A mathematical model for the cathodic protection of tank bottoms

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Abstract

A mathematical model previously developed for predicting the cathodic protection of pipeline networks is extended to treat cathodic protection of the bottoms of cylindrical above-ground storage tanks. A single tank was modeled for which protection was provided by an anode located infinitely far from the tank bottom, by a series of anodes distributed around the circumference of the tank, and by an anode grid laid directly underneath the tank bottom. The influence of an insulating barrier associated with secondary spill containment was also modeled for the arrangements in which anodes are placed adjacent to the tank bottom. The performance predictions are strongly dependent on anode placement, the oxygen content of the soil, and the presence of insulating barriers associated with secondary spill containment.

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1. Introduction

Storage facilities for petroleum products usually consist of a collection of above-ground storage tanks called a tank farm. The tanks are cylindrical in shape, are constructed of steel, and rest on the soil. The tank bottom, then, is subject to the same corrosion issues as are buried pipelines. The provision of cathodic protection to tank bottoms is, if anything, more critical than is provision of cathodic protection to pipelines. As the tank bottom is supported by the ground and is subjected to only hydrostatic pressures, the bottom can be made of thinner metal than is used for pipelines, which operate under pressure. Because the metal is thinner, it can be more easily perforated by even low rates of corrosion [1]. The provision of cathodic protection to the bottoms of above-ground storage tanks for petroleum products, however, presents unique design issues as compared to pipelines.

While the primary current distribution on a pipe is uniform, the primary current distribution for the circular area of the tank bottom is inherently non-uniform. Limitations to kinetics and mass-transfer may cause the distributions to become more uniform; nevertheless, the tendency toward a non-uniform current distribution compromises delivery of protective current to the center of the tank bottom. The delivery of current can also be influenced by the presence of electrically insulating barriers associated with secondary spill containment. Installation of secondary spill containment, motivated by past tank failures and associated environmental damage, is currently required for new tank installations [2]. Cathodic protection of tanks with secondary spill containment can be achieved using anodes placed between the liner and the tank bottom [3].

A final issue constraining design of cathodic protection systems is that the concentration profiles for oxygen under a storage tank are cyclic in nature. The principle cathodic reaction on the tank bottom is usually assumed to be reduction of oxygen. When the tank is filled, the bottom of the tank is in full electrical contact with the soil, allowing reduction of oxygen. Eventually the consumption of oxygen reduces the oxygen content of the soil under the tank. When the tank is empty, the center rises above the soil creating a void. The resulting bellows action replenishes the oxygen content of the soil. The mass-transfer-limited current density for reduction of oxygen must therefore be considered to be a function of both time and position.

While detailed mathematical models have been developed for cathodic protection of pipelines and other structures [4–12], relatively few attempts have been made to develop rigorous models for the corrosion behavior of tank bottoms under cathodic protection. Smyrl and Newman provided a criterion for determining the maximum size of tank that can be protected with a remote ground-bed without over-protection [13]. The current density was assumed to be uniform on the tank bottom. The maximum protected radius was given by [14]

\[ r_o = \frac{\Delta \Phi_o \delta}{0.363 \bar{i}_{avg}} \]  

(1)
where $\Delta \Phi_o$ represents the acceptable range of potential. Under the criterion that the material is under-protected for potentials more positive than $-0.85/V(CSE)$ and over-protected for potentials more negative than $-1.2/V(CSE)$, the acceptable range of protection is $0.35\,\text{V}$. For an average current density of $1.9/\mu\text{Acm}^{-2}$ and a soil resistivity of $10,000/\Omega\text{cm}$, Eq. (1) suggests that the maximum tank diameter that could be protected is only $1/\text{m}$. Reduction of soil resistivity increases the tank diameter, but soil resistivities significantly less than $10,000/\Omega\text{cm}$ are not usually seen. Li and Newman [15] have recently shown the influence of the more complex polarization behavior seen on steel structures. Their work showed that the maximum protected tank diameter can be increased to $1.1/\text{m}$. These values are significantly smaller than the usual size of storage tanks. Tank diameters of $20/\text{m}$ and larger are common.

Newman has also developed a calculation for the cathodic protection of a planar electrode by circular rods, again under the assumption that the current density on the planar electrode is uniform [16]. These calculations were intended to provide guidelines for placement and spacing of the anodes.

