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FIELD TESTS ON AN ADVANCED CATHODIC PROTECTION COUPON

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ABSTRACT

An advanced cathodic protection coupon design which eliminates almost all of the soil IR drop during current-on potential measurements has been developed. Potential measurements are made through a slot in the geometric center of the coupon, a design sometimes referred to as a concentric coupon. This design greatly minimizes the electrolyte distance between the reference electrode and the coupon, which, in turn, minimizes the IR drop error contained in the measurements. This paper presents results from laboratory and field tests on this advanced coupon design.

Keywords: concentric coupons, cathodic protection, voltage drop, pipelines, field study

INTRODUCTION

Background

Potential measurements made on cathodically protected underground structures often contain an inaccuracy known as IR drop or voltage drop error. Electric current from any source flowing through soil is the source of this voltage drop; it is proportional to both the amount of current and soil resistivity. This voltage drop becomes incorporated into potential measurements as an error. Since potential measurements are used to determine adequacy of cathodic protection (CP) on a structure, errors in these measurements can lead to incorrect conclusions. In recognition of this, NACE Standard RP0169[1] was modified to require that voltage drop error be considered when interpreting potential measurements made with CP current on.

Clearly, one way to obtain potential measurements that are free of voltage drop error is to interrupt the current by disconnecting the source of this current and measuring the potential of the structure before it has begun to depolarize. This practice, commonly called making instant-off measurements, can be a very accurate way to make potential measurements. In reality, however, making measurements completely free of voltage drop error is not always possible because some currents cannot be easily interrupted. Uninterruptible current sources may include: sacrificial anodes directly bonded to the structure, foreign rectifiers, stray currents, telluric currents and long-line cells. When several rectifiers protect a structure, it is necessary that all rectifiers be interrupted at the exact same instant in order to obtain meaningful measurements. The amount of time between current interruption and depolarization can vary from a fraction of a second to several seconds, depending upon details of the structure. In addition, capacitive spikes that occur shortly after current is interrupted may mask the instant-off potential. Measurements made with a recording voltmeter are preferred as they can be subsequently analyzed to determine the real instant-off potential.

Cathodic Protection (CP) coupons are now being used as an alternative method to make potential measurements that may be substantially free of voltage drop error. A CP coupon is a small piece of metal that is electrically connected to the structure at a test station. The potential of a coupon will closely approximate the potential of any exposed portion of the structure (holiday) located in the vicinity of the coupon. By disconnecting the coupon from the structure at the test station, an instant-off potential measurement can be made on the coupon without having to interrupt any other current sources. However, these measurements are still not completely free of voltage drop error. Any voltage drop occurring in the electrolyte in the distance between the reference electrode and the coupon surface will still be incorporated into measurements. Placing a reference electrode as close as possible to a coupon can minimize this error. However, the reference electrode must not be placed so close that it shields the coupon.

CP Coupon Designs

CP coupons must be made from a metal whose corrosion behavior in the electrolyte approximates that of the structure. Since most cathodically protected buried structures are steel pipelines or tanks, CP coupons are usually made from plain carbon steel. Earliest CP coupons were short steel rods with two lead wires attached. Dual lead wires are used so that the current carrying wire is separate from the wire used to measure potential, thereby eliminating a possible error source. Coupons of this design can be purchased commercially as stand-alone units or attached to a permanent reference electrode by a short lead wire. Ring shaped coupons bonded to the housing of a reference electrode are also available. This design does reduce electrolyte path length between the reference and the coupon, but in many cases, salts leaching from the reference electrode will attack the coupon changing its characteristics.

Attaching a CP coupon to the base of a test station riser can also reduce electrolyte path length. A reference electrode is placed in the riser and the measurement path is through the inside of the riser; in this case the riser is acting as a salt bridge. The only portion of the measurement path where voltage drop error can accumulate is between the bottom of the riser and the exposed coupon. A comprehensive discussion of CP coupon technology can be found in NACE Publication 35201 prepared by NACE TCC Task Group 210[2].

Concentric CP Coupon

Nekoksa has proposed the use of flat coupons with a sensing port in the center of the coupon[3] as a design which minimizes many limitations found with commonly used cylindrical coupons, either free standing or attached to a test station riser. Cylindrical coupons receive CP current from all sides. This results in a different electric field pattern in the soil adjacent to the coupon than would be found adjacent to a coating holiday that is only exposed and receiving current on one side. A cylindrical CP coupon may therefore have a higher current density and, consequently, a more negative potential, than a holiday located in the area. Under these conditions, potential data obtained using a cylindrical CP coupon would indicate a greater level of protection than actually does exist.

In a review article on CP coupons, Gummow pointed out that as much as 90% of the total voltage drop error can be developed within a 5 cm. radial distance of a 1 cm diameter holiday[4]. This rapid development of voltage drop error makes it impractical to place a reference electrode close enough to the coupon to significantly reduce error. The electrode itself would shield the coupon, preventing it from receiving the same amount of CP current that it would if it were not shielded. It would, therefore, not be representative of a holiday in the area but rather indicate an under-protected condition. The Nekoksa design avoids this problem by placing a sensing membrane in the geometric center of the coupon and the reference electrode on the backside[5]. This arrangement allows potential in the central area of the coupon to be measured without having the reference electrode shield the coupon. It also avoids having potential measurements influenced by the higher current density that can exist around the periphery of the coupon (edge effect).

