Bridges. TRB, Transportation Research Record 604, 1976, pp. 38-47.

26. H.J. Fromm. Electrically Conductive Asphalt Mixes for the Cathodic Protection of Concrete Bridge Decks. Proc., AAPT, Vol. 45, 1976, pp. 382-399.

27. H.J. Fromm. Examination and Reapplication of Cathodic Protection to the Duffins Creek Bridge. Research and Development Division, Ontario Ministry of Transportation and Communications, Downsview, Internal Rept., 1978.

28. J.C. Porter. Precepts of the Evaluation of Facilities for Human Use and the Application to Bridge Replacement Priorities. TRB, Transportation Research Record 664, 1978, pp. 14-21.

29. A.M. Shirole and J.J. Hill. Systems Approach to Bridge Structure Rehabilitation or Replacement Decision Making. TRB, Transportation Research Record 664, 1978, pp. 22-31.

30. A.M. Shirole and J.J. Hill. Systems Approach to Bridge Structure Replacement Priority Planning. TRB, Transportation Research Record 664, 1975, pp. 32-36.

31. R.I. Frascoia. Vermont's Experience with Bridge Deck Protection Systems. In Chloride Corrosion of Steel in Concrete. (D.E. Tonini and S.W. Dean, Jr., eds.), ASTM, Special Tech. Publ. 629, 1977, pp. 69-81.

32. M.G. Hagen. Bridge Deck Deterioration and Restoration. Minnesota Department of Transportation, St. Paul, Investigation 639, Vol. 3, 1978.

33. Task Force on Durable Bridge Decks: Activities in 1976 and 1977. Ontario Ministry of Transportation and Communications, Downsview, 1978, 60 pp.

Successful Application of Cathodic Protection to a Concrete Bridge Deck

H. J. FROMM

The effectiveness of the cathodic protection treatment of an Ontario concrete bridge deck after three years of service is evaluated. The Duffins Creek bridge was the first Ontario deck to be repaired and treated with cathodic protection. Half of the deck was treated, and the other half was left untreated. Corrosometer probes were placed in the treated half of the deck. These probes showed that cathodic protection was preventing further corrosion. After three years, the deck was stripped and the protected and unprotected sides were compared. It was found that the treated side had much less corrosion than the untreated side. It also became apparent that corrosion had occurred below the rebars, where the epoxy injection technique had been used for repairs. The most current Ontario system of cathodic protection has now been applied to the entire deck.

The Duffins Creek bridge, located on Ontario 7, 8 km east of Ontario 48, was the first of two Ontario bridges to be treated with cathodic protection. The bridge is 28 m long and 11 m wide and was built in 1967. Its concrete deck was left exposed. In 1974, the deck rebars were corroding, and this was causing serious spalling and delaminations to occur in the deck, especially along the centerline. The deck was surveyed for corrosion by using a copper/copper sulfate (Cu/CuSO$_4$) half-cell ($\underline{1}$). It was found that potentials in excess of -0.35 V existed in a good portion of the deck, which indicated an active state of corrosion. The original corrosion voltage survey is discussed elsewhere ($\underline{2},\underline{3}$).

The delaminations in the deck were repaired by using an epoxy injection, and the spalls were patched with concrete. Since at that time cathodic protection was still an experimental method, it was used only on the eastbound lane. The westbound lane was left unprotected for comparison. It was covered with dense asphaltic concrete to match the level of the protected eastbound lane.

A full description of the original method used for applying cathodic protection to the Duffins Creek bridge is given elsewhere ($\underline{2},\underline{3}$). In this method, a series of Duriron anodes were applied to the deck and attached to it with epoxy cement. The connecting wires were run along the deck to the curb, from the curb to the end of the deck, then down through a hole to the control panel. Graphite anodes were also used in order to compare their behavior and stability with those of the Duriron anodes. The entire deck surface was covered with an electrically conductive mixture of coke breeze and asphalt cement. The mixture was then compacted in the usual manner to a thickness of 5.0 cm and covered with 3.8 cm of surface mix, designated HL-1, which distributed the electric power evenly across the deck. Experiments showed that three electrodes down the center of the deck were sufficient to give an even distribution of power in the mix. Electrical resistance probes buried in the deck showed that corrosion stopped as soon as the power was applied.