The predictions for the size of tank bottoms that can be protected by remote anodes [13,15] and the placement guidelines established for circular anodes [16] employed the assumption that the oxygen content of the soil was uniform. As discussed above, the oxygen reduction reaction depletes the oxygen content of the soil underneath the tank. The oxygen content of the soil may be temporarily increased due to the bellows action of the tank bottom as it is emptied. In addition, the assumption that the current distribution is uniform must be relaxed to provide more realistic design scenarios. The objective of this work was to develop a mathematical model for the cathodic protection of tank bottoms, using standard anode configurations, that could account for realistic polarization kinetics, non-uniform current distributions, and non-uniform oxygen concentrations. This work represents an extension of previous models developed for pipelines [12,17,18].

2. Mathematical model

The passage of current through the soil is governed by Laplace’s equation which was solved using the boundary element method (BEM). The formulation of the boundary element method used for the present solutions here can be found elsewhere [18–22].

The important features of the model included the use of second-order elements to reduce the total number of elements needed, incorporation of adaptive integration for accurate integral evaluation, and inclusion of non-conducting surfaces (soil surface and insulating dielectric material in the secondary containment) within the Green’s function.

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1 CSE refers to potential values referenced to a copper/copper sulfate electrode.
where \( N_r \) is the number of reflections employed. While each of the above features is very important to obtaining a good model for cathodic protection, the most important feature is the manner in which boundary conditions were implemented. The model makes use of realistic polarization curves for both the metal of the tank and the anodes. The method of implementation is detailed in the subsequent sections.

2.1. Tank bottom mesh

The boundary element mesh for the tank bottom was created using a combination of isoparametric quadrilateral Lagrange elements and isoparametric quadratic triangles [23]. The triangles were used to increase the degree of freedom as the mesh proceeds radially from the center, yielding a uniform mesh density. An example of the mesh, presented in Fig. 1, reveals the manner in which triangles and quadrilateral elements were employed to generate a uniform mesh density on the tank bottom. Within the automated mesh generation algorithm, the number of rings and the den-
sity of elements at the center were specified. The appropriate combination of quadrilateral and triangular elements was then generated. The last ring was divided into two rings to accommodate the enhanced current density at the periphery of the disk. The outermost ring was given a radial dimension that is 1/3 that of the rest of the rings; while, the next to last was given a radial dimension that is 2/3 that of the rest of the rings.

2.2. Polarization of bare steel

The boundary condition for the bare steel was given by Nisançöglu [24–26] and adapted for steady-state soil systems by Yan et al. [27] and Kennelly et al. [28]. For bare steel it takes the form

\[
i = 10^{-\frac{\Phi - E_F}{RT}} \left( \frac{1}{i_{\text{lim,O}_2}} - 10^{-\frac{\Phi - E_{O_2}}{RT}} \right)^{-1} - 10^{-\frac{\Phi - E_{H_2}}{RT}} \tag{3}\]

where \(i_{\text{lim,O}_2}\) is the mass-transfer-limited current density for oxygen reduction. Under the assumption that sufficient water is available for the reaction, no corresponding mass-transfer limitation was assumed for hydrogen evolution.

Performance predictions are strongly dependent on the parameters for the polarization curve given as Eq. (3). These parameters should be identified for given soil conditions and material of construction. The parameters used for the present work were guided by the work of Kennelly et al. [28]. The parameters for the corrosion reaction were \(E_{F_e} = -0.522\,\text{V(CSE)}\) and \(\beta_{F_e} = 0.059/\text{V}\). The parameters for the hydrogen evolution reaction were \(E_{H_2} = -0.942/\text{V(CSE)}\) and \(\beta_{H_2} = 0.132/\text{V}\). The parameters for the oxygen reduction reaction were \(E_{O_2} = -0.172/\text{V(CSE)}\), \(\beta_{O_2} = 0.061/\text{V}\), and, for fully aerated soil, \(i_{\text{lim,O}_2} = 0.01/\text{A m}^{-2}\) (1/\text{µA cm}^{-2}). The corrosion potential was \(-0.520/\text{V(CSE)}\). The depletion of oxygen below the tank bottom was modeled by reducing the value of \(i_{\text{lim,O}_2}\).

