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AC CORROSION – A NEW CHALLENGE 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 when cathodic protection was 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 the initiation of several laboratory and field studies which indicated, that above a certain minimum AC current density, normal levels of cathodic protection will not control AC corrosion to acceptable levels and that AC mitigation is often required to prevent serious corrosion. Several other AC corrosion sites were discovered at coating holidays during the follow-up investigations in Germany. A graph, relating AC voltage to holiday size at the minimum AC current density for corrosion, is presented to assist the pipeline operator in determining whether or not a pipeline is susceptible to AC corrosion activity.

Keywords: AC corrosion, current density, corrosion rate, frequency, temperature, soil conditions, corrosion susceptibility, pipeline

INTRODUCTION

In 1994, the authors investigated a corrosion anomaly on a pipeline subject to induced AC and surmised 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

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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.

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[1], 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, are 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 $5 A/m^2$, and for 60 Hz the coefficient was less than 1 percent under natural soil conditions.

Kulman[2] cited a research investigation conducted by Fuchs et al.[3] in which steel electrodes were subjected to AC frequencies from 0.05 to 50 Hz at current densities of 1, 10, and 100 A/m^2 in sodium chloride and sodium sulphate electrolytes. In their tests an AC current density of $100 A/m^2$ 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[4] 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/m^2 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 [5], 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/m^2. Results obtained in the neutral soil are plotted as shown in Fig. 2 to compare to the results obtained by Fuchs et al.[6] from tests in 0.25N salt water solution. Added to this figure are the results of another study conducted by Luoni and Anelli [7] 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/m^2, 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/m^2) 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[8], in a paper containing results of AC corrosion testing of steel specimens in clay soil, reported that a Japanese research team (Miura et al.)[9] studied the effect of AC on the performance of magnesium anodes and found that, at an AC current density of 100 A/m^2, the magnesium anode potentials shifted electropositively by 0.3 to 1.8 V. Furthermore the anode corrosion rates increased, particularly at AC current densities greater than 100 A/m^2.

Bruckner's conclusion that the application of cathodic protection could reduce the AC corrosion rate was echoed by Hewes[10] 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[11] 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[12] paper in 1978, they commented that "*At present, no field data are available that indicate corrosion perforation of pipes has been caused by induced AC.*" Moore[13] 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[14] reiterated that "*metals under the influence of AC can be cathodically protected, but usually at higher current densities*".

The view that AC corrosion was insignificant when cathodic protection is applied was not supported by the results of laboratory testing by Dévay et al.[15] In 1966, the results of measuring the corrosion rate on a 1 cm^2 iron coupon in a 5% KCl solution when subjected to AC current densities from 0 to 250 A/m^2 at 50 Hz and DC current densities from 0 to 10 A/m^2, were published. The test results, summarized in Figure 4 demonstrate that although increasing DC current density does reduce corrosion, the corrosion rate was still greater than .025 mg/hr-cm^2 (11 mpy) for AC current densities of 100 A/m^2 and 250 A/m^2 even at the relatively high DC current density of 1000 μA/cm^2 (10 A/m^2).

The depolarization effect of AC on the cathodic and anodic polarization characteristics were also reported by Dévay at al[16] and are shown in Figure 5. The iron coupon cathodic potential is approximately 200 mV electropositive at the 250 A/m^2 AC current density.

Although it is clear from Dévay et al's investigation that AC corrosion could occur even at large applied cathodic protection current densities, it wasn't until 1986 that AC corrosion was identified in the field. In Germany 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[17], 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_{cse} and the corrosion product pH was 10, which indicated that the cathodic protection system was operating adequately with respect to current industry standards (NACE; DIN)[18,19]. A subsequent potential gradient survey indicated additional coating holidays, which upon excavation revealed "crater-like" corrosion pits underneath corrosion product "bulges" that had not been observed before, but whose appearance was apparently consistent with similar observations 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 cm^2 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/m^2 and a resulting 'ON' potential of 1800 to 2000 mV_{cse}, the coupon exhibited pitting corrosion at a rate of 210 mpy due to an AC current density which varied from 20 to 220 A/m^2.

As a result of these initial failures an extensive field and laboratory testing program was funded by various public and private organizations in the Federal Republic of Germany to address the subject of AC corrosion with operating cathodic protection systems.

