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Technical Alert

Criteria for the Cathodic Protection of Reinforced Concrete Bridge Elements

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Contents

List of Figures

Introduction

Cathodic protection is rapidly becoming accepted as a repair option for steel-reinforced structures that are undergoing corrosion caused by the presence of chlorides.

Tests used to assess the effectiveness of cathodic protection systems are known as "criteria". Several different criteria have been suggested for use with concrete structures, and many are in use today. Most of these criteria were adapted from those used in the underground cathodic protection industry and are only recently being verified in concrete. The number of tests, together with the complexity of some, has led to confusion and disagreement regarding the use of such criteria.

The Strategic Highway Research Program (SHRP) issued a contract on cathodic protection of reinforced concrete bridge elements. The objective of part of that contract was to investigate the feasibility of improved and simplified control criteria. Under this contract, corrosion rates of steel in a concrete environment were measured relative to many factors. These data were used to appraise control criteria. This technical alert presents the results and recommendations based on that part of the work.

Organization

This technical alert is divided into three sections, each of which describes a different cathodic protection criterion. Section 1 discusses the **100-mV Polarization Development/ Decay** criterion, which is already in common use. Section 2 describes a new criterion, the **Corrosion Null Probe**. Section 3 describes a new **Constant Current** criterion. These three criteria are presented in decreasing order of complexity, with the 100-mV Polarization Development/Decay criterion being the most complex and the Constant Current criterion being the easiest to apply.

Other criteria may be useful for the assessment of cathodic protection systems, but they are not discussed in this technical alert. The *E* log *I* criterion, for example, is not discussed since it is often difficult to conduct and interpret. This test normally is conducted only by consultants or service firms that specialize in using the *E* log *I* criterion.

The criteria described in this technical alert are intended for use by highway engineers without extensive training or experience. They are, nevertheless, technically accurate as shown by data developed in this study.

100-mV Polarization Development/Decay

The 100-mV Polarization Development/Decay criterion is one of three listed as acceptable in the National Association of Corrosion Engineers (NACE) Standard Recommended Practice RPO290-90. A survey that collected data on 287 cathodic protection systems in the United States and Canada identified this as the most popular criterion currently used for concrete structures. Since this criterion is already in common use, this technical alert does not describe it in great detail, but offers comments about its use and interpretation based on the study results.

The 100-mV Polarization Development/Decay criterion is based on the theory that polarization of corroding steel in the cathodic direction will inhibit anodic (corrosion) reactions. This idea is a well-established principle of electrochemistry. Most disagreement about this criterion is focused on the amount of polarization needed to control corrosion. This figure ranged from 250 mV to 50 mV or less. Based on these corrosion rate studies, the amount of long-term polarization needed is a function of chloride concentration at the reinforcing steel, as presented in table 1.

Direct use of these data requires determination of the chloride concentration in the concrete at the reinforcing steel. If chloride concentrations are not known, 100 mV of polarization is a reasonable compromise for a relatively broad range of salt concentrations, although 150 mV should be required if conditions are known to be very corrosive.

Polarization is usually estimated by measuring the polarization decay of the steel that occurs after the protective current is shut off. Steel potentials versus a saturated calomel electrode (SCE) may be plotted against time as shown in figure 1.

Table 1. Polarization Requirement as a Function of Chloride Concentration at the Steel Surface

Chloride Concentration		Polarization Needed*
(lb/yd^3 concrete)	(kg/m^3 concrete)	(mV)
<1	<0.6	0
1-2	0.6-1.2	60
2-5	1.2-3.0	80
5-10	3.0-6.0	100
10-20	6.0-12.0	150

*To achieve a corrosion rate of <0.1 mil/year, or >20 years until damage due to corrosion

