
Current and Potential Distribution on a Coated Pipeline with Holidays Part I—Model and Experimental Verification*

K.J. Kennelley,* L. Bone,* and M.E. Orazem**

ABSTRACT

A two-dimensional model was developed to predict the current and potential distribution of an underground coated pipe in high-resistivity soil under an impressed current, parallel anode, cathodic protection (CP) system. The model was designed to study the effect of discrete holidays of various sizes on coated pipe without having to assume that holidays simply reduce the efficiency of the protective coating. Full-scale experimental tests were conducted with a 0.508 m (20 in.) diameter pipe coated with 460 μm (18 mils) of fusion-bonded epoxy. The performance of a parallel anode CP system was measured in the presence and absence of a discrete longitudinal coating defect (2.4% of the pipe circumference) that exposed bare steel. All tests were conducted in 108,000 ohm-cm water. Good agreement was obtained between experimental results and modeling predictions. The results show that there can be a significant difference in the performance of a cathodic protection

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system when localized defects exist in the coating as compared to uniformly distributed holidays. This difference is expected to be most pronounced in high-resistivity soils with close anode to pipe spacing.

KEY WORDS: coated pipelines with holidays, current and potential distribution, mathematical model

INTRODUCTION

External corrosion on pipelines can be mitigated by coating the pipe with a high-resistance film. Cathodic protection (CP) is used to protect portions of the pipe that are inadequately coated. Defects in the coating are termed holidays, and such holidays can expose bare steel. While few coatings will remain holiday-free during their service life, the effect of the coating is to reduce the current requirement for a CP system since a much smaller portion of the bare pipe is exposed. In a conventional impressed current CP system for a pipe, multiple anode groundbeds are placed at discrete sites along the pipeline. The anode groundbeds are normally located at distances sufficiently far away from the pipe such that they can
be considered remote.\textsuperscript{1} The remote anode location allows protection of a larger section of the pipeline with a single source.

Another benefit of the remote anode placement is that current requirements can be predicted without considering the potential distribution on the pipe. The current density is much larger at the anode than at any other region of the system; therefore, the circuit resistance is dominated by the resistance of the earth near the anode. Anode to earth resistance formulas are tabulated in the literature for most common anode geometries\textsuperscript{2,3} and can be used without explicit consideration of the current and potential distribution on the pipe.

However, there are instances where the conventional approach to CP design cannot be used. Anode placement near the pipeline may be preferred, for example, for a warm pipeline buried in frozen soil. A thaw bulb is formed around the pipeline with a soil resistivity that is much lower than that of the frozen ground. In a recent study, the resistivity of the thaw bulb was approximately 10$^6$ ohm-cm, whereas the resistivity of the frozen soil was over 10$^7$ ohm-cm. A result of the large resistivity of ice is that remote anode placement within the frozen region outside the thaw bulb has large power requirements. In this situation, it is appropriate to consider a nonconventional CP design in which a continuous anode runs parallel to the entire length of the pipe and is located within the thaw bulb.

The reason for concern is illustrated in Figure 1. In high-resistivity soil, the ohmic potential drop between the anode and the upper portion of the pipe is significantly greater than that at the lower portion of the pipe. Therefore, it is possible to overprotect the portion of the pipe that is closest to the anode while underprotecting the part of the pipe that is furthest from the anode. The underprotected region of the pipe is subject to corrosion, whereas hydrogen evolution can occur on the overprotected region. Large negative potentials should be avoided because hydrogen embrittlement or stepwise cracking associated with hydrogen evolution can cause failure of the pipe. The nominal desired potential range for a pipeline under cathodic protection is between −850 and −1,200 mV measured with respect to a Cu/CuSO$_4$ reference electrode located at the surface of the steel or holiday.\textsuperscript{1} The close anode to pipe spacing addressed in this work can lead to a potential variation around the circumference of the pipe in excess of 350 mV. In this case, underprotection of the pipe (seen for potentials more positive than −850 mV Cu/CuSO$_4$) cannot be avoided without simultaneous overprotection of a portion of the pipe (seen for potentials more negative than −1,200 mV Cu/CuSO$_4$). Note that conventional CP design equations cannot be used to differentiate conditions under which the entire circumference of the pipe can lie in the protected potential region from conditions under which underprotection can be avoided only by overprotecting a portion of the pipe.