2.3. Drawdown of anode potential

Zinc and magnesium are often used in soil environments to protect buried steel structures. Aluminum can be used in sea water, but does not have a sufficient driving force to be effective in high-resistivity environments such as soils.

Under the assumption that hydrogen evolution can be neglected, oxidation of the metal is balanced by the mass-transfer-limited reduction of oxygen. Thus, the total current density is given by

\[
i_a = i_{0,M} \exp \left( \frac{\alpha_M F}{RT} (V - \Phi - E_M) \right) - i_{O_2} \tag{4}\]

where \(\alpha_M\) is the apparent transfer coefficient for the oxidation of the metal, \(i_{0,M}\) is the exchange current density for the oxidation of the metal, \(E_M\) is the equilibrium potential for the oxidation reaction, \(V\) is the applied potential, and \(i_{O_2}\) is the
mass-transfer-limited current density associated with reduction of oxygen. At the corrosion potential \( V = V_{\text{corr}} \), the net current \( i_n \) is equal to zero, and

\[
E_{\text{corr}} = E_M + \frac{RT}{\alpha_M} \ln \left( \frac{i_{O_2}}{i_{O_2,0}} \right)
\] (5)

Eq. (4) can be rewritten in terms of the corrosion potential as \([29]\)

\[
i = i_{O_2} \left( 10^{\left( V - \Phi - E_{\text{corr}} \right) / \beta_{\text{anode}} - 1} \right)
\] (6)

where \( \beta_{\text{anode}} = 2.303RT/\alpha_M F \) is the Tafel slope for the anode corrosion reaction.

To account for the decrease in anode potential associated with large current loads, the polarization model \((6)\) was used to relate the current density to the anode potential. For operation of anodes under external power supply, Eq. \((6)\) was modified by considering the anodic reaction term to be evolution of oxygen and/or chlorine and by adding an externally driven potential to the argument of the exponential term. For the simulations performed in the present work, \( E_{\text{corr}} = -0.172/V(\text{CSE}) \) and \( \beta_{\text{anode}} = 0.1/V \).

3. Oxygen depletion

The oxygen reduction reaction on the tank bottom serves to deplete the oxygen concentration in the soil, which is replaced by diffusion from the air–soil interface at the perimeter of the tank. A general material balance for oxygen can be written as

\[
\frac{\partial c_{O_2}}{\partial t} = \nabla \cdot N_{O_2} + R_{O_2}
\] (7)

where \( R_{O_2} \) is the rate of homogeneous production of oxygen and \( N_{O_2} \) is the flux of oxygen, given by

\[
N_{O_2} = -D_{O_2} \nabla c_{O_2}
\] (8)

where \( D_{O_2} \) is the diffusion coefficient for oxygen transport through the soil. Thus,

\[
\frac{\partial c_{O_2}}{\partial t} = -D_{O_2} \nabla^2 c_{O_2} + R_{O_2}
\] (9)

Under assumptions of a steady-state and that oxygen concentration does not vary with depth, Eq. \((9)\) can be expressed in cylindrical coordinates as

\[
D \frac{d^2 c_{O_2}}{dr^2} + \frac{D_{O_2}}{r} \frac{dc_{O_2}}{dr} - k c_{O_2} = 0
\] (10)

where the heterogeneous consumption of oxygen was treated as a first-order pseudo-homogeneous reaction with rate constant \( k \). The rate constant \( k \) accounts for the presence of a mass-transfer boundary layer next to the steel surface.
Under the variable transformation

\[ \xi = r \sqrt{\frac{k}{D}} \]  

(11)
a modified Bessel’s equation of parameter 0 is obtained as

\[ \xi^2 \frac{d^2 c_{O_2}}{d\xi^2} + \xi \frac{dc_{O_2}}{d\xi} - \xi^2 c_{O_2} = 0 \]  

(12)
whose solution is a modified Bessel’s function. The boundary conditions in the original cylindrical coordinates, i.e.,

at \( r = R \), \( c_{O_2} = c_{O_2,\infty} \)

(13)
and

at \( r = 0 \), \( c_{O_2} \) is finite

(14)
can be expressed in the transformed coordinates as

at \( \xi = R \sqrt{\frac{k}{D}} \), \( c_{O_2} = c_{O_2,\infty} \)