The deck was under constant current control rather than the constant potential control applied to later decks. The system worked very well and required only two adjustments per year. The reason for this was that during the summer the concrete deck was drier than in the winter and its resistance changed. If the current was set to produce a polarized potential of, say, 1.0 V during the summer, this would produce a lower potential during the winter when the deck resistance was lower because of absorption of deicing salt solutions. In this case, an adjustment would have to be made.

The bridge deck was protected by this system for three years. During the second year, however, several fine random cracks appeared in the asphalt surfacing on the protected half of the bridge while the unprotected half remained uncracked. It was believed that the cracks developed as a result of water saturation in the conductive layer. This conductive layer was 80 percent by weight coke breeze and 20 percent by weight asphalt cement. Although this mix had excellent conductive properties (resistivity = 0.0148 $\Omega \cdot$m), it was low

in stability and high in air voids (17-18 percent by volume). When the bridge was treated with cathodic protection, the conductive layer was applied one day and the wearing course the next. Unfortunately, it rained heavily the morning the wearing course was to be applied, saturating the conductive layer. The wearing course would have helped to retain this moisture. Even if some of the water evaporated, a fresh supply of water could slowly percolate through the surface after each rain.

The high voids and low stability of this mix led to the development of a conductive mix with more suitable properties--i.e., a Marshall stability of 4400 N and voids of less than 5 percent volume (4).

During the summer of 1977, it was decided to strip the entire surfacing of this bridge to compare the protected and unprotected sides. The latest developments in cathodic protection were then to be applied to the entire deck.

PRELIMINARY WORK

The entire operation of stripping the deck, examination, testing, repair, and reapplication of cathodic protection was to be done in five working days. Traffic would be maintained in a single lane during the working day and returned to a two-lane operation at the close of each day.

Before the stripping of the deck, some exploratory work was done to see whether the old anodes could be removed intact for examination. One Duriron and one graphite anode located in the curb lane at the west end of the bridge were bared. When the HL-1 surfacing mix and the conductive mix were removed, water from the surrounding conductive mix flowed into the hole. The conductive mix still contained a lot of water. It was found that the epoxy cement holding the anodes to the deck could be broken by hammering around the edge with a light jackhammer.

Despite the water saturation, the conductive mix was in good condition and still had plenty of adhesion. There was no visible stripping of asphalt from the coke particles.

STRIPPING AND EXAMINATION OF DECK

The westbound lane was stripped first. This lane had no cathodic protection and was paved with 7.5 cm of HL-1 surfacing mix. The material was very dense and almost nonporous. A large backhoe was used to remove the HL-1 surfacing mix. This procedure was difficult because the HL-1 mix had adhered strongly to the deck. In many places where spalling had occurred, the concrete surface came up adhered to the asphalt. In several spots, the deck appeared damp, which indicated some moisture penetration. For the most part, the deck surface was dry. After the lane was completely stripped, the traffic was rerouted and the eastbound lane on the south side was stripped. Great care was taken in stripping this lane to recover all of the anodes. Since the conductive mix was much less stable and less adhesive, it was removed with less difficulty from the deck than was the HL-1 mix on the north side.

When the south side was stripped, none of the concrete deck surface came up with the asphalt conductive mix as had happened on the north side.

The protected lane had been powered only by the four anodes located down the center of the lane (2). When these four anodes were examined, there did not appear to be any metal loss from the three Duriron anodes. The one graphite anode showed no deterioration at all, and the edges were still sharp. Some of the other Duriron anodes, which had not been used since the beginning of the test,

showed a slight stain of rust in some areas. The deck in the southeast corner had a slight rust stain from the anodes. This was caused by the water in the conductive mix. The powered anodes did not show rust stains.

Once each side was stripped, a preliminary $Cu/CuSO_4$ half-cell survey was run on each side to determine the corrosion potentials, which were found to be much higher than expected. Those read on the south (protected) side were expected to be high because they would be the polarized potentials remaining after the power had been shut off in the morning. These potentials were not plotted on a graph. It was planned to resurvey the deck two days later when the polarized potentials had leaked off and the normal corrosion potential was present.

EXAMINATION AND TESTING OF THE DECK

On the second day, the north side of the deck was chain dragged to enable the delaminations to be outlined and mapped. Many delaminations were found in addition to those in the areas where the concrete surface had come off adhering to the HL-1. The delaminations were removed with a jackhammer and patched with cement.