The need to consider the current and potential distribution at the pipe when designing a CP system with anodes close to the pipe raises questions about the nature of holidays and the way they are modeled. Three models are presented in Figure 2 for a pipe with coating holidays to bare steel that cover 10% of the surface. The holiday could be considered discrete and located in one position (Figure 2[a]). A single discrete holiday would be associated with a localized failure of the coating caused perhaps by disbonding or mechanical damage. The uncoated area could also be distributed over the surface of the pipe (Figure 2[b]). In case the holidays become infinitesimally small, the distributed holidays could be modeled as having reduced the effectiveness of the coating by reducing the effective coating thickness (Figure 2[c]).

The current and potential distributions associated with holidays are ignored in traditional CP design for remote anode placement. The effectiveness of the coating appears in design calculations only as a factor for reducing the current required to protect the structure. For example, a 90% effective coating reduces the current required to protect a structure to 10% of the current needed without the coating. Therefore, the model of a holiday as having reduced the uniform coating efficiency (Figure 2[c]) is implicit in the usual method of designing cathodic protection systems by using anode to ground formulas.

Newman recently presented design calculations that account for the potential distribution around the pipe under the assumption that holidays could be considered as having reduced the coating efficiency.\textsuperscript{3} Assumption of a uniform, reduced efficiency coating is justified when holidays are very small in size (pinhole defects) and are uniformly distributed around the pipe. However, large-sized defect areas in the coating may however be created during shipment of the pipe to the installation site, lifting of the pipe into the ditch, and backfill operations. The work presented here was motivated by the need to consider the influence of large holidays in the coating on the performance of a CP system. The capabilities of the model used here are compared in Table 1 to the features associated with the use of resistance formulas and with the model presented by Newman.\textsuperscript{3}

**SCOPE OF WORK**

The mathematical model presented in this work predicts the current and potential distribution on an underground pipeline under an impressed current, parallel anode, cathodic protection system. The model
was designed to study the effect of discrete coating holidays/defects of various sizes on the performance of the CP system. The calculations presented here are for a 0.508 m (20 in.) diameter fusion-bonded epoxy (FBE) coated pipe in an enclosure that was designed to simulate a highly resistive thaw bulb environment corresponding to 108,000 ohm-cm soil. Full-scale experimental tests were carried out on a 0.508 m (20 in.) FBE coated pipe to verify the model predictions. The anode was a parallel 2.54 cm (1 in.) diameter aluminum rod located either 0.305 or 1.52 m (1 or 5 ft) from the pipe.

MATHEMATICAL DEVELOPMENT

Prediction of the current and distribution associated with a CP system requires the solution of Laplace’s equation. Laplace’s equation, $\nabla^2 \Phi = 0$, can be written in rectangular coordinates as:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} = 0$$

To solve this equation, boundary conditions are used to describe relationships between current and potential that are appropriate for any surfaces within the CP system. This would include the pipe being protected, the anode, and any region through which current does not pass such as the edge of a thaw bulb that acts as an insulating surface.

Analytic solutions to this equation are possible for simple geometries and are the basis for the anode resistance formulas routinely applied to CP design. While the geometry for the parallel anode impressed current system studied here is relatively simple, the added complexity associated with holidays in the pipe coating necessitated the use of a numerical method. The numerical methods that could be used include finite element, finite difference, and boundary element techniques. A thorough review of the application of numerical methods for cathodic protection design is presented by Nisancioglu with an emphasis on boundary element techniques. Recently, a good review of the application of finite elements was presented by Munn and Deveraux. Finite element techniques were used previously to investigate cathodic protection of partially protected marine structures and were selected here to investigate the cathodic protection of pipes with coating holidays.

Finite element techniques are very flexible since nodes can be concentrated in regions of high current density and can be used to map out curved as well as rectangular surfaces. The mathematical model presented here can be used to model an arbitrary two-dimensional geometry. The specific system treated in this work is a pipe suspended in a square pool with a parallel anode (Figure 3). The cement-lined walls of the pool acted as the periphery of the thaw bulb.

At insulating surfaces such as the periphery of the thaw bulb, the current in the direction normal to the surface is equal to zero. Thus, the boundary condition

FIGURE 1. Impressed current CP system with a single anode located close to the bottom of the pipe.