(15)
and

at \( \xi = 0 \), \( c_{O_2} \) is finite

(16)
The solution to Eq. (12) is the modified Bessel function of the first kind. It takes the form

\[ c_{O_2}(\xi) = AI_0(\xi) + B \left[ \ln(\xi)I_0(\xi) + \sum_{m=1}^{\infty} \left( \frac{(-1)^{m-1}}{2^m (m!)^2} \sum_{n=1}^{m} \frac{1}{n} \right) \right] \]  

(17)
where \( A \) and \( B \) are constants to be determined from the boundary conditions. The solution is found as

\[ \frac{c_{O_2}(\xi)}{c_{O_2,\infty}} = \frac{I_0(\xi)}{I_0(R \sqrt{k/D})} \]  

(18)
where \( R \sqrt{k/D} \) represents the scaling parameter.

The dimensionless concentration given as Eq. (18) is presented in Fig. 2 as a function of radial position \( r/R \) for several values of the scaling parameter \( R \sqrt{k/D} \). For typical tank dimensions and values for diffusivity, \( R \sqrt{k/D} \) is expected to be very large. The sharp decrease in concentration shown as \( R \sqrt{k/D} = 50 \), therefore, may be representative of the steady-state oxygen distribution for commercial-scale tank bottoms. It should be noted that \( \rho \) is unaffected by the oxygen distribution as it is controlled by the concentration of electrolytic species, which was assumed in the present work to be uniform.

The oxygen concentration distribution was applied through the boundary condition at the steel surface of the tank bottom. The parameter, \( i_{O_2} \) in Eq. (3) was adjusted according to Eq. (18). However, the value of \( i_{O_2} \) could only be adjusted in a
step-wise manner. Each ring of elements in the boundary element mesh was assigned a single value of the parameter (see Fig. 1 for the element layout) which remained constant in that ring.

In addition to forcing a constant value of $i_{O_2}$ in each ring of elements, setting a different value at each ring introduced an error at the edge of the ring in the current density due to the step change in the nature of the boundary condition. The boundary element method compensates for the error at the center of the element. Therefore the point at which to sample the solution is critical for this type of simulation. The best points to sample are the Gauss points for a $2 \times 2$ point rule (square parent element) [30].

4. Results

The results are presented in a series of cases based upon three standard anode configurations used in industry [31]. A single tank was modeled for which protection was provided by an anode located infinitely far from the tank bottom, by a series of anodes distributed around the circumference of the tank, and by an anode grid laid directly underneath the tank bottom. The influence of an insulating barrier associated with secondary spill containment was also modeled for the arrangements in which anodes are placed adjacent to the tank bottom.

4.1. Remote ground-bed

The cathodic protection system was modeled using a deep-well remote ground-bed located 2000 feet below the tank. The ground-bed output was adjusted to a nominal value of 14.2/A and the anode was held at $-65.2/V$(CSE). The tank diameter was 30.5/m and the tank bottom was assumed to consist of bare steel. The soil resis-
tivity was assumed to be uniform throughout the soil domain at a value of 10,000/Ω cm. Two cases were calculated: one for the uniform oxygen concentration, to approximate the initial conditions when the tank is first filled, and one with an oxygen concentration profile calculated from Eq. (18), to approximate the case when pseudo-steady-state has been reached. The conditions for the simulation are summarized in Table 1 where \( V_a \) refers to the value of the anode potential.

Grey-scale images of the calculated potential distribution are presented in Fig. 3(a) for a uniform oxygen distribution and in Fig. 3(b) for a non-uniform oxygen distribution corresponding to the profile given in Fig. 2 for \( R \sqrt{k/D} \gg 1 \). The calculated current and potential distributions on the tank bottom were non-uniform but axisymmetric, as can be expected when a remote anode is used [13]. The corresponding distributions of potential and current density are presented in Fig. 4. The dashed line corresponds to both \( i/i_{avg} = 1 \) and to the nominal criterion of \(-0.85/V(CSE)\) for adequate protection against corrosion.

