rather than the AC voltage (notwithstanding the compliance with the above-referenced NACE Standard). The criterion will likely be a combination of AC current density and CP level. Data presented indicates that corrosion can be enhanced at an AC current density of 20 A/m^2; but CP can be effective in mitigating corrosion, although an increase in polarization level (150 to 200 mV) may be necessary. On the high side of AC current density, limited data indicate that CP was not effective in mitigating corrosion at ~500 A/m^2.

CONCLUSIONS

Based on the experimental data and the results of the corrosion rate assessment using direct measurements, the following conclusions are made.

- Experimental results are in general agreement with previously published data including: (i) corrosion rates due to application of AC, (ii) trend in the effect of increasing magnitude of AC, and (iii) effect of CP on AC corrosion.
- AC current density discharge in the order of 20 A/m^2 can significantly increase corrosion, as manifested by the higher rates of penetration and general attack. Therefore, this study reinforces previous studies that AC corrosion can be significant on pipelines in AC corridors. Moreover, it is likely that there is not a theoretical 'safe' AC current density, i.e., a threshold below which AC does not enhance corrosion; however, a practical one exists for which the increase in corrosion due to AC is not appreciably greater than the free-corrosion rate for a particular soil condition. Under the experimental conditions, an AC current density of 20 A/m^2 increased corrosion nearly two-fold relative to the control specimen; therefore the threshold current density is less than 20 A/m^2.
- However, if CP is significant enough to overcome the effect of the AC current, protection is likely to be achievable. Previous literature studies and limited data produced by the study indicate that CP can be effective at "low" AC current densities but not at "high" current densities; the following provides limits established in this study.
    - At an AC current density of 20 A/m^2, CP of 100-150 mV polarization decreased corrosion rate compared to the control (no AC and no CP); additional CP to 250-300 mV polarization decreased the corrosion rate even further.
    - At an AC current density of ~500 A/m^2, CP of ~100 mV polarization decreased corrosion rate; additional CP of 150-300 mV actually increased corrosion compared to the control.
- The mitigation threshold of 15 V recommended in NACE RP0177 for safety concerns is not necessarily sufficient to mitigate AC corrosion.

ACKNOWLEDGMENTS

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TABLE 1.

NUMBER OF TESTED SPECIMENS (NUMBER OF CONTROLS IN PARENTHESIS).

<table>
<tr><td colspan="2" rowspan="2"></td><td colspan="2">Target AC Current Density</td></tr>
<tr><td>High (500 A/m²)</td><td>Low (20 A/m²)</td></tr>
<tr><td rowspan="3">Target CP Shift</td><td>High (300 mV)</td><td>4 (2)</td><td>4 (2)</td></tr>
<tr><td>Low (100 mV)</td><td>4 (2)</td><td>4 (2)</td></tr>
<tr><td>None</td><td>4 (2)</td><td>4 (2)</td></tr>
</table>

TABLE 2.

TEST CONDITIONS CATEGORIES.

Test category	**Actual AC Current Density, A/m²**	**Actual CP shift, mV**
Low AC + No CP	<20	0
High AC + No CP	>300	0
Low AC + Low CP	<20	<150
Low AC + High CP	<20	>150
High AC + Low CP	>300	<150
High AC + High CP	>300	>150

TABLE 3.

RELATIVE CORROSION RATE DATA (RATIO) SHOWN IN CONTOUR PLOTS .

Condition	**AC density**	**CP shift**	**Relative depth of penetration (test specimen to control)**
Low AC + No CP	18.8	0	196.3%
Low AC + No CP	20	0	200.0%
High AC + No CP	313	0	289.2%
High AC + No CP	487	0	208.0%
Low AC + Low CP	16.5	112.5	33.0%
Low AC + Low CP	17.7	149	46.9%
Low AC + High CP	19.5	225.5	37.3%
Low AC + High CP	20.2	318	25.2%
High AC + Low CP	470	100	58.8%
High AC + Low CP	501	119.5	60.6%
High AC + High CP	495	164	275.1%
High AC + High CP	817	295	745.3%

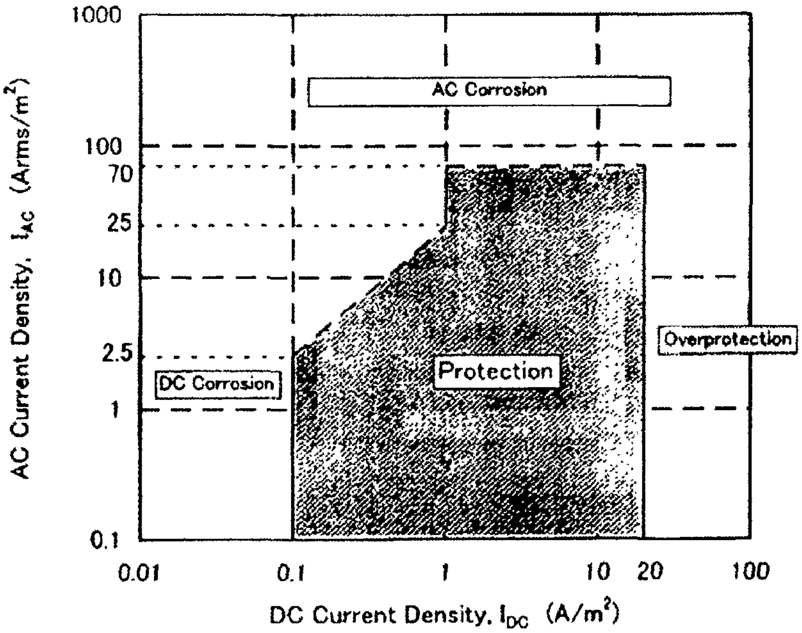

FIGURE 1. AC and DC current density relationship to achieve protection (from [20]).

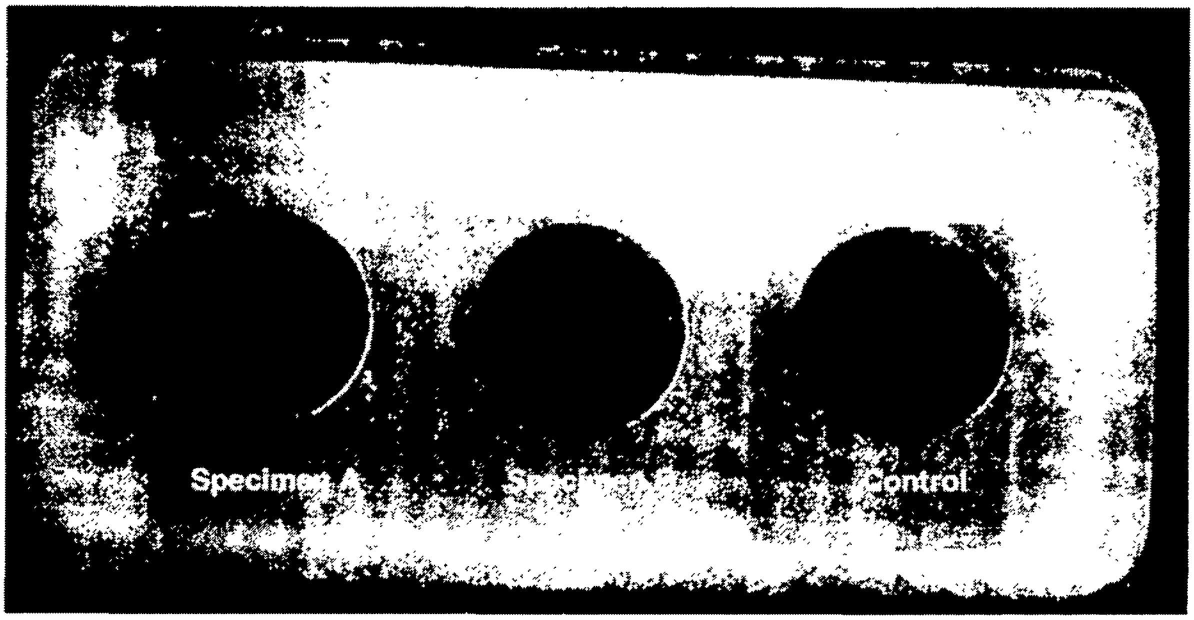

FIGURE 2. Test specimens.

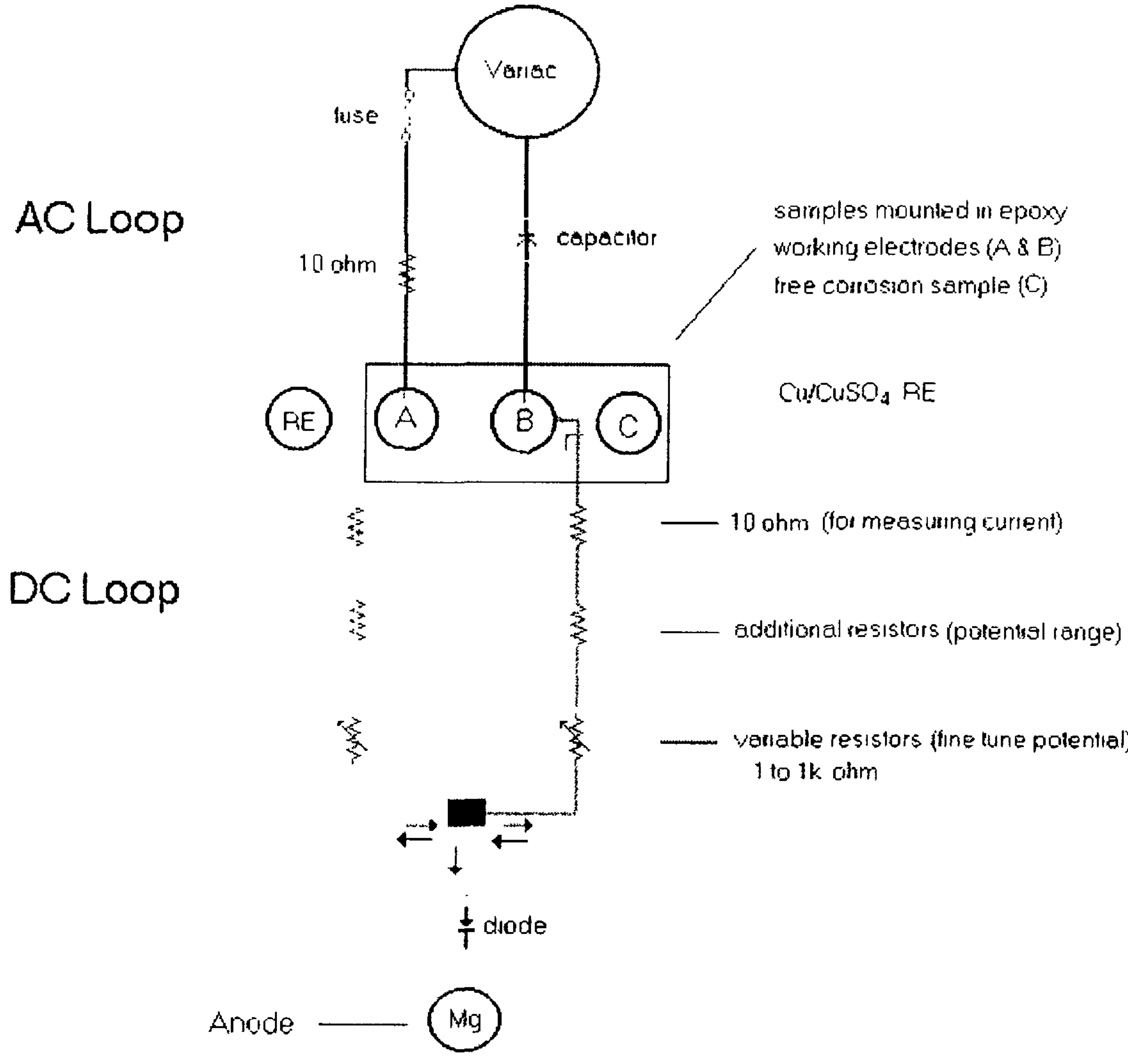

FIGURE 3. Schematic of electrical circuitry of the experimental setup.

