Cathodic Protection Potential Criterion for Underground Steel Structures

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This article traces the history and development of the –0.850 V_{CSE} (copper sulfate electrode) potential criterion over the last 60 years with respect to thermodynamic considerations and empirical testing in both the laboratory and field. The significance of reference electrode position and IR-drop voltages for the protective potential measurement and the influences of soil resistivity, sulfate-reducing bacteria, and temperature on the effectiveness of the minimum potential value are reviewed. In addition, the hazards of overprotecting a steel structure with respect to hydrogen embrittlement and coating disbondment are considered.

Few issues regarding the application of cathodic protection (CP) remain as controversial as the protection criteria and their interpretation. This situation has persisted for many years despite general agreement regarding the fundamentals of CP. Laboratory tests conducted by Mears and Brown in the 1930s showed that CP was "entirely effective" when the structure cathodes were polarized electronegatively to the open-circuit potential of the structure anodes.[1] For 50 years, this understanding of CP has never been in dispute. Unfortunately, structure anode open-circuit potentials normally cannot be measured on most structures. Therefore, for CP to be complete, the potential criterion must be at least as negative as the most negative open-circuit anode potential on the structure to be protected. The selection of this potential has understandably been open to conjecture and speculation, as has the manner in which the potential is measured. Because of these criteria issues, it took years to revise NACE Standard RP0169-83 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems." The preparation of a companion measurement standard by Task Group T-10A-3 could be an equally arduous process.

It is surprising that this difficulty with protection criteria has persisted. The potential of –0.850 V_{CSE} (copper-copper sulfate electrode), first proposed by R.J. Kuhn in 1933, is the most accepted and widely used criterion for CP of buried or immersed steel structures.[2] Kuhn gained CP experience while working for New Orleans Public Service Inc. during the late 1920s and early 1930s. His contributions to the early understanding of the application of CP were so notable that a medal was struck in Germany in 1970 to commemorate him as the "Father of CP."[3] By 1940, therefore, the CP process was well defined and an empirical protective potential criterion for field application had been proposed.

Thermodynamic Considerations

M. Pourbaix reasoned that an accurate and effective CP criterion could be calculated because corrosion is a process governed by thermodynamic principles.[4] Because the solubility of iron in equilibrium with a water environment decreases as its solution potential becomes more electronegative, at a small concentration of ferrous ions (10^{-6} g/L) the corresponding potential is –0.936 V_{CSE}. This potential is the theoretical dividing line between corrosion and immunity shown on potential vs pH diagrams (often known as Pourbaix diagrams) (Figure 1). Pourbaix originally referred to what is now called the immunity zone as the "passivity" zone.

Pourbaix also conducted tests using small pieces of piano wire in 1 N sulfuric acid and found that "when the potential becomes less (more electronegative) than about –0.6 V_{SHE} (standard hydrogen electrode) iron ceases to corrode."[4] This relation is illustrated in Figure 2.
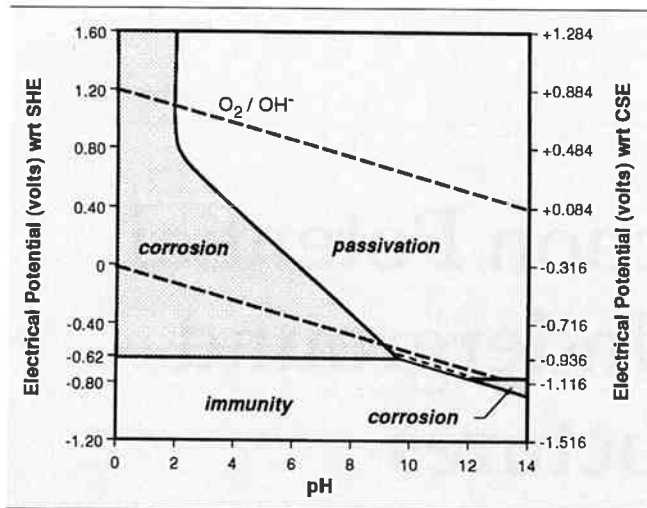
FIGURE 1
Regions of corrosion, immunity, and passivation of iron from thermodynamic considerations.[4]

FIGURE 2
Corrosion rate vs potential for iron in 1 N sulfuric acid solution.

Even though this potential value of -0.916 V_{CSE} is somewhat more negative than the standard -0.850 V_{CSE}, the corrosion rate is reduced by several orders of magnitude, although not completely stopped, at -0.850 V_{CSE}.

Several others have attempted to calculate a fixed potential criterion based on fundamental energy considerations. Wagner calculated a value of -0.956 mV based on the fact that the solubility of iron ions was reduced by a factor of 107.[5] Sudrabin calculated a protective potential of -0.868 mV using the Nernst formula for an iron surface saturated with ferrous hydroxide at pH 9.0.[6] Peterson, using the solubility product of ferrous hydroxide in a saturated solution of ferrous ions in pure water at pH 9.3, calculated a potential of -0.906 V_{CSE},[7] again using the Nernst equation; these results agreed with Uhlig's,[8] which were based on identical conditions.

Evans assumed that the electrode potential of steel in a 1 N solution of ferrous ions was about -0.756 V_{CSE} and that a reduction of 100 in the normal ferrous ion concentration would require an equilibrium potential of -0.756 V $- (2 \times 0.030$ V$)$, yielding a protective potential of -0.816 V_{CSE}.[9]

More recently, Davis and Kellner concluded that "holding the potential of a pipeline or any other buried, iron-based structure more negative than the redox potential for

the iron/ferrous reaction is the only valid way to satisfy the Mears and Brown criteria for CP." They contended that this redox potential ranged from -0.75 to -0.85 V_{CSE} at pH values less than about 9.5 (from Pourbaix) and depended on the ferrous ion concentration and the absence of other reactive species.[10]

Thus, the range of calculated values for the protection criterion straddles the -0.850 V_{CSE} value, although most have been more electronegative.