CORROSION FACTORS

The results of the German testing have been reported by a number of investigators [20-23] and combined with many other studies[24-34,52,72] 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.[35] conducted laboratory tests using 10 cm^2 coupons in synthetic soil solutions subjected to AC current densities of 100 and 50 A/m^2 and field tests using coupons in both sandy and clay soils at AC current densities of 10-30 A/m^2 and 300-1000 A/m^2 respectively. A test coupon was perforated after 168 days at an AC current density of 100 A/m^2 and corrosion rates greater than 42 mpy (1mm/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/m^2 caused corrosion rates greater than 4 mpy (0.1mm/a) at a constant cathodic protection current density of 2 A/m^2. The corrosion rates increased with increased AC current density but decreased with time as shown in Figure 6.

Helm et al.[36] 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/m^2 of AC there is "probably no risk" of accelerated corrosion using the conventional criteria, that between 20 and 100 A/m^2 corrosion is possible, since the conventional criteria are not reliable, and that at AC current densities in excess of 100 A/m^2 corrosion damage is to be expected.

Gustav Peez[37] reported corrosion rates of up to 55 mpy (1.3mm/a) at current densities of 100 to

200 A/m^2. In addition field inspections on the Erdgas Sudbayern (ESB) gas pipeline system indicated that corrosive attacks, starting at an AC current density of 15 A/m^2, could not be ignored.

Field inspections carried out by Hartmann[38] at identified coating holidays on the 30.8 km Hunze-Hamborn gas pipeline revealed corrosion pits after 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/m^2, which is an average corrosion rate of approximately 17 mpy.

Effect of Cathodic Protection Current Density

Increasing the cathodic protection current density from 2A/m^2 to 5A/m^2, as determined by Funk et al.[39], decreased the AC corrosion rate at an AC current density of 50A/m^2 by at least one half as shown in Figure 7.

Helm et al.,[40] from results on test specimens in flowing waters, found that although cathodic protection current densities up to 0.25 A/m^2 had no mitigating effect, there was a demonstrable benefit at 4 A/m^2.

Dévay et al.[41] observed that AC induced corrosion was reduced at increasing DC current densities, but was still significant even at 10 A/m^2 when the AC current density was 100 A/m^2 and 250 A/m^2.

Effect of AC Frequency

Helm et al.[42] from test results in flowing water, at an AC current density of 10-20 A/m2 and a DC current density of 0.2 A/m^2, could find no detectable difference between 16-2/3 Hz and 50 Hz. This is similar to the McCollum and Ahlborn[43] findings between 15 and 60 Hz.

Lalvani and Zhang[44] did however demonstrate a difference in corrosion rate, between 20 and 60 Hz, on 1018 carbon steel in nitrogen purged simulated seawater at an applied AC voltage of 180mV, as shown in Figure 8. It is also clear from this figure that the corrosion rate is relatively unchanged at AC frequencies greater than 130 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 on the type of environment. Both Prinz[45] and Helm et al.[46] found that the presence of $NaHCO_3$ and $CaCO_3$ 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 (McCollum and Ahlborn).[47]

Flowing water produced a higher corrosion rate than stagnant water of the same composition according to Helm et al.[48] and this was ascribed to the enhanced supply of Ca^{++} and HCO_3^- ions to the surface. Tests by Jones[49] on low alloy steel specimens in 0.1N NaCl solutions indicated that the corrosion rate compared to the control, at an AC current density of 300A/m^2, was unaffected in aerated conditions but increased by a factor of five in the deaerated conditions. Bertocci[50] 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 [51] found that the AC corrosion rate in deaerated conditions was greater than for aerated conditions although he was unable to explain this result. Frazier and Barlo[52] found that corrosion rates on steel coupons at AC current densities in the order of 1000 A/m^2 varied substantially in two different simulated groundwaters and that the highest corrosion rate was when the groundwater was deaerated. AC had a greater corrosion accelerating effect in a clay soil as compared to mineral waters according to Pookote and Chin.[53]

Temperature Effects

Several investigators observed an increase in test cell temperature with an increase in AC current density. Bruckner's[54] results are shown in Figure 8 for two different soil types and indicates a greater than 15°C rise in temperature from zero to 775A/m^2 of AC current density.

Also added to this figure are the results from Pookote and Chin's[55] 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. Dévay at al.[56] test results, also added to Figure 8, shows about a 37°C temperature rise with an AC current density of 830 mA/m^2.

Effect of Time

Figures 4 and 5 clearly indicate that the corrosion rate decreases with time regardless of the AC current density. Williams'[57] corrosion studies, conducted in the absence of cathodic protection, also verified that the AC corrosion rate decreases asymptotically with increased time. Moreover Prinz[58] reported that there was an "incubation" time of 30 and 120 days for AC current densities of 100 and 50A/m^2 respectively after which the corrosion rate increased but this has not been reported elsewhere. These short time test periods would not however have much significance with respect 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[59,60] 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 and AC voltage. In this regard Peez[61] 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 1cm^2 surface area. A second paper by Heim and Peez, [62] based on the same investigation, reported that corrosion activity was not observed at small holidays of 0.01 cm^2 and only minimal corrosion at one of two sites having a holiday area of 0.03 cm^2 as indicated Table 1. The lack of corrosion attack at the smaller holidays was attributed to "obstruction" of these relatively small openings.

Prinz[63] recounted that, when coupons having surface areas ranging from 0.5 cm^2 to 5 cm^2 were buried next to an AC affected pipeline, the highest corrosion rate occurred on the 1 cm^2 coupon.

Corrosion Mechanism

Unfortunately there is no consensus in the existing literature about the actual AC corrosion mechanism. McCollum and Ahlborn[64] 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[65] concluded however, that the corrosion mechanism was not rectification but rather due solely to the positive half cycle. Bruckner[66] thought that the observed AC corrosion may have been partially a result of "*thermal activation*" although Pookote and Chin[67], who attempted to investigate the influence of temperature on the rate of corrosion, were unable to draw a firm conclusion because of scattered data.

Bertocci[68] 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,[69] 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[70] were able to show, from anodic polarization tests on mild steel electrodes in a pH 7, 0.5M Na_2SO_4 solution, a breakdown in anodic passivity with increasing 60Hz current density.

Hamlin[71] concluded however, that "*AC does not have any significant effect on the polarization or depolarization of cathodically protected steel—*". In contrast Lalvani and Lin[72] were able to show by generating a number of potentiodynamic polarization curves that the corrosion characteristics can be classified in terms of the ratio of the anodic and cathodic Tafel slopes.

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.

Summary

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 previous and subsequent laboratory research and field investigations, demonstrated that AC induced corrosion can occur on coated steel pipelines that were otherwise satisfactorily protected by cathodic protection. Corrosion rates at an AC current density of $100 A/m^2$ were found to be approximately 0.5 mm/a (20mpy) even though the cathodic protection current density was $2A/m^2$. The corrosion rate on cathodically protected steel was found to vary proportionately with increasing AC current density and caused the German investigators to conclude the following;

(a) for AC current densities less than $20A/m^2$ there is no AC induced corrosion, and
(b) AC corrosion is unpredictable for AC current densities between $20\text{-}100A/m^2$, and
(c) for AC current densities greater than $100A/m^2$ 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 $1\text{-}3cm^2$. The magnitude of the AC current densities may at first seem unusually high but by calculating the AC voltage using the following equation that is required to produce a current density of $100A/m^2$ in 1000 ohm-cm soil at a 1 cm^2 holiday, it is apparent that this calculated voltage of 4.4 V is well below the recognized maximum safe AC voltage of 15V used in various standards.[78,79]

$$i_{ac} = \frac{8 V_{ac}}{\rho \pi d} \quad [80] \qquad (1)$$

where:

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

V_{ac} = pipe ac voltage to remote earth (V)

ρ = soil resistivity (ohm-m)

d = diameter of a circular holiday having a 1 cm^2 surface area (0.0113 m)

then:

for i_{ac} = $100\ A/m^2$ and $\rho = 10$ ohm-m

$$V_{ac} = \frac{i_{ac} \rho \pi d}{8} \qquad (2)$$

$$V_{ac} = \frac{100\ A/m^2 \bullet 10\ \text{omh-m} \bullet 3.14 \bullet 0.0113\ m}{8}$$

$$V_{ac} = 4.4\ V$$

It is clear from the foregoing calculation that cathodically protected pipelines subjected to AC voltages, that are well below the maximum safe operating level of 15 volts, can suffer from AC corrosion at holiday sites having a surface area of approximately 1 cm^2 in a soil resistivity of 3000 ohm-cm or less.

Using the foregoing relationship, the threshold AC voltages at which a $100\ A/m^2$ AC current density would be present in various soil resistivities and for a range of holiday areas is calculated and shown in Figure 10. This graph can be used by a pipeline operator to determine whether or not a pipeline subjected to an AC voltage would be likely to corrode. For instance, consider a pipeline surrounded by 1,000 Ω-cm soil and having an induced AC voltage of 6V. Plotting these values on the graph reveals that a holiday area of 1.5 cm^2 could have an AC current density of 100 A/m^2 or greater. To reduce this to a safer level of 20 A/m^2 would require mitigating the AC voltage to 1.2V (6V x 20/100).