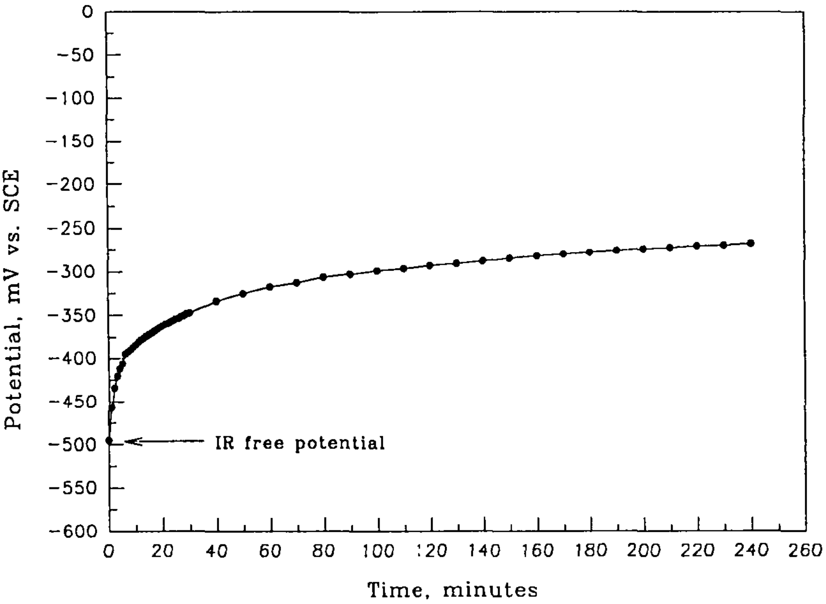
1 mil = 0.0254 mm

The time period used for this test may cause some problems. The initial potential, called the "instant-off" or "IR-free" potential, should be taken from about 100 to 1,000 msec after shutting off the current. Measuring the potential incorrectly could lead to significant error.

Another problem is that the polarization decay test is typically conducted over a 4-hour period. It was found that as little as 25% of the total polarization may be recorded in the first 4 hours of the test. This is especially true of very mature systems or systems in which concrete is water saturated.

Recording polarization decay over periods longer than 4 hours may be both impractical and misleading. It has been shown that changes in the environment (temperature, for example) can seriously distort the test results when data are taken over a very long period.

Figure 1. Polarization Decay of Steel in Concrete



This test requires a stable reference electrode, which is typically embedded in the concrete of the structure. The electrode should be installed in the most anodic (corrosive) location within the zone to be protected. Work has underscored the importance of properly locating the reference electrode. Location is established by conducting a potential survey according to ASTM C 876-91, "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete." Figure 2 shows a potential survey being conducted.

In summary, the 100-mV Polarization Development/Decay test is a reasonably accurate criterion for cathodically protecting steel in concrete, though 100 mV of polarization may be excessive when very little chloride is present, and inadequate when there is a very high chloride concentration. Also, complete polarization decay may not be recorded in the standard 4-hour test period.

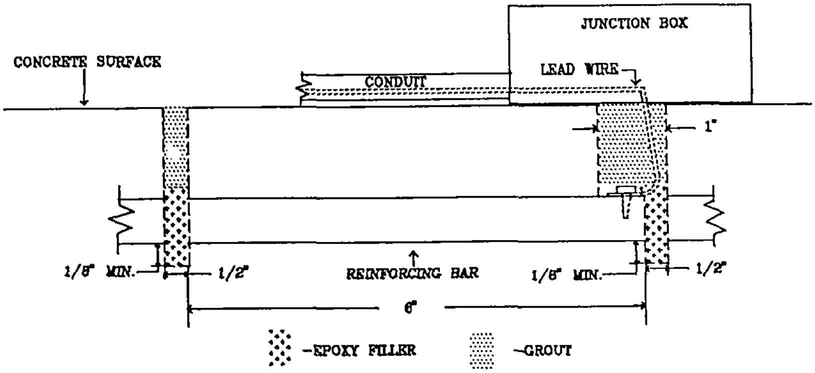
Figure 2. Measuring Static Half-Cell Potentials of Embedded Steel

Corrosion Null Probe[1]

This work found a direct correlation between the corrosion current flowing to the reinforcing steel and the corrosion rate. The data also showed that the cathodic protection current controls both macrocell corrosion and local corrosion. These results suggested a new criterion based on current flow to or from an element of the natively corroding steel. This concept has been termed the Corrosion Null Probe (CNP). The construction of the CNP is shown in figure 3.