Empirical Testing

Laboratory Testing

In the early 1950s, Schwerdtfeger and McDorman conducted testing at the National Bureau of Standards into the validity of the -0.850 V_{CSE} criterion for iron coupons in 20 air-free soils, which ranged in pH from 2.9 to 9.6.[11] Based on the assumption that air-free soils had a mean pH of 9.0 (which seemed to be derived from the literature) and a cathodic reaction involving the reduction of hydrogen, Schwerdtfeger and McDorman postulated that the critical protection potential would be the intersection of the hydrogen and steel electrode curves (Figure 3). This in-
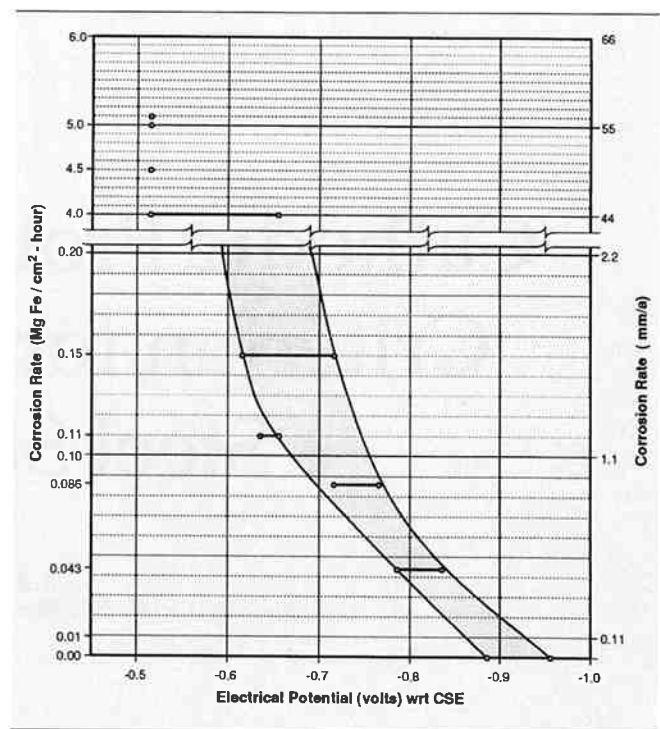
tersection potential of approximately -0.77 V_{SCE} (standard calomel electrode) (-0.845 V_{CSE}) should result in the electromotive force of the iron-hydrogen corrosion cell approaching zero.[12] Steel coupons held for 60 days at potentials about -0.77 V_{SCE} lost negligible weight, and the following was concluded: "Referred to the CSE the protective potential is approximately -0.85 V, which is in agreement with the practice for CP used by many corrosion engineers in those cases where the measurements are free of IR drop external to the electrical boundary of the corrosion circuit."

Barlo and Berry conducted laboratory tests in the early 1980s using corrosion cells identical to those used by Schwerdtfeger and McDorman, and confirmed that the -0.850 V_{CSE} criterion was similarly effective in both aerated and deaerated soils.[13] As in previous experiments, the corrosion rate was not always reduced to zero, but it was decreased to a "tolerable level" defined as less than 0.025 mm/y (1 mpy). Krivian reported on corrosion rates of steel in aerated water vs the corrosion potential; the results indicated that at a potential of -0.85 V_{CSE}, the corrosion rate was 0.007 mm/y
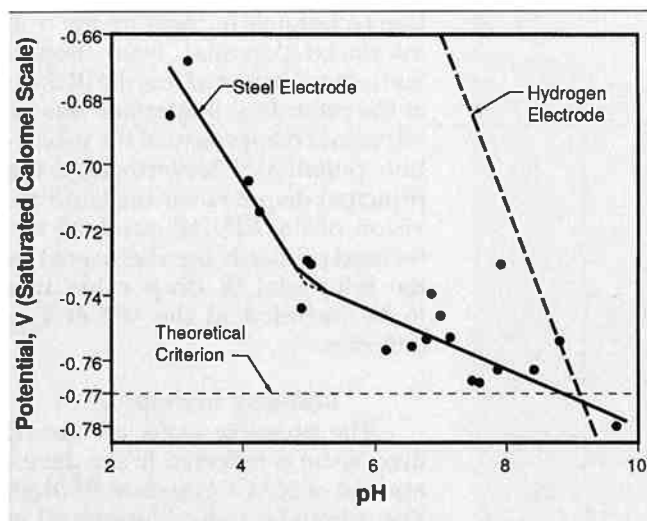
FIGURE 3
Relation between the potential of steel in air-free soil and the pH values of the soil.[11]
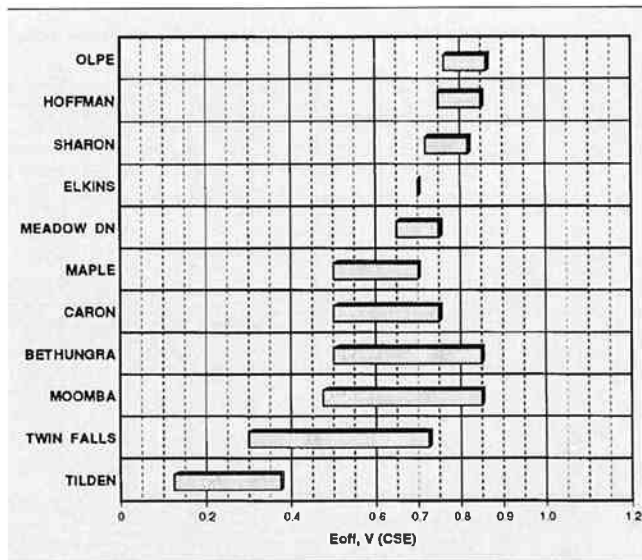

FIGURE 4
Range of polarized potentials for protection at 11 field sites.[17]

(0.29 mpy).[14] Similar results were reported in seawater and ground-water solutions for both deaerated and aerated conditions.[15]

Field Testing

Perhaps the earliest field criteria testing results were reported by Ewing in 1951.[16] He buried six 2-in.-diameter by 10-in.-long pipe specimens at four locations in Oklahoma, which involved three soil conditions and one water exposure. Based on the Mears and Brown premise that the cathodic areas must be polarized to the open-circuit potential of the anodic areas, he endeavored to control the CP current drain from five specimens at each location, with a sixth specimen serving as the control. The current and open-circuit potential of each specimen was measured weekly during the 70- to 80-day test. These tests indicated that the most electronegative potential required to prevent corrosion was −0.83 V_{CSE}.

After Ewing's work there was a paucity in criteria field testing until the 1980s, when the American Gas Association sponsored a major testing program involving 13 sites, eight in the United States, two in Canada, and three in Australia. This five-year research project, which began in 1983, involved protecting steel coupons at a number of commonly used CP criteria and removing the coupons semiannually for examination

and weight-loss determination. The 1987 interim report, with data for 11 of the 13 test sites, indicated that the range of polarized potentials for preventing corrosion was not more electronegative than −0.850 V_{CSE} at all except one site (Figure 4).[17]

Russian data from both laboratory experiments and field tests on pipelines indicated that a minimum protective potential between −0.838 and −0.850 V_{CSE} was required.[18]

Measurement Considerations

Influence of IR Drop and Reference Electrode Position

Sudrabin raised the issue of IR drop when he referred to the influence of the reference electrode's position on the measured potential in reference to Kuhn's −0.850 V_{CSE} criterion.[19] He conducted laboratory tests to demonstrate the significance of the reference electrode's location on the validity of the −0.850 V_{CSE} criterion and concluded that "long line and intermediate corrosion currents are controlled when the protective potential (−0.85 V_{CSE}) is measured to a reference electrode placed over the pipeline," whereas "local cell corrosion currents are controlled when the protective potential is measured close to the pipe surface."

