Computer Modeling Aids Traditional Cathodic Protection Design Methods for Coated Pipelines

Ross M. Degerstedt
Alyeska Pipeline Service Co., 1835 South Bragaw Street, Anchorage, AK 99512

Kevin J. Kennelley
ARCO Exploration and Production Technology, 2300 West Plano Parkway, Plano, TX 75075

Mark E. Orazem and J. Matthew Esteban
Department of Chemical Engineering, University of Florida, Gainesville, FL 32611

Traditional methods for designing cathodic protection (CP) systems for pipelines involve assumptions pertaining to coating efficiency, current density requirements, and current output based on anode-to-earth resistance formulas. Such methods are compared to an approach that considers the possibility that coating damage can be discrete and also allows for nonuniform current and potential distributions. Through a combined experimental and modeling program, the nature of coating damage is seen to have a significant impact on the performance of a CP system.

A fundamental premise in the application of cathodic protection (CP) systems on pipelines is that the systems should be designed to provide an adequate level of CP. Systems that are oversized, waste material and energy. They may cause damage to coatings or the structure if not properly regulated. Undersized systems will not provide the level of CP necessary to mitigate the corrosion process. A few of the assumptions and methodologies used to design CP systems using traditional manual calculations, as well as a two-dimensional and three-dimensional modeling program, will be explored. Comparisons will be made among different results derived from each method.

Discussion of Methodologies

The most common approach to designing CP systems is that put forward by A.W. Peabody.[1] Based on the principles of Ohm's law:

$$E = I_T R_T \qquad (1.1)$$

Where E is the potential difference between the anode and the cathode in volts, I_T is the total current flowing in the circuit, and R_T is the total circuit resistance in the CP system. This approach allows the designer to estimate the circuit resistance based on the summation of the resistances.

$$R_T = R_{Anode\text{-}to\text{-}Earth} + R_{Pipe\text{-}to\text{-}Earth} + R_{Conductors} \qquad (1.2)$$

The summation would normally include the resistance of the conductors in the circuit, the anode-to-earth resistance, and the resistance of the structure to the earth including any coating resistance. Computing the resistance of the conductors is usually a simple matter of referring to appropriate data for the various wire types being considered for use on the project.

The electrical resistance through the structure or along an anode string can be estimated empirically from engineering resistance data for the type of material used or by actual field measurement. The anode-to-earth resistance is usually calculated during the design phase, based on measured or estimated values for soil resistivity (ohm-cm) in the area of application. This information is used in a formula that describes or models the type of ground bed design being considered. Many such formulas exist for specific ground bed arrangements such as this one used by Dwight to describe a horizontally buried wire, rod, cable, bare pipe, or ribbon anode:[2]

$$R_A = (0.05\,\rho/\pi L)[\ln(400L/d) + \ln(L/h) - 2 + (2h/L)] \qquad (1.3)$$

Where R_A is anode to earth resistance (ohm), π is soil resistivity (ohm-cm), L is length of the electrode (m), d is diameter of the electrode (cm), and h is distance from the surface to the center of the electrode (cm).

The pipeline-to-earth resistance should be calculated based on the assumption that the coating will degrade with time. For well coated pipelines this value can be quite high. The calculated resistance includes that of the coating on the pipe as well as the electrode resistance to remote earth. Since these resistances are in series, they are additive. The electrode pipe-to-earth resistance can be calculated from Equation (1.3) above.

Most commercial coatings have a factory specified coating resistance. Degradation of coating resistance is usually calculated based on the assumption the coating will uniformly decompose and the remaining coating resistance will have uniform characteristics. A typical calculation for coating degradation might look like this:

$$R_c = (R'A)\epsilon \qquad (1.4)$$

where R_c is coating resistance (ohm), R' represents original coating resistance (ohm/m²), A represents total surface area of the pipe (m²) and ϵ represents coating efficiency after a specified period of time (example: $\epsilon = 85\% \div 100 = 0.85$).

While this assumption about uniform coating failure is convenient for design purposes, it often does not represent the actual condition of the pipeline. Under field conditions few coatings will remain perfect. Some form of coating damage exposing the underlying metal substrate to the electrolyte generally exists. The net resistance of the pipeline actually falls somewhere between that calculated for the perfect coating and that calculated for the pipe-to-remote earth. Holidays in the coating will act as a parallel path for current flow in the circuit and thereby reduce the circuit resistance.