CP coupons with a centered sensing membrane are sometimes referred to as concentric CP coupons. One such coupon, which was designed and manufactured under license, is shown in Figure 1. The dark strip in the center is an end-grain wood membrane that resists clogging during dry-out. The steel coupon is the lighter strips on either side of the membrane; these strips are electrically bonded to each other so they function as a single coupon. The exposed area on this coupon is 10 sq. cm. and is defined during manufacture by the size of the cover plate window. By adjusting the window size accordingly, other exposed areas are possible. The coupon has dual lead wires that, as stated earlier, provides for separate lead wires for current connection and potential measurements. This feature is particularly important on coupons of this design because they are intended to allow accurate potential measurements without having to interrupt current.

The coupon housing is made from 2-inch IPS PVC pipe and the interior is filled with a conductive backfill. When the coupon is installed, it is placed vertically near the pipe and screened local backfill is placed against it as shown in Figure 2a. A 2-inch IPS PVC coupling and an appropriate length of 2-inch IPS PVC pipe are cemented in place to the top of the coupon housing (Figure 2b). The interior of the riser is then filled with a conductive backfill consisting of 25% bentonite and the balance sand or screened local soil. Measurements on the coupon are made with a reference electrode contacting the fill in the riser column. Alternatively, a reduced diameter reference electrode can be placed in the riser column and encased in the riser fill.

This paper describes laboratory and field testing done to characterize concentric coupons of this design. Specifically investigated was the degree to which voltage drop is eliminated in current-on potential measurements. Also investigated was the effect of coupon placement, both distance from the pipe and orientation. The test program consisted of two phases: laboratory testing done in a small tank and field testing conducted in a way so as to simulate a typical application.

PROCEDURE

Laboratory Tests

Laboratory testing in a tank was conducted prior to field testing in order to characterize the coupons and assist in field test planning. The test arrangement, shown in Figure 3, consisted of a 22 inch x 14 inch x 11 inch (55 cm x 35 cm x 28 cm) tank filled with tap water with a resistivity of about 6,600 Ω-cm. The anode consisted of four equi-spaced mixed metal oxide coated titanium wires at one end of the tank; the "structure" was four equi-spaced 1-inch IPS black iron pipes at the other end. Measuring structure potential from various locations around the tank showed that a very uniform voltage drop field was developed. Individual CP coupon assemblies could be located at defined positions between the anode and structure for testing.

Field Tests

Field testing was conducted in a rural area remote from any other known underground cathodic protection systems. The test bed consisted of two 60-foot (18 m) lengths of 2-inch IPS pipe. One pipe was bare; the other had an extruded plastic coating on it. Three "defects" were cut into the coating on the second pipe, one each at 1 sq. cm., 3 sq. cm. and 10 sq. cm. A cluster of test CP coupons were located in the immediate vicinity of each defect, as shown in Figure 4, as well as at several location along the bare pipe. Four special salt bridges were constructed and located in order to be able to measure the potential near the center of each defect on the coated pipe (see Figure 5) as well as at a location on the bare pipe. A plan view of the test bed is shown in Appendix A.

Each pipe had its own rectifier driving a silicon iron anode in a coke column. The anodes are located about 30 feet (9 m) from the end of the pipe and off to one side. Because large numbers of test coupons could easily distort the current field around the coated pipe defects, no more than two CP coupons were connected to this pipe at any one defect location and at any one time. Coupons were connected a minimum of 24 hrs before measurements were made. Only one of the two CP systems (bare pipe or coated pipe) was in operation when measurements were made to further eliminate outside interference during measurements; the other one was temporarily disconnected.

Potentials were measured in both lab and field tests with a recording voltmeter set to record at 20 times per second. Testing consisted of measuring CP coupon potential with current on and then disconnecting the rectifier while still recording. Whenever coupons were tested, an instant-off potential of the pipe was measured using a reference electrode located on the surface over the pipe in the vicinity of the coupon. All potentials reported in this paper were measured using a copper/copper sulfate reference electrode (CSE).

RESULTS

Elimination of Voltage Drop

Lab Tests. Initial characterization of these concentric CP coupons was done in the test tank previously described. Several replicates were tested along with a ½ inch (1.2 cm) diameter steel rod coupon. A 5 milliamp current polarized the structure 200 mV to –800 mV as measured 5 mm from the pipe. A rod coupon with a reference electrode secured adjacent to it was positioned 10 cm from the pipe. Disconnecting this coupon from the structure caused an immediate voltage drop of about 120 mV with an additional voltage drop occurring when the rectifier was next disconnected. The combined voltage drop was the same as when the rectifier was interrupted with the rod coupon still connected to the structure (Figure 6). This suggests that coupon-disconnect potentials with a rod coupon still contain a residual voltage drop error in the presence of a current field.