As seen in Fig. 4, the calculated current density distribution was independent of the oxygen distribution. The value of \( i/i_{avg} \) at the center of the tank bottom was 0.13, which is smaller than the value of 0.5 obtained for a primary current distribution for a disk electrode with an electrode at infinity [32].

While the anode potential required to deliver 14.2/A and the current distribution was not influenced by the oxygen content of the soil, the potential on the tank bottom was influenced significantly. Under assumption of a uniform oxygen distribution, the center of the tank was under-protected, using the nominal criterion for protection of \(-0.85/V(CSE)\). The potential of \(-0.605/V(CSE)\), calculated at the center of the tank, represents a shift from the local corrosion potential of only 75 mV, which does not meet even the 100 mV polarization shift criterion for adequate protection [33]. The outside edge of the tank was polarized to \(-1.189/V(CSE)\). This value is significantly more positive than the \(-10.5/V(CSE)\) predicted by Eq. (1) for a uniform current distribution. The much smaller change in potential results from the non-uniform current density distribution seen in Fig. 4. Eq. (1), which was based on assumption of a uniform current distribution, grossly over-predicts the potential drop across the tank bottom when the oxygen distribution is not uniform.

<table>
<thead>
<tr>
<th>Anode Liner</th>
<th>( R \sqrt{k/D} )</th>
<th>Figures</th>
<th>( V_a/V(CSE) )</th>
<th>Current/A</th>
<th>( i_{avg}/A m^{-2} )</th>
<th>Protected</th>
</tr>
</thead>
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<tr>
<td>Remote No</td>
<td>0</td>
<td>3(a), 4</td>
<td>-65.2</td>
<td>14.193</td>
<td>0.0195</td>
<td>No</td>
</tr>
<tr>
<td>Remote No</td>
<td>( \infty )</td>
<td>3(b), 4</td>
<td>-65.2</td>
<td>14.178</td>
<td>0.0194</td>
<td>Yes</td>
</tr>
<tr>
<td>Perimeter No</td>
<td>0</td>
<td>5(a), 6</td>
<td>-78.4</td>
<td>14.201</td>
<td>0.0195</td>
<td>No</td>
</tr>
<tr>
<td>Perimeter No</td>
<td>( \infty )</td>
<td>5(b), 6</td>
<td>-78.4</td>
<td>14.183</td>
<td>0.0194</td>
<td>Yes</td>
</tr>
<tr>
<td>Perimeter Yes</td>
<td>0</td>
<td>7(a), 8</td>
<td>-77.0</td>
<td>14.219</td>
<td>0.0195</td>
<td>No</td>
</tr>
<tr>
<td>Perimeter Yes</td>
<td>( \infty )</td>
<td>7(b), 8</td>
<td>-77.0</td>
<td>14.208</td>
<td>0.0195</td>
<td>Yes</td>
</tr>
<tr>
<td>Beneath No</td>
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<td>9(a), 10, 11</td>
<td>-1.75</td>
<td>0.4906</td>
<td>0.00105</td>
<td>No</td>
</tr>
<tr>
<td>Beneath Yes</td>
<td>0</td>
<td>9(b), 10, 11</td>
<td>-1.75</td>
<td>2.455</td>
<td>0.00526</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Fig. 3. Calculated potential distribution for the tank bottom protected by a remote ground-bed: (a) with a uniform oxygen distribution; (b) with an oxygen distribution following the profile given in Fig. 2 corresponding to $R \sqrt{k/D} \gg 1$. 
The value of $\text{C}0_{1.189/V(CSE)}$ is very close to the cathodic limit of $\text{C}0_{1.2/V(CSE)}$, which is a point where hydrogen evolution is a significant concern. Depletion of the oxygen content of the soil, however, resulted in adequate levels of protection. The calculated range of potentials on the entire tank bottom fell between $\text{C}0_{0.85/V(CSE)}$ and $\text{C}0_{1.2/V(CSE)}$. The principal difference between the two cases is that, for the depleted oxygen distribution, the potential distribution was much closer to uniform and the entire tank bottom was protected. The uniform oxygen distribution case, corresponding to a newly filled tank, clearly represents a worse-case scenario. It is easier to provide protection when the soil below the tank is depleted of oxygen.