The second part of Ohm's law concerns itself with the current flowing in the circuit. For purposes of this discussion, that will be the CP current needed to mitigate the corrosion process. For the designer fortunate enough to have access to the structure needing CP, it may be possible to perform a current requirement test. When conducted properly, the test yields enough information about the current demand necessary to adequately polarize the structure and to accurately size the CP system. In lieu of tests, current density requirement estimates must be made for structures in like environments. A number of sources exist including those given in the NACE Corrosion Engineers Handbook.[3] The current density requirements listed in such tables are usually related to unit areas of bare metal exposed to a given electrolyte. The designer must estimate how much bare metal will be exposed on the pipeline or structure in question. This estimate multiplied by the current density requirement will yield the design current required to provide cathodic protection to the metal surfaces (coating defects or holidays) exposed to the electrolyte.

$$I_H = I'A \qquad (1.5)$$

Where I' is current density (mA/m²), A is total area of exposed metal (m²) on the pipeline, and I_H is total CP current (mA) required to protect the holidays in the coating. The current flowing through the coating is usually quite small compared to that flowing to the holidays. In many cases it can be ignored. However, for older pipelines or poorly coated lines, the current flowing through the coating should be considered,

$$I_c = E/R_T \qquad (1.6)$$

The total current required for the CP system can then be expressed as,

$$I_T = I_c + I_H \qquad (1.7)$$

The sum of the resistances and the total current demand can be used in Equation (1.1) to calculate the driving potential needed to make the CP system function adequately. Attenuation may not allow for the even distribution of current at all points. The value estimated for the resistance of the pipeline-to-remote earth may inaccurately represent actual conditions. In spite of these limitations, sizing CP systems using this method has provided corrosion engineers with a reasonable degree of success in mitigating corrosion using CP.

For many years corrosion engineers and pipeline operators recognized there were limitations to the manual calculation approach in the design of CP systems. As regulators and operators began to demand more proof of design concept prior to installation, additional efforts to understand and predict the performance of CP systems was needed. One such effort resulted in the development of computer based modeling systems to allow the design professional to accurately predict how a CP system will perform over a wide range of holiday configurations, soil types, and anode potentials. The designer first characterizes the system by inputting the physical dimensions of the system components and identifying the holiday geometry. The program requires characterization of the parameters impacting the corrosion process; soil resistivity, coating resistivity, anode potential, and polarization curve data for the soil in question. Accurate polarization curve data is essential for good results. Lastly, the models compute the current flowing in the system and predicts the current and

TABLE 1
Case 1 Comparison

Parameters	Manual Method	2-Dimensional Model	3-Dimensional Model	Nordale Test Site
Pipe diameter: cm	121.92	121.92	121.92	121.92
Pipe segment length: m	30.48	30.48	30.48	30.48
Coating resistivity: ohm-cm	5.00E+12	5.00E+12	5.00E+12	5.00E+12
Coating thickness: mm	0.5842	0.5842	0.5842	0.5842
Soil resistivity: ohm-cm	20,000	20,000	20,000	20,000
Anode type: ribbon	Zinc	Zinc	Zinc	Zinc
Open circuit potential of anode: V wrt $Cu/CuSO_4$	0.97	0.97	0.97	0.97
Coating efficiency after 20 years: %	85	85	85	85
Conductor resistance: ohm	0.001	0.001	0.001	0.001
Pipe-to-soil resistance: ohm	5.78	5.78	5.78	5.78
Anode-to-soil resistance: ohm	5.16	10.32	10.32	10.32
Coating resistance: ohm	212,672.19	212,672.19	212,672.19	212,672.19
Area of exposed bare metal: cm^2	0	0	0	0
Driving potential of circuit: V (initial/final)	–0.44/–0.12	–0.44/?	–0.44/?	–0.44/?
Estimated current density: mA/cm^2	0	N/A	N/A	N/A
Calculated current density: mA/cm^2	4.83E-07	1.66E-06	1.73E-06	4.30E-04
Corrosion potential of exposed steel: wrt $Cu/CuSO_4$	–0.53	–0.53	–0.53	–0.53
Desired potential of pipe: wrt $Cu/CuSO_4$	–0.85	–0.85	–0.85	–0.85
Predicted potential of pipe: wrt $Cu/CuSO_4$	?	–0.97	–0.97	N/A
Measured potential of pipe: wrt $Cu/CuSO_4$	N/A	N/A	N/A	–0.9528
Calculated current: mA (initial/final)	2.0688E-3/5.642E-4	N/A / 1.9412E-3	N/A / 2.0498E-3	N/A
Measured current: mA	N/A	N/A	N/A	0.502

potential distribution at the surface of the coating defects. This is accomplished using first principles of thermodynamics and LaPlace's Equation.