The same procedure was repeated with a concentric CP coupon located at the same position. A 30 mV drop was observed when the concentric coupon was disconnected from the structure; no further drop was observed when the rectifier was next disconnected. The same voltage drop was noted when the rectifier was interrupted with the coupon still connected to the structure. Both curves were virtually identical as shown in Figure 6. This indicates that current-on measurements with concentric CP coupons contain only minor voltage drop error and that either disconnecting the coupon or interrupting the rectifier will substantially eliminate this error when necessary.

Field Tests. Initial testing was intended to measure the effectiveness of the special salt bridges located at each intentional defect as shown in Figure 5. Pipe potential was measured from the surface as the rectifier was interrupted; this was repeated with the measurement being made through the salt bridge. These tests were conducted three times at progressively higher current levels. Test results shown in Figure 7 indicate that salt bridges eliminated only a very minor amount of voltage drop error from current-on measurements. The amount of error eliminated increased as the current field intensified.

A similar procedure was used to test concentric CP coupons: first, pipe potential was measured from the surface while the rectifier was interrupted; then, potential of a concentric coupon connected to the pipe was measured while current was interrupted. The results, shown in Figure 8, were as predicted by our lab tests. The amount of voltage drop error in current-on measurements of concentric CP coupons ranged from 2 to 10 millivolts while the error in surface measurements at those sites ranged from 700 to 1,000 millivolts. This further validates that current-on measurements made with concentric CP coupons contain negligible voltage drop error.

Effect of Electrolyte Resistivity

The summer of 2004 was exceptionally rainy at the field test location. As a result, ground resistivity was extremely low for this location, typically less than 1 kilo-ohm-cm as measured using the four-pin method with 5 foot (1.5 m) rod spacing. All the data reported above was collected during the summer and fall of 2004. The test site was actually established during the summer of 2002 with limited data being collected then and a more extensive set of measurements being made the following year (2003) when resistivity at the site was a more typical 3 kilo-ohm-cm measured in undisturbed soil in the test area. Significant settling occurred over the pipe during the winter of 2003-2004. This suggests that soil resistivity adjacent to the pipe and coupons in 2003 may have been higher than the measured value of 3 kilo-ohm-cm because that soil had not yet fully compacted.

Rectifier-interrupt measurements made on the same coupon in 2003 and 2004 are shown in Figure 9. Since the primary difference between these two measurements is electrolyte resistivity, a measurement from the test tank containing 6 kilo-ohm-cm tap water is included to further explore the effect of electrolyte resistivity. The data presentation remains as before: a rectifier-interrupt measurement from the surface paired with one using a concentric CP coupon.

The amount of voltage drop error contained in current-on measurements made with concentric CP coupons is proportional to electrolyte resistivity. In 1 kilo-ohm-cm soil, voltage drop errors in surface vs. concentric coupon measurements were 600 mV and 2 mV respectively. In this case, over

99% of this error was eliminated. In 3 kilo-ohm-cm soil, values were about 300 mV and 30 mV which means the coupon eliminated about 90% of the voltage drop error in current-on measurements. Finally, in 6 kilo-ohm-cm tap water in the test tank, values were 300 mV and 35 mV showing that the concentric CP coupon eliminated 88% of the error. The small difference in coupon effectiveness between the 3 and 6 kilo-ohm-cm electrolytes makes us further suspect that actual soil resistivity adjacent to the coupons was higher than that measured in 2003 as discussed above. Others have also observed that the amount of voltage drop error in current-on measurements eliminated by concentric CP coupons is greater in low resistivity electrolytes.[6]

Effect of Distance from the Pipeline

At several of the test locations, coupons were located at varying distances from the pipe to determine whether this had an effect on measurements. The results, shown in Figure 10, are for three separate current levels that created voltage drop errors in surface measurements of 100, 200 and 400 mV. A coupon 6 inches (15 cm) from the pipe had current-on voltage drop errors of 1, 1 and 3 mV respectively while one 18 inches (45 cm) from the pipe had 0, 2 and 4 mV errors in the measurements. These coupons were at a different location than the ones discussed above, but the results were the same: over 99% of the voltage drop error was eliminated in current-on measurements. Furthermore, there did not seem to be any effect of distance on the amount of error eliminated but there was a distance effect in the actual potential reported. Coupons further away from the pipe showed a more electropositive potential indicating they are receiving less current, which is to be expected.

Directional Effects

At cluster #1, located at the end of the bare pipe closest to the anode, four concentric CP coupons facing 90 degrees apart were placed about 6 inches (15 cm) from the pipe (refer to Appendix A for plan views of the test site). Current-on potential measurements were made with these coupons at two different current levels which produced voltage drop errors in surface readings of 600 mV and 1,100 mV. A clear directional effect is shown in the data below. Current-on measurements with concentric coupons contain the least voltage drop error when the coupon faces both the pipe and the anode. The greatest contained error occurs when the coupon faces the anode and is perpendicular to the pipe.

Coupon # and Orientation	Contained error, mV (%) at 600 mV	Contained error, mV (%) at 1,200 mV
#1-1: Facing anode & pipe	0 (0%)	3 (0.3%)
#1-2: Facing anode, perpendicular to pipe	8 (1.3%)	15 (1.3%)
#1-3: Back to anode and pipe	4 (0.7%)	6 (0.5%)
#1-4: Back to anode, perpendicular to pipe	4 (0.7%)	6 (0.5%)

Directionality effects were also explored in the laboratory tank tests where the coupon was located between the anode and the structure. The voltage drop error in a surface reading during this test was 300 mV. The error in measurements made through concentric coupons was as follows:

Coupon orientation	Contained error, mV (%)
Facing structure, back to anode	35 (12%)
Perpendicular to structure and anode	56 (19%)
Back to structure, facing anode	67 (22%)

On reviewing both data sets, it is apparent that when the coupon faces the structure, current-on readings through it contain the least amount of contained voltage drop error. The effect of electrolyte resistivity, discussed previously, is also apparent on comparing the two data sets.

CONCLUSIONS

1. Concentric CP coupons are a very effective way to substantially eliminate voltage drop error from current-on readings.

2. The effectiveness of concentric CP coupons varies with electrolyte resistivity. In high resistivity electrolytes, using these coupons will eliminate about 90% of the voltage drop error. In lower resistivity electrolytes, virtually all the voltage drop error is eliminated from current-on readings made with concentric CP coupons.

3. The performance of concentric CP coupons can vary depending on their orientation with respect to the structure. Best results are achieved when the coupon is positioned so that it faces the structure.

4. The distance a concentric CP coupon is placed from the structure does not appear to affect its ability to eliminate voltage drop from current-on measurements. However, if it is placed too far away from the structure, the measured potential may be more electro-positive than that on the structure. A compromise position should be sought where the coupon is placed far enough away from the structure so that it is not shielded by it, but not so far away that it is not representative of conditions at the pipe.

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6. G. Nekoksa, Private communication.

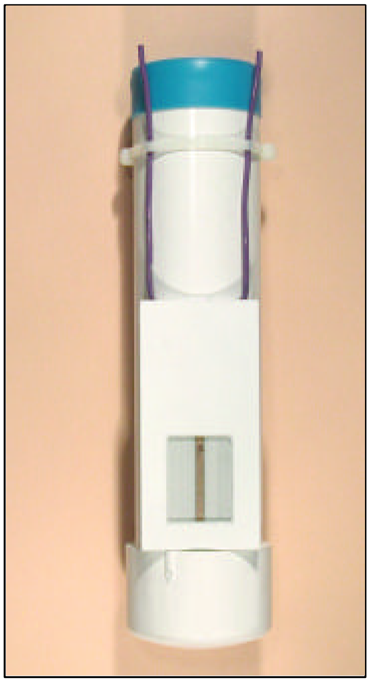


Figure 1

Concentric CP coupon designed to be fitted to the base of a test station riser. The dark strip in the center is an end-grain wood membrane that resists clogging during dry-out. The lighter strips on either side are electrically bonded to each other and make up the steel cathodic protection coupon. Potential measurements on this coupon are made with a reference electrode placed in the riser tube.

Figure 2a

The coupon assembly is installed vertically near the pipe. Screened local soil is packed tightly around the coupon.

Figure 2b

Installation is completed by cementing a 2-inch IPS PVC coupling and an appropriate length of 2-inch IPS PVC riser pipe to the top of the coupon housing. The interior of the riser is then filled with a conductive backfill consisting of 25% bentonite, with the balance sand or screened local soil.

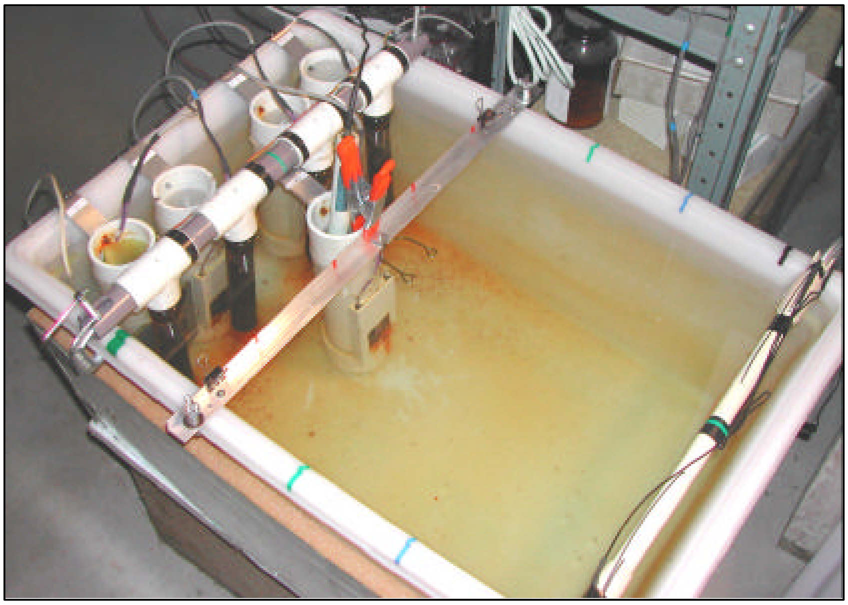


Figure 3

Initial testing of the coupons was done in a tank filled with tap water. The anode wires are on the right; four sections of pipe representing the structure are on the left. The coupon being tested is clamped to the cross-bar in the left-center.