The CNP can be established by first locating the most anodic (corrosive) area in the zone to be protected. This is done by conducting a potential survey according to ASTM C 876-91 (see figure 2). This step is very important and must be done with care. The survey should be done using a 4-ft (1.2-m) spacing between measurements. The most anodic areas then should be resurveyed using 1-ft (0.3-m) centers, or else the most corrosive areas may be missed. An example of a static potential survey map is shown in figure 4.

Figure 3. Corrosion Null Probe Schematic



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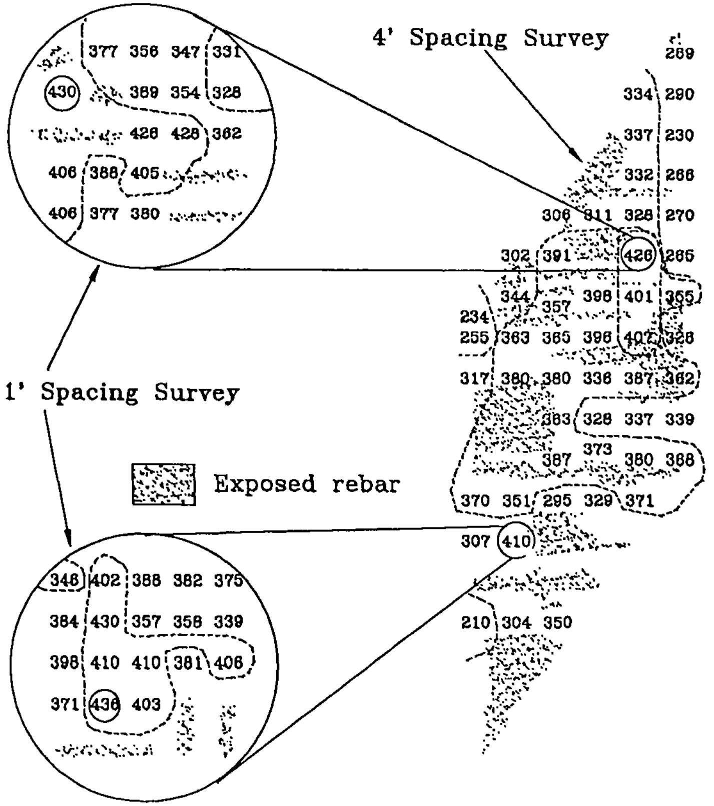
[1] Bartholomew, J., et al. 1993. Criteria and Materials Performance for the Cathodic Protection of Reinforced Concrete Bridge Elements. Report no. SHRP-S-670. Washington, DC: SHRP, National Research Council.

Figure 4. Static Potential Survey Map



Potentials are −mV vs SCE

Once the most corrosive spot is identified, the location of the reinforcing steel can be determined using a concrete cover meter (figure 5). A short length of reinforcing bar, typically 6 in. (15 cm) is isolated from the rest of the reinforcing bar by saw-cutting (figure 6). The isolated bar should be in sound concrete, and care should be taken not to disturb the concrete near it. A wire is attached to the bar as shown in figure 3. The wire connection and the cut ends of the bar are sealed with epoxy. The saw cuts are filled with mortar or grout.

Figure 5. Locating Embedded Steel Reinforcement

After installation, the CNP should not be left electrically isolated from the rest of the reinforcement, or the corrosion cell will be disturbed. Therefore, the CNP should be connected to electrically continuous reinforcing steel during the construction process. The connection can be made with a temporary wire if necessary.

Before testing, the wire attached to the CNP is connected to the rectifier negative terminal through a 10-ohm resistor. Current flow to, or from, the probe is measured as a voltage drop across the resistor. When the positive lead of a