Sudrabin conducted additional tests in 160- and 22,000-ohm-cm water; the results indicated that to obtain potential readings meaning-

ful for localized or pitting corrosion the reference electrode had to be placed approximately as close to the cathode surface as was the diameter of the corresponding anode surface. Furthermore, he contended that it was important to include in the protective potential the IR drop across "the cathode surface resistance" and "the electrolytic cell adjoining the cathode surface."[20]

It was not then clear what constituted the protection potential, but Schwerdtfeger and McDorman stated that the −0.85 V criterion was valid providing "the measurements are free of IR drop external to the electrical boundary of the corrosion circuit."[11] It is intuitive that for localized corrosion cells (pitting) the electrical boundary is very close to the steel surface. Pearson, in testing a null circuit to compensate for bulk IR drop influence in a potential measurement, confirmed Sudrabin's findings when he concluded that the "electrical boundary of our mill-scale-contaminated iron is perhaps a centimeter thick."[21]

It was clear by the late 1940s and early 1950s that IR drop external to the corrosion cell boundary was not to be included in the potential measurement for comparison with the −0.850 V_{CSE} criterion. Most of the laboratory and field studies referred to previously,[11,13,17] which verified the effectiveness of the −0.850 V_{CSE} criterion, incorporated current interrup-
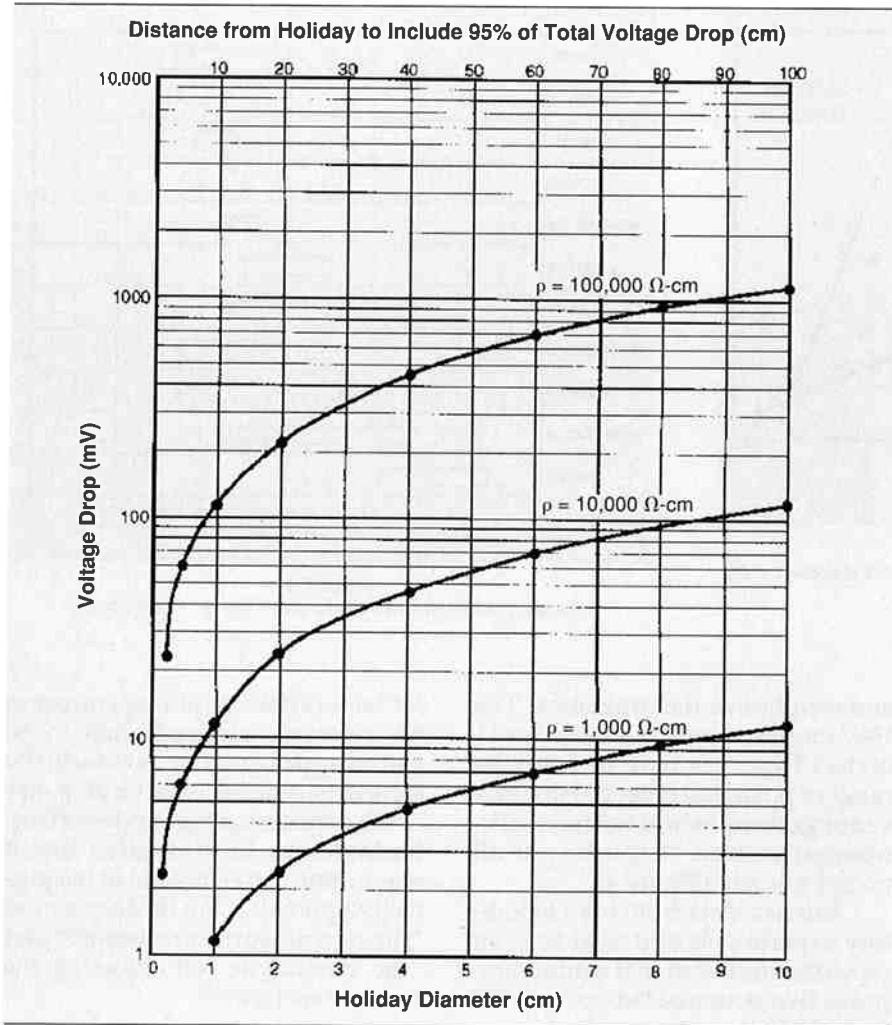
FIGURE 5
Calculated voltage (IR) drop from remote earth to steel surface of a circular holiday at a CP current density of 3 µA/cm².

tion techniques to measure the true interfacial potential, even though Sudrabin considered that the IR drop at the cathode-soil interface was an important component of the protection potential.[20] Nevertheless, the principal dispute over the latest revision of the RP0169 standard has focused primarily on whether or not the interfacial IR drop value was to be included in the −0.850 V_{CSE} criterion.