Figure 4

The coated pipe had defects of a known size cut through the coating. Several coupons of varying designs were clustered around the defect.

Figure 5

Special salt bridges were fitted to the pipe at each defect. The photo shows the base of the salt bridge in position. The next step was to attach a riser tube and fill with a conductive backfill. Potentials were measured through the riser tube.

Figure 6

Comparison of instant-off potentials in the test tank as measured by a rod coupon vs. a concentric coupon. In the curves labeled CR, first the coupon was disconnected with the rectifier on and then the rectifier was disconnected. In the curves labeled R, only the rectifier was disconnected. The two curves are virtually identical for the concentric coupon but very different for the rod coupon. This indicates that for concentric coupons, coupon-disconnect potentials are nearly equivalent to rectifier-interrupt potentials in minimizing voltage drop error.

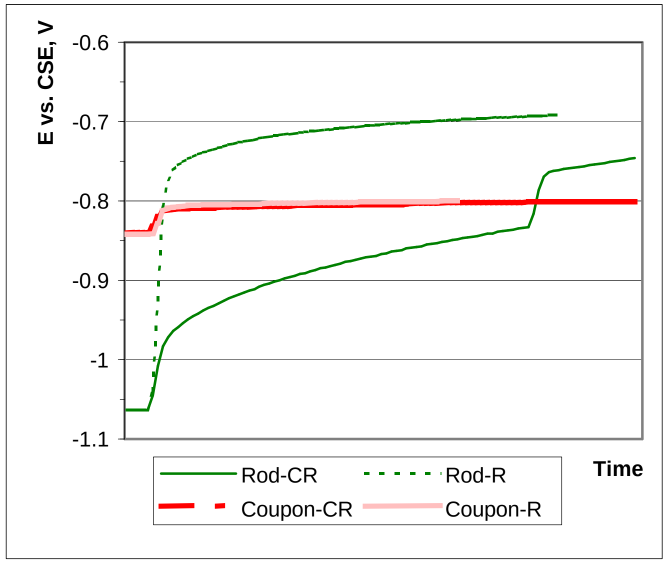


Figure 7

Comparison of rectifier-interrupt potentials as measured from the surface and through a salt bridge (Figure 5) at three different intentional defects in the coated pipe. The comparison was done three times at different current levels. Salt bridges eliminate only a very small amount of the voltage drop error from current-on measurements.

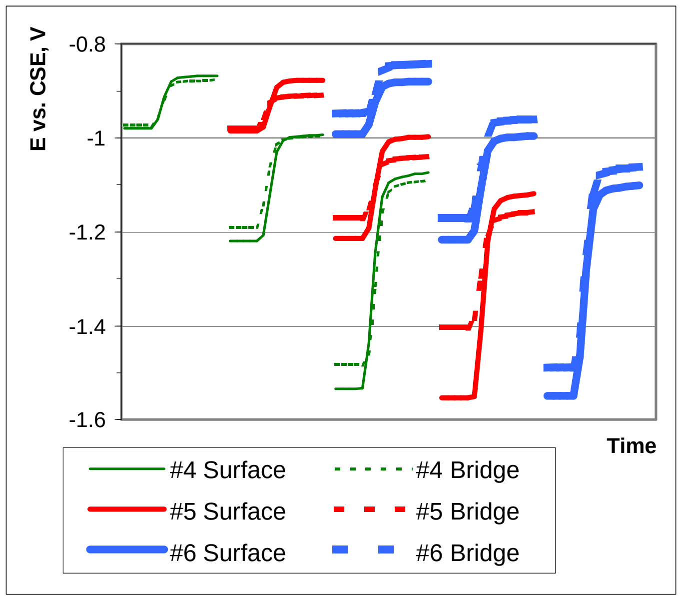


Figure 8

Comparison of rectifier-interrupt potentials as measured from the surface and through a concentric coupon (Figure 1). Coupons at three different locations with differing current levels were tested and all gave similar results: current-on potentials were virtually the same as rectifier-interrupt potentials. This indicates very little voltage drop error in current-on potentials made using concentric coupons.

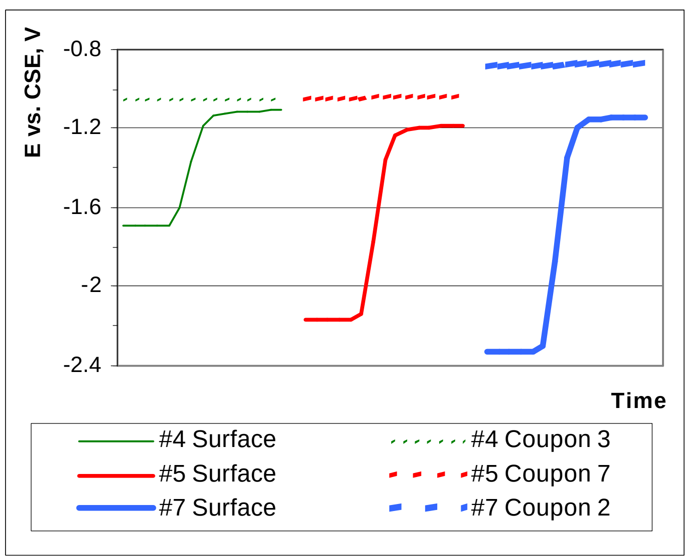


Figure 9

Comparison of rectifier-interrupt measurements made using concentric coupons in electrolytes of three different resistivities: 1 kΩ-cm, 3 kΩ-cm and 6 kΩ-cm. The amount of residual voltage drop error in current-on measurements is much smaller in low resistivity electrolytes than it is in high resistivity electrolytes.

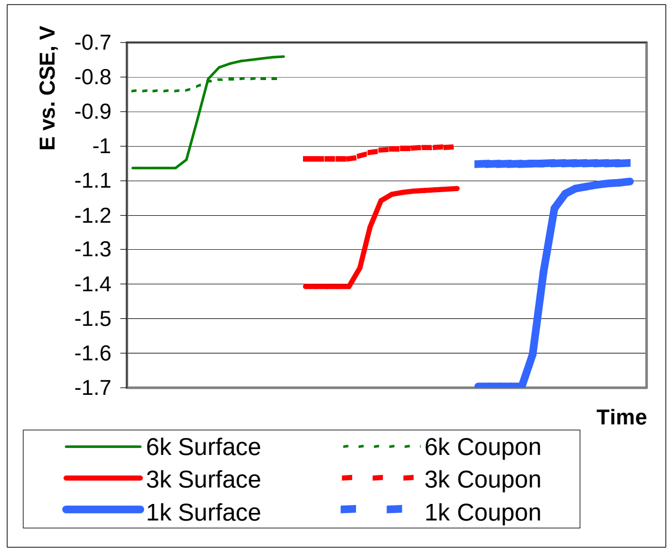
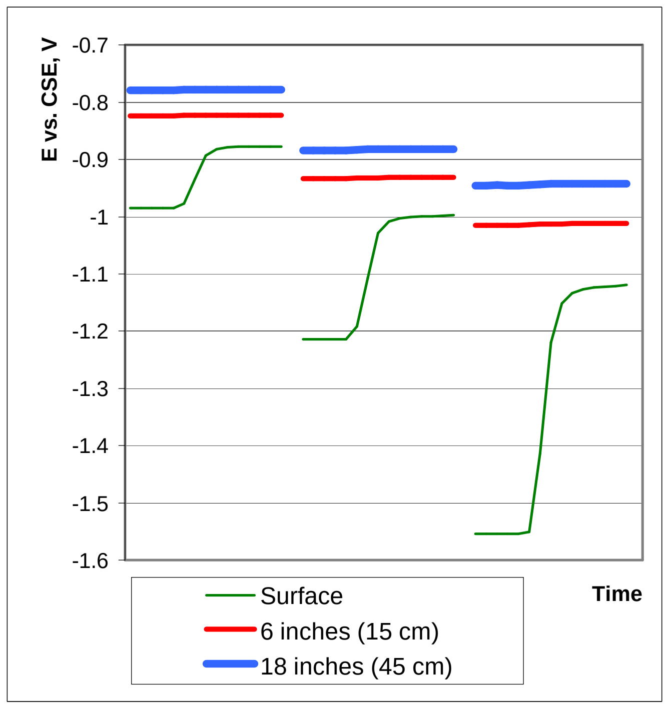