The south side of the deck was chain dragged, and the delaminations were outlined and plotted. Here, they were much fewer in number and smaller than on the north side. A map of both sides of the bridge deck that indicates the areas of delamination and spalling is shown in Figure 1. These delaminations, too, were removed with a jackhammer and patched with cement.

It was noted that several delaminations on the south side had previously been repaired by use of epoxy injection. It was thought that in these cases a delamination level with the top of the rebar had been repaired. The injected epoxy resin then prevented the flow of current to the bar in this area, and further corrosion took place below the bar. Several other shallow delaminations on the south side of the deck could have been the result of freeze-thaw action, since so much water was trapped in the conductive mix. The delaminations on the south side were, however, less frequent than on the north side.

The delaminations that occurred along the bridge-deck centerline (concrete cover of 19 mm or less) were more serious on the north (unprotected) side but did spread over the south side. This extension into the south side is believed to be a result of the forces generated by the corrosion produced on the rebars in the north side of the centerline.

On Thursday, August 25, 1977, the entire deck was again surveyed for corrosion potentials by using a $Cu/CuSO_4$ half-cell. Again, very high potentials were found on both sides of the deck. The protective current had been cut off for three days. These potentials are shown in Figure 2.

INSTALLATION OF CATHODIC PROTECTION

The most recent system of cathodic protection used by the Ontario Ministry of Transportation and Communications (MTC) was used on this deck. All anodes and voltage probes were counter sunk in the deck so that their surfaces were bare and were flush with the deck. The half-cells were buried in slits cut in the deck level with the upper rebars and were covered with concrete. All connecting wires were set in saw cuts in the deck and were run to the curb. The wires along the curb were encased in concrete 10 cm wide and 5 cm thick. Thus, all electrical elements were flush with the deck or

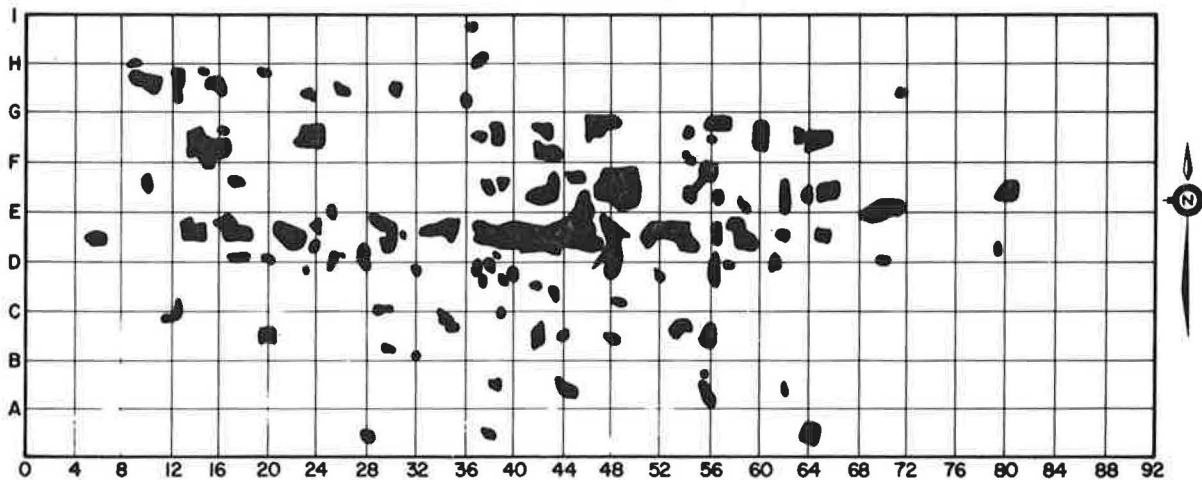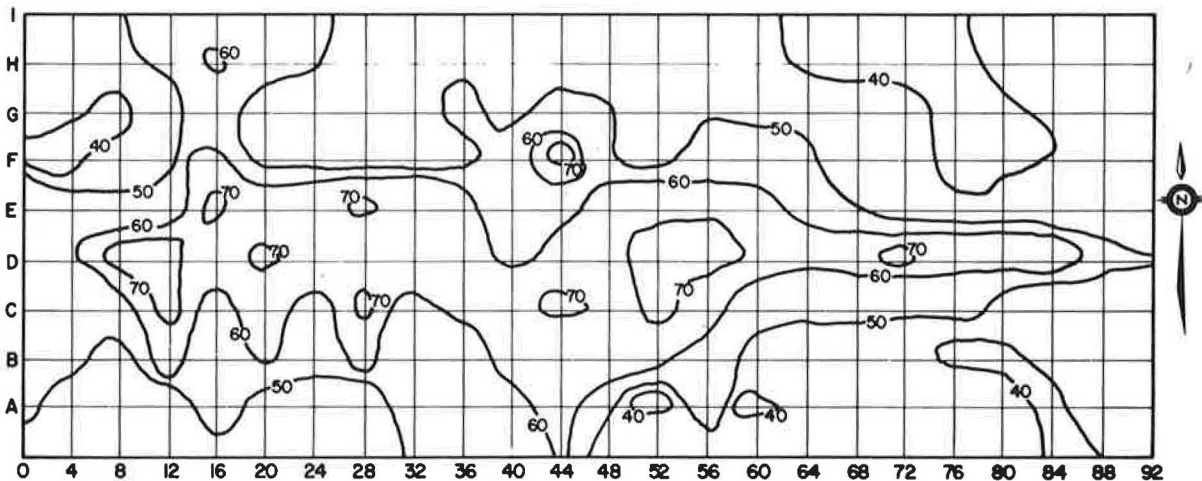Figure 1. Spalling and delaminations in Duffins Creek bridge deck.