Specimen A Specimen B Control

Prior to exposure

After cleaning

FIGURE 4. Low AC + No CP

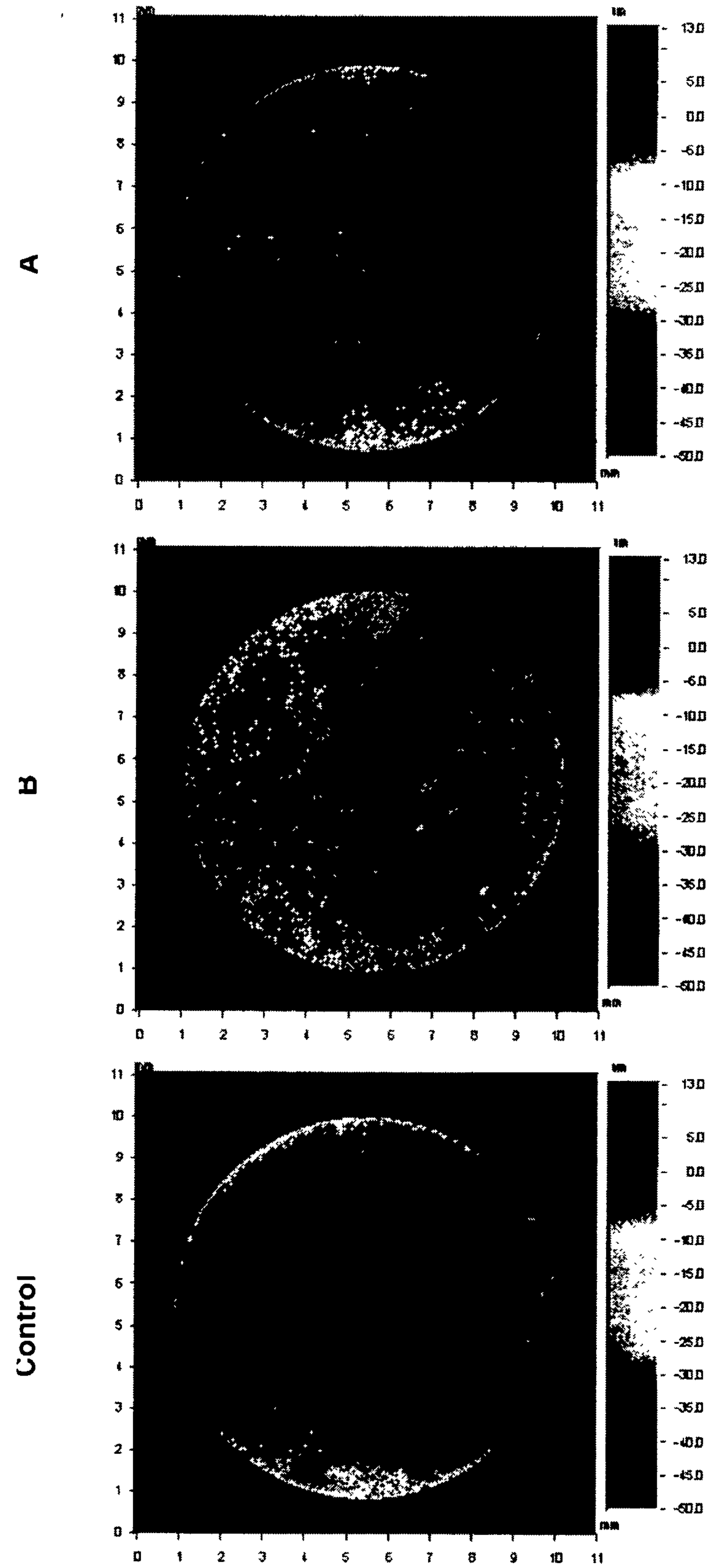

FIGURE 5. Low AC + No CP

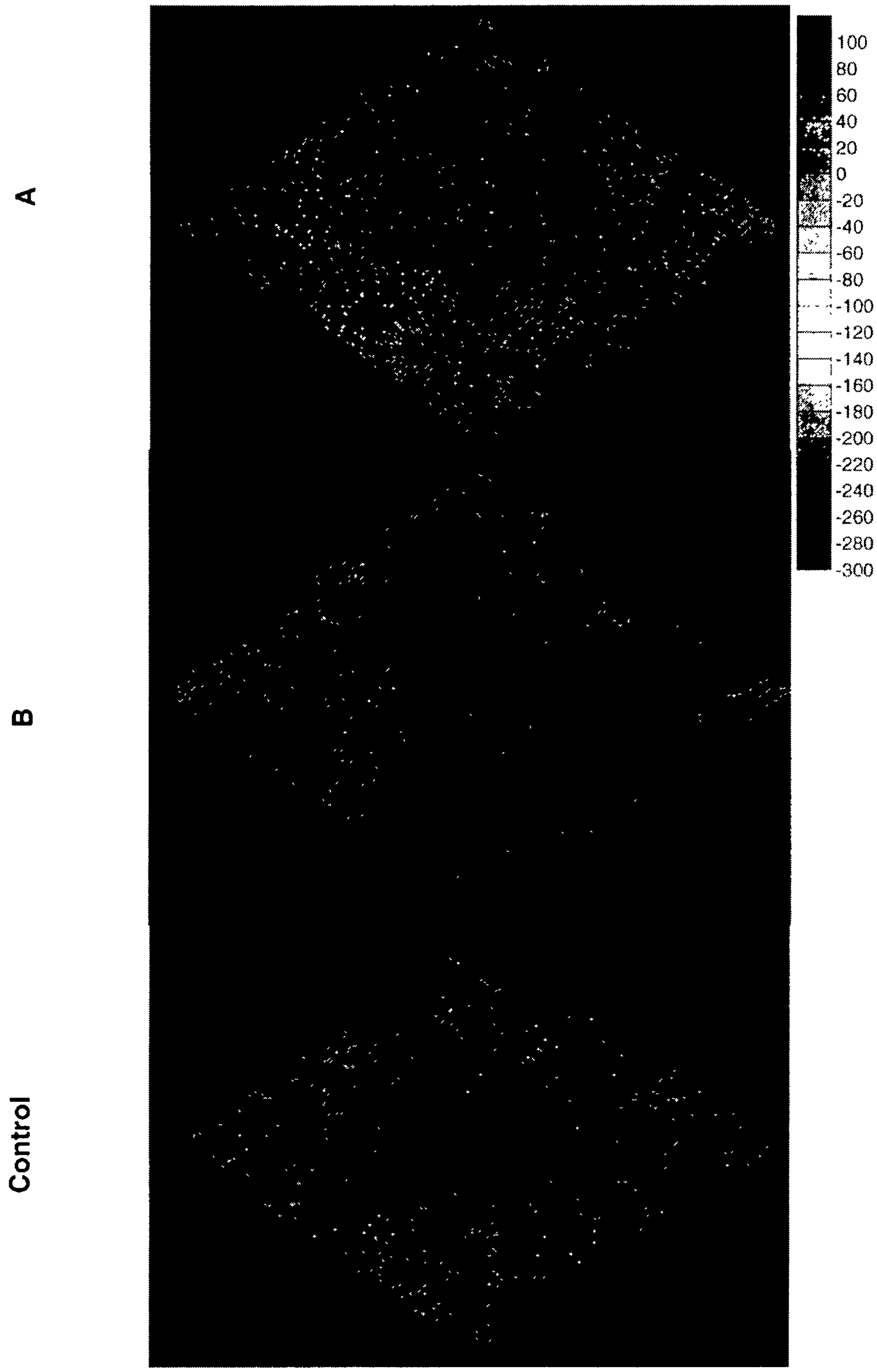

FIGURE 6. Low AC + No CP

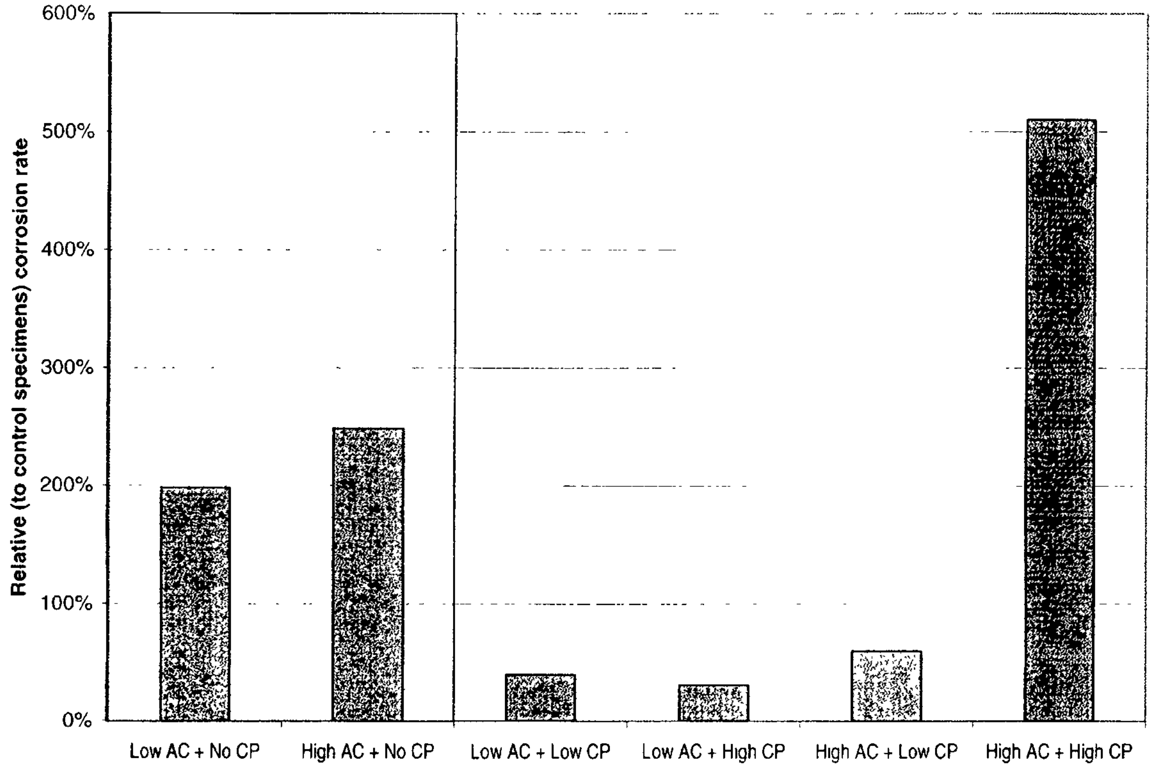

FIGURE 7. Averaged depths of penetration (pitting rate) for tested conditions.