4.2. Distributed anodes

In a second configuration, eight shallow distributed anodes were arranged around the periphery of the tank. The anodes were placed 0.15/m inches below the soil surface and extended 0.91/m. The anodes were placed such that they were distributed at equal intervals around the tank and were placed 0.61/m from the edge of the tank. The placement of anodes close to the surface allowed use of this configuration with an underlying secondary containment. The dimension of the tank was identical to that used in the previous section, and the total output of the anodes was set to match that of the previous two examples (i.e., 14.2/A). The soil resistivity was set to 10,000/Ωcm. The conditions for the simulation are summarized in Table 1.

4.2.1. Configuration without secondary containment

Grey-scale images of the calculated potential distribution are presented in Fig. 5 for a uniform oxygen distribution. In contrast to the results for a remote groundbed, the distributions were not axisymmetric, but showed a periodicity corresponding to the angular distance between anodes. The potential distribution for the system

![Fig. 4. Radial current density and potential distributions for the conditions presented in Fig. 3. The dashed line corresponds to both $i/i_{avg} = 1$ and to the nominal criterion of $-0.85/V(CSE)$ for adequate protection against corrosion.](image-url)
Fig. 5. Calculated potential distribution for the tank bottom protected by eight anodes placed around the perimeter of the tank: (a) with a uniform oxygen distribution; (b) with an oxygen distribution following the profile given in Fig. 2 corresponding to $R \sqrt{k/D} \gg 1$. 
with depleted oxygen levels is presented in Fig. 5(b). The current and potential distributions corresponding to Fig. 5 are presented in Fig. 6. As the distributions were not axisymmetric, it is important to note the location of the distribution presented. The distributions presented in Fig. 6 are given along a line extending from the center to the periphery adjacent to an anode. The value of $i/i_{avg}$ at the center of the tank bottom was 0.2, which is slightly larger than the value obtained for the configuration with a remote anode.

The current distribution and the driving potential required to achieve the target current value were not influenced by the oxygen content of the soil. The level of protection provided, however, was strongly influenced. For a uniform oxygen content, the center of the tank was polarized only $-0.016/V$ from the corrosion potential. This result can be contrasted to that obtained for the remote ground-bed, where the center was polarized by $-0.075/V$ at the same total current. The corrosion current density was $0.66/\mu A cm^{-2}$ which is close to the value of $1.0/\mu A cm^{-2}$ expected for unprotected general corrosion. The corrosion current at the center of the tank was significantly higher than that of the remote ground-bed, which yielded a value of $0.022/\mu A cm^{-2}$. In contrast, the tank bottom met the nominal criterion for protection when the oxygen content of the soil was reduced.

### 4.2.2. Configuration with secondary containment

The US Environmental Protection Agency has specified that a secondary spill-containment system be provided for all new tanks [2]. The membranes used for a secondary spill-containment system typically act as electrical insulators. Distributed anodes can therefore be used with secondary spill-containment systems only if they can be placed within the soil between the membrane and the tank. The performance of the cathodic protection system of Fig. 5 was calculated with an insulator placed 1.23/m below the tank bottom. The resulting grey-scale images for potential are presented in Fig. 7(a), and the corresponding current and potential distributions are presented in Fig. 8. Again, the current density distribution and the driving potential
Fig. 7. Calculated potential distribution for the tank bottom protected by eight anodes placed around the perimeter of the tank and with an insulating barrier placed 1.23/m below the tank bottom: (a) with a uniform oxygen distribution; (b) with an oxygen distribution following the profile given in Fig. 2 corresponding to $R\sqrt{k/D} \gg 1$. 
is nearly independent of the oxygen content of the soil. The value of $i/i_{avg}$ at the center of the tank bottom was 0.14, which is smaller than the value of 0.2 obtained in the absence of an insulating layer. The potential distribution is influenced by oxygen content, and, for the case presented here, the potential distribution reaches the accepted protection level when the oxygen is depleted.

The performance of the distributed-anode configuration is constrained by the difference between the Ohmic resistance from the anode to the periphery and from the anode to the center of the tank bottom. The current path to the periphery is much shorter than that to the center of the tank bottom. The amount of current that can be delivered to the center of the tank is correspondingly smaller than can be delivered by a remote anode. The presence of an insulating layer increases the variation in Ohmic resistance and thereby further impedes delivery of current to the center of the tank bottom. A smaller distance between the tank bottom and the spill-containment barrier reduces the level of current that can be provided to the center of the tank bottom.

### 4.3. Ribbon anodes

The use of secondary containment motivates use of ribbon anodes placed very close to the tank-bottom. For the simulations presented here, a 24.4/m-diameter tank bottom was assumed to be protected by 21 0.05/m-diameter ribbon anodes placed 0.30/m below the tank bottom. The center-to-center distance between ribbons was 1.2/m. The ribbons were assumed to consist of high-performance Magnesium with a service potential of $1.75/V$(CSE). The worse-case scenario of a uniform oxygen concentration was assumed to apply. The conditions for the simulation are summarized in Table 1.

A grey-scale image for the potential distribution on the tank bottom in the absence of secondary containment is presented in Fig. 9(a), and the corresponding result for an insulating plane placed 0.61/m below the tank bottom is presented in
Fig. 9. Calculated potential distribution for the tank bottom protected by 21 Mg ribbon anodes placed directly underneath the tank with a uniform oxygen distribution: (a) with no insulating barrier; (b) with an insulating barrier placed 0.61 m below the tank bottom.
In the absence of a liner, the potential distribution is highly non-uniform and resembles that shown in Fig. 3(a) for a remote anode. The tank bottom does not meet the $-0.85/V$(CSE) criterion for adequate protection. The calculated corrosion current at the center of the tank was $0.04/\mu$Acm$^{-2}$. The influence of the insulating liner was to make the potential distribution more uniform and to enable the anodes to provide adequate protection to the entire surface.

The current and potential distributions corresponding to Fig. 9 are presented in Fig. 10. The current distribution in the absence of a liner is non-uniform, but the degree of non-uniformity is much less than seen when the anodes are placed around the perimeter of the tank or at infinity. The value of $i/i_{avg}$ at the center of the tank bottom was 0.65, which is significantly larger than the values obtained for the remote-anode and distributed-anode cases.

In the absence of the secondary containment, the potential driving force provided by the Mg ribbons was not sufficient to protect the tank bottom. In contrast, the presence of an insulating barrier forced the current density to be uniform, and the resulting uniform potential distribution met the $-0.85/V$(CSE) criterion for adequate protection. Note that the line along which the current and potential were sampled is directly above a ribbon. For this reason, the scaled current density is greater than unity. The current density is lower between ribbons, but, when a liner is present, those regions are protected as well. The enhanced protection afforded by the liner is seen because, as seen in Table 1, the total current yielded by the system with a liner is five times larger than that yielded in the absence of a liner.

The explanation for this seemingly anomalous behavior can be found in the current distribution along the ribbon anodes shown in Fig. 11, where the axial current density on the central anode is presented as a function of position for both systems. The containment forces the current distribution along the anode to be more uniform. The current is therefore better distributed on the tank bottom, thereby reducing the effective kinetic resistance associated with the tank bottom.
5. Conclusions

The simplistic models developed to date for assessing cathodic protection of tank bottoms are seen here to be inadequate for the complex geometries and polarization behavior seen on practical systems. The assumption of a uniform current distribution on the tank bottom, used in previous models [13,16], was found to be invalid, even for cases where the anodes are placed directly underneath the tank bottom. The presence of the secondary containment barrier influences the current distribution and, in the case of ribbon anodes, facilitates protection of the tank bottom.

For the cases considered here, each of the anode configurations could provide adequate protection to the tank bottom when the oxygen content of the soil was reduced. Only the combination of ribbon anodes and an insulating spill-containment barrier provided protection to a tank bottom in contact with soils containing a uniform oxygen level corresponding to \( \lim_{O_2} = 1 \text{ A cm}^{-2} \).

It should be noted that the performance predictions are strongly dependent on the parameters for the polarization curve given as Eq. (3). These parameters should be identified for given soil conditions and material of construction. The oxygen content of the soil influences the current required for protection and can fluctuate due to periodic emptying and filling of the tank. In addition, growth of calcareous and rust scales can change the polarization curve parameters. It may be, therefore, important to include reference electrodes in the design of the cathodic protection system to monitor the polarization of the steel.

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References


[33] NACE, NACE Standard Recommended Practice RP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems, NACE, Houston, TX (revised 1983).