Figure 2. Copper half-cell potentials in Duffins Creek bridge deck.

encased in concrete along the curb. If at any time in the future it is necessary to remove and replace the surfacing of the concrete deck, this can be done without disturbing the electrical elements or the circuitry.

The layout of the anodes, voltage probes, and half-cells is shown in Figure 3. The design called for three anodes down the centerline—anodes 1, 3, and 5 in Figure 3. These are connected in parallel to the main bus, which in turn runs to the power supply. Anodes 2 and 4 are connected to a secondary bus. These were also installed in the event of unforeseen problems. Anodes 2 and 4 can be run separately or in addition to those on the main bus.

Six graphite voltage probes were sunk in the deck so that their upper sides were flush with the top of the deck. These probes were individually connected to the jacks on the control panel.

Six half-cells, three $Cu/CuSO_4$ and three zinc/zinc sulfate ($Zn/ZnSO_4$), were buried in the deck and connected by individual wires to the control panel. Four of the half-cells—Cu_1, Cu_3, Zn_1, Zn_2—were located about 2.5 cm below the surface and roughly midway between the rebars. Half-cells Cu_2 and Zn_3 were located within 1 cm of a rebar. This was done to determine whether cell location relative to the rebars would have any bearing on the polarized voltage indicated and also

to select the location best suited for potential control, the system later to be added to the bridge. A wiring diagram is shown in Figure 4 (all wires from probes and half-cells north of the centerline run to the north curb duct, and those from probes and half-cells south of the centerline run to the south curb duct).

At the end of the fourth day, all of the electrical equipment had been installed, the bridge-deck repairs were complete, and the deck was ready for paving. Resistance checks were run on all anodes, voltage probes, and half-cells to make sure that no shorts to ground had occurred. All systems checked out, and no adjustments had to be made.

PAVING OF DECK

On the morning of the fifth day, the surfaces of all anodes and voltage probes were cleaned with wire brushes and abrasives to ensure good electrical contact. A special conductive mix was designed for this project. Its composition and properties are given below:

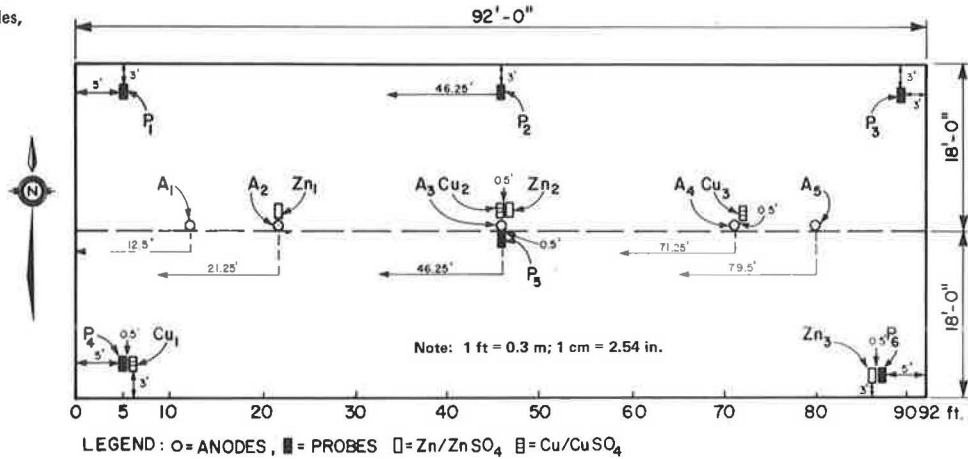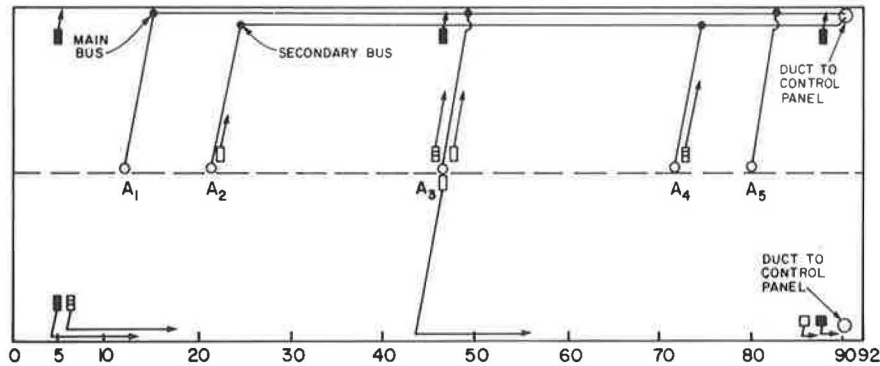| Item	Value
Mix composition (%)	
Stone retained on 4.75-mm sieve (by weight)	40

Figure 3. Placement of anodes, probes, and half-cells.

LEGEND: O = ANODES, ▮ = PROBES ▯ = Zn/ZnSO₄ ▤ = Cu/CuSO₄

Note: 1 ft = 0.3 m; 1 cm = 2.54 in.

Figure 4. Wiring diagram.

Item	Value
Sand passing 4.75-mm sieve (by weight)	15
Coke breeze (by weight)	45
Asphalt cement, 85/100 penetration (by weight of total aggregate)	14
Mix property	
Marshall stability (N)	4359
Marshall flow	13.8
Voids in mineral aggregate (percent by volume)	32.5
Voids (percent by volume)	8.2

A better mix would have been one that contained 15 percent asphalt. Such a mix would have had 5 percent air voids and a stability of >1000.

The mix was laid with a regular paver and compacted to a depth of 5 cm with steel and rubber-tired rollers. There were no problems in laying or compacting the mix. The conductivity of the mix was tested behind the steel finishing roller and was found to be acceptable.

The mix was kept away from the expansion joints by laying 5x15-cm planks on the deck against the edges of the steel joints. After the mix was compacted, it was dug away from the curb scuppers for a distance of 15 cm. These actions prevented any short circuits between the conductive mix and the bridge steel.

The eastbound lane was the first to be paved with the conductive mix. After it was compacted, the traffic was routed onto it while the westbound lane was paved. The conductive mix was able to bear the traffic, including trucks, with no problems or dam-age. Once both lanes were covered with the conductive mix, 3.8 cm of HL-1 wearing course was paved over the deck to complete the job.

POWER DISTRIBUTION ACROSS THE DECK

Once the paving was complete, power was applied to the deck by the original constant current rectifier to provide cathodic protection. Power was applied to anodes 1, 3, and 5 of the main bus. A larger current than necessary (0.8 A) was applied to build up the polarized potential on the steel more rapidly. Three days later, this current was reduced to 0.4 A, and the bridge was allowed to reach electrical equilibrium. At equilibrium, the power distribution was as follows:

Probe Number	Power On (V)	Polarized Potential (V)
1	1.25	1.14
2	1.24	1.14
3	1.18	1.12
4	1.22	1.15
5	1.30	1.16
6	1.20	1.12

Anodes 1, 3, and 5 were sufficient to distribute the power across the deck so that an even, polarized potential was obtained on the steel. Anodes 2 and 4 were not used.

The potential on the rebars was also measured by taking voltage readings between the half-cells in the deck and ground. The technique used is described elsewhere (5). Initially, it was found that the two zinc and copper cells closest to the rebars gave higher readings than the four placed

midway between the rebars. After a few days, the readings between the two sets became similar. It was concluded that a half-cell close to a rebar would give a better, more sensitive type of control than one placed farther away.