FIGURE 2. Three models for holidays in pipe coatings that encompass 10% of the pipe surface.
**TABLE 1**

Comparison of Design Calculations for Cathodic Protection of a Pipe

<table>
<thead>
<tr>
<th>Model Features</th>
<th>Calculation by Resistance Formulas&lt;sup&gt;1,2&lt;/sup&gt;</th>
<th>Calculation by Newman&lt;sup&gt;3&lt;/sup&gt;</th>
<th>Calculation Presented Here</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holidays as in:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Figure 2(c)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Figure 2(b)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Figure 2(a)</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Predicts potential variation on pipe</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The reactions to be considered on bare steel include corrosion (oxidation of the metal), reduction of dissolved oxygen, and evolution of hydrogen. The total current and the contributions from these reactions are illustrated in Figure 4 for reactions that take place in alkaline waters. The kinetic parameters needed to generate Figure 4 were estimated, and values of standard electrode potentials were used for the equilibrium potentials of the reactions. Mass transfer limitations were assumed for the reduction of ferrous ion (curve b), for the reduction of oxygen (curve d), and for the oxidation of hydrogen (curve e). The dominant reactions are the oxidation of iron (curve a), the reduction of oxygen (curve d), and the evolution of hydrogen (curve f). At anodic potentials (V > V<sub>corr</sub>), corrosion (reaction a) dominates, whereas hydrogen evolution dominates at potentials cathodic to −1.2 V. The potential range for which the metal is protected is typically −1.2 > V > −0.85 V (Cu/CuSO<sub>4</sub>). In the protected region, the reduction of oxygen is the dominant reaction. The corrosion potential is determined by the balance between corrosion and the mass transfer limited reduction of oxygen. Near the corrosion potential, a linear relationship between current and potential may be assumed, whereas the more complete current potential relationship must be used at more cathodic potentials.

While the model has the flexibility to handle mass transfer controlled, Tafel, and linear reaction kinetics, linear kinetics were applied to the anode and to the bare portion of the pipe because Tafel kinetics were invalid at the low current densities seen in this work. A linear relationship was used as a result of the small shift in potential observed on the bare steel in the experiments. A linear relationship is generally valid for the coated steel as a consequence of the high coating resistivity.

**Linear Reaction Kinetics on Bare Steel**

Close to the corrosion potential, hydrogen evolution is unimportant, and the oxidation of steel can be assumed to be balanced by the mass transfer limited reduction of oxygen (Figure 4). Thus, the total current density normal to the pipe surface is given by...
\[ i_n = i_{0,Fe} \exp \left( \frac{\alpha_{Fe} F}{RT} (V - V_{Fe}) \right) - i_{O_2} \] (2)

where \( \alpha_{Fe} \) is the apparent transfer coefficient for the oxidation of iron (or steel), \( i_{0,Fe} \) is the exchange current density for the oxidation of iron, \( V_{Fe} \) is the equilibrium potential for the oxidation of iron, \( V \) is the applied potential, and \( i_{O_2} \) is the mass transfer limited current density associated with reduction of oxygen. Note that a cathodic current is assumed to be negative following the conventions used in electrochemical literature, whereas a cathodic current is generally treated as being positive in the cathodic protection literature. At the corrosion potential \( V_{corr} \), the net current \( i_n \) is equal to zero, and

\[ i_{O_2} = i_{0,Fe} \exp \left( \frac{\alpha_{Fe} F}{RT} (V_{corr} - V_{Fe}) \right) \] (3)

Equation (3) shows that an increase in the mass transfer limited current for oxygen reduction will shift the corrosion potential to more positive values and, thereby, increase the rate of corrosion. Equation (2) can be rewritten in terms of the corrosion potential as

\[ i_n = i_{O_2} \left( \exp \left( \frac{\alpha_{Fe} F}{RT} (V - V_{corr}) \right) - 1 \right) \] (4)

At low current densities, the exponential term can be linearized about the corrosion potential, i.e.,

\[ i_n = \frac{i_{O_2} \alpha_{Fe} F}{RT} (V - V_{corr}) \] (5)

The potential, \( V \), is the potential of the pipe referenced to the solution adjacent to the pipe. While the pipe is assumed to be at a fixed potential, the potential relative to the adjacent solution is a function of position because the potential of the solution is governed by the current distribution in the solution. Current can be eliminated in Equation (5) by writing it in terms of Ohm's law.

While the linear boundary condition used was valid for the small shifts from the corrosion potential observed here, the more general nonlinear boundary condition (References 4, 6, and 9) will be used in future work. It is also important to note that polarization of the bare steel associated with film formation (ferrous hydroxide, ferric hydroxide, or calcareous deposits) will reduce the current required to shift the potential of the bare steel to protective values. The time-dependent nature of the surface was observed in this work and will be treated quantitatively in future work.

**FIGURE 4.** Current contributions for a steel pipe in alkaline waters: (a) \( \text{Fe} \rightarrow \text{Fe}^{2+} + 2e^- \); (b) \( \text{Fe}^{2+} + 2e^- \rightarrow \text{Fe} \); (c) \( 4\text{OH}^- \rightarrow \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \); (d) \( \text{O}_2 + 2\text{H}_2\text{O} + 4e^- \rightarrow 4\text{OH}^- \); (e) \( \text{H}_2 + 2\text{OH}^- \rightarrow 2\text{H}_2\text{O} + 2e^- \); and (f) \( 2\text{H}_2\text{O} + 2e^- \rightarrow \text{H}_2 + 2\text{OH}^- \).

**Linear Current Potential Relationship on Coated Surfaces**

Under the assumption that the coating is a high-resistance ionic conductor and that the electrochemical reaction takes place on the surface of the steel pipe, the overall potential drop will be the sum of potential drops through the film and across the steel-film interface. When the film resistance dominates, the relationship between current and potential is given by

\[ i_n = \frac{1}{\rho_{film} \delta_{film}} (V - V_{corr}) \] (6)

where \( \rho_{film} \) and \( \delta_{film} \) are the film resistivity and thickness, respectively.

**Method for Solution**

A finite element technique was used to solve Laplace's equation for potential subject to boundary conditions that describe insulating and metal surfaces. One advantage of finite element methods over use of finite differences is that complicated or curved geometries can be conveniently treated since the elements do not have to be of regular shape or size. However, setting up a problem can be tedious since the location of each node and the identity of the nodes making up each matrix must be fully specified. An algorithm was written to generate the node distribution interactively by computer.

The nodal distribution for the two geometries treated here are given in Figures 5 and 6. These figures provide a top view of the geometry presented as a side view in Figure 3. The computer storage requirements for the numerical calculations were
reduced by sectioning the system along a mirror plane. The 999 nodes and almost 1,800 elements were concentrated near the pipe and the anode. Along the pipe, 101 nodes (100 elements) were used, and 21 nodes (20 elements) were used along the anode. These nodes were concentrated at the top and bottom sections of the pipe. A measure of the adequacy of this nodal distribution is provided by the extent to which the current integrated over the anode was equal to that on the pipe. The closure error was a strong function of the uniformity of the current distribution as well as of the nodal density and distribution. The error ranged from less than 1% when modeling the holiday-free coating to 8 to 12% when modeling the effect of holidays. For a given nodal density, the closure error can be improved dramatically by using boundary element rather than finite element techniques.4,10

EXPERIMENTAL PROGRAM AND OBJECTIVES

Full-scale experiments were conducted in a 3.05 by 3.05 by 2.44 m deep (10 by 10 by 8 ft) cement-lined pit using 108,000 ohm-cm water. A 2.44 m (8 ft) long piece of 0.508 m (20 in.) OD pipe was used as the cathode. The pipe was externally coated with 460 μm (18 mil) thick Scotchkote 200N1 FBE coating. The impressed current system used a 2.54 cm (1 in.) OD 6061 T-6 (UNS1 A96061) aluminum tubular for the anode and an external power supply. The anode was placed in close proximity to the coated pipe. A side view of the experimental system is shown in Figure 3, and top views are provided in Figures 5 and 6.

To verify that the model could be used to predict the effect of system design, five cases were studied experimentally and then compared to predictions of the model. The cases studied were:

-A holiday-free coating with an anode placed 0.305 m (1 ft) from the pipe;
-A 2.4% holiday to bare steel in an otherwise holiday-free coating with the pipe rotated to have the holiday as far as possible from an anode placed 0.305 m (1 ft) away from the pipe;
-A 2.4% holiday to bare steel with the pipe rotated to have the holiday as close as possible to an anode placed 0.305 m (1 ft) from the pipe;
-A 2.4% holiday to bare steel with the pipe rotated to have the holiday as far as possible from an anode placed 1.52 m (5 ft) from the pipe; and
-A 2.4% holiday to bare steel with the pipe rotated to have the holiday as close as possible to an anode placed 1.52 m (5 ft) from the pipe.

The applied potential from the power source, the total system current, the potential of the pipe relative to the solution adjacent to the pipe, and the potential of the anode relative to the solution adjacent to the anode were measured and compared to the modeling predictions.

EXPERIMENTAL TEST PROCEDURES

The 2.44 m (8 ft) length of 0.508 m (20 in.) OD coated pipe was checked to ensure that it was holiday-free. Six pinhole-sized holidays were identified with a 3,500 V arc holiday detector and were repaired with silicone sealant. Two small regions of the FBE coating were removed with a 600 grit grinder to simulate holidays in the coating to bare steel. The holiday dimensions were 3.8 by 5 cm (1.5 by 2 in.) and 3.8 by 61 cm (1.5 by 24 in.) These defects were initially covered with duct tape for the experiments conducted with a holiday-free surface. The tape was then removed to simulate holidays to bare steel.

Closed foam urethane pads were attached to the bottom of the pipe and sealed with silicone. This was done to isolate the interior of the pipe from the exterior water environment. For each test, a six foot section of 0.508 m (20 in.) OD pipe and 2.54 cm (1 in.) OD aluminum anode was immersed in the water environment. The 3.8 by 5 cm (1.5 by 2 in.) defect was located at the 0.61 m (–2 ft) water level and the 3.8 by 61 cm (1.5 by 24 in.) defect was located at the 0.305 m (–1 ft) to 0.91 m (–3 ft) water level. The total surface area of the pipe immersed in the water was 2.9 m² (31.4 ft²) and the total area of exposed holiday was 0.025 m² (0.271 ft²). Along the 61 cm (24 in.) length of holiday, the holiday encompassed 2.4% of the pipe circumference [100 x 3.8 cm/(51 cm π)].

The pipe was suspended in a 3.05 by 3.05 by 2.44 m (10 by 10 by 8 ft) deep pit containing deionized (424,000 ohm-cm) water using an overhead crane. Nonconductive lifting straps were used to isolate the pipe from the crane. The aluminum anode was supported above the pit using a wooden support member. The water resistivity was adjusted to 108,000 ohm-cm for the experiments by addition of approximately 1,135.5 L (300 gal) of tap water.

Potential measurements were taken with a saturated calomel reference electrode attached to a 3.66 m (12 ft) long 5 cm (2 in.) OD polyethylene pipe. To minimize errors associated with ohmic potential drops, a jig was attached to the end of the pipe, which allowed accurate placement of the reference electrode at a position 0.16 cm (1/16 in.) from the pipe or the holiday. No “instant off” potential measurements were conducted.

The potential of the pipe was measured with respect to the reference electrode at three water

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1 UNS numbers are listed in Metals and Alloys in the Unified Numbering System, published by the Society of Automotive Engineers (SAE) and cosponsored by ASTM.

1 Trade name.
depths (0.305, 0.91, and 1.52 m levels [-1, -3, and -5 ft]). At each water depth, potentials were measured along the pipe at three positions corresponding to 0, 90, and 180° (12, 9, and 6 o'clock, respectively). Separate measurements of the pipe potential were made with respect to the reference electrode held along the holiday when it was exposed. The potential of the anode was also measured at the 0.305, 0.91, and 1.52 m (1, 3, and 5 ft) depths. The current was measured with a zero-resistance ammeter capable of accurate measurements in the picoAmp range.

RESULTS AND DISCUSSION

This discussion is divided into two sections. A comparison between experimental results and the model calculations is presented in the first section. The physical consistency of the kinetic parameters and apparent time dependency of certain kinetic parameters is discussed in the second section. The explicit treatment of discrete holidays to bare steel (as done here) is compared in a separate paper to the assumption of a uniform reduced coating efficiency.

Comparison Between Model and Experiment

Comparison between calculation and experiment was made for three series of cases. The first was in the absence of holidays with an anode placed 0.305 m (1 ft) away from the pipe (Figure 5). The second was with both holidays exposed and with the anode placed 0.305 m (1 ft) away from the pipe. The final series was
with both holidays exposed and the anode placed 1.52 m (5 ft) from the pipe (Figure 6).

Selection of Physical Parameters—Explicit modeling of cathodic protection requires a fairly complete knowledge of the physical parameters that influence the system. The dimensions of the test container, the length of pipe exposed, the location of the pipe and anode in the pit, and the diameters of the pipe and anode used in the calculations were the same as those measured. The solution resistivity was 108,000 ohm-cm, and that value was used in the calculations. The film thickness was measured to be 460 μm (18 mils); therefore, it was also fixed in the calculations. The corrosion potential for the pipe was measured initially between -0.420 and -0.450 V (Cu/CuSO₄). The adjusted parameters were the film resistivity, the corrosion current on the bare pipe, and the exchange current density on the anode. The procedure for choosing values for these parameters was as follows:

The film resistivity and the exchange current density on the anode were adjusted to provide good agreement to measured potentials at the pipe and at the anode in the absence of a holiday. No other parameters were adjusted to fit the measured current. The results are presented in Figure 7 where the calculated and measured potentials of the pipe are presented as a function of reference electrode position for an applied potential of 0.8 V. On the pipe, 180° corresponds to the portion of the pipe closest to the anode. The agreement between calculated and observed current was within 0.08%. In order to achieve this agreement, film resistivity \((1 \times 10^9\ \text{ohm-cm})\) was adjusted to \(1.1 \times 10^{10}\ \text{ohm-cm}\). The film was expected to have a resistivity of \(10^9\ \text{ohm-cm}\) upon uptake of water; therefore, the value obtained by this fitting procedure is consistent with a new film.

Since these were short-term experiments, the film resistivity was held at \(1.1 \times 10^{10}\ \text{ohm-cm}\) for all other data sets. The corrosion potential on the bare steel was assumed to be constant at a value of \(-0.430\ \text{V (Cu/CuSO}_4\)\). The corrosion current density on the bare steel and the exchange current density for the anode were adjusted slightly for the other data sets to account for an apparent change in these values during the course of the experiments. No other adjustments to physical parameters were made.

Holiday-Free Coating with the Anode 0.305 m (1 ft) from the Pipe—As shown in Figure 7, a perfectly coated pipe can be maintained in the protected potential regime with an anode located 0.305 m (1 ft) away and held at a potential of 0.8 V. The current distribution on the pipe is uniform (Figure 8), and the current requirements are low \((10.9 \mu\text{A/cm}^2\ [1.01 \mu\text{A/ft}^2])\). The current densities reported in Figure 8 are based on the total area of the exposed pipe. Note that both the current density and the potential were uniform at the anode, and this is consistent with the assumptions usually made in designing cathodic protection systems.

2.4% Holiday with the Anode 0.305 m (1 ft) from the Pipe—As seen in Figure 9, an applied potential of 0.8 V will not provide sufficient protection if the coating contains a 2.4% holiday to bare steel at the top of the pipe (0°). Under these conditions, the entire pipe is unprotected. The current distribution on the pipe (Figure 10) is very nonuniform, and the calculated current density at the bare surface reaches 80 times the average value \((6,780 \mu\text{A/cm}^2 [630 \mu\text{A/ft}^2])\). The concentration of current at the bare portion of the coated steel seen in Figure 10 illustrates the way cathodic protection augments the use of high-resistance coatings. However, both the experimental results and the model calculations show that while current was concentrated at the holiday as intended, an applied voltage of 0.8 V was insufficient to polarize the base steel. However, the current and potential at the anode remain uniform. The calculated potential shows good agreement with the measured potential at the holiday and along the coated portion of the pipe, and the calculated current agrees with experimental measurement within 23%. An increase in the applied cell potential to 1.2 V was insufficient to protect the entire surface. Even a holiday located at the bottom of the pipe (closest to the anode) was not protected at an applied potential (1.7 V) sufficient to overprotect the coated portion of the pipe (Figures 11 and 12).

In the presentation of this work, regions where the potential of the coated pipe is more negative than
-1.2 V (Cu/CuSO₄) have been identified as being overprotected. This is not strictly correct because, aside from a deliberately formed holiday, the coating used in these experiments was holiday-free. Hydrogen evolution will not be observed on holiday-free coated metals, even at large negative potentials, because the majority of the potential drop occurs across the film. However, a cathodic limit (e.g., -1.2 V [Cu/CuSO₄]) is still used in designing CP systems for coated pipes to avoid hydrogen evolution at a pinhole holiday that could cause disbonding of the coating. In order to be consistent with current practice, the designation of overprotected was applied to pipe potentials more negative than -1.2 V (Cu/CuSO₄). Note that while the experimental and model results presented here treat a holiday in an otherwise perfect coating, model calculations for a holiday in a coating with an efficiency reduced to 95% by pinhole holidays gave qualitatively similar results.

2.4% Holiday with the Anode 1.52 m (5 ft) from the Pipe—Even at an anode to pipe spacing of 1.52 m (5 ft), it was not possible to protect the entire pipe. At an applied cell potential of 1.2 V, the coated portion of the pipe was in the protected regime, but the holiday remained underprotected. It was not possible to protect the entire pipe because an increase in the applied potential to 1.7 V caused the holiday at the top of the pipe to remain underprotected while the coated portion of the pipe became overprotected (Figures 13 and 14). A similar situation is observed at an applied potential of 1.7 V for a holiday at the bottom of the pipe (Figures 15 and 16).

**Discussion**—In this work, the kinetic parameters were treated as adjustable fitting parameters; therefore, the comparison presented here demonstrates only that the model is consistent with experimental observation. The assumption that linearized reaction kinetics can be applied on bare steel (Equation [5]) restricts the model to cases where the steel potential is not shifted to protected values. Subsequent calculations with the full nonlinear kinetic expression showed that, for the cases presented here, the use of a linearized expression was justified.
FIGURE 11. Calculated (solid line) and measured (o) potential distribution for a pipe with a 2.4% holiday at 180° and a 0.305 m (1 ft) anode to pipe spacing. The applied cell potential was 1.7 V.

FIGURE 12. Calculated current distribution for the conditions of Figure 11. The calculated average current density was 273 $\mu$A/m² (25.4 $\mu$A/ft²), and the experimentally observed current density was 189 $\mu$A/m² (17.6 $\mu$A/ft²).

Agreement between the model and experiment can be improved by including more nodes in the calculation or by further adjustment of kinetic parameters. The finite dimension of the artificial holiday used also introduces a possible source of error. The two-dimensional model assumes that the holiday extends the length of the exposed pipe section (1.8 m [6 ft]), whereas the holiday used in this experiment extended only 0.61 m (2 ft). A three-dimensional model for this system is being developed.

Time Dependence of Kinetic Parameters

The kinetic parameters obtained by fitting the model to the experimental results are presented in Table 2. The changes in the anode exchange current density and the bare pipe corrosion current that were required to obtain a good fit to the experimental data were correlated to the time at which the experiments were conducted (Figure 17). The model fit indicated that the exchange current density on the anode increased slightly during the course of the experiment. The exchange current density on the anode was lower than expected, and this may be due to passivation of the aluminum rod since no effort was made to remove the native oxide. Therefore, the observed increase in this value with time is attributed to depassivation of the aluminum. Observation of a white substance on the surface of the water adjacent to the anode during the course of the experiment suggested that an aluminum-based corrosion product was present. The polarization of the steel was treated here as having caused the mass transfer limited current for oxygen reduction on the bare pipe to decrease slightly. The values represent the adjustment required to fit the experimental data under the assumption that the corrosion potential was constant at -430 mV Cu/CuSO₄. Following Figure 4, an alternative approach would be to adjust the corrosion potential to more negative values. Growth of ferrous and ferric hydroxide films on the base steel will reduce the mass transfer limited current for oxygen reduction, and, if formed, iron oxides could reduce the active area available for corrosion. While the parameters presented in Table 2 must be regarded as adjustable fitting parameters only, the values obtained for the mass transfer limited current for oxygen reduction are consistent with values expected for scale-covered steel.

This work (and that of Newman³) shows that consideration of the current and potential distribution at the pipeline is essential for proper design of a CP system with an anode in close proximity to the pipeline. In addition, the results presented in this section show that the influence of discrete holidays to bare steel cannot be predicted without considering the way in which film growth influences the reactions taking place on the steel. An approach to characterizing the time-dependent polarization of steel buried in soil can be borrowed from the techniques developed for offshore oil production platforms. Nisancioglu¹²,¹³ presented a formalism to account for the time-dependent polarization of steel caused by formation of calcareous deposits in seawater. He assumed that film growth reduces the value for oxygen reduction and hydrogen evolution current densities. A similar approach is necessary to model the kinetics of the reactions taking place on buried steel pipes as well as for steel pipes immersed in even
FIGURE 13. Calculated (solid line) and measured (o) potential distribution for a pipe with a 2.4% holiday at 0° and a 1.52 m (5 ft) anode to pipe spacing. The applied cell potential was 1.7 V.

FIGURE 14. Calculated current distribution for the conditions of Figure 13. The calculated average current density was 192 μA/m² (17.8 μA/ft²), and the experimentally observed current density was 167 μA/m² (15.5 μA/ft²).

FIGURE 15. Calculated (solid line) and measured (o) potential distribution for a pipe with a 2.4% holiday at 180° and a 1.52 m (5 ft) anode to pipe spacing. The applied cell potential was 1.7 V.

FIGURE 16. Calculated current distribution for the conditions of Figure 15. The calculated average current density was 236 μA/m² (21.9 μA/ft²), and the experimentally observed current density was 163 μA/m² (15.1 μA/ft²).

high-purity water where the deposits may not be calcareous in nature.

CONCLUSIONS

♦ For a close anode to pipe spacing, the influence of the pipe on the current and potential distribution is critical to the successful operation of a CP system. The geometry of the pipe, the quality of the coating, and size and distribution of coating holidays will determine whether a given anode can protect bare steel exposed by holidays without overprotecting coated portions of the pipe.

♦ The purpose of this work was to verify the results of a two-dimensional mathematical model of an impressed current CP system in which a cylindrical anode is placed parallel and in close proximity to a coated pipe. Calculated values of current and potential were compared to experimental results obtained for a 0.508 m (20 in.) diameter pipe submerged in high-resistivity water. Experiments were conducted both with a holiday-free coating and with a single large
TABLE 2
Kinetic Parameters Used to Fit Model to Experimental Results

<table>
<thead>
<tr>
<th>Exposure Time for Holiday</th>
<th>Figure Number</th>
<th>$\alpha_e^{\text{obs}}$, A/(ft²) for Bare Steel</th>
<th>$i_p$, A/(ft²) for Anode</th>
</tr>
</thead>
<tbody>
<tr>
<td>—</td>
<td>7.8</td>
<td>—</td>
<td>2.50 x 10⁻⁶</td>
</tr>
<tr>
<td>0.08</td>
<td>9.10</td>
<td>3.0 x 10⁻⁴</td>
<td>1.20 x 10⁻⁶</td>
</tr>
<tr>
<td>0.58</td>
<td>13.14</td>
<td>1.5 x 10⁻⁴</td>
<td>1.75 x 10⁻⁶</td>
</tr>
<tr>
<td>0.83</td>
<td>15.16</td>
<td>1.0 x 10⁻⁴</td>
<td>2.00 x 10⁻⁵</td>
</tr>
<tr>
<td>1.08</td>
<td>11.12</td>
<td>1.0 x 10⁻⁴</td>
<td>2.00 x 10⁻⁵</td>
</tr>
</tbody>
</table>

$^\text{(A)}$ 1 A/ft² = 10.76 A/m².

FIGURE 17. Exchange current density $i_p$ for the anode and apparent oxygen reduction current density $\alpha_e^{\text{obs}}$ for the bare steel as functions of time.

In the experimental work, the mathematical model treated the same conditions as used in the experimental results. For each applied voltage and anode placement, the calculated potential and resistance agreed within 5% (50 mV). The agreement between calculated and measured current was 0.08% for the holiday-free coating and within 20 to 40% for a 2.4% holiday to bare steel.

Based on comparison to experimental data, the model correctly predicted that an anode placed 0.305 m (1 ft) away from the pipe would protect the pipe with a holiday-free coating. The model also correctly predicted that an anode placed either 0.305 m (1 ft) away or 1.52 m (5 ft) away from the pipe could not protect a single 2.4% holiday to bare steel without driving potentials on the coated portions of the pipe into the nominally overprotected regime.

The time-dependent polarization behavior of bare steel was of critical importance when predicting the behavior of discrete holidays in a coated pipe. An experimental program is currently underway to measure the time-dependent corrosion rates of steel in high-resistivity soils.

ACKNOWLEDGMENTS

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REFERENCES

1. A.W. Peabody, Control of Pipeline Corrosion (Houston, TX: NACE, 1967).