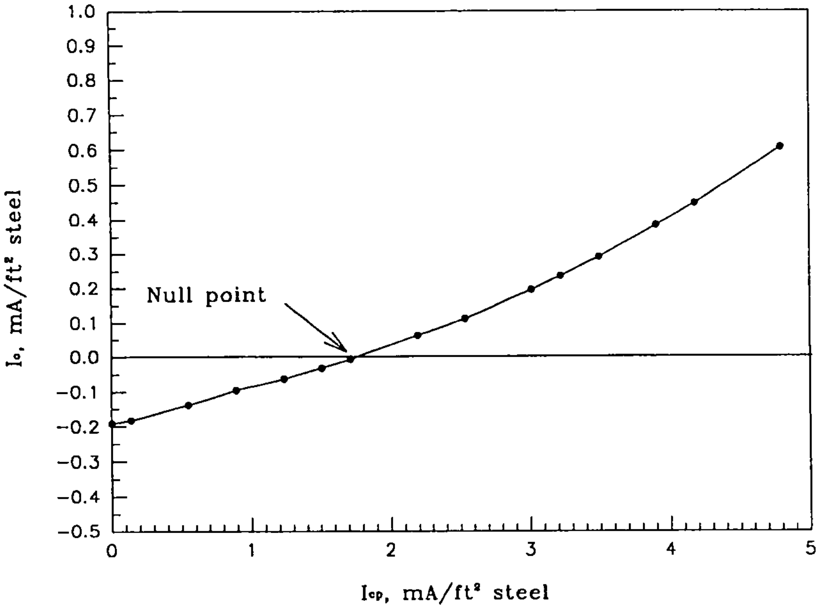
Figure 6. Saw-Cutting Reinforcing Steel

voltmeter is attached to the probe and the negative lead is attached to the system negative, a negative reading indicates that the probe steel is corroding. When cathodic protection current is slowly applied, the voltage across the resistor will eventually reverse polarity and become positive. At this point, the CNP is cathodic and is no longer corroding. Figure 7 illustrates a CNP's response to increasing cathodic protection current.

When the CNP is located in the most corrosive area in the zone, that area is protected, and all the other steel in the zone will be protected as well.

A small safety factor of 0.25 mA/ft^2 (2.5 mA/m^2) concrete is recommended. This safety factor is normally adequate to compensate for current variations caused by anode resistance, concrete cover, and chloride and moisture

Figure 7. Typical Nulling Curve



content. The test should be repeated after 1, 3, and 6 months, and annually thereafter.

The CNP criterion is technically accurate and relatively simple to apply. It is site specific and will show diminishing cathodic protection current requirement with time. Installation is simple, and the test is easy to perform. An important feature is that the criterion does not rely on the long-term stability of embedded reference electrodes. At this time, it has had very limited use in the field, and additional field validation is needed.

Constant Current Criterion

Corrosion rate studies have demonstrated good correlation between the concentration of the chloride ion at the surface of the reinforcing steel and the amount of cathodic protection current required to protect the steel. Thus, if the maximum chloride ion concentration at the surface of the steel can be approximated, a good estimate of the current required for protection can be made.

The difficulty with estimating the chloride ion concentration is that, when cathodic protection is applied, the chloride ion concentration at the surface of the steel decreases with time. A mathematical model for predicting the chloride and hydroxide ion concentration profiles as a function of the total charge passed by a cathodic protection system was used to correct for this occurrence. The result, shown in figure 8, is a good estimate of the required cathodic protection current.

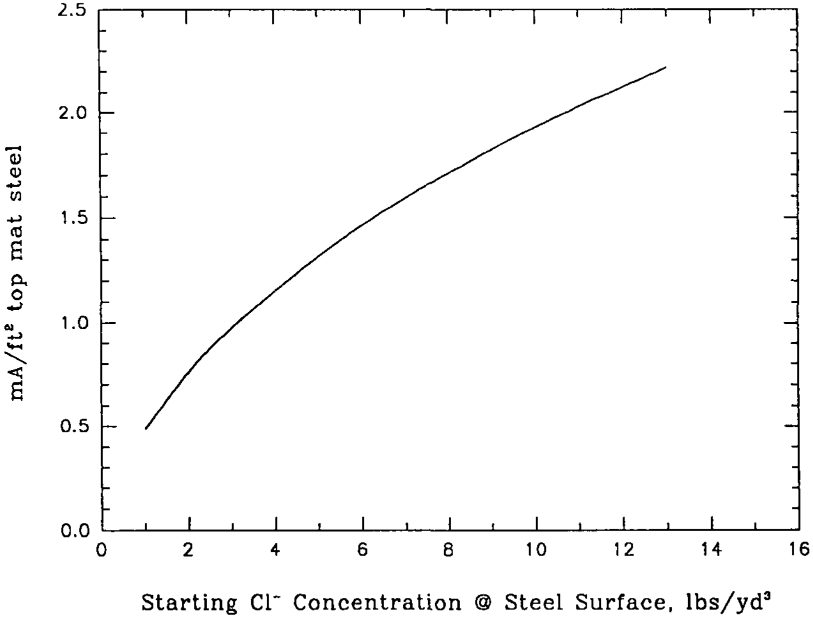
An alternative approach for estimating the chloride concentration at the surface of the steel is to use a random sampling procedure throughout the zone under study. SHRP research has demonstrated that a sampling of 12 points will give a representative mean and standard deviation for the zone. Thus, if the mean plus two standard deviations is used, a good estimate of the maximum chloride concentration at the surface of the steel can be made.