Industry Standards

The ongoing focus on the IR drop issue is reflected in the development of NACE Standard RP0169. The original standard, produced in 1969,[22] somewhat reflected Sudrabin's conclusion that the portion of the potential representing the IR drop across the interface resistance was part of the protection criterion, and the −0.850 V_{CSE} criterion was described as the desired potential "with the protective current applied." Within the same clause, however, the practitioner was directed to "consider voltage (IR) drops other than those across the structure-electrolyte boundary for valid interpretation of the voltage measurement." Heverly, who was the leader of Work Group T-10-1(e), which prepared the "Criteria" section of NACE Standard RP0169, confirmed that the criterion was described that way "because [the work group] wanted to include
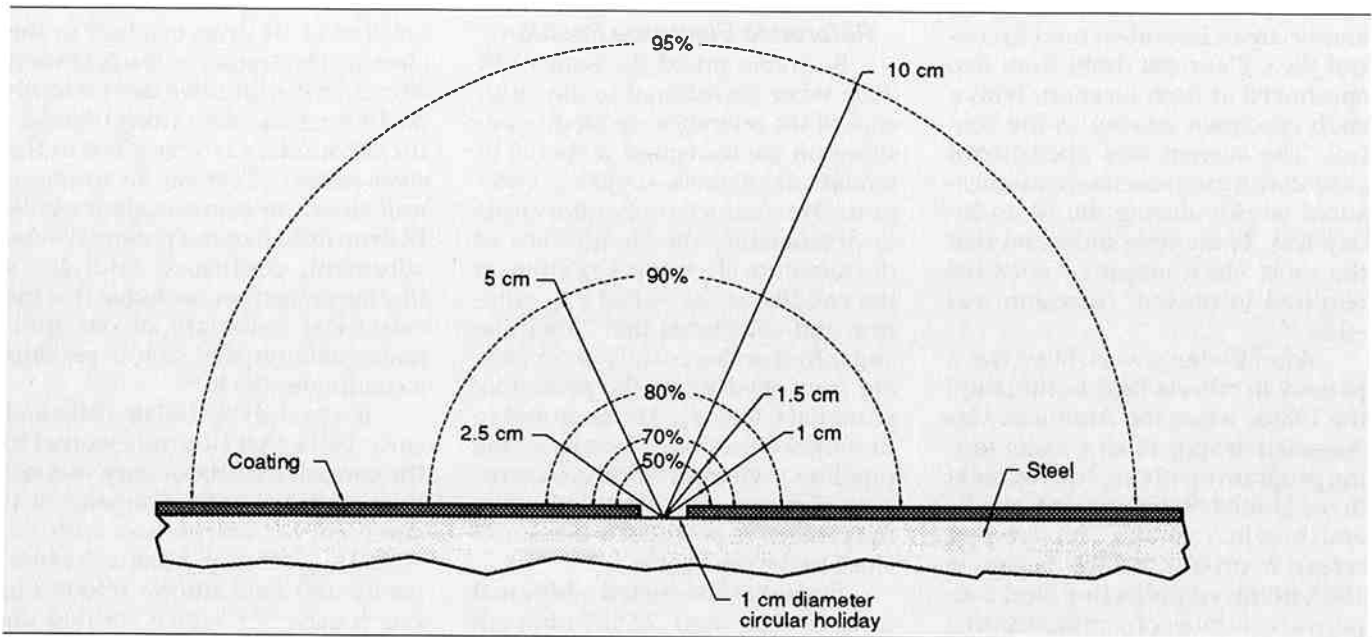

FIGURE 6
Total voltage drop to remote earth vs distance from holiday (%).

the voltage (IR) drop across the structure-electrolyte boundary but not the voltage (IR) drop through the soil for a valid interpretation of the voltage measurement."[23]

Curiously, the 1983 revision to RP0169 contained the precautionary clause only as an introductory clause (6.24) to the criteria section; in addition, its wording was softened to "consideration should be given to voltage (IR) drops other than those across the structure-electrolyte boundary. . . ."[24] This revision reflected the practice of many pipeline companies, who routinely measured the pipeline potential on the soil above the pipe for which the current was applied and gave no real consideration to IR drop. Many companies with well-coated lines simply considered the IR drop outside a holiday in the coating to be negligible.

This assumption is easily proved erroneous, however. Assume the pipe surface at a holiday to be a disc with diameter d exposed to soil having resistivity ρ; the resistance (R) of the disc to remote earth is given by

$$R = \frac{\rho}{2d} \text{ (ohm).}[3]$$

Even for modest CP current densities of 3 μA/cm² at the holiday, significant IR drop can be present (Figure 5). About 95 percent of the resistance of a holiday to remote earth occurs within about a 10-holiday-diameter distance from the holiday. Therefore, for a 1-cm-diameter holiday most of the IR drop occurs within 10 cm of the holiday (Figure 6). This means that a reference electrode placed on the surface of the soil will be at remote earth compared with the holiday. Accordingly, it is incorrect to consider IR drop to be negligible on buried coated structures when measuring the potential with the reference placed on grade. McCoy confirmed that the IR drop on coated piping could be substantial when either the holiday diameter or soil resistivity were significant.[25]

The 1992 revision of NACE Standard RP0169 appeared uncertain about the $-0.850 V_{CSE}$ criterion; it was first referred to as a CP current applied measurement (clause 6.2.2.1.1), but methods of considering the IR drop or a polarized potential mea-
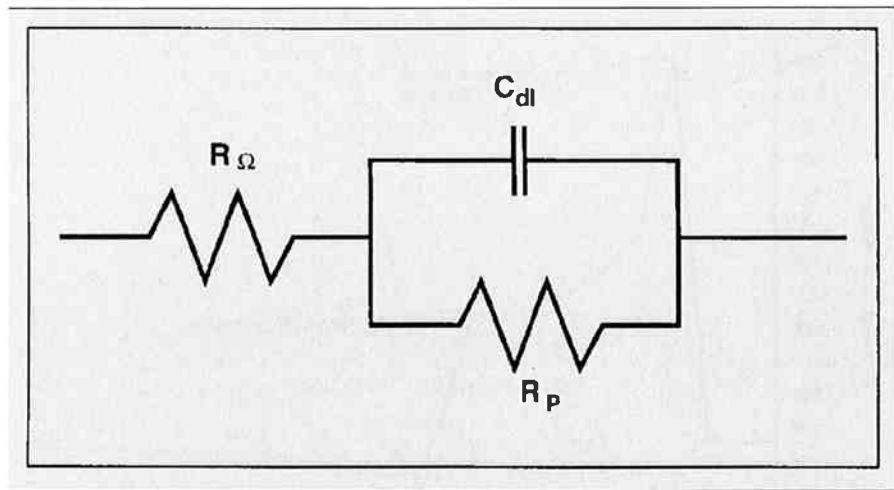

FIGURE 7
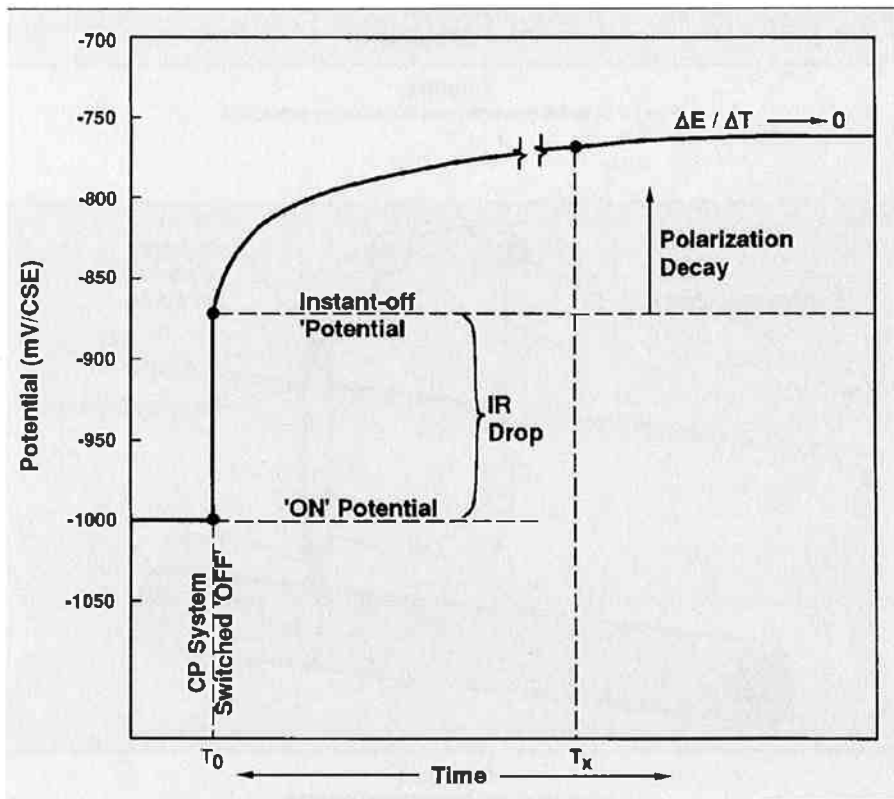Randles' equivalent circuit for metallic corrosion.[30]

FIGURE 8
Ideal potential vs time relationship after CP-current interruption.

surement (clause 6.2.2.1.2), which by definition is the potential across the structure-electrolyte interface only, followed closely.[26] This dichotomy is an obvious concession to both sides of the controversy, which has gone on in the industry since the early 1950s.

That situation is not, however, reflected in other world standards. British Standard CP1021, for in-

stance, says that "CP is achieved by ensuring that the metal-electrolyte potential is at or more negative than" the potential criterion but only advises about the importance of reference electrode placement in high-resistivity soils or for high cathode current density situations.[27]

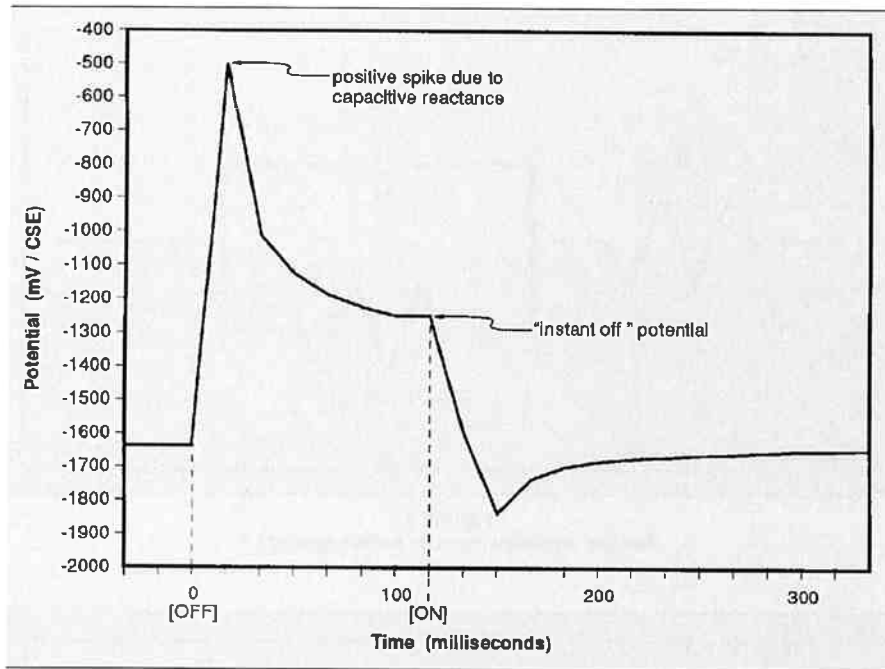The British Gas Code of Practice stipulates the maintenance of a –0.85 V_{CSE} polarized potential on existing

FIGURE 9
Typical potential response due to capacitive reactance.

FIGURE 10
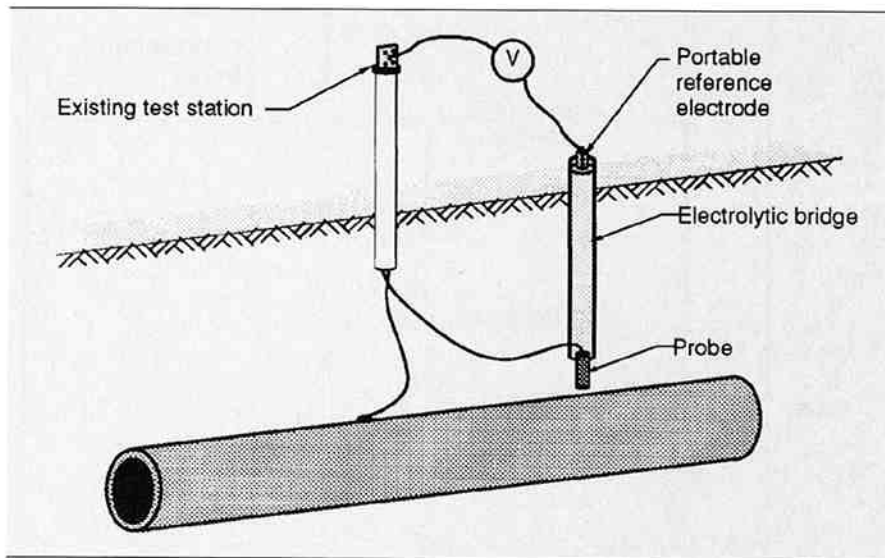Probe for measuring polarized potential.

TABLE 1
Protection Potentials
for Sandy Soils
with High Electrical Resistivity[35]

Resistivity (ohm-cm)	Protection Potential (V_{CSE})
<10,000	−0.850
≥10,000, ≤100,000	−0.750
>100,000	−0.650

erence electrode must either be placed directly at the structure-electrolyte interface or be electrolytically connected to the structure-electrolyte interface by a capillary bridge to determine the polarized potential while the CP current is being applied. Otherwise, the CP current must be interrupted and the "instant-off" potential measured for comparison with the potential criterion.

Early representation of the structure-electrolyte interface as purely resistive meant that the voltage drop across the structure-electrolyte interface would disappear instantaneously when the protection current was interrupted, and therefore the instant-off potential would indicate a value of lesser magnitude. Randles' equivalent circuit for a metallic interface as proposed in 1947 (Figure 7) modeled the interface as a resistor (polarization resistance, R_p) in parallel with a capacitor (double-layer capacitance, C_{dl}).[30] The electrolyte resistance between the interface and remote earth is given as R_Ω. Except for very small CP currents, the interface potential that develops across the polarization resistance is the same as that across the double-layer capacitance because they are connected in parallel. Theoretically, when the CP current is turned off the potential across the structure electrolyte does not disappear instantaneously but starts to decay at a rate governed by the time constant of this R_p-C_{dl} circuit (Figure 8). The instant-off potential therefore is theoretically the polarized potential of the structure-electrolyte interface independent of reference electrode position relative to the structure.

