USE OF CORROSION COUPONS

Thomas J. Barlo, Ph.D.
CC Technologies, Inc.
359 Kensington Court
Palatine, Illinois 60067
U.S.A.

Osvaldo Rossi
Transportadora de Gas del Norte S.A.
Don Bosco 3672
Federal Capital, Buenos Aires 1206
Argentina

Abstract: The use of coupons in a corrosion integrity management program is reviewed. Their use includes monitoring the level of cathodic protection, relating the corrosion rate to the level of protection, and estimating the corrosion growth rates of in-line inspection defects for re-inspection and maintenance scheduling. The results from several field studies are analyzed to illustrate the significance of various coupon design parameters and features, and environmental conditions. Methods to determine the general and maximum pitting rates using coupons are illustrated and discussed.

Key Words: coupons, corrosion rate, cathodic protection, pipelines, integrity management.

INTRODUCTION

There are a number of threats to pipeline integrity that constitute risk to operating companies. One of the principal threats is external corrosion, caused by interaction of the steel pipe with the environment. The principal pro-active way of managing that threat is the application and maintenance of an effective anti-corrosion coating and cathodic protection system. Evaluation of the efficacy of cathodic protection depends on the monitoring practices and interpretation of the data with respect to criteria used by industry world-wide. However, supplemental inspection methods, such as by in-line inspection tools or inspection digs, help to determine if modifications are needed in the cathodic protection and/or coating systems, or if pipe replacement or recoating may be warranted. Today, monitoring and inspection data are often put into databases, which are part of the framework of an integrity program. The integrity program integrates those data to assess the pipeline condition, evaluate risk to select and prioritize mitigation approaches, and report results to utilize the information for future monitoring and condition assessment.

Various types of monitoring measurements are used to assess the effectiveness of cathodic protection. These primarily involve measurements of the output of cathodic protection current sources and the protection level with respect to the criteria for cathodic protection. Those criteria from NACE International RP0169-96[1] include the following: (a) –850 mV ($Cu/CuSO_4$)

polarized potential, (b) –850 mV ($Cu/CuSO_4$) potential corrected for IR drops, and (c) 100 mV polarization. The most frequently used criterion is the –850 mV ($Cu/CuSO_4$) potential, whether as the polarized potential determined by rectifier interruption or by other methods of IR drop correction. The 100 mV polarization criterion is used most often on older, less well-coated pipelines. To accurately interpret either criterion requires that the IR drop component(s) be determined and removed from the measurement. There are situation, however, when this cannot be done. Such situations include areas where all influencing impressed-current or sacrificial-current sources cannot be interrupted or where interference exists from foreign or other non-interruptible current sources, such as traction systems or telluric activity.

One of the methods to overcome these problems is to use corrosion coupons or probes to determine the protection level. More recently, they have been used also to quantify the effectiveness of cathodic protection by local measurements of the corrosion rate or to generate corrosion rate data to predict the growth of corrosion defects found by in-line inspection so that future inspection runs and maintenance can be scheduled more cost effectively. This paper will review the various types of coupons and probes used for these purposes, and, where possible, the type of results obtained.

PURPOSES AND USES

There are a variety of coupons that have been used in the field to monitor cathodic protection levels and measure the associated corrosion rate. The designs used for some of those coupons are described here and the importance of physical and time-based measurement features are discussed below.

Corrosion coupons have been used by researchers and corrosion engineers for many years to resolve monitoring problems and measure corrosion rates. Interpretation of the results from coupons usually has one of the following purposes: (1) to infer the corresponding protection level on the pipeline, (2) to infer satisfactory operation of the cathodic-protection system, or (3) to assess the corrosion rate for the environment and cathodic protection level present on the pipeline. To determine the protection level on the pipeline, the potential or polarization level measured on the coupon is assumed to be that which exists locally on the pipeline. The exposed area on the coupon is selected to represent a known or assumed holiday area in the coating. To infer satisfactory operation of the cathodic protection system, the exposed area on the coupon is selected to represent the largest known or assumed holiday. If the polarized potential or the amount of polarization on the coupon is sufficient to satisfy either one or both of the appropriate criteria, then the cathodic protection system is assumed to be capable of providing adequate protection to the pipe. By choosing the largest assumed exposed area, the coupon potential should represent the least negatively polarized holiday locally, thus giving a conservative indication of the level of protection.[2] If, however, the holiday is shielded, then the potential of the largest holiday may no longer represent the least negatively polarized holiday on the pipe.[2] To determine the corrosion rate for the protection conditions, the exposed area of the coupon is usually selected to allow accurate corrosion and appropriate criteria-related measurements rather than to necessarily represent any particular holiday in the coating. The combination of the criteria-related measurements of potential or polarization and the corrosion loss or rate are used to judge the adequacy of the level of protection.

One type of measurement situation that a coupon cannot accurately assess is that where shielding of the cathodic protection current from disbonded coating exists. All of the various types of coupons used to date have only freely exposed steel, a situation which will not replicate shielding.

The breadth of coupon usage can be gauged from a recent 1991 survey of 29 gas distribution and transmission companies in Europe and North America.[3] Nearly half (14) of the 29 companies surveyed are now using coupons to monitor cathodic protection on their pipelines. Five of the remaining 15 not using coupons at present plan to use them in the future. These companies operate collectively more than 100,000 km of pipelines, have nearly 8,000 coupons in place, and have less than 10 years of experience with coupons. Four of the companies, however, have been using coupons between 20 and 30 years.

DESIGNS

There are perhaps as many designs for coupons as there are researchers and engineers using them. Several coupon designs are commercially available, but even those are still very different from each other and for their own reasons.[4,5,6] None the less, coupons all have several common features, which include being (1) buried in the soil near the pipeline, (2) electrically connected to the pipeline, and (3) often provided with a means of placing a reference electrode near the coupon surface to reduce the IR voltage drop when the coupon potential is measured.

Because of the variety of coupon designs used in the field, it will not be possible to review all of them here. Rather, a few will be described to illustrate the variety. The use of coupons for pipeline monitoring has been discussed in some detail in two technical reports,[3,7] articles in the open literature,[8-22] and in reports or papers of research studies conducted for individual pipeline companies and technical organizations.[18,19,22,23,24] The basic differences among the coupons mainly involve the shape, size, and number of coupons; the location of the reference electrode; and the method of interrupting the coupon from the pipe and cathodic protection source.

One of the simplest types of coupon is a flat, rectangular or square steel plate buried in the soil. Barlo[18,24] used a 49 cm^2 square coupon design like that illustrated in Figure 1. Coupons with one clean, machined surface and coupons with one mill-scaled surfaces were used; the other surfaces were masked off with a good anti-corrosion coating. Above each coupon was a 100 cm diameter polyvinylchloride (PVC) tube to permit the reference electrode to be placed within about 76 to 127 cm of the top of the coupon when measurements were made. Otherwise, the tube was capped to exclude moisture. The tube and coupon were placed 30 cm from the pipe and at the pipe centerline. A coated, solid copper wire threaded into the coupon provided a means of completely removing the electrical lead from the coupon for coupon weight-loss measurements before and after installation.

Beside being used to determine the general corrosion rate from weight loss, the coupon surface was used to determine the maximum pitting rate from pit depth measurements made on coupons removed serially from each group of eight at selected pipe potentials. The PVC tube above the coupon not only permitted the reference electrode to be placed near the coupon, but it allowed the coupon to be easily extracted by pushing the tube down over the coupon, capturing it in a sample of soil, and lifting the tube and its contents from the earth. The coupon lead was electrically connected to the pipe through a resistor that allowed the current direction and magnitude to be determined. Coupon current measurement is important because, in some cases, the coupon may actually be discharging current, which can lead to an inaccurate indication of the level of protection and corrosion rate. Over 400 of this type of coupon were used in North America to quantitatively assess the effectiveness of the cathodic protection level. Coupon potentials were measured with the protective current flowing and the coupon lead temporarily disconnected to determine the instant-off potential.

Figure 2 illustrates a somewhat more complicated permanent coupon design developed by von Baeckmann et. al.(3,8,9,10) some years ago, and still used quite frequently in Europe today.(3) The coupon is either a 10 cm² or 30 cm² steel disk fixed into the bottom of a plastic canister that houses a permanent calomel or copper sulfate reference electrode. The integral reference electrode measures the coupon potential through a porous plug in the center of the coupon. The coupon is typically oriented at an angle to the pipe. Because the reference electrode is so near the coupon surface, the potential of the coupon may be considered free of IR voltage drop error. However, the lead between the coupon and pipe can be disconnected also to interrupt the cathodic protection current and allow an instant-off potential to be determined.

Figure 3 shows a simple circular-shaped coupon used by Kasahara et. al.(14,15) with an electronic current interruption method. The coupon was 0.12 cm² in area and oriented horizontally near the pipe and a reference electrode buried in the soil. A zero-resistance ammeter, current interrupter, electrometer, and pen recorder were used to electronically disconnect the coupon lead from the pipe and measure the coupon instant-off potential and current. This coupon design was used primarily in stray current areas to determine the polarized potential.

A coupon shaped differently from a circular disk or flat plate is being used by Moghissi et. al.,(21) and Stears et. al.(22) in their studies on the Trans Alaska Pipeline. This design,(6,20) shown in Figure 4, utilizes two 40 cm² pipe-shaped coupons separated by approximately 3 cm on a 3.2 cm diameter polycarbonate tube. A porous plug at the bottom of the access tube and a 13-cm deep mixture of silica sand and screened native soil allow the reference electrode to measure the potential of cylindrical coupons that are about 2.5 cm away. One or both of the coupons can be electrically connected to the pipe through test station connections that allow interruption of the circuit between the coupon and the pipe. In some cases, the second coupon is used for replication, while in others it is allowed to remain at its free-corrosion potential for comparison purposes and possible indications of the polarization level of the polarized coupon.

A slightly different coupon test station from that in Figure 4 is shown in Figure 5. The design in Figure 5 also integrates two coupons with a test station.(4) The coupons are two 9 cm² cylindrical rods mounted at the end of a 7.6 diameter plastic tube that is filled with native soil. The soil in the tube is in contact with the native soil near the pipe and acts like a Lüggin capillary when the reference electrode is placed in the interior tube soil. This arrangement effectively places the reference electrode near the coupon to minimize IR voltage drops when the coupon potentials are measured. Disconnecting the coupon lead from the pipe lead allows the coupon instant-off potential to be measured. Also, a separate connection allows the coupon current and direction to be measured with a zero-resistance ammeter. Both coupons can be polarized and used for replication purposes, or one can be used as a backup. Also, one can be left disconnected from the circuit and used to indicate the free-corrosion potential for estimating the polarization level on the polarized coupon. The head of the coupon test station is fitted also with an RS232 receptacle to allow on-potentials, instant-off potentials, and free-corrosion potentials and current to be monitored automatically with a compatible data logging instrument.

Coupons used to determine the corrosion rate have had several different designs depending on the method of determining the corrosion rate and the form of corrosion to be measured. The flat, square coupons in Figure 1 have been used to determine the general corrosion rate by weight loss, as well as the average and maximum pitting rates related to various criteria parameters.[18] In another study of the criteria for cathodic protection,[19] small-diameter cylindrical steel rods were used for coupons, approximately 7.1 mm in diameter and 7.6 cm long, placed under soil-filled PVC tubes and connected as in Figure 1 to cathodically protected large-diameter pipe specimen coupons. The small coupons were monitored and weight loss measurements were made from which the general corrosion rate was determined. These coupons were companions to the 61-cm diameter, 3-m long pipe sections which were analyzed as coupons by wall-thickness loss measurements before and after test to determine the general corrosion rate, and pit depth measurements to determine the average and maximum pitting corrosion rates.

Commercially available electric-resistance probes have been designed to measure the corrosion rate by changes in thickness.[5,25] This type of coupon uses either a thin, flat rectangular steel element or a thin, cylindrical element electrically connected to the structure to be protected. One type is illustrated in Figure 1. The area of these coupons is typically of the order of 5 cm^2 and 0.2 mm thick, or greater. They are monitored with regard to the criteria in the usual manner. The general corrosion rate, however, is determined while cathodically protected (or not protected) by measuring the change in thickness as the specimen corrodes using a specially designed bridge instrument that measures the change in resistance of the thin sensing element. Electric resistance probes have been used in various studies either connected to the structure being protected or unconnected at their free corrosion potential.[18,24,26]

A different approach to measuring the corrosion rate is to use the coupon design in Figure 5, for example, and measure the corrosion rate of an unpolarized coupon by the linear-polarization resistance (LPR) technique. This can be done using available coupons and commercially available instrumentation.[4] There are no restrictions on the size or orientation of the coupon for this method, except that the area be known and sufficiently small to be used within the instrument current supply capabilities. This technique is limited to measurement of the general corrosion rate on unpolarized coupons only. The justification for determining the unpolarized coupon corrosion rate is that it likely reflects a worst-case condition, which may occur under disbonded coating that is shielded from cathodic protection current.

Using the coupon design of Figure 5, again for example, an alternative approach is being used to determine the corrosion rate for defect growth rate predictions.[19,26,27] Here also, there are no restrictions on the size or orientation of the coupon other than its area be known and sufficiently small to be polarized to at least –1000 mV ($Cu/CuSO_4$) by the current source available. Although the method can be applied to a depolarized coupon that has been protected or one that has never been protected, it is capable of characterizing the general corrosion rate for a range of polarized potentials. The method requires the development of the cathodic portion of a polarization (E - Log I) curve using a small, temporary current source to produce step-wise current increments and their associated polarized potentials. From analysis of the relationships among the potentials, currents, and the cathodic Tafel slope line, the anodic Tafel slope line is determined and extended into the cathodic region where the anodic current or corrosion rate is calculated as a function of the polarized potential.

Despite the diversity in the coupon designs as indicated above, most all apparently have been used to successfully monitor the structure to which they were connected and generate corrosion rates. In the following sections, the physical features and dimensions of coupons, as well as temporal aspects of their initial and long-term monitoring will be discussed and critiqued where possible. Also, an extension of coupons to quantitatively determine the level of protection by the corrosion rate will be presented to demonstrate their utility beyond conventional monitoring.

DIMENSIONS

Installation of coupons and their associated test stations have been discussed in some of the literature references, but will not be discussed here. However, the physical features of a coupon design, namely the shape, size, orientation, and surface condition of the coupon, and the location of the reference electrode, will be reviewed and critiqued. Most of these features are selected on the basis of convenience, but there are some reasons to choose one type of feature or condition over another, as discussed below.

Table 1 summarizes some of these features from an earlier survey on coupons and the literature. Table 2 is a summary of some physical features from the more recent GERG survey.[3] The information in Table 1 agrees with the GERG survey in that there is no consistent shape and size for the coupon, though the coupon area is typically less than 100 cm². Moreover, there is no consistent location for the reference electrode, although there is a propensity to have a permanent reference electrode as part of the coupon test station design, which may be expected for long-term use. Further, the physical orientation of the coupon is variable, and tends to be 0°, 45°, or 90° with respect to ground level. Only the separation between the pipe and coupon has any consistency, which favors distances between 10 and 50 cm. However, for the coupon to polarize to potentials like those on the pipe, the coupon should be no closer to the anode than the pipe coating defect.[21] This is only a concern when a close galvanic or distributed impressed anode is present. In this case, the coupon should be no closer than about 10 coupon diameters from the nearby anode.

It is interesting to note that despite the wide range of coupon sizes and shapes, all of the data reported suggest that the coupon instant-off potential is in good agreement with that on the pipe when such comparisons can be made; more will be said about this later. It is impossible to believe that this agreement can be attributed to the coupon area selected in each case being exactly that of the holidays on the pipe. Thus, it is more likely that other factors force the coupon potential to assume a value like that of the pipe. This latter view agrees with the field observations of Polak[12] and Barlo,[24] and the laboratory observations made by Moghissi et. al.[21] They found that the effect of geometry and bare area of coupons (with areas from 1 to 100 cm²) was significant for short periods of polarization, but was not significant after extended periods of time (about 2 months) of polarization. This effect can be attributed to the increase and dominance in the polarization resistance[*] of the coupon in time when compare to the time-insensitive ohmic field resistance.[†]

There is not enough information to determine the surface condition of the coupons in all cases. However, coupons are usually machined or grit blasted to give a uniform and clean surface condition. The surface condition may be especially important if the coupon is to be used for weight-loss measurements. In some cases, though, a surface devoid of mill scale[‡]is not desirable. In the study by Barlo,[18,24] the free-corrosion potential of a machined coupon was found to be sufficiently more negative than the instant-off potential of the pipeline in some

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[*]The soil/steel interfacial resistance developed from concentration polarization when current is flowing to the coupon. As the coupon polarized potential increases in magnitude with time, the current decreases because the polarization resistance increases with time.
[†]The ohmic field resistance to remote earth of the coupon attributed to its geometry and the soil resistivity.
[‡]Mill scale is tightly adherent iron oxides produced on steel from the steel-making and finishing processes.

locations that the coupon discharged current galvanically to protect the pipe, despite the impressed-current cathodic protection system that was present. A change to a mill-scaled coupon made the free-corrosion potential about 100 mV less negative to reverse the current discharge situation. Thus, for older pipelines, or for pipelines on which the 100 mV polarization criterion results in instant-off potentials less negative than -850 mV, mill-scaled coupon surfaces should be used. Using pipe skelp or plate, the mill scale can be sufficiently reproducible and uniform to be correctable in weight-loss measurements; in many cases, the correction is insignificant.

TIME

Once the coupon is installed, the coupon may be electrically connected to the pipe. Here again, there seems to be no consistency regarding whether the coupon should be connected to the pipe immediately or allowed a period of time for the free-corrosion potential to stabilize. In the GERG survey, 50 percent of the companies responding indicated that the coupon was installed immediately following installation. The other 50 percent waited typically from 1 to 3 months to establish a stable free-corrosion potential. Waiting to observe a stable free-corrosion potential has the advantage of having some degree of assurance that the coupon is functioning properly. For example, a coupon free of surface oxide in moist soil (e.g., 15 to 20 percent) should achieve a free-corrosion potential in the range from about -650 mV to -750 mV ($Cu/CuSO_4$). Values less negative than these or erratic may be an indication of poor contact with the soil or exposed copper from the lead wire; neither condition may be clearly discerned if the coupon is energized immediately upon installation. During the stabilization period, the coupon corrodes. If corrosion rate measurements are to be made on the coupons, a correction for this corrosion must be made for an unprotected coupon in the same soil. For time of exposure greater than about one year, the correction may be insignificant.(10)

After being electrically connected to the pipeline, the coupons are monitored. The frequency of monitoring depends upon the individual purpose. However, in view of the decrease in the effect of geometry and area, meaningful data may not be obtained for at least 2 months, though some researchers believe that up to 9 months or longer may be needed.(10)

CATHODIC PROTECTION MONITORING

The design of coupons permits their polarized potential and the polarization level to be determined and assessed relative to the -850 mV ($Cu/CuSO_4$) polarized (instant-off) potential criterion and the 100 mV polarization criterion. With the protective current flowing, the so-called on-potential and the IR voltage drop also can be measured, as can the current density and current direction if the coupon area is known and a means of measuring the current are provided.

The validity of the use of coupons is based upon the ability of the coupon polarized potential and polarization to replicate that on the pipe for most situations. Accordingly, the correlation between coupon and pipeline criteria parameters are discussed below to verify the correspondence. The results are taken from portions of the field study by Barlo,(24) since it represents a relatively large database with over 350 corrosion coupons (49 cm^2) and over 130 electric-resistance coupons (5 cm^2) monitored by field personnel for more than 4 years. The coupons were set out in groups of eight, 1 m apart longitudinally, and 30 cm from the pipe. The coupons were monitored with the reference electrode in the tube above it (See Figure 1) and the coupon lead disconnected to determine the instant-off potential. Companion measurements were made on the pipe at the location of each coupon tube and with the rectifiers interrupted. Since the effects of geometry and coupon area should not be significant for the reasons discussed above, the results should be meaningful for most coupon sizes and shapes used thus far.

Figures 6 shows the on-potential, instant-off potential, IR drop, and polarization for the 49 cm² coupons with those on the pipe. The results in Figure 6 are for coupons in a corrosive soil with an average resistivity of 1,000±200 ohm-cm and moisture content of 25±2 percent determined over a distance of about 26 km. Shown in each figure are the 1:1 reference line that represents a perfect correlation; the linear regression line for the data; the value for R^2, which is a measure of how well the data are fit by the regression line; and the standard error of estimate S_y in the coupon parameter for the regression line that is a measure of the standard deviation in the predicted value for the criterion parameter. The criteria parameters cover a wide range, which provides an opportunity to evaluate the correlation more fully.

For this type of coupon, the on-potentials in Figures 6a agree reasonably well with those of the pipe as judged by the slope of the regression line and the value of R^2. However, the instant-off potentials of the coupons agree much better with those of the pipe and the standard errors of estimate are smaller than those for the on-potential. The small values for the standard error are an indication of the lower amount of scatter in the data about the regression line. In Figure 6b, the coupon instant-off potentials are within about 5 percent of those of the pipe, and the uncertainty is about ±32 mV. The IR voltage drops in Figures 6c show more deviation from the 1:1 reference line than for the on-potential or instant-off potential, and the standard errors are greater, suggesting poorer agreement between the coupon and pipe for this parameter. As illustrated in Figures 6d, the polarization levels of the coupons and pipes do not agree very well and the standard errors are comparable to or greater than the minimum value of 100 mV. There are fewer data points for the polarization measurements since they were only determined at the end of the exposure, but the scatter is self evident for both environments. As will be seen below, that pattern of behavior is consistent for other coupons.

Similar experiments were run with coupons on the same pipeline system, but about 1,000 km away in a much higher resistivity soil of 1,360,000±500,000 ohm-cm with about 9±4 percent moisture. The agreement between coupon and pipe potentials and polarization were similar to those described above in Figure 6. Therefore, the results indicate that the agreement between coupon and pipe parameters is not measurably influenced by the resistivity of the soil environment. Moreover, despite the considerable length of pipeline and range of potentials represented by the data and the single coupon size, the agreement was good for the instant-off potential.

All of the coupons were placed at the same relative location, about 30 cm from the pipe. To illustrate the effect of orientation around the pipe, the results from the 5 cm² electric-resistance coupons in the 1,000 ohm-cm soil only are shown in Figure 7. The coupons were placed at the side of the pipe like the other coupons, as well as at the top of the pipe and on the bottom of the pipe. Too few coupons were used for the top location to permit statistical treatment of the data. Therefore, the regression lines in Figure 7 and the standard error of estimate are for the side and bottom locations only. The same general behavior is found for these coupons as was found for the coupons in Figure 6. Thus, neither the location of the coupon around the pipe nor the area of the coupons, which differed by about a factor of ten, had any significant effect on the agreement between the coupon and pipe criteria measures.

The worst agreement between the coupon and pipe criteria parameters was for the level of polarization. The reason for this has to be related to the depolarized potential of the coupon, because the instant-off potential potentials show very good agreement and the polarization level is simply the difference between the instant-off potential and the depolarized potential. Coupon data from the study discussed above, as well as from another extensive field study with coupon,(19) has shown that the depolarized potential of polarized coupons comes less negative with decreasing amounts of moisture and increasing amounts of polarization; there is no reason to believe this is not true for pipelines also. Although the free-corrosion potential of unpolarized coupons shifts also, and typically toward less negative values in time, the effect of polarization on the depolarized potential is prominent. Figure 8 shows the effect of polarization on the depolarized potential of coupons subjected to cathodic protection. A shift from the original free-corrosion potentials of -740 ±22 mV toward less negative values is evident, the shift amounting to approximately 500 mV to 600 mV. