC PROTECTION

Corrosion of iron in soil environments by alternating current has been investigated for many years. In the early 1900’s the effect of AC electrolysis was known and to some degree had been quantified. A comprehensive study by McCollum and Ahlborn (1916), at the U.S. Bureau of Standards, concluded that AC corrosion decreases with increasing frequency, does not occur beyond a limiting frequency between 15 and 60 Hz, and is due to irreversibility during the negative half cycle of the corrosion which occurs during the positive half cycle. Their results for both indoor and outdoor tests on iron electrodes exposed to normal
soils at various frequencies is shown in Fig. 1. Here the amount of corrosion is expressed as a 'coefficient' percentage of the amount of corrosion which would be caused by an equivalent amount of direct current. All electrodes were operated at an AC current density of 5A/m², and for 60 Hz the coefficient was less than 1 percent under natural soil conditions.

Kulman (1961) cited a research investigation conducted by Fuchs et al. (1958) in which steel electrodes were subjected to AC frequencies from 0.05 to 50 Hz at current densities of 1, 10, and 100 A/m² in sodium chloride and sodium sulphate electrolytes. In their tests an AC current density of 100A/m² produced a corrosion rate of 10 mpy. Kulman then calculated that such a corrosion rate could occur on a coated pipeline having a 1 inch diameter holiday, a soil resistivity of 1000 ohm-cm, and an AC voltage of 10 V. It is interesting to note that he also cited an AGA corrosion committee survey in 1955 wherein 7 of 27 pipeline respondents that had experienced induced AC had also suspected that AC current was a cause of corrosion on their facilities.

Williams (1966) tested iron electrodes in an artificial water, formulated to simulate the average ground water found in the midwestern states, at various current densities and determined that the corrosion rate increased with increased current density but levelled off beyond 200 A/m² at a value less than 0.2% of a like amount of direct current.

One of the most comprehensive AC corrosion experiments was conducted by Bruckner (1964) under the sponsorship of the AGA to determine whether or not alternating currents induced in coated steel pipelines would cause accelerated corrosion exceeding that normally expected in soils. This 2-1/2 year project investigated steel and other metals in a variety of soils at varying current densities. Corrosion rates were found to increase with increasing current density with the highest corrosion rate being 21 mpy at a current density of 775 A/m². For the neutral soil conditions the results were plotted as shown in Fig. 2 to compare to the results obtained by Fuchs et al. (1958) from tests in 0.25N salt water solution. Added to this figure are the results of another study conducted by Luoni and Anelli (1976) on galvanized steel specimens in a 3.5% salt water solution. Corrosion rates in salt water are clearly greater than for the neutral soil (series 'H') environment used by Bruckner.
The series 'H' soil had the highest corrosion rate whereas the series 'K' soil with a pH 9 had the lowest corrosion rate over the range of current densities as shown in Fig. 3. Bruckner attributed part of the accelerated corrosion to thermal activation of the corrosion reaction due to the temperature rise within the test cells.

AC CORROSION WITH CATHODIC PROTECTION

Bruckner, who was perhaps the first investigator to study the effects of AC on cathodically protected steel, observed that cathodic protection reduced AC corrosion to "negligible values", but the DC current density, at 0.42 to 0.53 A/m², was considered "much greater than appears necessary in practice".

He also discovered that the magnesium anode potential became more electropositive with increased AC current density (>150 A/m²) and actually reversed with respect to the steel electrode at higher AC current densities. The DC potential of the steel electrodes in the cathodic protection tests also became more electropositive with increasing AC current density. Reversal of the magnesium anode potential was investigated using an oscilloscope and special measuring circuit and it was concluded to be caused by rectification of the AC by a surface film on the magnesium. Pookote and Chin (1978), in a paper containing results of AC corrosion testing of steel specimens in clay soil, reported that a Japanese research team (Miura et al., 1973) studied the effect of AC on the performance of magnesium anodes and found that, at an AC current density of 100 A/m², the magnesium anode potentials shifted electropositive by 0.3 to 1.8 V. Furthermore the anode corrosion rates increased, particularly at AC current densities greater than 100 A/m².