A new potential control rectifier has now been obtained, and the bridge is now being controlled by the zinc half-cell close to a rebar.

Cathodic protection is now accepted as a suitable system for bridge-deck repair by MTC. Other accepted methods in Ontario are the use of low-slump concrete and the use of latex-modified concrete overlays.

CONCLUSIONS

1. Cathodic protection is successful in preventing or retarding the corrosion of bridge-deck steel. This was shown on the Duffins Creek bridge through the corrosometer probes and by the fact that there was a much lower degree of damage on the protected side of the bridge deck.
2. Examination of the deck after three years of cathodic protection showed that epoxy injection was not a good method of bridge-deck repair.

3. A conductive mix that has a low void content should be used to prevent water absorption.
4. Cathodic protection is now accepted in Ontario as a method for protecting bridge decks after repair.

REFERENCES

1. D.L. Spellman and R.F. Stratfull. Chlorides and Bridge Deck Deterioration. HRB, Highway Research Record 328, 1970, pp. 38-49.
2. H.J. Fromm and G.P. Wilson. Cathodic Protection of Bridge Decks: A Study of Three Ontario Bridges. TRB, Transportation Research Record 604, 1976, p. 38.
3. H.J. Fromm. Cathodic Protection of Rebar in Concrete Bridge Decks. Materials Performance, Vol. 16, Nov. 1977, pp. 21-29.
4. H.J. Fromm. Electrically Conductive Asphalt Mixes for the Cathodic Protection of Concrete Bridge Deck. Proc., AAPT, Vol. 45, 1976, p. 382.
5. H.J. Fromm. Measurement of Polarized Potentials in Concrete Bridge Decks. TRB, Transportation Research Record 692, 1978, pp. 23-28.

New Approach to Cathodic Protection of Bridge Decks and Concrete Structures

J. P. NICHOLSON

Until now, cathodic protection of bridge decks has been accomplished by installing anodes on the concrete surface or by recessing them into the concrete and covering them with a conductive paving layer to spread the current over the entire surface of the structure to be protected. Tests are reported in which wire anode consisting of platinized niobium was installed in a bridge deck in sawed slots with conductive backfill. Tests to date indicate that if the wire anode is carefully spaced a bridge structure can be protected without using a conductive paving layer. This eliminates to a great extent the cost of conductive paving and of other wearing courses required to protect the conductive paving layer.

The deterioration of concrete bridge decks and support structures occurs worldwide, but the deterioration can be accelerated by the use of deicing salts or by salt spray in coastal areas. Since the pH of concrete is generally in the range of 12.5-12.8, one would normally anticipate that steel would not corrode in concrete. In this pH range, steel is usually passive; in the presence of chlorides, however, corrosion of the reinforcing steel can occur quite rapidly. In the United States, the U.S. Environmental Protection Agency estimates that the annual cost of bridge damage caused by deicing salts is about $0.5 billion/year. No doubt the damage to bridge structures in Canada is high, since deicing salts are used extensively during the winter months, but I have not been able to locate any estimates in the literature of the cost of this damage.

Slater and others (1) have suggested that chloride levels of 0.02 percent or less be considered the threshold value for corrosion of reinforcing steel. In their investigations, the steel remained passive at levels below this figure and, at chloride concentrations above the 0.02 percent level, corrosion occurred. Slater and others did some investigation on chloride concentration at various depths in concrete bridge structures. As data given in Table 1 show, chloride concentration decreases with the depth of concrete cover. This is no doubt attributable to the permeability of the concrete and the ability for ionic transfer.

Before a bridge deck can be protected, the criteria for protection of steel in concrete must be determined. Many papers suggest that National Association of Corrosion Engineers (NACE) standard RP-01-69 should apply to concrete structures that contain reinforcing. This standard offers three criteria for establishing whether or not a structure is cathodically protected.

To intelligently use these criteria, it is necessary to understand how they were established. Schwertdferger and McDorman (2) did some analytic work on the current and potentials required for the protection of steel in soils. Their investigation indicated that "cathodic protection is the maintenance of a critical potential at the surface of the cathode." This potential, which Schwertdferger and McDorman define by the point of intersection of the potential-pH curve for steel in air-free soils and the potential-pH curve for the hydrogen electrode at atmospheric pressure, was found to be approximately -770 mV referred to the saturated calomel electrode, or -530 mV referred to the standard hydrogen electrode. This converts to -850 mV re-