Proper current for the zone is calculated using the following formula:

$$\text{mA/ft}^2\text{ concrete} = (\text{mA/ft}^2\text{ top mat steel}) \bullet (\text{ft}^2\text{ top mat steel/ft}^2\text{ concrete})$$

(for double-mat construction, divide mA/ft^2 concrete by 0.7 to get the total current required per square foot of concrete.)

Figure 8. **Graph for Determining Required Cathodic Protection Current**

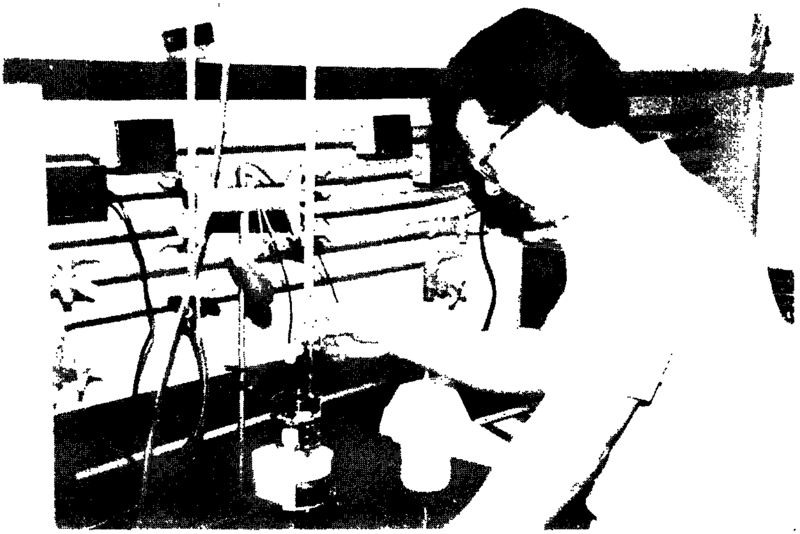


The current, as determined from this graph and calculation, can be expected to keep the steel corrosion rate below 0.1 mil/year (0.025 mm/year) after the first two months of operation. This is an acceptable rate to prevent corrosion damage. The corrosion rate will be slightly higher at first, but not high enough to justify a program of varying current with time. The graph also includes a safety factor of 0.25 mA/ft^2 concrete, which is appropriate for a well-designed system and assures that all the steel will be protected, regardless of its position within the zone.

To use this criterion, the highest chloride concentration at the level of the steel must be found. This can be done by first conducting a potential survey according to ASTM C 876-91, "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete." After the most corrosive sites have been located in the zone, concrete samples are taken and analyzed according to the American Association of State Highway and Transportation Officials (AASHTO) T 260-84, "Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials," or according to a SHRP guideline, "Method for Determination of Total Chloride Content" (figure 9).[1]

This method provides a very simple, but reasonably accurate criterion for cathodic protection of steel in concrete. Like the Corrosion Null Probe, it does not rely on the long-term stability of embedded reference electrodes, and its use in field structures is very limited. Additional field validation is needed. The Constant Current criterion could be the simplest method for establishing the needed level of protection for the steel while avoiding unnecessary overprotection.

Figure 9. Titration for Total Chloride Determination



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[1] Cady, P., et al. 1992. Condition Evaluation of Concrete Bridges Relative to Reinforcement Corrosion, Volume 6: Method for Field Determination of Total Chloride Content. Report no. SHRP-S-328. Washington DC: SHRP, National Research Council.