Although cathodic protection current densities up to 10 A/m^2 were found to decrease the AC corrosion rate, the resulting attack could not be reduced to negligible values. The magnitude of these DC current densities also seem excessively high compared to the 0.01-0.03 A/m^2 recommended for bare steel (NACE)[81]. Experiments, using 0.4 cm diameter probes by Kasahara et al.,[82] has verified however, that the cathodic protection current density at holidays on a coated pipeline can be 10 A/m^2 at a pipe-to-soil potential of 1000 mV_{cse}. 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.

CONCLUSIONS

Although there is a lack of consensus in the literature as to the exact mechanism of AC corrosion, it is nevertheless evident that AC can cause corrosion on steel despite otherwise satisfactory levels of cathodic protection current.

Furthermore the corrosion rate has been found to vary as follows:

- increase with increased AC current density greater than 20 A/m^2 and to be significant at AC current densities greater than 100 A/m^2 regardless of the magnitude of cathodic protection current density.
- increase in deaeration or chloride content in soil or water environments.
- increase with decreasing holiday surface area reaching a maximum for a holiday surface area of 1 cm^2.
- increases with decreasing frequency below about 100 Hz.
- decrease with increasing cathodic protection current density.
- decrease with time.

It would be prudent for operators of cathodically protected steel pipelines to keep the AC current density well below 100 A/m^2 for a 1 cm^2 holiday to prevent AC corrosion especially in deaerated or chloride containing soils and waters. The AC voltage corresponding to this threshold can be calculated or obtained from the graph of Figure 10 for various soil resistivities. The AC voltage may need to be mitigated well below the otherwise safe operating level of 15V.

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82. Kasahara, K., Sato. T., and Adachi, H., March 1979, "An Improved Method for Measuring Pipe-to-Soil Potential and Current Density at Cathodically Protected Pipelines", Materials Performance, Vol. 18 (3), pp. 21-25.

Size of Holiday (cm^2)	Corrosion Attack	Max. Penetration (mm)
100	no	—
1 to 2	yes	2
0.01	no	—
1	yes	3
0.01	no	—
3 @ 0.5 to 1.5	yes	2
1	yes	3.5
1	yes	4.5
1	yes	4.5
1	yes	3.5
6 @ 0.01	no	—
0.03	yes	0.1
0.03	no	—

Table 1 – Corrosion Penetration at Holidays on the Freilassing-Bad Reichenhall Pipeline [62]

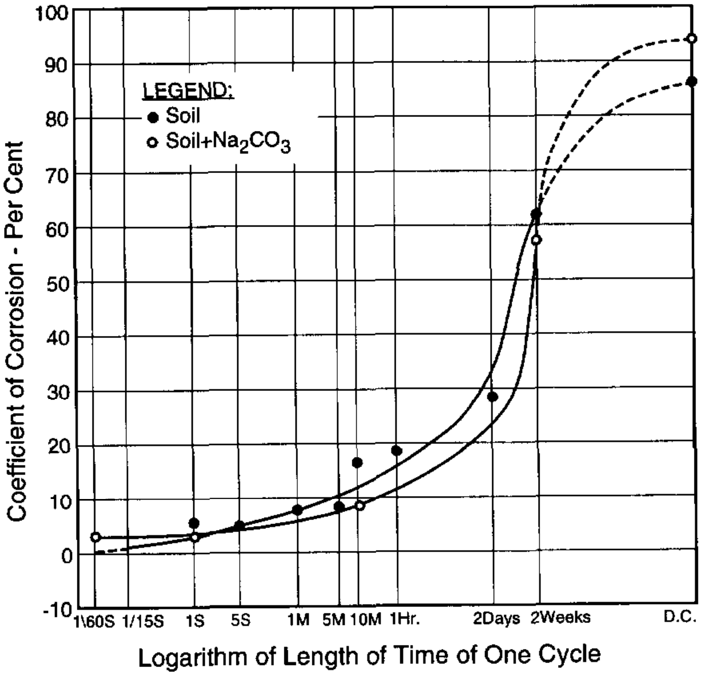

Figure 1 – Co-efficient of Corrosion at Different Frequencies for Iron Electrode Denoted as Average Electrode Loss
(McCollum and Ahlborn, 1916) [1]