Computer modeling using desk top computers has progressed rapidly in the last several years. Today's computers run simulations that until recently were only possible on a mainframe computer. Software evolution has closely tracked advances in computer hardware. The first modeling efforts were aimed at two-dimensional models that simulated coating defects as slots or uniform scrapes down the side of the pipe.[4-5] The latest versions of CP modeling software simulate multiple discrete defects at various locations in three dimensions.

When computer based modeling techniques are compared to established manual calculation methods, the basic design assumptions used can dramatically change the outcome of the design. The following examples represent the various stages of design evolution, and the impact it can have on the design process.

Case 1: A 30.48 m (100 ft) long, 121.92 cm (48 in.) diameter pipeline segment is coated with a fusion bonded epoxy coating having an initial coating resistivity of 5.00+E12 ohm-cm. The coating is estimated to be only 85% as effective after 10 years of service. The pipeline is assumed to have a perfect coating over the 30.48 m length. The soil is damp, well drained, sand and gravel, slightly aerated, with a resistivity of 20,000 ohm-cm. The anodes used are two zinc ribbons placed at the bottom of the pipe trench approximately 0.46 m (1.5 ft) from the pipe. The open circuit potential of the zinc is estimated to be –0.970 mV with respect to (wrt) $Cu/CuSO_4$ after 10 years of service. The free corroding potential of the steel in this environment is known to be –0.530 mV wrt $Cu/CuSO_4$.

Case 2: A 30.48 m long, 121.92 cm diameter pipeline segment is coated with a fusion bonded epoxy coating with an initial coating resistivity of approximately 813,770 ohm-cm. The coating is estimated to be only 85% as effective after 10 years of service. The pipeline is assumed to have a bare surface area equal to 0.039% over the 30.48 m length. These defects are assumed to be small, evenly distributed perforations in the coating for the manual calculation approach. For the two-dimensional model, the defect is characterized by a very small scratch-like holiday approximately 0.1524 cm (0.06 in.) wide in the coating on the bottom of the pipe. The three-dimensional case models a single large defect 15.24 x 30.48 cm (6 x 12 in.). The soil is assumed to be damp, well drained, sand and gravel, slightly aerated, with a resistivity of 20,000 ohm-cm. The anodes used are two zinc ribbons placed at the bottom of the pipe trench approximately 0.46 m from the pipe. The open circuit potential of the zinc is estimated to be –0.970 mV wrt $Cu/CuSO_4$ after 10 years of service. The free corroding potential of the steel in this environment is known to be –0.530 mV wrt $Cu/CuSO_4$ in similar soils.

To validate the results from the computer model, field tests were conducted at a location near Fairbanks, Alaska known as the Nordale Test Site. At this site, an active portion of the Trans Alaska Pipeline was reconditioned with new coatings and retrofitted with a series of CP monitoring coupons. The polarization data collected from this site was used to program the computer models used for the following comparison.