Unfortunately, the idealized potential response is not normal for a short time after turning off the CP

pipelines and a minimum potential of −0.950 V_{CSE} on new pipelines.[28] This difference may reflect an allowance for incomplete backfill compaction on new lines.

The German standard also interprets the potential criterion as the potential "directly at the material-electrolyte interface" and then describes the current-interrupt method to eliminate the IR drop inherent in potential measurements.[29]

Measurement Techniques

Interpreted properly, the potential criterion must be considered the potential across the structure-electrolyte interface if localized corrosion is to be effectively controlled. Other voltages arising in the measuring circuit must be eliminated for valid interpretation. Therefore, to determine whether a structure is protected with respect to a potential criterion such as −0.850 V_{CSE}, the ref-

current because the capacitive reactance causes a positive spike in the first fraction of a second (Figure 9). Wyatt noted that this unstable period can extend for up to 80 ms.[31] It is therefore advisable to wait for an appropriate period before attempting to record the instant-off, or polarized, potential. This measurement technique is feasible only on impressed-current systems and sacrificial-anode systems in which the conductor between anode and structure can be disconnected.

On distributed galvanic anode systems, wherein the anodes are connected directly to the pipe, the current-interruption method is not practical. This is the predominant circumstance on gas distribution piping throughout North America. Consequently, companies often use an on (current-applied) potential, usually ranging from −0.850 to −1.00 V_{CSE}. Considering that −0.850 V_{CSE} has been demonstrated empirically as the potential at the structure-electrolyte interface, then the choice of a −0.850 V_{CSE} on criterion is difficult to justify when the IR drop is likely to be greater than a few millivolts.

Many companies have adopted a more conservative on potential criterion that is more negative than −0.850 V_{CSE}, thereby incorporating a certain amount for IR drop. The weakness of this procedure is that the soil and coating quality can be so variable that the level of corrosion protection afforded may be insufficient for poorly coated structures in high-resistivity soils but be overly conservative for well-coated structures in low-resistivity soils. To apply an on potential criterion more effectively, it is necessary to install probes (Figure 10), which can be used to determine the typical IR drop from which a proper on potential criterion can be chosen for similar pipe and soil conditions.[32]

Other Considerations

Zero Corrosion

Although it has been claimed that a "zero" corrosion rate cannot be obtained,[11] a corrosion rate as high as 0.025 mm/y (1 mpy) may be unacceptable on some structures and a higher potential criterion may be required even in neutral soil conditions. Results of one study, using
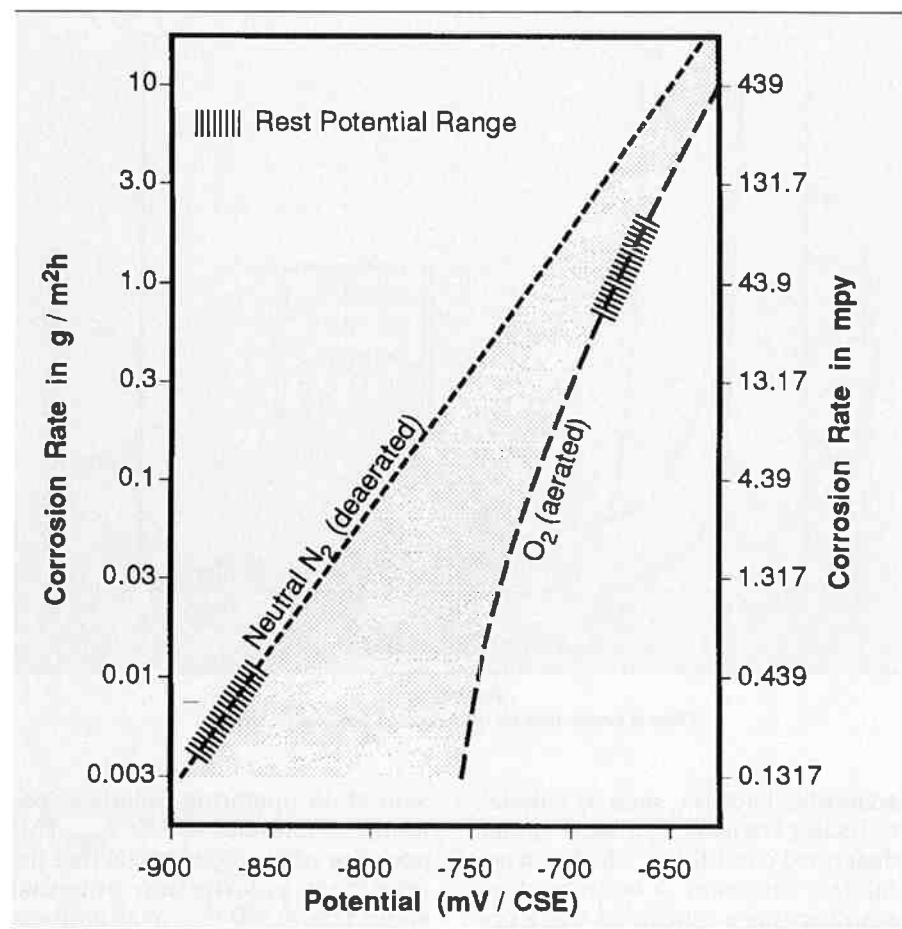

FIGURE 11
Corrosion rate vs potential curves for mild steel in aqueous solutions at 25°C.[15]

polarization probes installed at 87 points on existing buried pipelines, indicated that a "more adequate protection criterion would be the off potential more negative than −1.0 V_{CSE}" because considerable corrosion attack was suffered at more positive potentials.[33] Toncre advocated a −1.0 V_{CSE} criterion as a more realistic value, estimated to contain up to a 17 percent safety factor and therefore to provide an allowance for residual errors other than IR drop.[34]

High-Resistivity and Well-Aerated Soils

A polarized potential of −0.850 V_{CSE} should be sufficient to at least reduce the corrosion rate of steel exposed to a neutral soil environment to less than 0.025 mm/y (1 mpy). In fact, several investigators[11,16,17] have found that corrosion can be not only reduced but stopped in some soils at polarized potentials less negative than −0.850 V_{CSE}. In sandy, well-aerated soils, for in-

stance, the potential criterion for protection in one study depended on the soil resistivity (Table 1).[35] The German standard acknowledges this lesser potential criterion by stipulating a −0.750 V_{CSE} criterion for steel in soils having a resistivity of 50,000 ohm-cm or greater.[29] This lower potential criterion also appeared to be valid for well-aerated aqueous solutions (Figure 11).[36] The figure shows that for aerated aqueous solutions the corrosion rate at a −0.750 V_{CSE} potential was the same as that at a −0.900 V_{CSE} potential under deaerated conditions. Accordingly, this graph defines the typical potential range between aerated and deaerated conditions for any corrosion rate.

Deaerated Soils and Anaerobic Bacteria

Corrosion rates in deaerated aqueous environments (Figure 11) are low at potentials in the −0.850 to −0.900 V_{CSE} range. Unfortunately,
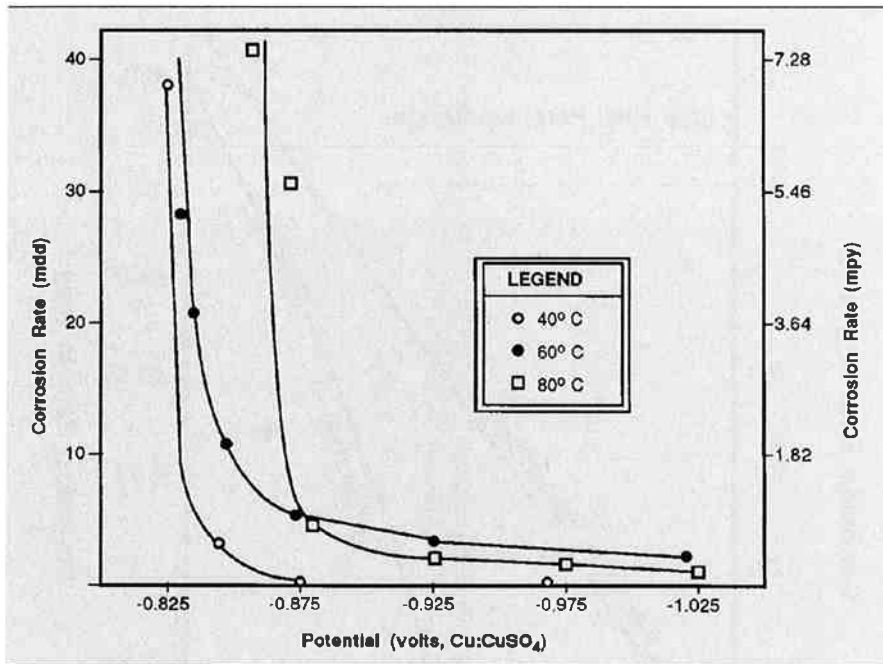
FIGURE 12
Effect of temperature on the protection potential for steel.[43]

at elevated temperatures the minimum potential criterion may require an increase in the electronegative direction. Laboratory tests in both aerated and deaerated aqueous solutions at 100°C (212°F) indicated that the potential criterion must be increased electronegatively by 0.10 V to achieve the same corrosion protection as at 25°C.[3] This increase is in the range recommended by Morgan ($-2\,mV/°C$),[41] and the results of laboratory testing in two soils by Barlo and Berry.[13] Ashworth reported recommended values of $-1\,mV/°C$ for structures in seawater.[42]

Kobayashi conducted laboratory tests at elevated temperatures in 3% NaCl solution and compared corrosion rates vs potential (Figure 12).[43] The results showed that a potential more electronegative than about $-0.900\ V_{CSE}$ was required to reduce the corrosion rate to 0.025 mm/A (1 mpy) or less.[43]

Nevertheless, some evidence concludes that a change in the -0.850 V_{CSE} potential criterion is not required for the protection of hot riser pipes in cold seawater.[42,44,45]

anaerobic bacteria, such as sulfate-reducing bacteria, can exist under deaerated conditions, which can accelerate corrosion. A number of researchers have concluded that a polarized potential of $-0.950\ V_{CSE}$ is required to control corrosion under these circumstances.[37-39] Fischer, using North Sea saline muds, found in laboratory tests that the residual corrosion rate at a polarized potential of $-0.950\ V_{CSE}$ was only about "6 to 7 mm/y" (0.25 mpy).[37] Potentials significantly more electronegative than $-0.850\ V_{CSE}$ are required in the presence of anaerobic bacteria because the natural corrosion potential of steel under these conditions has been very electronegative.[38] Fischer calculated the reversible corrosion potential to be $-1.020\ V_{CSE}$ and considered this value a "reasonable theoretical" estimate of the potential criterion for zero corrosion.[37]

CP at polarized potentials of $-0.950\ V_{CSE}$ does not prevent the development of sulfate-reducing bacteria.[39] The corrosion protection mechanism, therefore, even under bacterial conditions is consistent with the Mears and Brown theory that cathodes must be polarized to the anode potential.

One pipeline operator reported that 80 percent of corrosion failures were attributed to bacterial corro-

sion at an operating polarized potential criterion of $-0.850\ V_{CSE}$. This operator now recommends that the minimum polarization potential should be $-0.950\ V_{CSE}$ in all soils except sand.[40]

Elevated Temperatures

Most studies previously referred to were conducted at the soil's ambient temperature or in the laboratory at temperatures in the range of 20 to 25°C (68 to 77°F). Therefore,

Stress Corrosion Cracking and Hydrogen Embrittlement

Over the last 25 years, the number of incidents of stress corrosion cracking (SCC) failures on high-pressure gas transmission piping has increased. Most of these failures, which occurred within 10 miles down-
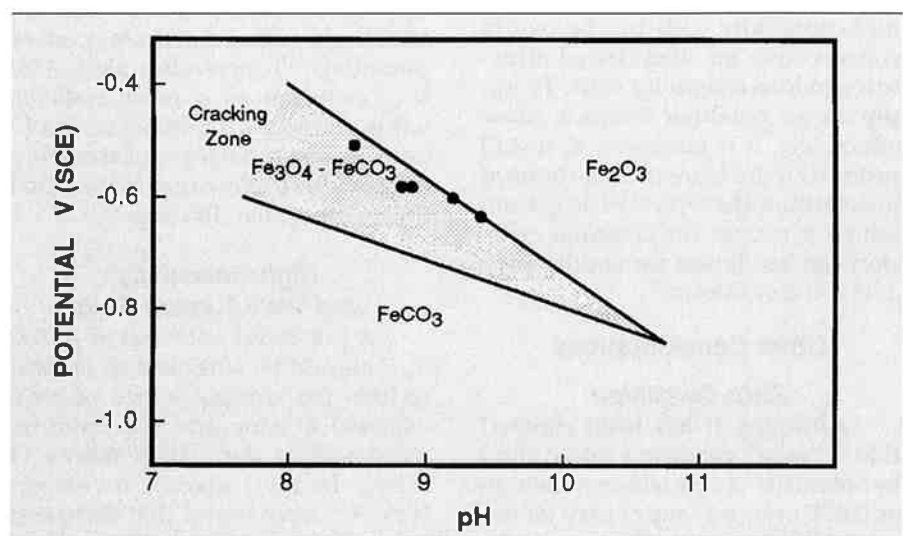

FIGURE 13
Comparison of the results from stress corrosion tests with those from polarization curves at fast and slow potential sweep rates for different carbonate-bicarbonate solutions, indicating the extent to which the experimentally observed cracking range could be predicted from electrochemical measurement.[47]
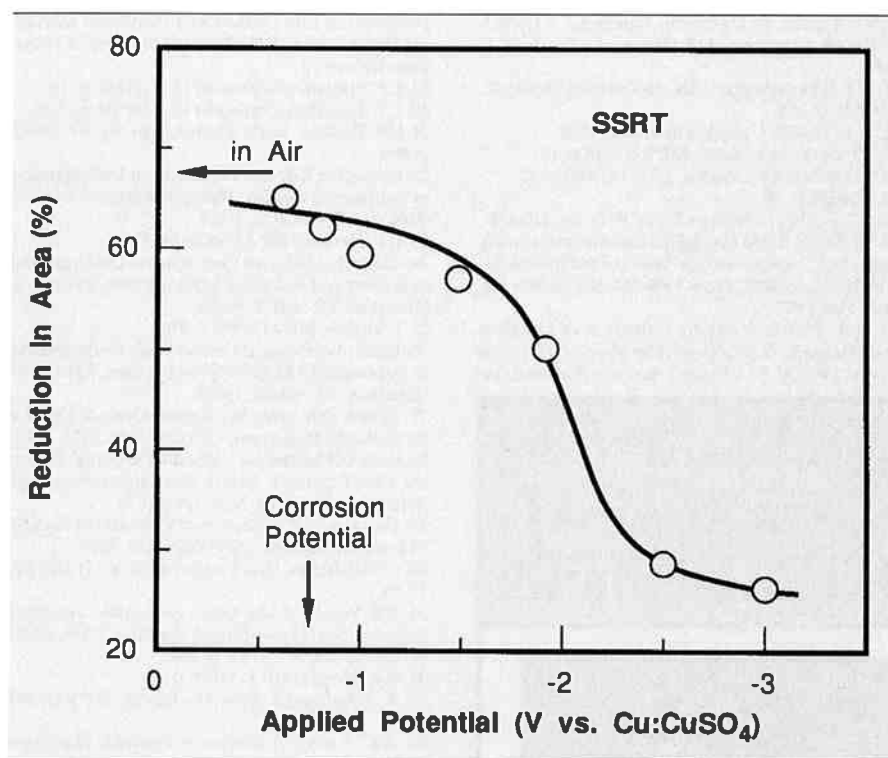
FIGURE 14

SSRT-determined relation between reduction in area and applied potential for low-tensile steel in a marine clay (ρ = 1,300 ohm-cm, pH 7.7).[51]

stream of a compressor station and at operating temperatures above 35°C (100°F), were transgranular in nature. Parkins contends that CP is a key factor in these failures because SCC is potential dependent.[46] The experimental results showing this interdependency of potential and pH on cracking susceptibility is shown in Figure 13.[47] It appears that if a steel pipe is not polarized to a minimum of about –0.850 V_{SCE} then there is an opportunity for SCC to occur. A potential more negative than –1.100 V_{CSE} may also be detrimental because of hydrogen production and entry into an existing crack, causing the metal beyond the tip to be embrittled.

Highly negative potentials can also produce hydrogen-induced cracking (HIC) under some specific metal-electrolyte conditions. Pipeline steels subjected to considerable plastic deformation during the pipe fabrication process or exposed to environmental poisoners such as sulfides and arsenic can fail by HIC even with galvanic CP systems.[48] Generally, low-carbon steels are not susceptible to hydrogen embrittlement (HE) unless they are severely cold worked or have tensile strengths

greater than 120 ksi (827.4 MPa) or a hardness greater than RC22-23.[49]

The fracture toughness of an ASTM A53 grade B pipeline steel, which would not normally be susceptible to HE, has been shown to decrease when protected at –1.200 V_{SCE} for 1,344 h.[50] Furthermore, low-tensile-strength steel specimens, buried in soils, were examined by means of slow strain rate tensile (SSRT) tests, which revealed that the reduction in fracture area depended on applied potential (Figure 14).[51]

Although HE can be demonstrated in lab experiments, it has yet to be a noticeable factor in the failure of pipelines. Nevertheless, as corrosion practitioners are required to extend the service life of existing pipeline systems, the possibility of embrittlement failures may limit the polarized potential to values more electropositive than –1.100 V_{CSE}.

Summary

Considerable progress has been made over the last 50 years with regard to the technical explanation of the potential criterion for CP, but much of the information has not been widely disseminated. It was reported

that in 1949 a survey sent to NACE members "yielded such a diversity of answers that no consensus criterion for CP was available from the replies."[7] A similar survey conducted more than 40 years later revealed a similar lack of consensus: The most frequent answer to the question "Do you routinely correct for IR drop in your pipe/soil potential measurement?" was "No." This response was concluded to indicate that "operators feel that IR drop is not a significant factor in protection of their facilities."[52] If true, then progress in the application of "state-of-the-art" CP criteria appears to have been minimal during the last 50 years.

The literature does not reflect this lack of consensus; it is overwhelmingly consistent with respect to the potential criterion. Under conditions of neutral soil temperature and pH, steel corrosion rates are almost always reduced to at least 0.025 mm/y (1 mpy) at a polarized (free of IR drop) potential of –0.850 V_{CSE}. At elevated temperatures or under deaerated conditions in soils, this potential should be more electronegative. In sandy, well-aerated, and high-resistivity soils, the potential can be less negative than –0.850 V_{CSE}.

In applying the potential criterion, care must be taken to limit the polarized potential to about –1.10 V_{CSE} to minimize the possibility of HIC and cathodic disbondment damage to protective coatings. It is likely that future efforts will be directed toward operating CP systems within a protection potential window (e.g., –0.850 to –1.100 V_{CSE}). These are operator-type decisions. In addition, when there exist techniques or devices that allow an operator to determine the polarized potential on a structure with directly connected galvanic anodes, then a general appreciation of the significance of IR drop should follow; otherwise, there is likely to be little progress in providing more effective CP. Indeed it would be easy to conclude that Kuhn's postulation in 1933 that the protective potential is "probably in the neighborhood of –0.850 V" is as accurate today as it was then and, furthermore, may not change substantially over the next 60 years in terms of its practical application.

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