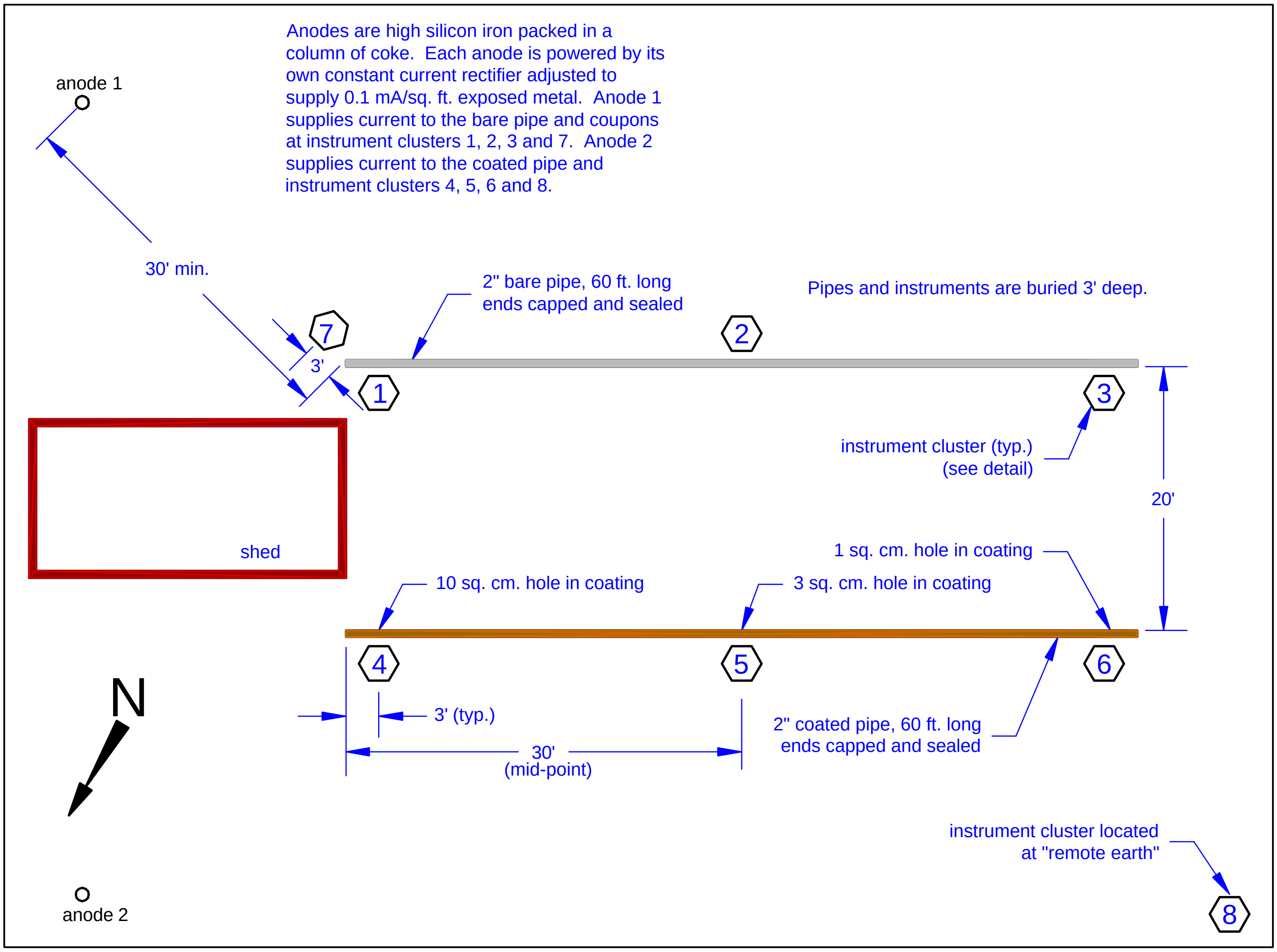
Figure 10

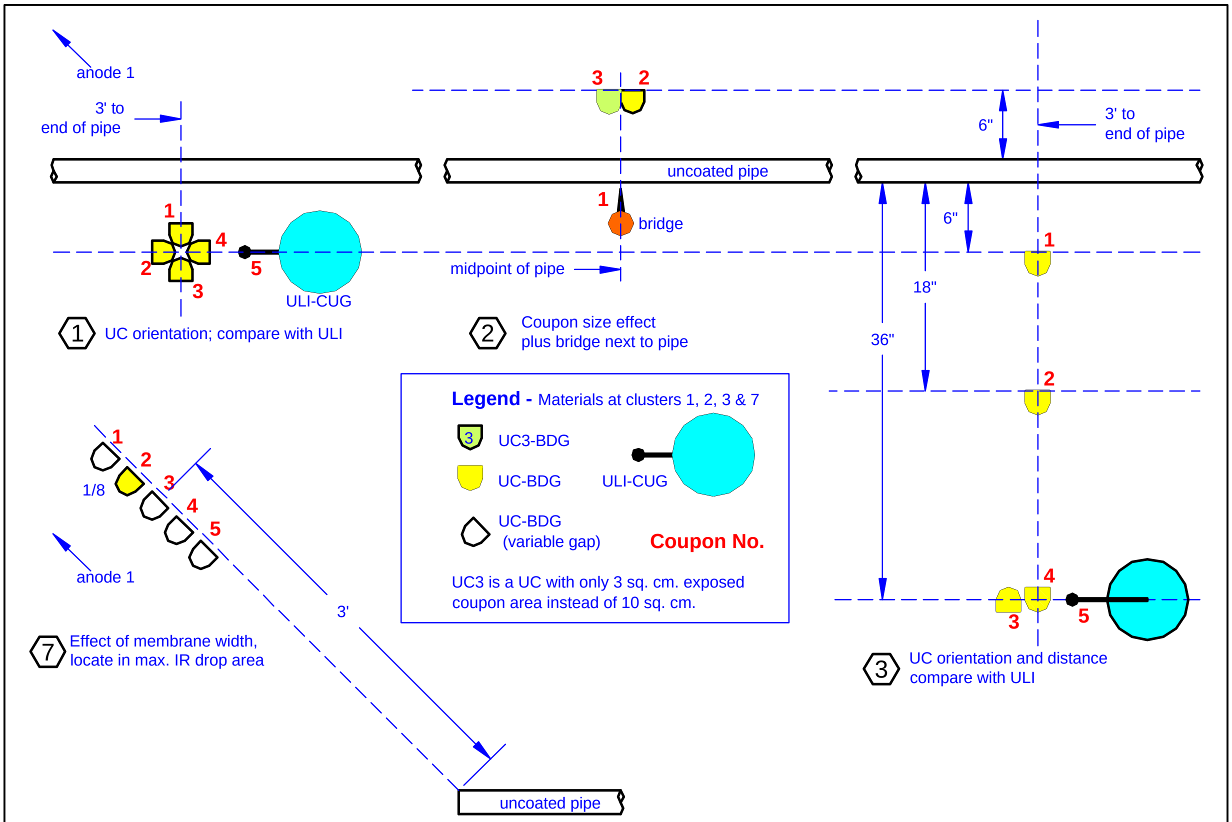
Comparison of rectifier-interrupt measurements made using concentric coupons at two different distances from the same defect. Coupons tested at three different current levels all gave similar results. The coupon furthest from the pipe showed a more electro-positive potential. Coupons at both locations had negligible voltage drop error in the current-on measurements.