TABLE 2
Case 2 Comparison

Parameters	Manual Method	2-Dimensional Model	3-Dimensional Model	Nordale Test Site
Pipe diameter: cm	121.92	121.92	121.92	121.92
Pipe segment length: m	30.48	30.48	30.48	30.48
Coating resistivity: ohm-cm	5.00E+12	5.00E+12	5.00E+12	5.00E+12
Coating thickness: mm	0.5842	0.5842	0.5842	0.5842
Soil resistivity: ohm-cm	20,000	20,000	20,000	20,000
Anode type: ribbon	Zinc	Zinc	Zinc	Zinc
Open circuit potential of anode: V wrt $Cu/CuSO_4$	0.97	0.97	0.97	0.97
Coating efficiency after 20 years: %	85	85	85	85
Coating resistance after 20 years: ohm	212,672.19	212,672.19	212,672.19	212,672.19
Conductor resistance: ohm	0.001	0.001	0.001	0.001
Pipe-to-soil resistance: ohm	5.78	5.78	5.78	5.78
Anode-to-soil resistance: ohm	5.16	10.32	10.32	10.32
Area of exposed bare metal: cm^2	464.51	464.51	464.51	464.51
Driving potential of circuit: V (initial/final)	–0.44/–0.12	–0.44/?	–0.44/?	–0.44/?
Distribution of bare metal	small holidays	slot 0.1524 cm wide	holiday 15.24 x 30.48 cm	holiday 15.24 x 30.48 cm
Estimated current density @ holidays: mA/cm^2	2.153	N/A	N/A	N/A
Calculated current density @ holidays: mA/cm^2 (defect edge/center)	N/A	8.027/7.77	5.786/1.375	5.19
Corrosion potential of exposed steel: wrt $Cu/CuSO_4$	–0.53	–0.53	–0.53	–0.53
Desired potential of pipe: wrt $Cu/CuSO_4$	–0.85	–0.85	–0.85	–0.85
Predicted potential of pipe: wrt $Cu/CuSO_4$ (defect edge/center)	?	–0.2087/–0.2046	–0.642/–0.586	N/A
Measured potential of pipe: wrt $Cu/CuSO_4$	N/A	N/A	N/A	–0.8932
Calculated current: mA	1	3.643	1.027	N/A
Measured current: mA	N/A	N/A	N/A	2.61

Comparison of Results

Case I (no defects) represents a situation seldom encountered in actual practice. All three methods indicated extremely small amounts of current flowing in the circuit. This was due to the initial assumption of a perfect coating, which resulted in a high coating resistance that was several orders of magnitude greater than the other resistance factors in the circuit. Data for the Nordale Test Site indicates that it does not have a perfect coating. The line segment was recoated in 1992 approximately 10 months before testing began. All three methods of calculation produced similar results. Data and calculated results for Case I can be found in Table 1.

Case 2 introduces exposed metal as a parameter in the calculations. The exposed metal is in the form of holidays in the coating with a total area of 464.51 cm^2 (72 $in.^2$). When designed using the manual calculation method, it was assumed the holidays were small imperfections in the coating and that they were uniformly distributed about the pipe. The two-dimensional model viewed the holiday as a 0.1524 cm slot or scratch in the coating at the bottom of the pipe. The three-dimensional model saw the holiday as a single defect with dimensions 15.24 x 30.48 cm at the mid point of the pipe segment. The Nordale Test Site data was for a coated steel plate placed horizontally under the newly recoated pipeline with a 15.24 x 30.48 cm defect in the test panel coating. The test panel was connected to the pipeline using insulated wires run through an instrumented test station. Data and calculated results for Case 2 can be found in Table 2.

The results from Case 2 calculations yield a range of results. For the manual method it was assumed that approximately 2.153 mA/cm^2 (2 mA/ft^2) would be needed to adequately polarize the exposed metal areas. Knowing that the total resistance for the circuit will be somewhere between 16.1 and 212,688.29 ohm, the output of the anodes can be calculated using 0.120 V as the driving potential. This results in possible current outputs of 14.9 to 0.56 mA from the zinc anodes. To simplify the calculations for this exercise, the parallel zinc anodes were assumed to have no mutual interference and were reduced to a simple parallel resistance. Depending on the precise circuit resistance to each holiday site, the system may or may not provide enough CP to protect the exposed metal at the holidays.

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The two dimensional model of the slot shaped defect indicates the pipeline will receive enough protection to meet the –0.850 mV wrt $Cu/CuSO_4$ instant off criteria. This will apply if the holidays are configured as modeled and the soil conditions are uniform down the length of the line. Current densities much higher

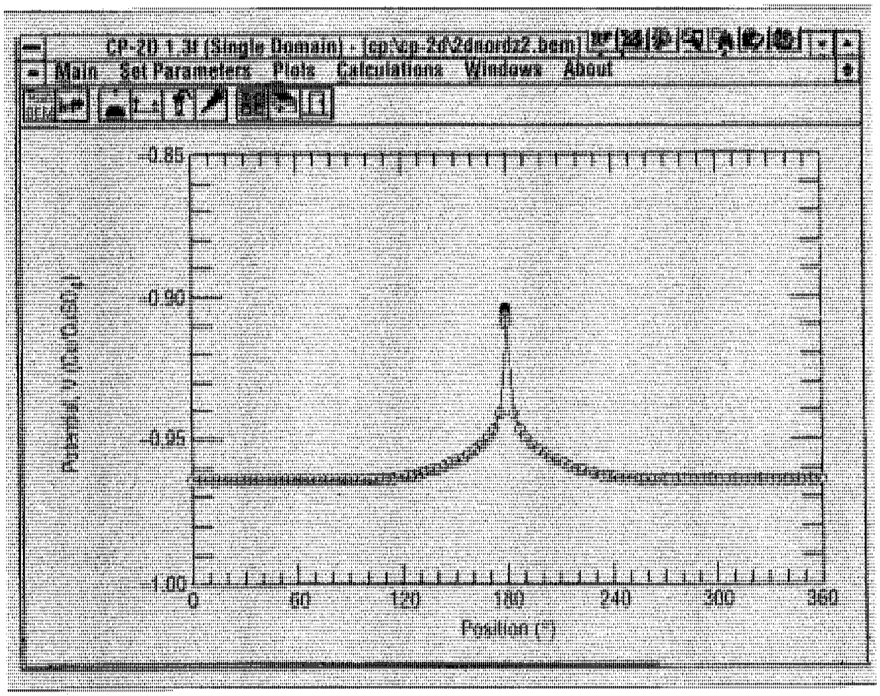

FIGURE 1
Two-dimensional model, pipe potential distribution.

than those estimated using the manual method are indicated. Figure 1 shows the distribution of potential around the pipeline.

The three-dimensional model simulates a single large defect in the coating, only partially protected by the CP system. The pipe-to-soil potential profile of the holiday indicates a range of potentials from –0.586 V at the center of the holiday to –0.642 V at the edge. If using the 100 mV shift criteria, the edge would appear protected. However, the center of the defect does not meet any of the established criteria. The designer may wish to consider another anode material, such as magnesium, or explore the uses of an impressed current system.

The Nordale Test Site was configured much like the case run using the three dimensional model. The reference cell used for the potential reading was approximately 15.24 cm below the test panel. It therefore reports an average reading of the potentials on the panel. The pipe-to-soil potential of the test panel indicated that it exceeded the 100 mV polarization criteria and would therefore be protected. The test panel potential, while not a precise match of the three-dimensional model, suggested that with some fine-tuning a very good match could be achieved between model and field conditions. Fine-tuning would include a better approximation of the soil resistivity or slight changes in the polarization curve. Since the test site at Nordale was somewhat dynamic, with a variable water table near the bottom of the pipe, polarization behavior also varied over time. Soil samples from the area indicated a resistivity range from 16,000 to 25,000 ohm-cm when saturated.

Conclusions

A review of the results from Tables 1 and 2 indicate that design assumptions made about the size and distribution of holidays on the pipeline have a major impact on the performance of the CP system. Pipelines with perfect coatings require very little CP but are unlikely to be encountered in actual practice. Manual design practices are still a viable method for designing CP systems where a more precise estimate of system performance is not required.

Computerized modeling using two or three dimensional algorithms have improved to the point where they can be run on a personal computer and provide timely design support. Regardless of the method used, the judgment of the design professional will determine the success or failure of a specific design. Computer based modeling systems can aid the design professional in predicting, with a greater degree of certainty, the performance of a new CP system. To be used successfully, all of the methods mentioned require a substantial understanding of the principles of corrosion engineering and specifically their application to CP.

The test panel potential suggested that with some fine-tuning a very good match could be achieved between model and field conditions.

Acknowledgments

The authors would like to express their appreciation and thanks to Alyeska Pipeline Service Co. and ARCO Transportation Alaska for their financial support of this project. In particular, we would like to thank B. Steel and C. O'Donnell of Alyeska for their managerial support. We would also like to thank L. Bone of ARCO, and T. Widin of BP for their peer review of this work and technical support which helped ensure the success of this project.

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More information is available in paper no. 346 presented at CORROSION/95, in Orlando, Florida.