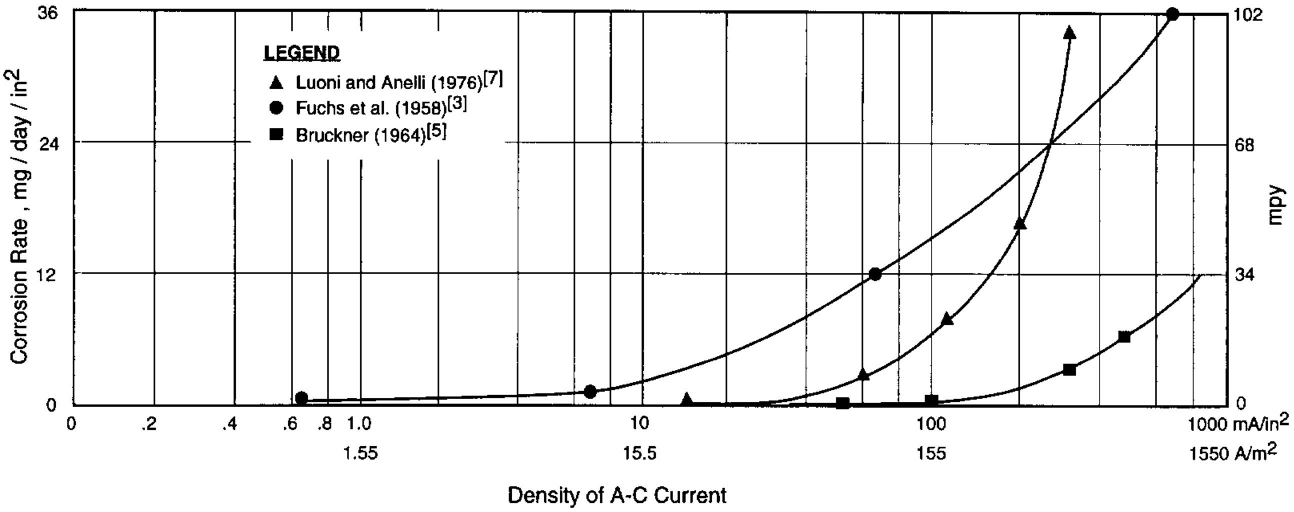

Figure 2 – Corrosion Rate Versus Current Density

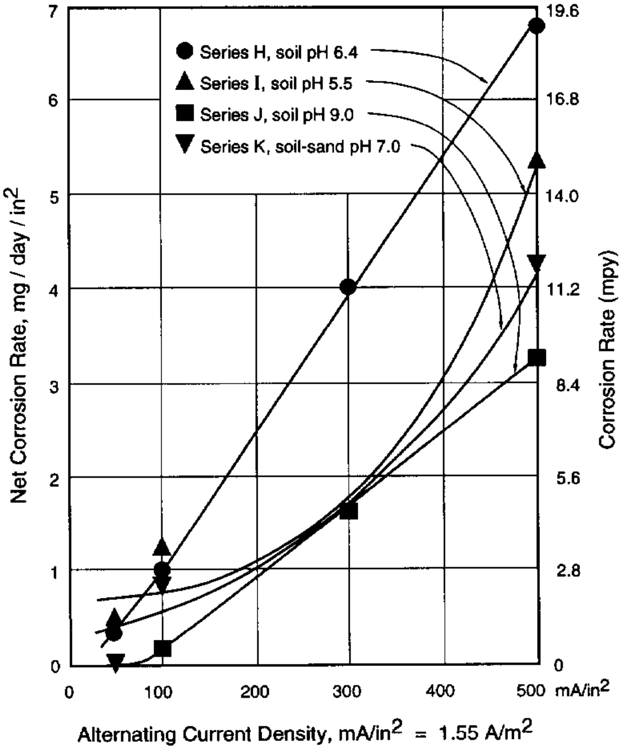

Figure 3 – Net Corrosion Loss of Electrodes Versus Alternating Current Density (Bruckner, 1964) [5]

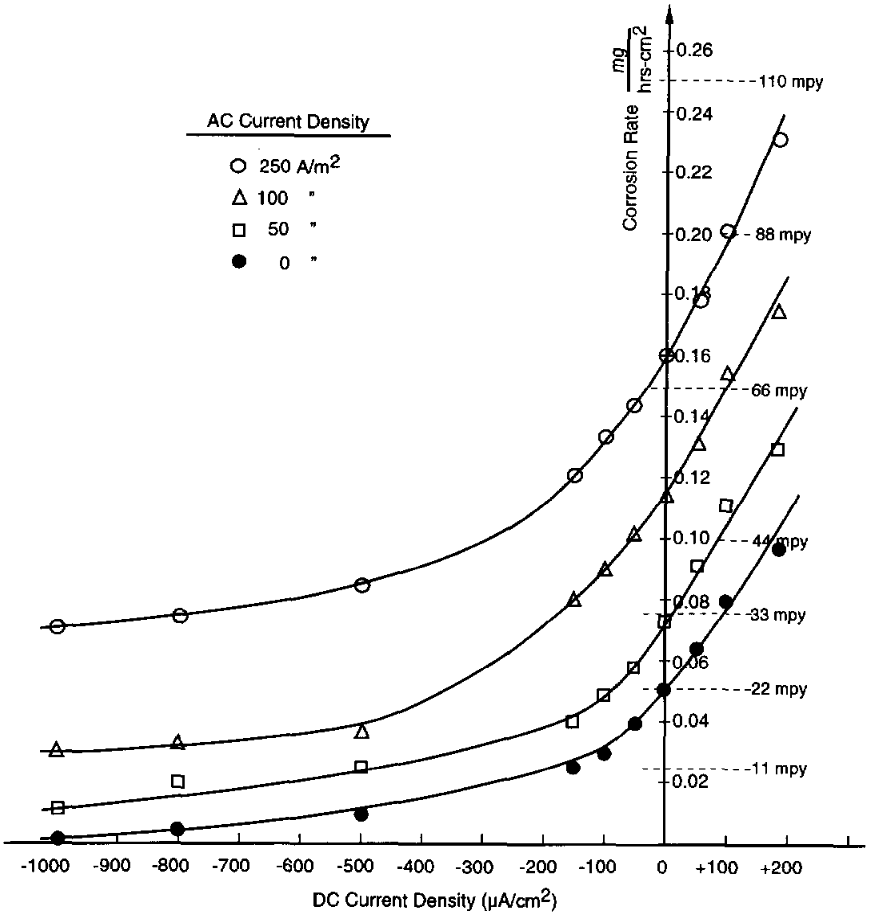

Figure 4 – Corrosion Rate of Iron vs AC and DC Current Densities in a 5% KCl Solution (Dévay et al., 1967) [15]

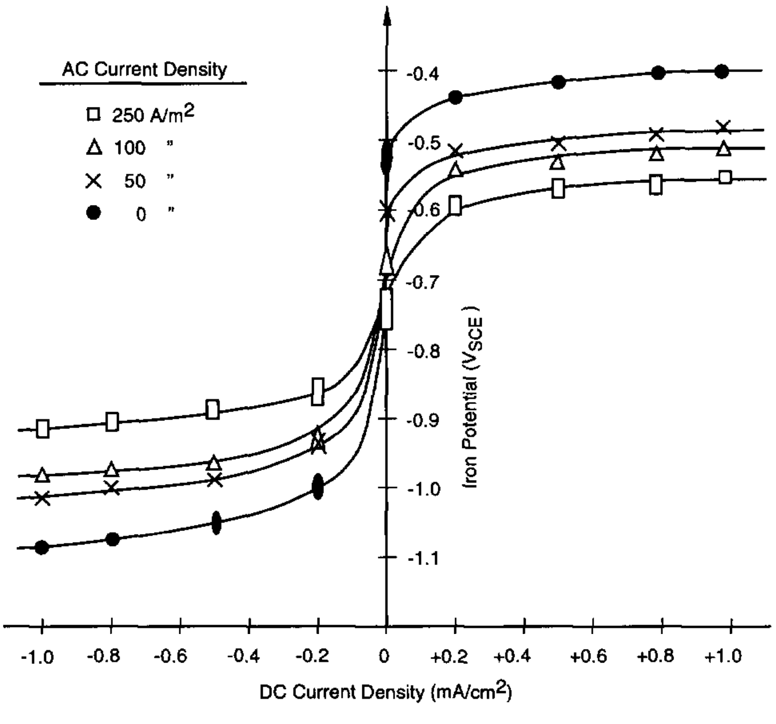

Figure 5 – The Effect of AC on the Polarization of Steel (Dévay et al., 1967) [35]

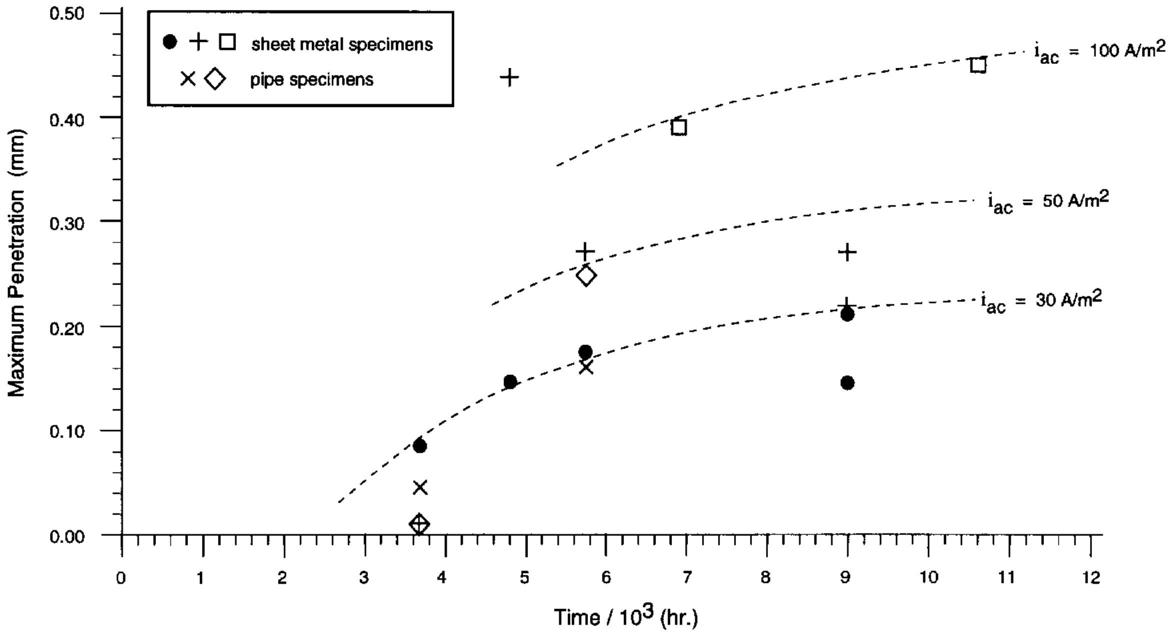

Figure 6 – Maximum Penetration Depth as a Function of Test Duration at Constant Cathode DC Current Density (2A/m^2) and Differing AC Current Density (Funk et al., 1992) [35]

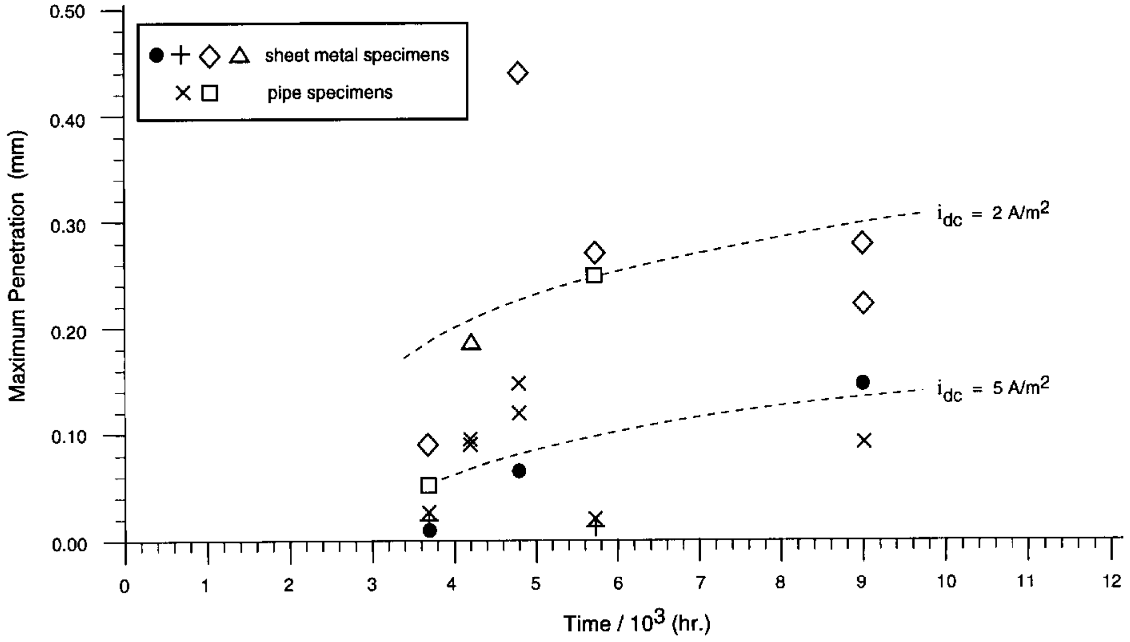

Figure 7 – Maximum Penetration Depth as a Function of Test Duration at Differing Cathode DC Current Density and Constant AC Current Density (50A/m^2) (Funk et al., 1992) [35]

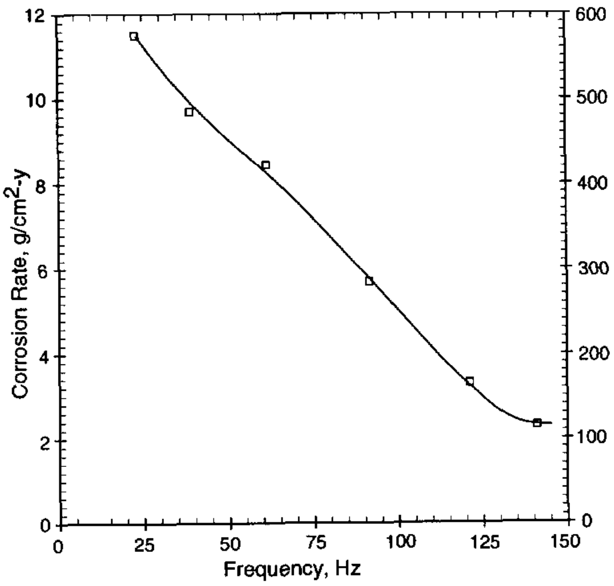

Figure 8 – Corrosion Rate of 1018 Carbon Steel in a 3.3% NaCl Solution vs. Frequency at an AC Peak Potential of 180mV
(Lalvani and Zhang, 1995) [44]

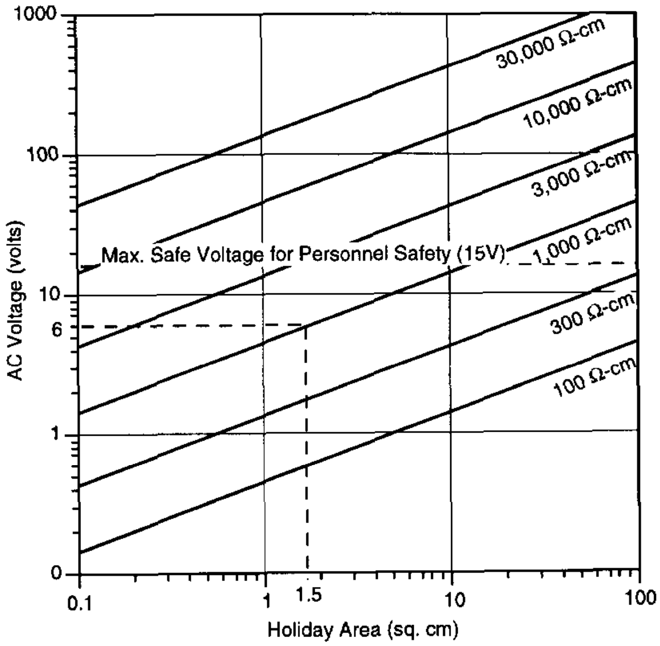

Figure 10 – Graph of AC Voltage vs. Holiday Surface Area for Various Soil Resistivities at an AC Current Density of 100 A/m^2

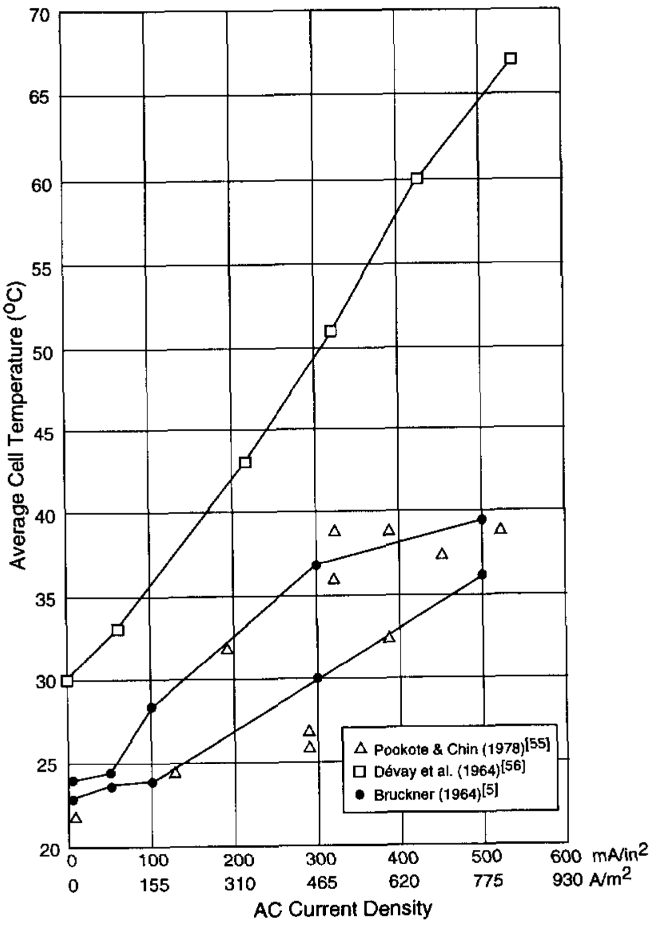

Figure 9 – Cell Temperature Versus AC Current Density