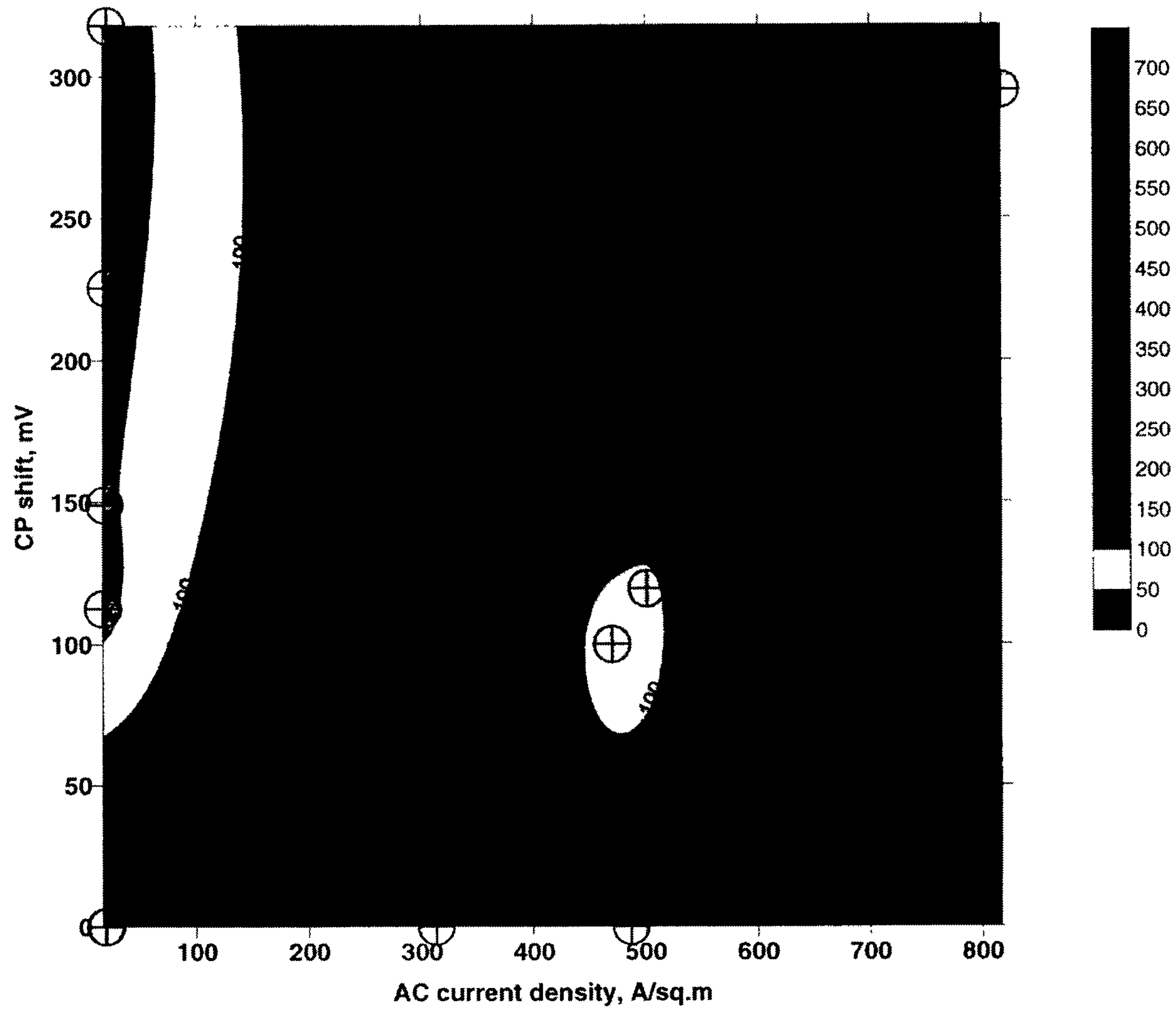

FIGURE 8. Contour plot of AC current density – CP shift – Depth of penetration relative to control (%). The plot is based on data in TABLE 3 (all data). Actual data points are represented by "⊗" symbols.

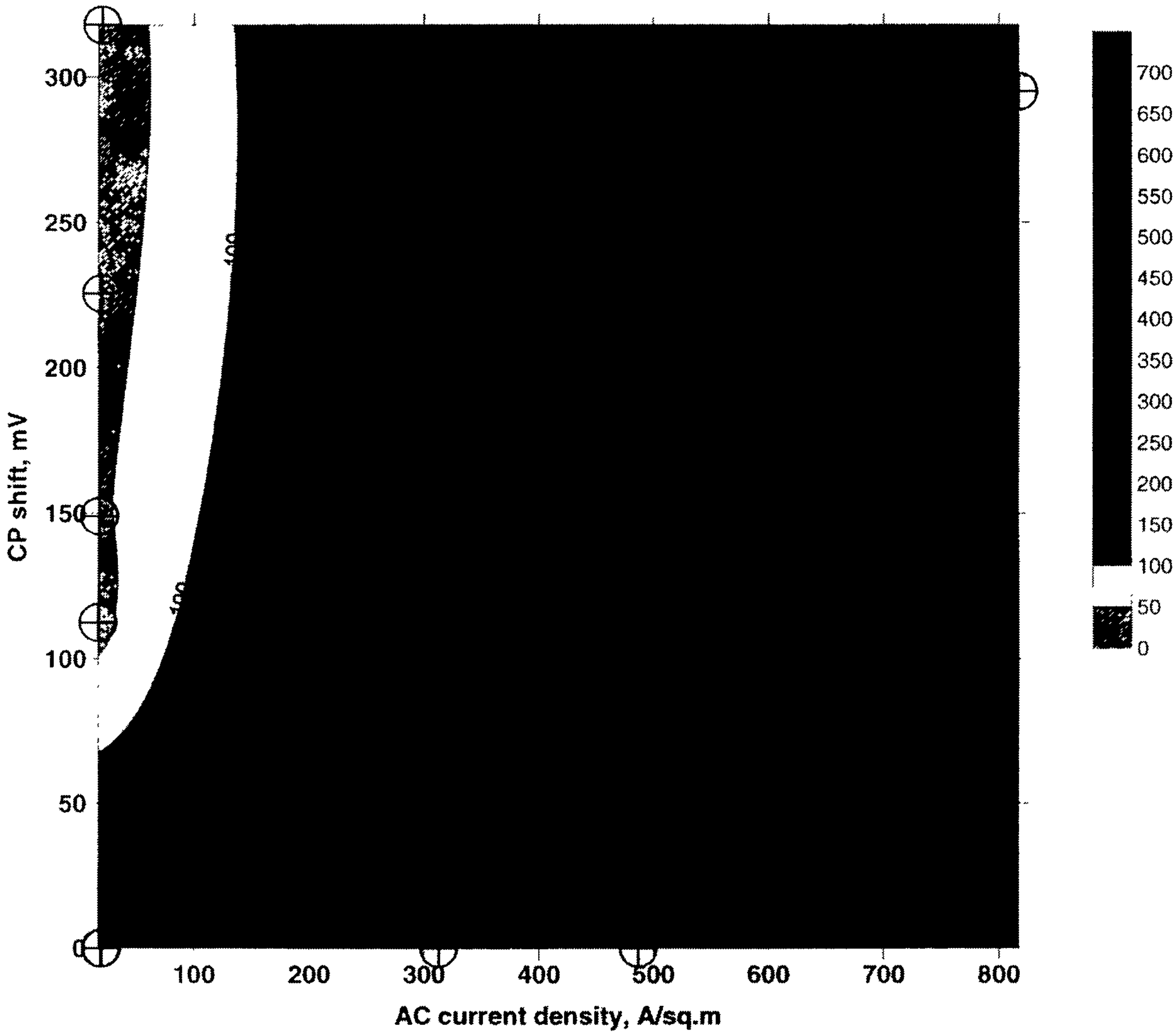

FIGURE 9. Contour plot of AC current density – CP shift – Depth of penetration relative to control (%). The plot is based on data in TABLE 3 with the exception of two shaded rows. Actual data points are represented by "⊗" symbols. See Figure 10 for a greater detail.

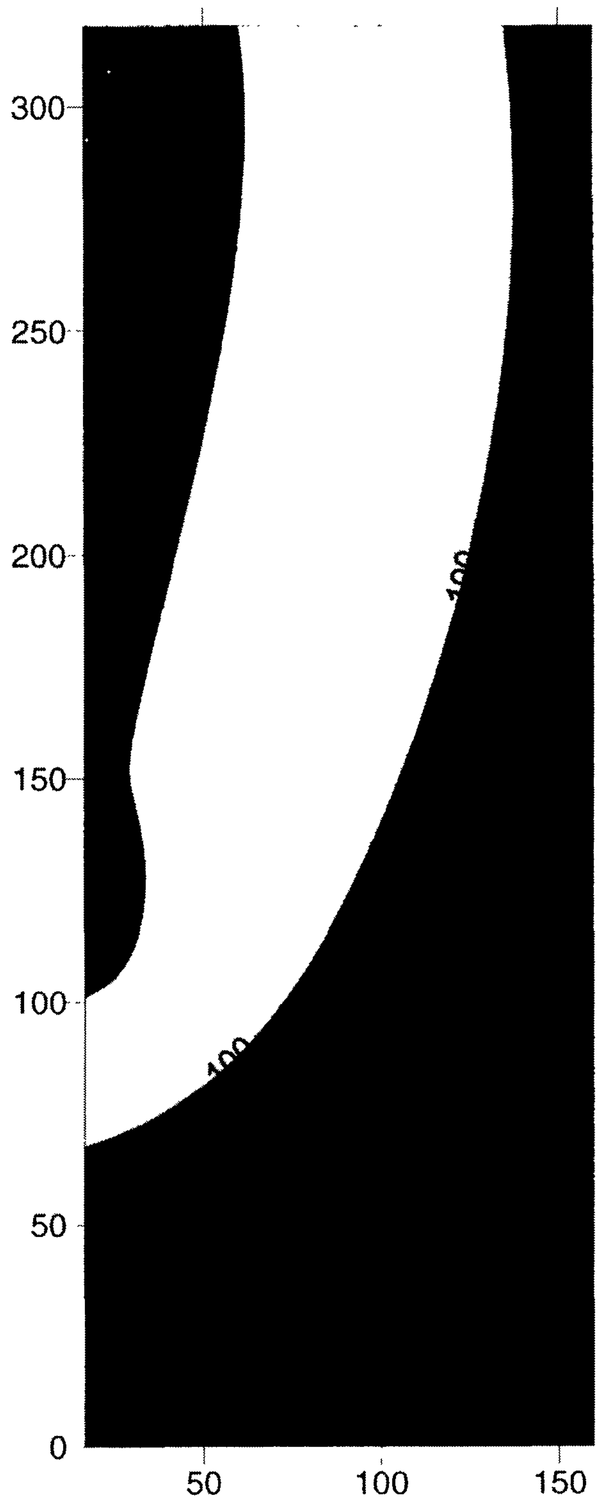

Figure 10. Magnified section of the contour plot of AC current density – CP shift – Depth of penetration relative to control (%) shown in FIGURE 9.