Bruckner's conclusion that the application of cathodic protection could reduce the AC corrosion rate was echoed by Hewes (1969) who stated that the corrosion rate, being in the order of 0.1% of an equivalent magnitude DC current, is "readily overcome by normal cathodic protection procedures". This opinion was also evident in the editors note of Pookote and Chin's (1978) paper where a reviewer expressed the following opinion; "Up to this point I have believed together with many of my peers in the corrosion business, that AC which may be present on a buried pipeline has negligible effect on the corrosion rate of that pipeline. I remain unconvinced that in practical terms AC does accelerate corrosion of buried pipelines." It is fair to say that the foregoing opinion has prevailed to the present. Indeed, in Pookote and Chin's (1978) paper, they commented that "At present, no field data are available that indicate corrosion perforation of pipes has been caused by induced AC." Moore (1988) reflected the prevailing opinion that AC corrosion was not significant when he said "The data available suggests that though AC can influence corrosion in soils in general the effect is not great." Even if AC could cause steel to corrode, Hamlin (1986) concluded that "metals under the influence of AC can be cathodically protected, but usually at higher current densities".

Then in Germany during 1986 two corrosion perforations occurred on a polyethylene coated gas pipeline that was installed in 1980 parallel to an AC (16-2/3 Hz) powered rail transit system. A subsequent investigation, as reported by Prinz (1992), attributed the corrosion to induced AC arising from the transit system operation. At the corrosion sites the polarized potential due to the cathodic protection system was -1000 mV and the corrosion product pH was 10, which indicated that the cathodic protection system was operating adequately with respect to current industry standards (NACE, 1992; DIN, 1985). A potential gradient survey indicated additional coating holidays, which upon excavation revealed "crater-like" corrosion pits beneath corrosion product "bulges" that had not been observed before, but whose appearance was apparently consistent with similar findings on other pipelines in Germany and Switzerland. The relatively low soil resistivity of 1900 ohm-cm was a result of de-icing salt contamination. A steel rod coupon having a holiday surface area of 1 cm² was installed and monitored for a period of 220 days before removal for examination. Despite a cathodic protection current density of 1.5 to 2 A/m² and a resulting 'ON' potential of 1800 to 2000 mV, the coupon exhibited pitting corrosion at a rate of 210 mpy due to an AC current density which varied from 20 to 220 A/m².

As a result of these initial failures and a paucity of information in the literature, extensive field and laboratory testing was funded by various public and private organizations in the Federal Republic of Germany to address the subject of AC corrosion and cathodic protection.
CORROSION FACTORS

The results of the German testing have been reported by a number of investigators (Funk et al., 1992; Helm et al., 1993; Peez, 1993; Hartmann, 1991) and combined with many other studies (McCullam and Ahlborn, 1916; Kulman, 1961; Fuchs et al., 1958; Williams, 1966; Bruckner, 1964; Luoni and Anelli, 1976; Pookote and Chin, 1978; Bertocci, 1979; Jones, 1978; Chin and Fu, 1979; Pagano and Lalvani, 1994) indicate that there are a number of variables which affect the severity of AC corrosion activity.

Effect of AC Current Density on Corrosion Rates

Funk et al. (1992) conducted laboratory tests using 10 cm² coupons in synthetic soil solutions subjected to AC current densities of 100 and 50 A/m² and field tests using coupons in both sandy and clay soils at AC current densities of 10-30 A/m² and 300-1000 A/m² respectively. A test coupon was perforated after 168 days at an AC current density of 100 A/m² and corrosion rates greater than 42 mpy (1 mm/a) were observed. After these preliminary results additional testing to better define the influence of current density was carried out which indicated that AC current densities greater than 30A/m² caused corrosion rates greater than 4 mpy (0.1 mm/a) at a constant cathodic protection current density of 2 A/m². The corrosion rates increased with increased AC current density but decreased with time as shown in Fig. 4.

Helm et al. (1993) conducted short term tests (up to 1000 hrs.) and long term tests (up to 1 year) in flowing and stagnant waters while varying the AC and DC current density in an attempt to establish an effective corrosion control criterion for pipelines exposed to alternating current. They concluded that up to 20 A/m² there is "probably no risk" of accelerated corrosion using the conventional criteria, that between 20 and 100 A/m² corrosion is possible since the conventional criteria are not reliable, and that at AC current densities in excess of 100 A/m² corrosion damage is to be expected.

Gustav Peez (1993) reported corrosion rates of up to 55 mpy (1.3mm/a) at current densities of 100 to 200 A/m². In addition field inspections on the Erdgas Sudbayern (ESB) gas pipeline system indicated that corrosive attacks starting at 15 A/m² could not be ignored.