APPENDIX A

The test site is located in a rural area in northeastern Ohio, well away from any known underground cathodic protection systems. It was installed in the summer of 2002. Below is an overall plan view of the site as well as detail plan views of each pipe.





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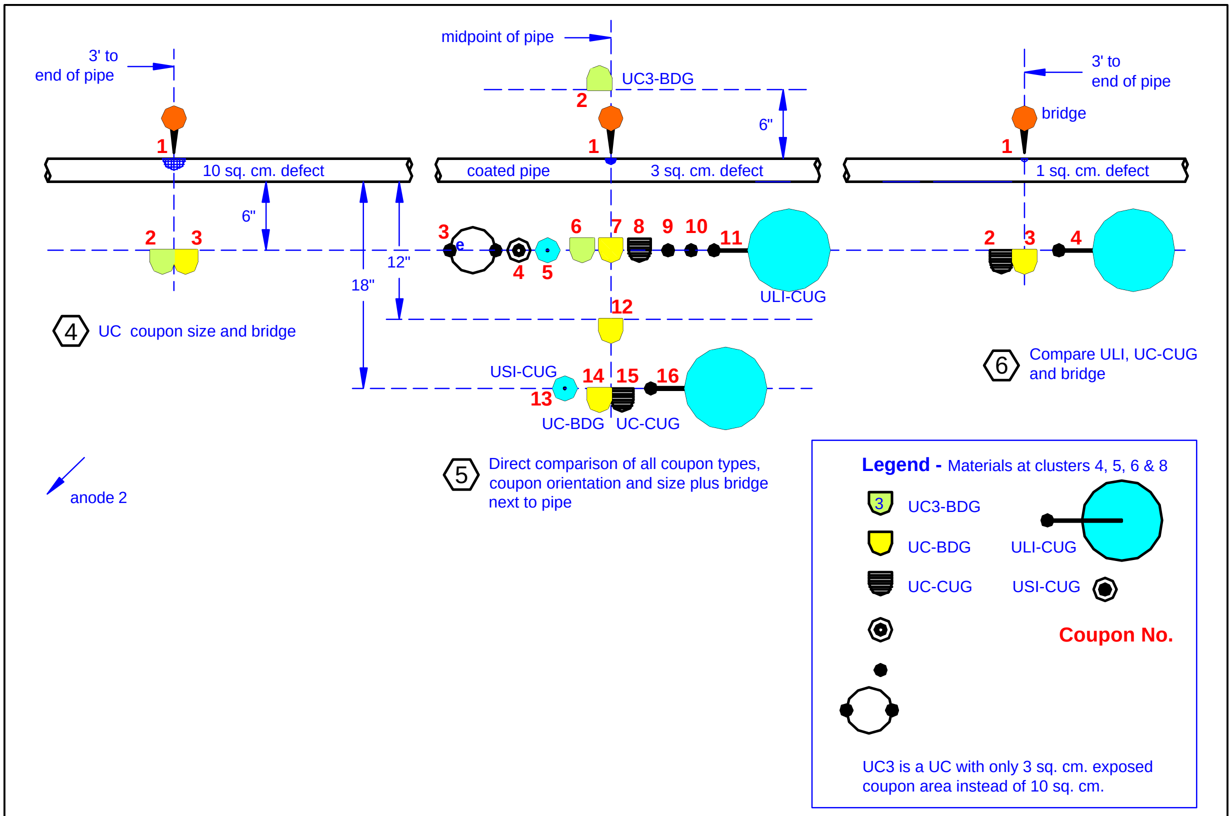

Ohio Underground Test - Instrument Cluster Detail: 4, 5, & 6