Exhibit H

Paper No.
566

CORROSION98

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

* *A wholly owned subsidiary of Corrosion Service Company Limited.*

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 $\mu A/cm^2$ (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 $300 A/m^2$, 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 $775 A/m^2$ 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 $50 A/m^2$ 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 $1 cm^2$ 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 $2 A/m^2$. 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 $20 A/m^2$ there is no AC induced corrosion, and
(b) AC corrosion is unpredictable for AC current densities between $20\text{-}100 A/m^2$, and
(c) for AC current densities greater than $100 A/m^2$ 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 $1\text{-}3 cm^2$. 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 $100 A/m^2$ 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]

$$i_{ac} = \frac{8\, V_{ac}}{\rho\, \pi\, d} \quad [80] \tag{1}$$

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

$$V_{ac} = \frac{i_{ac}\, \rho\, \pi\, d}{8} \tag{2}$$

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

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

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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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]

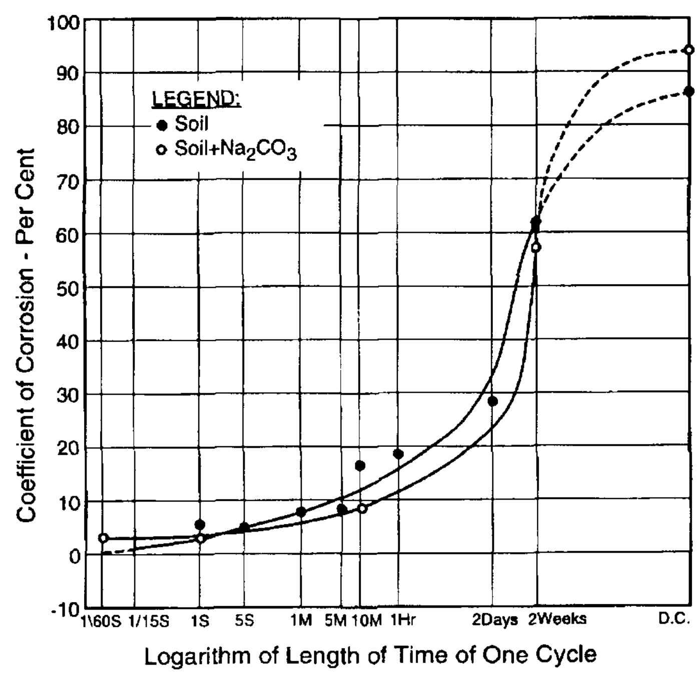

Figure 1 – Co-efficient of Corrosion at Different Frequencies for Iron Electrode Denoted as Average Electrode Loss
(McCollum and Ahlborn, 1916) [1]

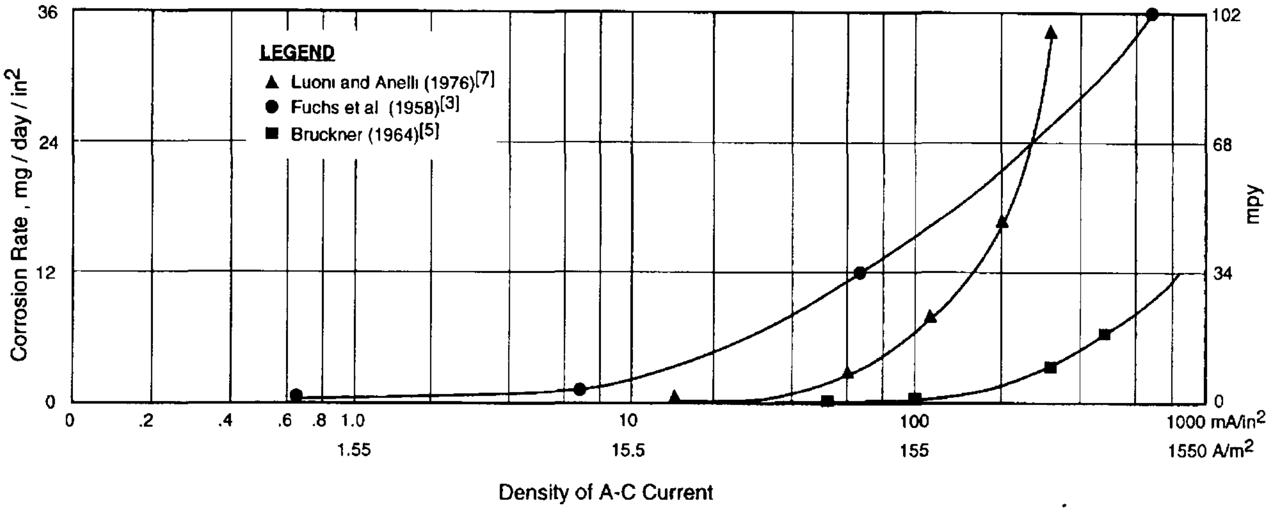

Figure 2 – Corrosion Rate Versus Current Density

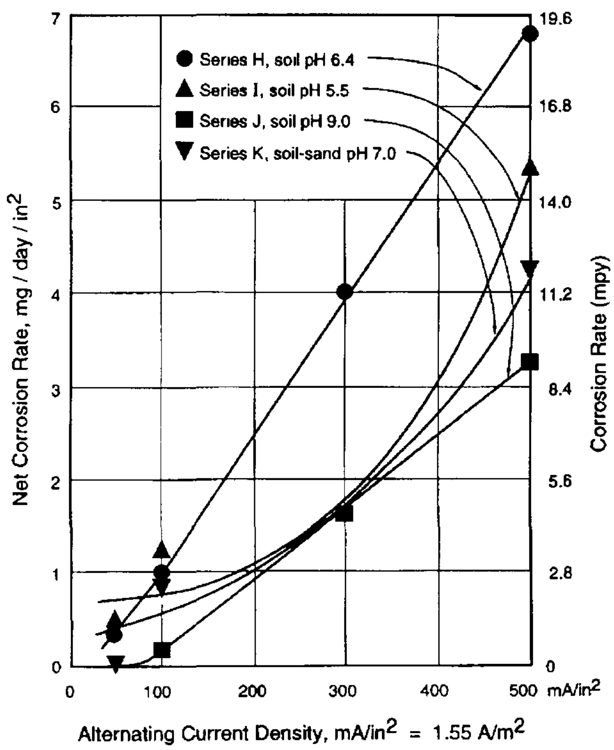

Figure 3 – Net Corrosion Loss of Electrodes Versus Alternating Current Density (Bruckner, 1964) [5]

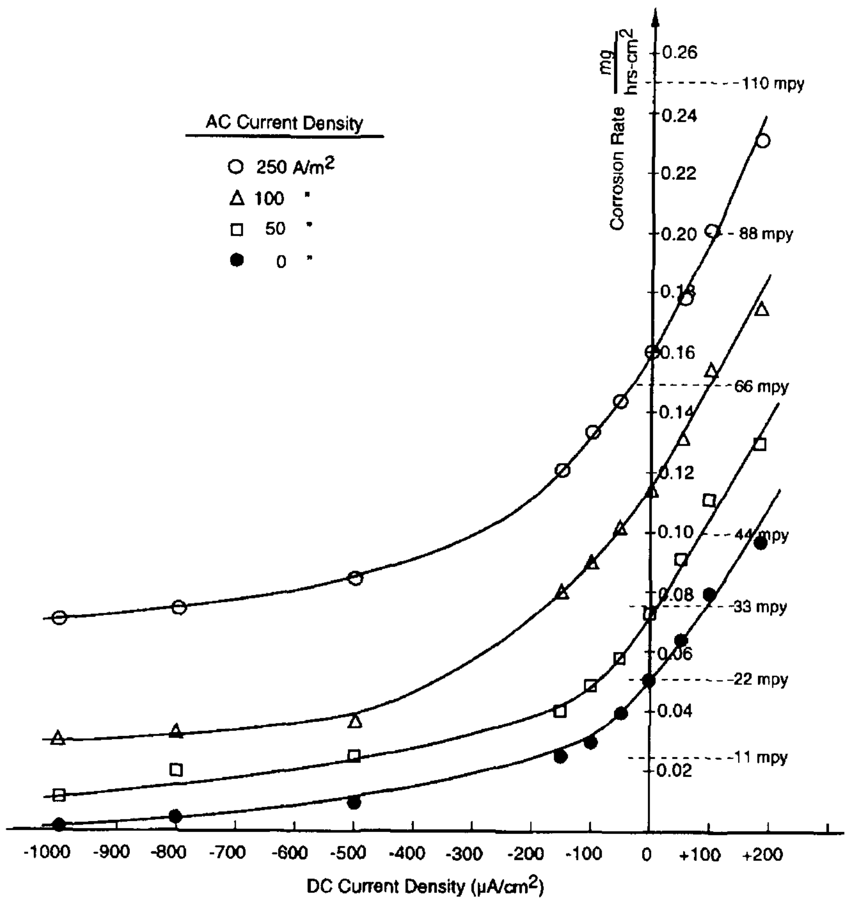

Figure 4 – Corrosion Rate of Iron vs AC and DC Current Densities in a 5% KCl Solution (Dévay et al., 1967) [15]

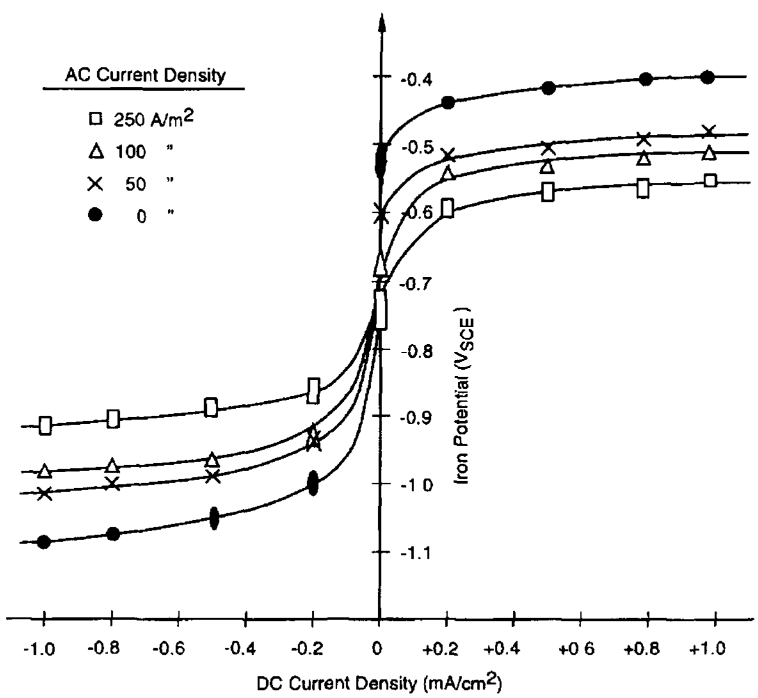

Figure 5 – The Effect of AC on the Polarization of Steel (Dévay et al., 1967) [35]

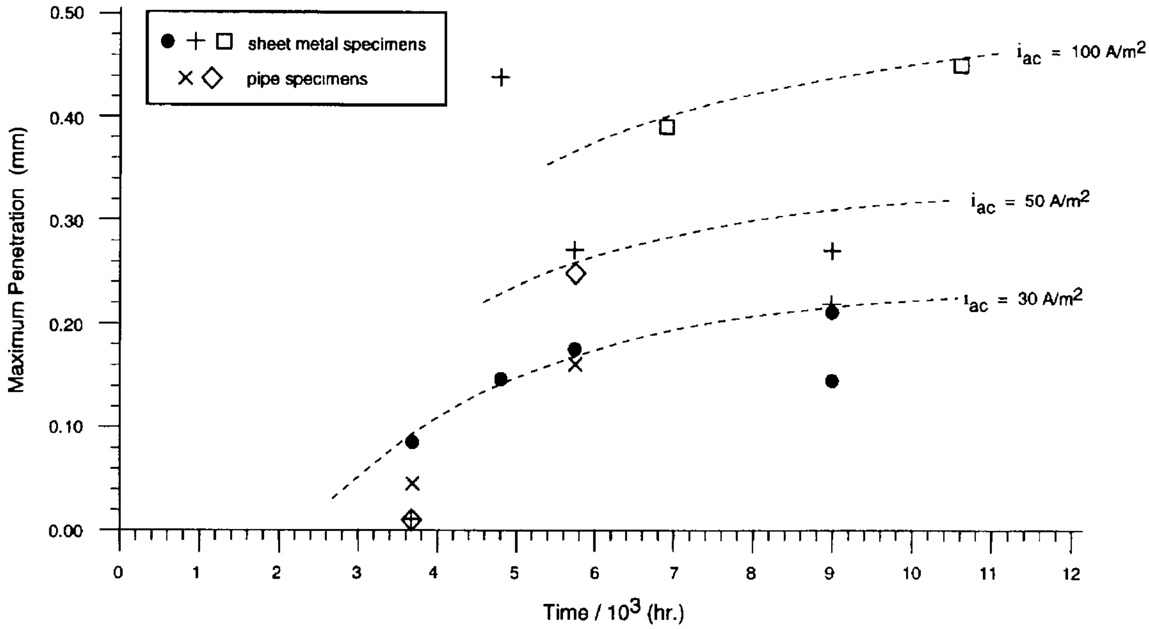

Figure 6 – Maximum Penetration Depth as a Function of Test Duration at Constant Cathode DC Current Density (2A/m^2) and Differing AC Current Density (Funk et al., 1992) [35]

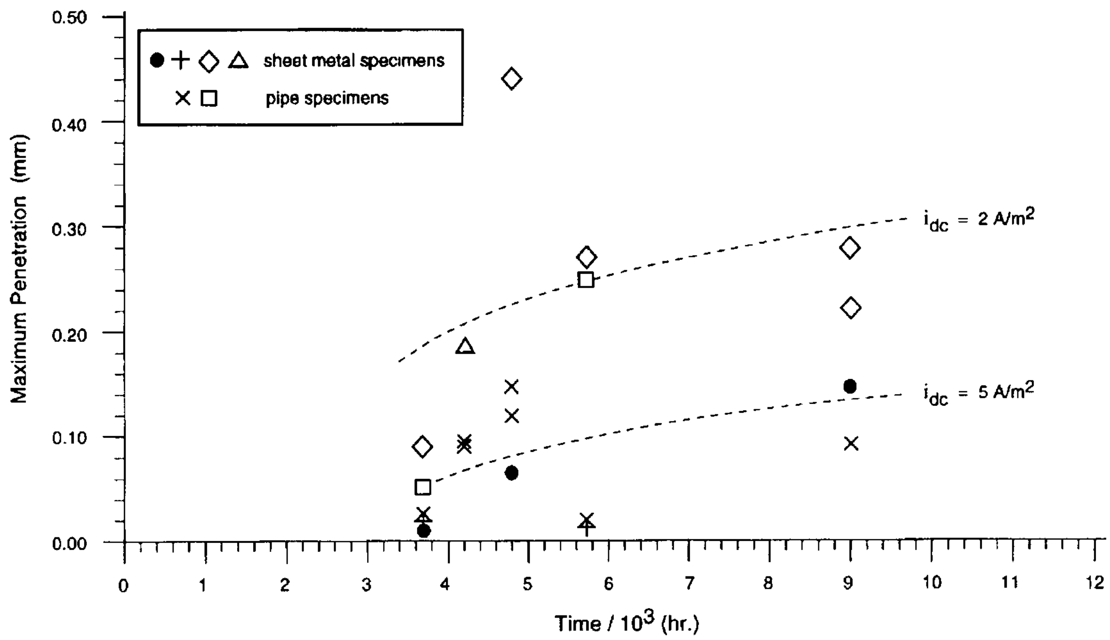

Figure 7 – Maximum Penetration Depth as a Function of Test Duration at Differing Cathode DC Current Density and Constant AC Current Density (50A/m^2) (Funk et al., 1992) [35]

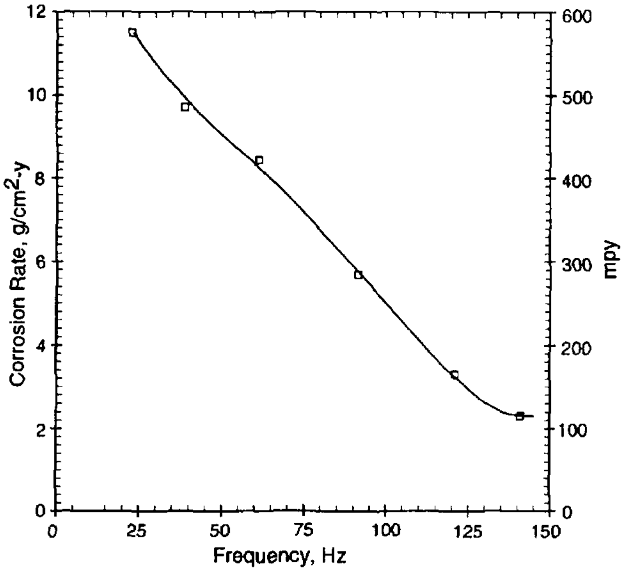

Figure 8 – Corrosion Rate of 1018 Carbon Steel in a 3.3% NaCl Solution vs. Frequency at an AC Peak Potential of 180mV
(Lalvani and Zhang, 1995) [44]

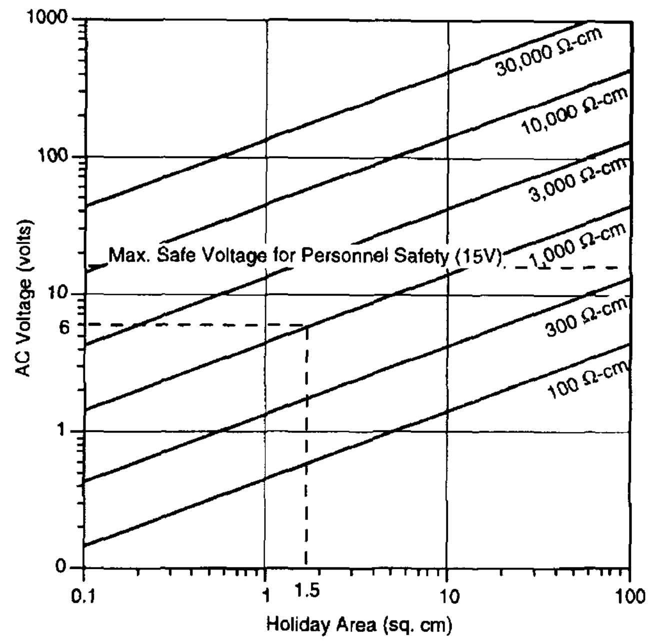

Figure 10 – Graph of AC Voltage vs. Holiday Surface Area for Various Soil Resistivities at an AC Current Density of 100 A/m²

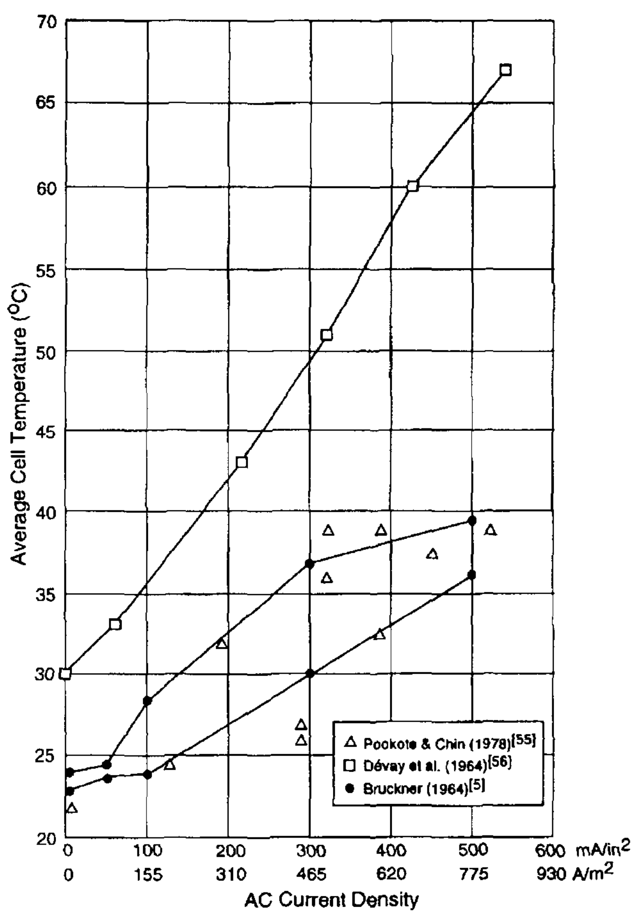

Figure 9 – Cell Temperature Versus *AC Current Density*

Exhibit I

Paper No.
4421

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Advances in HVAC Transmission Industry and Its Effects on Pipeline Induced AC Corrosion

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ABSTRACT

Pipelines collocated in close proximity to high voltage alternating current (HVAC) transmission lines may be subjected to electrical interference from capacitive, electromagnetic inductive and conductive effects. If these effects are high enough they may pose a safety hazard to personnel, or may compromise the integrity of the pipeline. The effects of HVAC interference from a personnel safety and corrosion risk standpoint are well documented, however recent developments in the electric power transmission industry have driven trends toward increasing HVAC transmission line voltages and currents. Renewable energy generation and corresponding technologies have shown rapid growth in recent years. Multiple factors are driving the generating facilities, be it wind, hydro-electric, solar, or other, further from the major consumption centers requiring the power. This creates a well-documented challenge for efficient electric power transmission over increasing distances.[1,2,3,4] Multiple technologies have been developed recently to help overcome long distance transmission line loss, each having its own unique benefits and detriments. However, nearly all involve significant increases to the transmission line operating capacity, and will result in elevated line currents whether they are short term dynamic loads, or steady state. The increasing HVAC transmission currents present a significant challenge for pipeline owners operating utilities sharing the corridor, crossing, or paralleling the power transmission lines. This paper focuses on reviewing the recent trends in the HVAC transmission industry, and their effects on collocated buried pipelines, specific to induced AC potentials, current density, and ground fault hazards.

Key words: HVAC Interference, AC Corrosion, Power Transmission

INTRODUCTION

HVAC Transmission Line Effects on Adjacent Pipelines

Industry trends, topography, permitting requirements, land access, and environmentally protected regions have led to an increase in sharing of common utility corridors. While there are numerous benefits to sharing common corridors, there are also many concerns. Pipelines sharing, paralleling, or crossing HVAC transmission line (typically defined as 69 kV or higher) right-of-ways may be subjected to electrical interference from electrostatic coupling, electromagnetic inductive and conductive effects.

Electromagnetic induction is the primary effect of the HVAC transmission line on the buried pipeline during normal (steady state) operation. This interference is due to the magnetic field produced by AC current flowing in the conductors of the transmission line coupling with and inducing a voltage on the pipeline. If the inductive interference effects are high enough during operation, a possible shock hazard exists for personnel who may come in contact with an exposed part of the pipeline, such as a valve, CP test station, or other aboveground appurtenance of the pipeline.

Inductive interference can also contribute to AC accelerated corrosion. AC accelerated corrosion may occur at coating defects where the AC current built up on the pipeline through inductive interference discharges from the pipe to ground. AC induced corrosion is a significant integrity threat due to the possibility of very high localized corrosion rates which have been reported up to 20 mpy (0.5mm/yr) with pitting rates considerably higher.[5]

Conductive interference results from currents traveling through the soils and into the pipeline. Conductive effects are primarily a concern when a fault occurs in an area where the pipeline is in close proximity to the transmission line and the magnitudes of the fault currents in the soil are high. The electromagnetic induction effects are also significant during a fault condition because the phase current of at least one conductor is very high. Additionally, damage to the pipeline or its coating can occur if the voltage between the pipeline and surrounding soil becomes excessive during a fault condition.

In terms of personnel safety, the concern is the voltage a person is exposed to when touching or standing near the pipeline. The "touch potential" is the voltage between an exposed feature of the pipeline such as a CP test station or valve and surrounding soil or a nearby isolated metal object such as a fence that can be touched at the same time. The "step potential" is the voltage across a person's two feet and is defined as the difference in the earth's surface potential between two spots one meter apart. The touch potential can be a concern during both normal steady state inductive and fault conductive/inductive conditions. Typically, the step potential is a concern during conductive fault conditions due to high currents and voltage gradients in the soil.

Electrostatic coupling, or capacitive interference, is primarily a concern during construction when sections of the pipeline are aboveground. While this paper primarily focuses on inductive interference, it should be noted that under the influence of elevated line currents (1,000A and higher) capacitive interference may be high enough such that hazardous potentials exist on a single joint of pipe, which would require adequate grounding during construction operations.

An evaluation of the possible risk to personnel safety for those working on the pipeline and possible pipeline coating damage should take place whenever a pipeline is in close proximity to a HVAC transmission line. A mitigation system can be designed for those areas where potentials are above permissible limits as specified in the Institute of Electrical and Electronics Engineers Standard IEEE-80[6] and NACE International Recommended Practice SP0177-2007 (Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems) [7]. These Standards indicate mitigation is necessary in those cases where step or touch potentials are in excess of 15.0 VAC.

A phase-to-ground fault on a power transmission line causes large currents in the soil at the location of the fault and large return currents on the phase conductor and ground return. Although these faults are normally of short duration (less than one second), pipeline damage can occur from high potential breakdown of the coating, resistive conductive arcing across the coating near the fault and high-induced currents along the right of way (ROW). These high current magnitudes may result in arc damage at locations remote from the fault where a low resistance path to power ground is found. If these currents are high enough, they may cause damage to the pipe wall even to the point of burn through. The high current density can cause molten pits on the pipe surface with cracks developing when the fault ceases and the pipe cools.

Obviously these conductive currents and induced voltages represent a significant safety hazard if personnel are working on or testing the pipeline during the fault condition. Seventy percent (70%) of AC transmission line faults are phase-to-ground faults and are usually caused by lightning, phase insulator failure, mechanical failure of the phase conductor, or support tower allowing the phase conductor to touch the ground and transformer failure.

Pipeline corrosion control considerations involving AC transmission lines include coating damage during faults and accelerated corrosion (even in the presence of cathodically protected DC potentials) due to high AC current density at coating holidays. Fault current conditions that produce excess voltages across the coating are of concern for dielectric coatings. It should be noted that the steady state 15 VAC threshold (in the standards listed above) was established with personnel safety in mind and not with consideration of corrosion influences. Recent research and experience has shown that AC accelerated corrosion can occur in low resistivity soils at AC voltages well below this threshold.

The effects of the power transmission line on an adjacent pipeline are a function of geometry, soil resistivity, coating resistance, and the transmission line operating parameters. The geometry characteristics include separation, depth of cover (DOC), pipe diameter, angle between pipeline and transmission line, tower footing design and phase conductor spacing and average distance above the ground. These remain constant over the life of the installation. The coating resistance, power system ground resistance and soil resistivity may change slightly with the seasonal variations and as the installation ages but remain reasonably constant. The operating parameters of the transmission line such as phase conductor load, phase balance, voltage, and available fault current and clearing time also have significant influence on the effects of AC accelerated corrosion. The individual conductor current load and balance is dynamic and changes significantly with load requirements and switching surges.

Theoretical AC Current Density

In January of 2010, the National Association of Corrosion Engineer (NACE) International prepared and published a report entitled "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements," which provides the following insight on AC corrosion current density.

"In 1986, a corrosion failure on a high-pressure gas pipeline in Germany was attributed to AC corrosion. This failure initiated field and laboratory investigations that indicated induced AC-enhanced corrosion can occur on coated steel pipelines, even when protection criteria are met. In addition, the investigations ascertained that above a minimum AC density, typically accepted levels of CP would not control AC-enhanced corrosion. The German AC corrosion investigators' conclusions can be summarized as follows:

- AC-induced corrosion does not occur at AC densities less than 20 A/m^2 (1.9 A/ft2).
- AC corrosion is unpredictable for AC densities between 20 to 100 A/m^2 (1.9 to 9.3 A/ft^2).
- AC corrosion occurs at current densities greater than 100 A/m2 (9.3 A/ft^2)."

The AC current density is related to the soil resistivity, the induced voltage and the size of a holiday in the coating. Additionally, research has indicated the highest corrosion rates occur at holidays with surface areas of one to three square centimeters. Holiday testing during installation of the pipeline should catch all holidays of this magnitude, but in general smaller holidays could be missed; so the smallest, or one square centimeter, is considered in calculation of AC current density.[5]

$$i_{ac} = (8xV_{ac}) / (\rho \times \pi \times d) \tag{1}$$

Where:

i_{ac}	=	ac current density (A/m^2)
V_{ac}	=	pipe ac voltage to remote earth (V)

ρ	=	soil resistivity (ohm-m)
π	=	3.1416
d	=	diameter of a circular holiday having a one square centimeter surface area (0.0113 meter)"

Transmission HVAC Industry Trends

Renewable energy technologies and generation have seen rapid growth in recent years due to a market shift toward sustainable resources, and state level regulations supporting renewable energy sources. Much of the industry shift toward renewable energy generation is driven by regulations, as numerous states enact mandates for renewable energy generation. Transmission of renewable energy was recently the subject of federal U.S. Senate hearing for the first time in 2010.[2] The proceedings of this hearing detail the increased attention to infrastructure development as critical to growth of sustainable electricity sources. Presently, wind power generation has been the primary focus, but many of the same concepts discussed apply equally to hydro-electric, geothermal power generation, and large scale solar power generation. Large scale implementation of renewable energy sources faces numerous challenges from both a generation and transmission standpoint. The generation challenges are met with continuously evolving technologies aimed at making the power generated more accessible and more efficient. Specific to wind energy, research and concepts have been proposed to push generating structures further offshore or further up in the atmosphere, to utilize the consistency and higher energy of offshore winds, and jet streams. The common challenge faced by all technologies is power transmission capacity and transmission over longer distances.

Many factors are pushing generating facilities further from their primary load sources. Texas, for example, is currently the largest producer of wind power, and has the largest installed wind generating capacity at 10,135 MW[2]. Research and studies have shown the most consistent high energy wind resources are located in the Northwestern Panhandle region, as shown in Figure 1 below. Wind power facilities are likewise most efficient and best developed in these regions. The difficulty comes with the fact that the highest population density and primary load sources are located in the Eastern part of the state, as shown in the map on the right in Figure 1 below. This requires increased transmission capacity, and a need to improve existing infrastructure to overcome line losses associated with the long distance transmission. Similar issues affect many renewable energy resources, as the generation sites are driven by many geological, climate, and geographical conditions and often do not coincide with high population density locations.

Texas is in process of implementing the Competitive Renewable Energy Zones (CREZ) project, which defines target geographic areas for development of renewable energy generation, and requires associated transmission necessary to deliver the wind generated energy to consumers. By rules set forth by the Electric Reliability Council of Texas (ERCOT), the costs associated with the infrastructure upgrades are allocated to the transmission operators, and eventually the energy users, rather than the power generators. This creates incentive for the transmission companies to increase system capacity through cost efficient means, which can mean upgrading existing systems or adding transmission systems through accessible ROW.

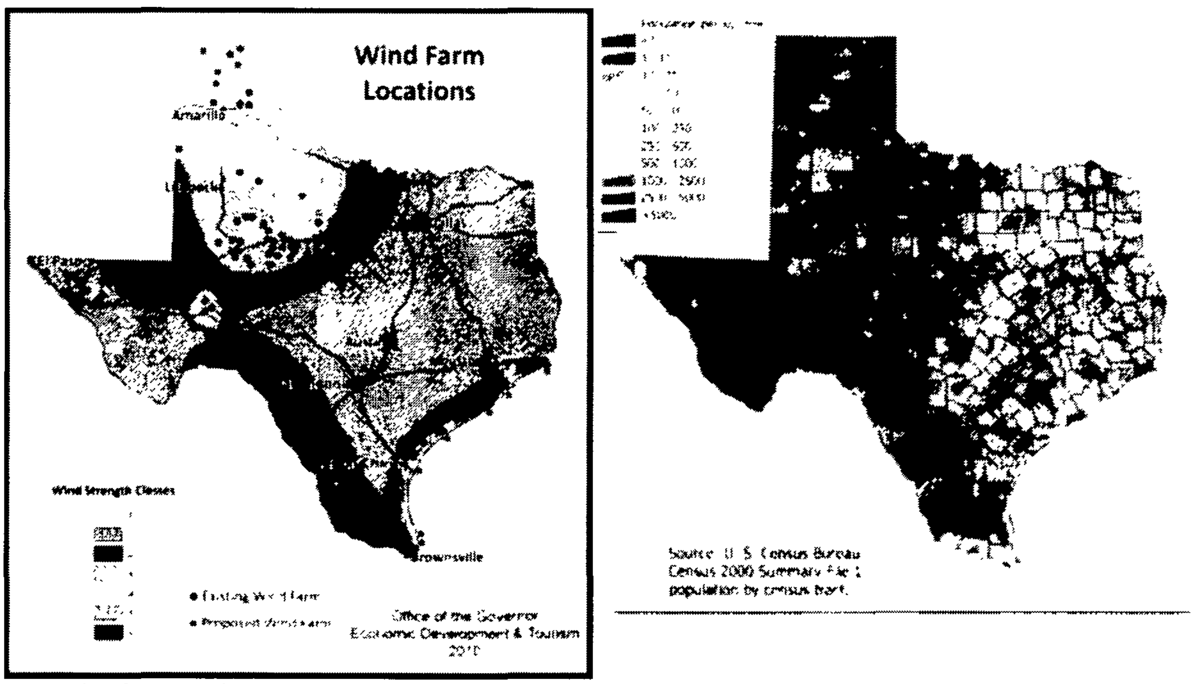

Figure 1: Comparison maps of Texas wind strength classifications, and wind farm locations, and population density. [8,9]

A well-documented trend exists within the transmission industry toward increasing transmission capacity. Numerous technological advancements exist for increasing transmission capacity with minimal modification of existing structures, each having their own benefits and detriments. The most prevalent include Dynamic Line Rating (DLR), High Temperature Low-Sag Conductors (HTLS), Voltage Uprating, and Flexible AC Transmission Systems (FACTS).[1]

HVAC transmission conductors subjected to elevated power flow for extended time can heat and expand axially to the point at which the conductors begin to sag between the support towers. Typically a maximum power rating is limited by the conductor's specific thermal constraints. That is, the maximum power level defined above which the conductors may sag to hazardous levels. Regulatory codes often mandate HVAC transmission systems maintain a minimum clearance between the conductors and the ground, trees, or any structures beneath the power lines. These regulations dictate this minimum clearance must be maintained through all operating and weather conditions. For typical HVAC transmission lines a static thermal rating may therefore be based on the worst case environmental conditions, considering peak ambient temperatures and minimal wind. It is therefore likely that this maximum power rating, based on worst case static conditions, may be conservative for all but the worst case operating conditions.

Dynamic Line Rating

The approach of Dynamic Line Rating (DLR) is that through precise real-time monitoring of the critical environmental variables, a more accurate maximum capacity of the line can be calculated for any given point in time. This effectively allows for a dynamically varying line allowable capacity, the magnitude of which may vary significantly. DLR equipment vendors estimate that a 10°C change in ambient temperature may increase the line capacity greater than 10%, and considering a change from stagnant wind to low velocity 1 m/s cross-wind may increase the capacity greater than 40%.[1] While incorporating DLR technology requires additional real-time monitoring equipment be installed along the line, it can often utilize the existing structures and ROW.

High Temperature Low-Sag conductors

New conductor designs and materials are continually being considered for improved strength to expansion characteristics, to control conductor sag. High-temperature low-sag (HTLS) conductor designs may for example replace standard steel cores with composite cores with reduced thermal expansion coefficient, and often reduced line loss. Replacing existing transmission line conductors with HTLS conductors allows for operating the same circuit, utilizing the same transmission structures and ROW, with a comparable diameter conductor capable of operating at a higher power level. This means that for a given voltage rating, the transmission lines are capable of operating with a higher current load with relatively little visible change.

Voltage Uprating

An alternate method of increasing the overall power capacity of a transmission line is through voltage uprating, increasing the voltage of a transmission line to the next standard voltage level. This allows for an increase in overall power capacity without increasing line current, and avoiding the additional thermal concerns with typical power increase. Voltage uprating however often requires replacing standard conductors with larger or bundled conductors, and replacement of transformer. As such, this can prove to be a relatively large scale upgrade both in terms of modifications and costs associated.

Flexible AC Transmission Systems

Flexible AC Transmission Systems (FACTS) devices offer an indirect means of increasing transmission capacity. Through utilization of improved system devices, controllers, and data systems FACTS devices act to improve overall system stability and control, enabling operators to operate transmission systems closer to their capacity limits for longer durations.

While various other technological approaches exist, and others are undergoing constant research and development, the underlying concept is that each of these methods advances toward the same goal of increased system capacity, and likewise higher operating loads, with minimal modifications to structures or ROW access. From a power transmission perspective, the best case scenario is to increase transmission line capacity utilizing existing structures, therefore not requiring additional ROW access.[1] The possible hazard here exists in that owing to lack of required permitting and the overall ROW procurement process, utilities collocated with or crossing the affected ROW may not be aware of the increased operating capacity, or the associated risks. This is especially true for the technologies which present no notable visible modifications to the existing infrastructure. Even with close consideration of the collocated utilities, it is possible that these upgrades may be incorporated without a pipeline operator ever being aware, if not notified by the transmission utilities.

Impact on HVAC Interference

The power transmission industry trends toward development and installation of higher capacity HVAC transmission systems has presented collocations with near order of magnitude increases in typical transmission line currents. For example, previous references indicate a typical load for 345kV to 500kV systems to be on the order of 500 to 1,000 amps per circuit.[10] Recent research indicates increased capacity for 345kV lines carrying up to 5,000 amps per circuit, and over 6,000A for 500kV systems.[3] Not only does this increased transmission load significantly increase the interference levels on affected pipelines, but it also well exceeds previously understood 'rule of thumb' guidelines.

Numerical modeling can be utilized to examine the collocated pipeline's susceptibility to HVAC interference, help identify locations of possible AC current discharge, and where necessary, simulate and design appropriate mitigation systems to reduce the effects of induced AC voltage, fault currents, and induced AC corrosion to meet accepted industry standards. While numerical methods allow for modeling of highly complex collocations, several basic analyses are presented here to provide a fundamental comparative overview of the effects of elevated line currents.

Consider a typical pipeline segment with an HVAC transmission line crossing at a constant angle as in Figure 2 below. Calculations were run based on typical 345kV HVAC transmission tower geometry, considering a 6-inch pipeline with FBE coating in 1,000 ohm-cm soil. Based on the current density limits set in the NACE State of the Art report, applying Equation 1 above, we can calculate the induced potential corresponding to a given current density limit. Considering a current density of 20 amps/m^2, referenced as a limit below which increase in corrosion rate due to AC induction is low, a corresponding potential of 0.9VAC is calculated. Considering a current density of 100 amps/m^2, referenced as a limit above which AC accelerated corrosion is likely, a corresponding potential of 4.4 is calculated. These limits and the corresponding potentials calculated for a range of crossing angles and transmission line loads are given in Figure 3 below.

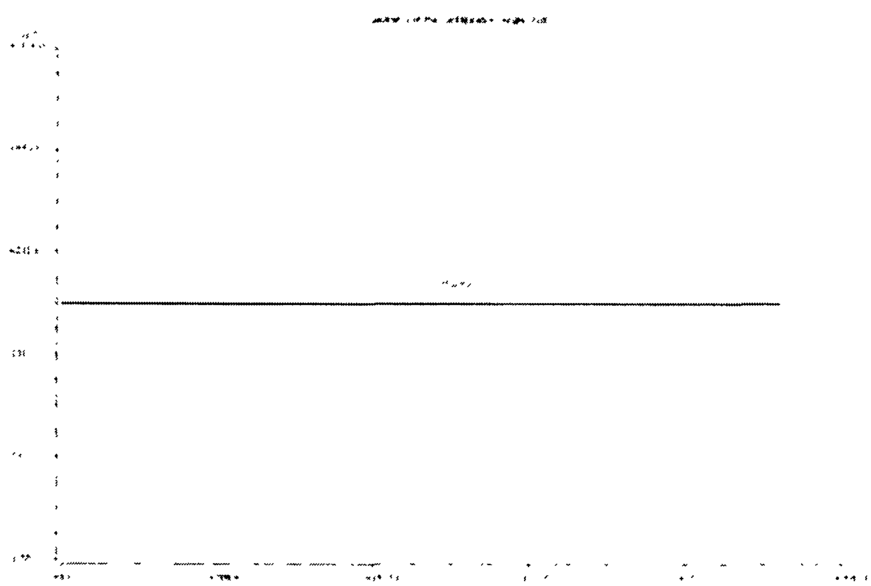

Figure 2: Simplified pipeline and HVAC Transmission line crossing model

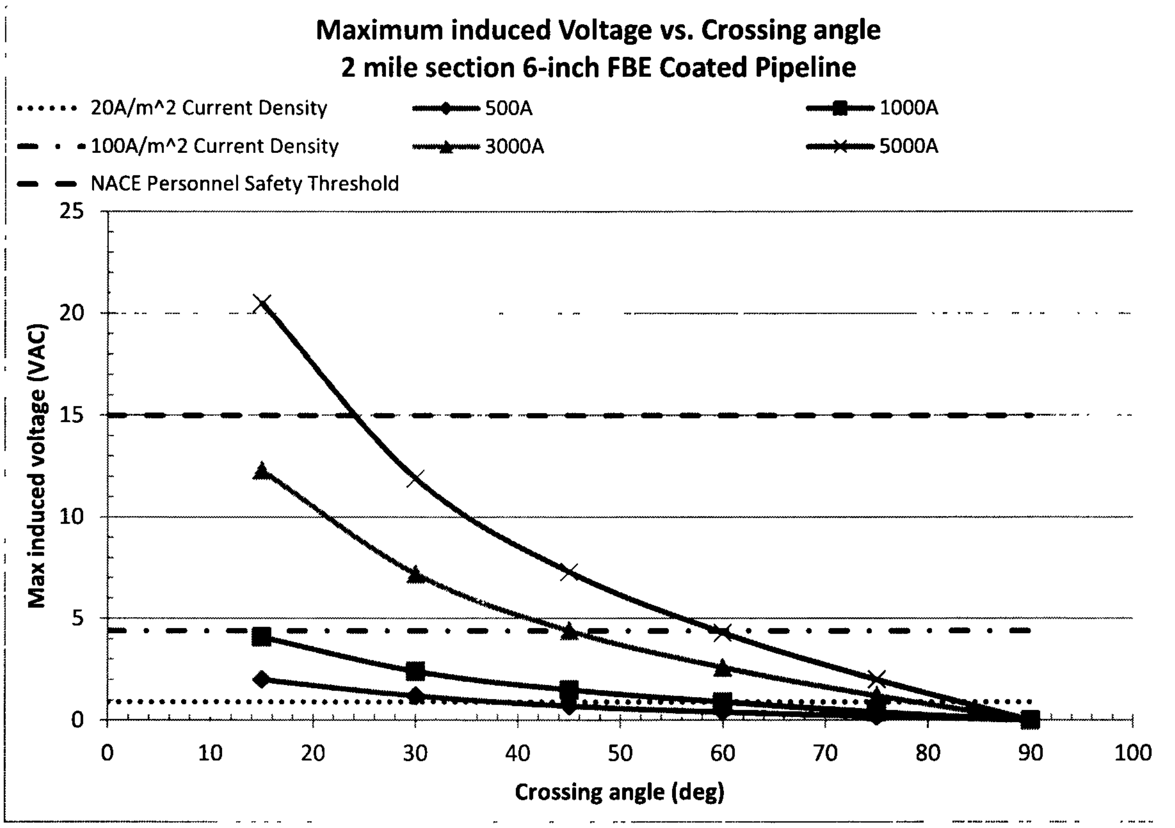

Figure 3: Maximum calculated induced voltage at various HVAC line crossing angles

It can be seen that for a given crossing angle, considering all other variables equal, a generally linear relationship exists between HVAC line current and induced voltage. While this may seem apparent, the results are presented graphically here to demonstrate the practical effects of the increase in HVAC transmission current. Considering a typical 345kV circuit, and current loads of up to 1000A, it can reasonably be determined from the results above that a crossing angle of greater than 45° degrees would induce less than 2VAC, and that a crossing of greater than 60° induces minimal potential such that the corresponding current density is less than 20amps/m^2 even in a relatively low soil resistivity at 1,000 ohm-cm. Previous industry experience and general 'rule-of-thumb' practices across industry appear consistent with this understanding that crossings of less than 60° are often not considered significant.

However, as the transmission line load is increased to 3,000 or 5,000A, it can be shown that crossing angles up to 60° may induce potentials such that corresponding current density exceeds 100amp/m^2. Depending on governing limits set on current density, it can be shown that crossing angles of 80° may even be considered significant in terms of accelerated AC corrosion, a noteworthy change from previous accepted understanding.

Consider the generalized hypothetical collocation presented below in Figure 4. This collocation geometry was analyzed assuming a 6-inch FBE coated pipeline, in 10,000ohm-cm soil. For a given transmission line load of 1,000A, the analysis calculated a maximum potential of 8VAC, corresponding to a maximum theoretical current density of approximately 18 amps/m^2, per Equation 1 above. This segment would therefore be considered acceptable per both the 15VAC safety standard, and is less than the 20amps/m^2 level referenced as below which AC accelerated corrosion is not likely. However, increasing the HVAC line load 5,000A yields a calculated potential of 40VAC for this same collocation, and a corresponding current density greater than 90amps/m^2, as shown in Figure 5 below.

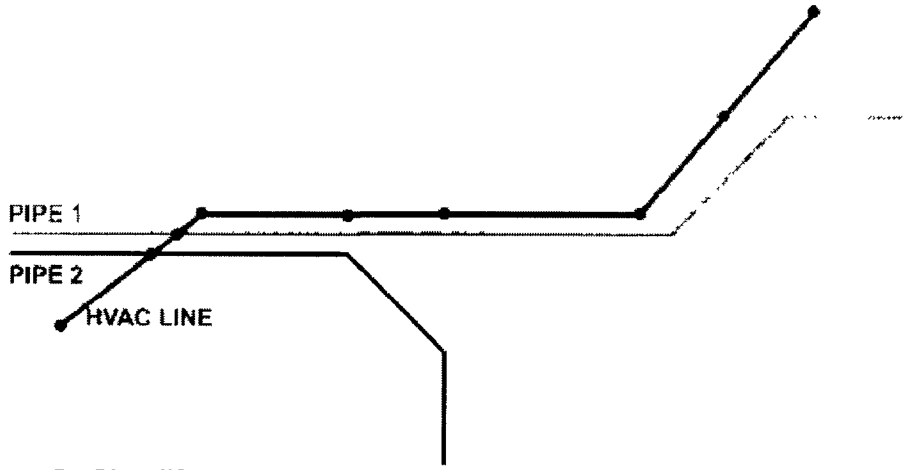

Figure 5: Simplified pipeline and HVAC Transmission line crossing model

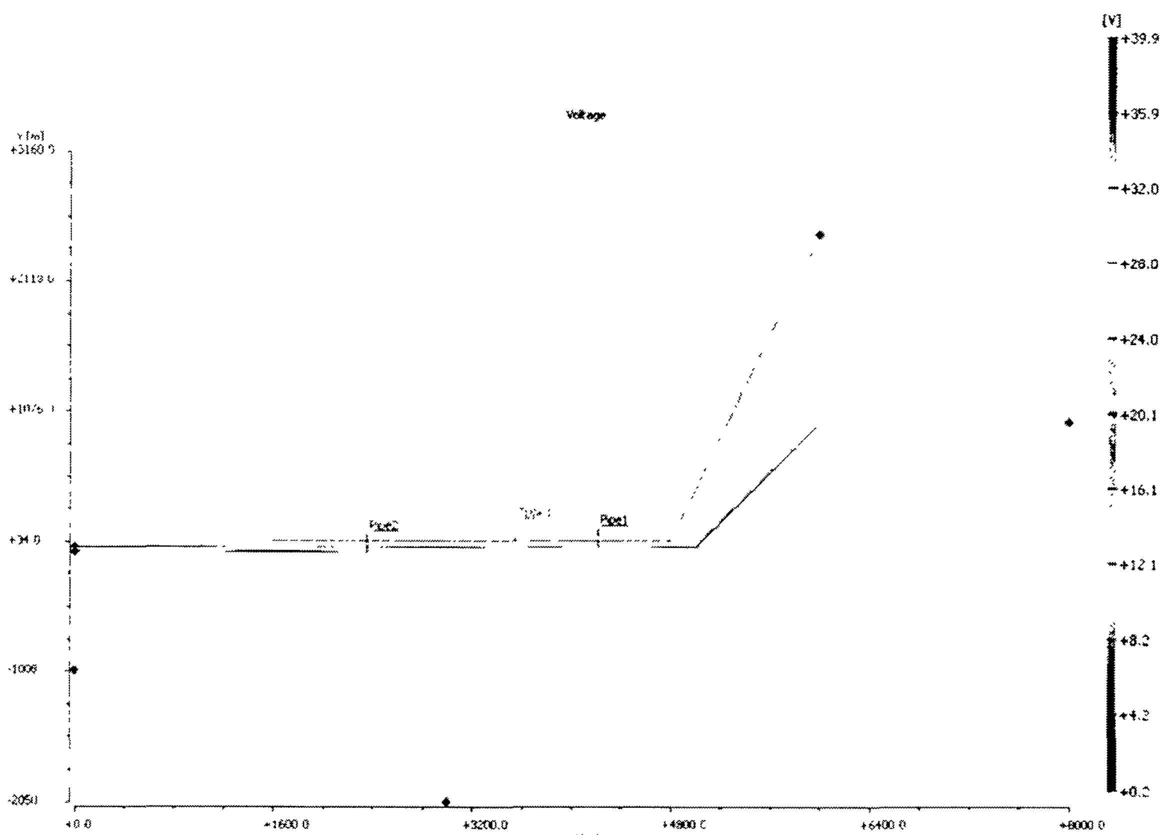

Figure 5: Simulations Results considering a 5,000A load

CONCLUSIONS

It can be seen that due to the long distance transmission requirements related to renewable energy development, trends within the power transmission industry are toward developing increased capacity systems. Often, this is achieved with little visible alteration to existing infrastructure. If increased or altered ROW access is not required, changes may be implemented without informing collocated utilities. It can be shown that the corresponding elevated transmission currents produce a significantly larger inductive effect on collocated and crossing pipelines. Continued research is being pursued into the effects of such elevated transmission current on adjacent pipelines in real world applications considering capacitive effects present during construction, inductive effects during normal operations, and fault effects during ground fault conditions.

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1. J. Holma, "Increasing Transmission Capacity", Wind Systems Magazine, January 2011, http://windsystemsmag.com/article/detail/191/increasing-transmission-ca (April 30, 2013)

2. M. Fishlein, E. Wilson, T. Peterson J. Stephens, "States of Transmission: Moving Towards Large-Scale Wind Power", Energy Policy 56(2013) p101-113 Miriam Fischlein, ElizabethJ.Wilson, TarlaR.Peterson, JennieC.Stephens

3. L. Weimers, "Bulk Power Transmission at Extra High Voltages, a Comparison Between Transmission Lines For HVDC at Voltages Above 600 kV DC And 800 kV AC", ABB Power Technologies AB

4. S. D. Wright, "Transmission Options for Offshore Wind Farms in the United States", American Wind Energy Association (AWEA) 2002, http://www.umass.edu/windenergy/publications/published/2002/ (May 2, 2013)

5. NACE Item No. 2424, "AC Corrosion State-of-the-Art: Corrosion Rate, Mechanism, and Mitigation Requirements" (NACE International 2010)

6. IEEE-806-1986, "Recommended Practice for System Identification in Fossil-Fueled Power Plants and Related Facilities"

7. NACE SP0177-2007, "Standard Practice Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems

8. Office of the Governor Economic Development & Tourism http://governor.state.tx.us/ecodev/business_research/maproom/, (July, 2013)

9. U.S. Census Bureau Census 2000 Summary File 1. U.S. Census Bureau Census 2000 Summary File 1, http://www.census.gov/prod/cen2000/doc/sf1.pdf, (July, 2013)

10. J. Dabokowski, "AC Predictive and Mitigation Techniques", PRCI Report L51835e, 1999, Pipeline Research Council International, Inc.

Exhibit J

KINDER MORGAN

Requirements for Overhead Power Lines in the Vicinity of Kinder Morgan Pipelines

- No poles or structures, including anchors, grounding rods or guy wires shall be placed or located within the easement of any Company (Kinder Morgan, Inc. or its subsidiaries) pipelines (except for service lines associated with Company CP systems, if it cannot be avoided).

- No guy wires shall cross over any Company pipeline easements.

- Conductors shall at all times be at least thirty (30) feet above the top of the ground, i.e. ground clearance to the lowest conductor must be a minimum of thirty (30) feet.

- No heavy equipment shall enter any Company pipeline easement or cross any Company pipelines without the review by Company of the size and weight of that equipment. Special mitigation measures may be necessary before such a crossing may be made.

- Local One Call System or Underground Service Alert (include phone number), shall be contacted minimum forty-eight (48) hours or according to applicable state laws, whichever is more stringent, before beginning work anywhere near or within Company's pipeline easement.

- Company must be notified in advance and must have its own personnel on-site before any equipment is moved or located twenty-five (25) feet or closer to any Company pipeline or pipeline easement.

- Company's Right-of-Way or Project Management personnel must notify the area Corrosion Technician/Supervisor about any newly proposed power lines that cross or parallel Company pipelines.

- The electric power (high-voltage AC or DC) conductors and support poles/towers shall be maintained at sufficient distances from Company pipeline(s) to minimize induced AC pipeline voltages, fault currents and DC stray currents that can be potentially harmful to Company's pipelines or personnel. The electric transmission power company shall:

    - Provide electrical current loading conditions (including AC power line voltage, AC current and % maximum load current, maximum ground fault current, fault clearance time, etc.) free of cost to the Company upon request to ensure appropriate consideration of induced voltages.

    - Provide drawing details such as power line alignment, pole configuration, crossing locations, crossing angle, paralleling length and distance from pipeline.

- Be responsible for funding an AC interference study in accordance with Company's requirements when induced voltages greater than 2.0 Volts AC are measured or anticipated, when any suspected AC related damage has been identified, or as other conditions warrant as deemed appropriate by Company. The study shall include consideration of AC fault currents, induced AC voltages and personnel safety considerations.

- Be responsible for any costs associated with maintaining theoretical induced AC current densities on Company's pipeline(s) to a level of less than 30 Amps/square meter assuming a 1 cm^2 coating holiday, and costs associated with remediation of potential fault currents.

- In the case of high-voltage DC transmission, provide line current, fault current, duration of discharge, location of grounding electrodes, etc., as needed; assess and minimize any associated stray current corrosion on Company pipeline, at no cost to the Company.

- Be responsible for the cost of any required mitigation as indicated by the study in accordance with Company's standard E1300, section 5.4.

- Be responsible for the cost of monitoring the AC mitigation system (or DC stray current mitigation system) at least annually for a period of 3 years after installation, to ensure proper operation in accordance with Company's standards.

- Notify the Company when power loads are increased or circuits are changed in the future. Be responsible for follow-up studies and additional mitigation upon changes or increased capacities to the circuits.

References:

i. E1300 – Corrosion Control and Coatings
ii. C1005 - Construction Near Company Facilities (O&M 204)
iii. C1280 – Mitigating Induced AC Voltage During Construction
iv. C1002 - Survey Standards
v. O&M 903 - External Corrosion Control for Buried or Submerged Pipelines