Field inspections carried out by Hartmann (1991) at identified coating holidays on the 30.8 km Hunze-Hamborn gas pipeline revealed corrosion pits after a 2-1/2 years in operation of 42 mils (1mm) in 20,000 ohm-cm sandy soil at AC current densities of 74 -165 A/m² which is a corrosion rate of approximately 17 mpy.

![Figure 4 - Maximum Penetration Depth as a Function of Test Duration at Constant Cathode DC Current Density (2A/m²) and Differing AC Current Density (Funk et al., 1992)](image-url)
**Effect of Cathodic Protection Current Density**

Increasing the cathodic protection current density from 2 A/m² to 5 A/m², as determined by Funk et al. (1992), decreased the AC corrosion rate at an AC current density of 50 A/m² by at least one half as shown in Fig. 5.

Helm et al. (1993), from results on test specimens in flowing waters, found that although cathodic protection current densities up to 0.25 A/m² had no mitigating effect, there was a demonstrable benefit at 4 A/m².

**Effect of AC Frequency**

Helm et al. (1992) from test results in flowing water and an AC current density of 10-20 A/m² and DC current density of 0.2 A/m² could find no detectable difference between 16-2/3 Hz and 50 Hz. This is similar to the McCollum and Ahlborn (1916) findings between 15 and 60 Hz as shown in Fig. 1 where there is no significant difference in corrosion coefficient.

Pagano and Lalvani did however demonstrate a difference in corrosion rate, between 20 and 60 Hz, on carbon steel in nitrogen purged simulated seawater at an applied AC voltage of 1000 mV, as shown in Fig. 6.

It is also clear from this figure that the corrosion rate is relatively unchanged at AC frequencies greater than 100 Hz.

They attributed the lower corrosion rate with increased frequency to the decrease in double layer impedance with increased frequency such that there is proportionately less charge transfer through the surface polarization resistance. In addition they concluded that at the higher frequencies there would be less time for ferrous ions to diffuse away from the steel surface.
**Effect of Environment**

AC corrosion rates appear to be dependent to a minor extent on the type of environment. Both Prinz (1992) and Helm et al. (1993) indicate that the presence of NaHCO₃ and CaCO₃ increases corrosion whereas NaCl containing media seem to inhibit corrosion. This accelerating effect of carbonates was also apparent at 60Hz in the Bureau of Standards study (McCullum and Ahlborn, 1916).

Flowing water produced a higher corrosion rate than stagnant water of the same composition according to Helm et al. (1993) and this was ascribed to the enhanced supply of Ca²⁺ and HCO₃⁻ ions to the surface. Tests on low alloy steel specimens in 0.1N NaCl solutions by Jones (1978) indicated that the corrosion rate compared to the control, at an AC current density of 300A/m², was unaffected in aerated conditions but increased by a factor of five in the deaerated conditions. Bertocci (1979) also demonstrated, based on polarization theory, that when the cathode is under diffusion control, such as one might expect in aerated conditions, corrosion acceleration would be minimized. Bruckner (1964) deduced that the AC corrosion rate in deaerated conditions was greater than under aerated conditions although he was unable to explain this result. AC had a greater corrosion accelerating effect in a clay soil as compared to mineral waters according to Pookote and Chin (1978).

**Temperature Effects**

Two investigators observed an increase in test cell temperature with an increase in AC current density. Bruckner’s (1964) results are shown in Fig. 7 for two different soil types and indicates a greater than 15°C rise in temperature from zero to 775A/m² of AC current density.

Also added to this figure are the results from Pookote and Chin’s (1978) experiments in an 8000 ohm-cm resistivity clay soil. The latter investigators also attempted to determine the corrosion activity, if any, caused by a temperature increase in 5°C increments up to 40°C but the result was inconclusive. There is no data on whether or not a similar temperature rise occurs under actual field conditions.

**Effect of Time**

Figures 4 and 5 clearly indicate that the corrosion rate decreases with time regardless of the AC current density. Williams’ (1966) corrosion studies, conducted in the absence of cathodic protection, also verified that the AC corrosion rate decreases asymptotically with increased time. Prinz (1992) however reported that there was an “incubation” time of 30 and 120 days for AC current densities of 100 and 50A/m² respectively after which the corrosion rate increased but this has not been reported elsewhere. Furthermore these short time test periods would not have any significant relation to a pipeline in the long term.

Another time factor is the general increase in resistance with time and a consequent decrease in AC current density as reported by two investigators (Williams, 1966; Bruckner, 1964) when a constant AC voltage is applied. As this type of AC situation closely simulates actual field conditions, it implies that lower corrosion rates are to be expected in practice as time increases.
Effect of Steel Surface Area

The surface area of the pipe at a coating holiday should be important since the corrosion rate increases with increasing current density and hence large holidays would therefore have a lower current density than smaller holidays if both are exposed to the same soil conditions. In this regard Peez (1993) reported on observations made at a number of holiday sites on the Erdgas Sudbayern system that indicated the majority of the corrosion occurred at holidays having about 1 cm² surface area. A second paper (Heim and Peez, 1992), based on the same investigation, reported that corrosion activity was not observed at small holidays of 0.01 cm² and only minimal corrosion at one of two sites having a holiday area of 0.03 cm² as indicated in the following table. The lack of corrosion attack at the smaller holidays was attributed to obstruction of these relatively small openings.

<table>
<thead>
<tr>
<th>Size of Holiday (cm²)</th>
<th>Corrosion Attack</th>
<th>Max. Penetration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>no</td>
<td>—</td>
</tr>
<tr>
<td>1 to 2</td>
<td>yes</td>
<td>2</td>
</tr>
<tr>
<td>0.01</td>
<td>no</td>
<td>—</td>
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<tr>
<td>1</td>
<td>yes</td>
<td>3</td>
</tr>
<tr>
<td>0.01</td>
<td>no</td>
<td>—</td>
</tr>
<tr>
<td>3 @ 0.5 to 1.5</td>
<td>yes</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>yes</td>
<td>3.5</td>
</tr>
<tr>
<td>1</td>
<td>yes</td>
<td>4.5</td>
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</tr>
<tr>
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<td>yes</td>
<td>3.5</td>
</tr>
<tr>
<td>6 @ 0.01</td>
<td>no</td>
<td>—</td>
</tr>
<tr>
<td>0.03</td>
<td>yes</td>
<td>0.1</td>
</tr>
<tr>
<td>0.03</td>
<td>no</td>
<td>—</td>
</tr>
</tbody>
</table>

Prinz (1992) recounted that, when coupons having surface areas ranging from 0.5 cm² to 5 cm² were buried next to an AC affected pipeline, the highest corrosion rate occurred on the 1 cm² coupon.

CORROSION MECHANISM

Unfortunately the existing literature does not describe definitively the actual AC corrosion mechanism. McCollum and Ahlborn (1916) generally reasoned that AC corrosion was due to the irreversibility of the corrosion reaction such that metal ions created during the anodic half cycle were not re-plated during the negative half cycle. Although this was equated to a rectification effect, Williams (1966) concluded however, that the corrosion mechanism was not rectification but rather due solely to the positive half cycle. Bruckner (1964) thought that the observed AC corrosion may have been partially a result of "thermal activation" although Pookote and Chin (1978), who attempted to investigate the influence of temperature on the rate of corrosion, were unable to draw a firm conclusion because of the very scattered data.

Bertocci (1979) explained the relatively low corrosion efficiency of AC compared to DC by demonstrating that the majority of the sine function alternating current and higher frequency harmonics are shunted by the double layer capacitance "without causing material transport across the electrode interface". He also showed that this effect could be particularly pronounced under diffusion controlled (i.e. aerated) conditions. Jones (1978), in explaining why there was greater corrosion acceleration on steel in deaerated environments than in aerated, demonstrated that superimposed AC current caused depolarization of the anodic reaction and inferred that this could be caused by anion desorption or surface film reduction during the cathodic half cycle. Similarly, Chin and Fu (1979) were able to show, from anodic polarization tests on mild steel electrodes in a pH 7, 0.5M Na₂SO₄ solution, a breakdown in anodic passivity with increasing 60Hz current density. Hamlin (1980) concluded however, that "AC does not have any significant effect on the polarization or depolarization of cathodically protected steel—".

The extreme complexity of determining all the variables influencing AC corrosion is apparent in the literature and several investigators emphasized the need for additional research. There are two ongoing research projects being conducted by the University of Manchester Institute of Science and Technology (UMIST, 1994-95) with regard to the influence of alternating currents on corrosion and cathodic protection. This research activity is attempting to develop a model that will explain AC corrosion and to demonstrate the relationship between corrosion rate, AC current density, and cathodic protection current density. A report on this research will probably not be available until near the end of 1996.

DISCUSSION OF LITERATURE REVIEW

Early research studies into AC corrosion of steel indicated that the AC corrosion rate was small, being in the range of 0.1% to 1% of a like amount of DC, and therefore of negligible effect on steel pipelines. Furthermore it was generally understood, by pipeline operators and cathodic protection practitioners alike, that the modest amount of AC corrosion which would be anticipated could be adequately controlled by applying cathodic protection in accordance with industry standards. But in 1986 in Germany a number of pipeline corrosion incidents arose which, together with subsequent laboratory research and field investigations, demonstrated that AC induced corrosion had occurred on
coated steel pipelines that were otherwise satisfactorily protected by cathodic protection. Corrosion rates at an AC current density of 100A/m² were found to be approximately 0.5 mm/a (20mpy) even though the cathodic protection current density was 2A/m². The corrosion rate on cathodically protected steel was found to vary proportionately with increasing AC current density and caused the German investigators (Prinz, 1992; Funk et al., 1992; Helm et al., 1993; Peez, 1993; Hartmann, 1991) to conclude the following:

(a) for AC current densities less than 20A/m² there is no AC induced corrosion, and
(b) AC corrosion is unpredictable for AC current densities between 20-100A/m², and
(c) for AC current densities greater than 100A/m² corrosion is to be expected.

It was also determined that the highest corrosion rates were at holidays having a surface area in the range of 1-3cm². The magnitude of the AC current densities may at first seem unusually high but by calculating the AC voltage required to produce a current density of 100A/m² in 1000 ohm-cm soil at a 1 cm² holiday it is apparent that this calculated voltage of 4.4 V is well below the recognized maximum safe AC voltage of 15V (CSA, 1991).

\[
\text{\(i_{ac} = \frac{8 V_{ac}}{\rho \pi d}\)} \quad \text{(Funk et al., 1992)} \tag{1}
\]

where:
- \(i_{ac}\) = ac current density (A/m²)
- \(V_{ac}\) = pipe ac voltage to remote earth (V)
- \(\rho\) = soil resistivity (ohm-m)
- \(d\) = diameter of a circular holiday having a 1 cm² surface area = 0.0113 m

then:

for \(i_{ac} = 100\) A/m² and \(\rho = 10\) ohm-m

\[
V_{ac} = \frac{i_{ac} \rho \pi d}{8}
\]

\[
V_{ac} = \frac{100\text{ A/m}^2 \cdot 10\text{ ohm-m} \cdot 3.14 \cdot 0.0113\text{ m}}{8} = 4.4\text{ V}
\]

It is clear from the foregoing calculation that cathodically protected pipelines subjected to AC voltages, that are below the maximum safe operating level of 15 volts, can suffer from AC corrosion at holiday sites having a surface area of approximately 1 cm² in a soil resistivity of 3000 ohm-cm or less.

Although a cathodic protection current density above a minimum of 0.25 A/m² up to 5 A/m² was found to decrease the AC corrosion rate (Funk et al., 1992; Helm et al., 1993), the resulting attack could not be reduced to negligible values. Again these DC current densities seem excessively high compared to the 0.01-0.03 A/m² recommended for bare steel (NACE, 1983). Experiments, using 0.4 cm diameter probes by Kasahara et al. (1979), has verified that the cathodic protection current density could be 10 A/m² at a pipe-to-soil potential of 1000 mV. Accordingly standard levels of cathodic protection will have a demonstrable beneficial effect in mitigating AC corrosion.

Although there have been numerous investigators who have attempted to explain the AC corrosion mechanism, there is at present no technical consensus. In addition the testing procedures needed to address this issue appear to be relatively complex.

### CASE HISTORIES

The investigations regarding the 3 case histories which follow were sufficiently comprehensive that causes other than AC corrosion could be reasonably ruled out. This led the authors to conclude that induced AC was the primary cause of corrosion in each instance. There are also other less well documented corrosion anomalies, of which the authors are aware, that in retrospect are suspected to be caused by AC corrosion.

#### Case History No. 1

A 300mm diameter high pressure gas pipeline, having an extruded polyethylene coating, was installed in 1987 parallel to a high voltage AC power line about 15 m away from the centerline of the towers. The cathodic protection system on this 4400m pipeline consisted of 7.7 kg. magnesium anodes at approximately 100m spacings. Despite satisfactory levels of cathodic protection in the range of 1.45V_{cse} - 1.50 V_{cse}, a leak at a road crossing was discovered in September of 1991.

A subsequent inspection revealed that the leak was caused by a 25mm diameter corrosion pit within 50 mm of a weld at the 8 o'clock position. A second pit of similar size, but which had not yet penetrated the pipe wall, was discovered at the 4 o'clock position. The joint coating, a hot applied tape, was generally intact except for the two corrosion sites and the coating damage was thought to have been caused by a welding clamp because of the position of these holes. As the pipe nominal wall thickness was 5.56 mm, the average penetration rate was about 1.4 mm per year at the failure.

The soil at the failure site, which was under the middle of the road, was a dark brown sandy clay having a pH of 8.8, an electrical resistivity of 130 ohm-cm and a chloride ion concentration of 3600 ppm. The soil on both sides of this road exhibited resistivities of
1000 ohm-cm or greater and chloride contents of less than 500 ppm, and an inspection of the piping did not reveal any serious corrosion at other coating holidays.

The high chloride concentrations were attributed to de-icing salt application as this road was situated on a hill that would normally receive frequent applications.

AC voltages induced from the adjacent power line had been mitigated, since installation, to a 6-10V level at test stations using capacitors except for periods when one or more of these devices failed and induced voltage levels rose to 26 volts in some locations. The peak voltage location however was at the road crossing and was measured at 28V in January of 1992. Subsequent installation of grounding devices reduced this voltage to less than 15V.

The cause of the corrosion failure was not confirmed, although it was speculated that the corrosion could have been the result of an occluded cell because of the high chloride concentration. Because trace sulphides were found in the corrosion product, bacterial induced corrosion was also suspected. More likely, in retrospect, the corrosion was probably AC induced. The AC current density, using Eq. (1) at a peak induced voltage of 28V in 130 ohm-cm soil, is calculated to be 2195 A/m², which is extremely high and certainly well in excess of the 100A/m² threshold wherein corrosion can be anticipated according to the German experience.

**Case History No. 2**

In 1976 a 275 mm diameter oil products pipeline operated by TNPI was rerouted around a future site of an electrical transformer station at Leslie St. in Toronto. The new piping was coated with extruded polyethylene and cathodically protected with impressed current from common systems serving a number of other pipelines that also shared the power line corridor across the top of Toronto.

An internal inspection tool, using a magnetic flux, was passed through the piping in 1986 and a minor anomaly (much less than 25% wall penetration) in the rerouted section was identified as a result of this survey. Another internal inspection in 1994 using an ultrasonic tool indicated a significant anomaly at the same location as the previous minor anomaly. A subsequent excavation revealed an active corrosion pit which was 6.9 mm deep (88% through the 7.8 mm wall). Assuming the penetration at the first internal inspection was 25% of the wall thickness then another 5 mm of corrosion penetration occurred during the intervening 8 years for an average corrosion rate of 0.6 mm per year.

Pipe-to-soil potentials more electronegative than -1270 mV

\[
\text{were recorded in the vicinity of this corrosion site during previous surveys, thus indicating a satisfactory level of protection. Moreover the potential with the reference electrode located at the pit was -1180 mV compared to -1470 mV with the electrode located on the surface. Tests on the soil adjacent to the pit indicated that the soil resistivity was 300 ohm-cm with a chloride concentration of 1920 ppm. The high chloride concentration was attributed to de-icing salt applications as this corrosion anomaly was located under the east curb of the street. A sulphide ion test using a 3% sodium azide in 0.1N iodine solution had negative results. The reddish brown corrosion product had a pH of 10.7 compared to the bulk soil pH at this site of 7.98. After introducing the corrosion product into a sulphate reducing bacteria kit the resulting bacterial count was below the detectable limit.}
\]

The induced AC voltage at this location was measured at 15 V at the time of the investigation and was 12 V during the previous year's cathodic protection survey. The corrosion pit, which had a crater-like shape, had dimensions of approximately 50 mm long by 45 mm wide, and the resulting current density was calculated using Eq. (1) for \( 12 \text{V}_{se} \) to be 190 A/m², which is well above the 100 A/m² threshold. Except for the possibility that this was an occluded corrosion cell, the cause of corrosion was induced AC.

**Case History No. 3**

A 500 mm diameter coal tar coated high pressure natural gas pipeline was installed in 1972 by Union Gas. About 40 km of this 74 km pipeline was routed alongside an AC power line. In 1995 an internal inspection using an ultrasonic inspection tool identified a number of anomalies, all of which were in the pipe section located on 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 clustered in two discrete piping lengths from 7.55 to 8.14 km and from 18.1 to 19.5 km. Two of these anomalies at 7.59 km and 18.53 km were estimated to be 80% and 63% through the wall respectively.

The pipe-to-soil potential records at test points and from close interval surveys for this pipeline were searched back to 1972 with no indication of subcriterion potentials. Rectifier data for the influencing impressed current systems back to 1983 indicated that there was only a total of 10 days downtime, all in 1994 when distributed AC mitigation in the form of banked magnesium anodes was being installed.

At the first dig location the maximum pit depth was 6.1 mm (86% of wall thickness) and covered an area of approximately 20cm². The adjacent soil was damp clay having a measured resistivity of 2000 ohm-cm. A hard tightly adhering tubercle, which protruded about 50 mm, covered the pit. The coating around the pit was disbonded for a radius of 200 mm. A pH test using litmus paper indicated that the pH was greater than 8.5 at each of the three pits examined at this first dig. Furthermore there was no evidence of bacterial induced corrosion and the local cathodic protection potential was -1.56 \( \text{V}_{se} \). Accordingly there was no apparent cause for the observed corrosion. The induced AC voltage at this site had been an average of 33V before magnesium anode mitigation was installed in 1994, and the AC current density was calculated to be 84A/m² which could explain the relatively lower penetration rate of 0.27 mm per year.

At the second dig site three anomalies were investigated.
Surrounding each of the three anomalies was a large hemispherically shaped shell of extremely hard soil having a thickness varying up to 150 mm. The maximum pit depth at this location was 6.34 mm (89.3% of wall thickness) at the 2 o’clock position and had a diameter of 56 mm. Also a 25 mm diameter steel pipe was found to be wedged against the pipe at the pit. The pH of the soil immediately adjacent to the pit was 8.2 and the soil resistivity of the moist clay soil was measured at 1350 ohm-cm. There was only a trace of chlorides and sulphides. The pipe-to-soil potential with the reference electrode on top of the corrosion product was -1.050 V cse compared to -1.490 V cse with 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 also likely that as corrosion progressed the pipe-to-pipe contact would likely be broken and there would be no more shielding. Once the contact was broken the small pipe would serve to focus both cathodic protection current and AC current to the pit location because of its lower resistivity compared to the surrounding soil. The pipe-to-soil potential suggests that the pit did not lack for cathodic protection current. Moreover 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.

Before the distributed AC mitigation system was installed on this pipeline in 1994, the AC voltage at the second dig site was about 25 V. The calculated AC current density is approximately 84.3 A/m² which is almost identical to the AC current density at the maximum pit depth at the first dig site. Also the corrosion rates were similar. Accordingly it was concluded that the observed corrosion at both dig sites was AC induced.

**SUMMARY**

It is clear from the German experience and from recent investigations by the authors that, under certain conditions, AC can cause corrosion of steel pipelines that are cathodically protected in accordance with industry standards. The corrosion rate appears to be directly related to the AC current density such that corrosion can be expected at AC current densities of 100 A/m² and may occur at AC current densities greater than 20 A/m².

To a lesser extent the corrosion rate is also influenced by environmental factors such as degree of aeration, the presence of chlorides and carbonates, and the surface area at the coating holiday.

Cathodic protection cannot reduce the corrosion rate to negligible values when the AC current density is greater than 100 A/m².

In low resistivity soils the AC current density can exceed 100 A/m² even if the AC voltage has been mitigated to less than or equal to the accepted personnel safety level of 15 V as shown in Fig. 8. The information on this figure was calculated from Eq. (2) and illustrates the 100A/m² threshold for various soil resistivities, voltage levels, and holiday surface areas. This figure can be used to assess the AC corrosion risk if the soil resistivity and AC voltage at the holiday are known.

![Figure 8](image_url)

From Eq. (2) it follows that if the ratio of \( \frac{V_{ac}}{\rho} \) (V) / (ohm-m) is \( \leq 0.44 \) or \( \leq 0.09 \) then the AC current density is less than 100 A/m² and 20 A/m² respectively.

At the present, the only method of identifying AC corrosion is by the systematic elimination of other causes. Accordingly corrosion investigations on pipelines subjected to induced AC must be conducted carefully. The authors are presently testing a set of procedures incorporating the use of dual pH/potential micro-electrodes to facilitate a more dependable methodology.

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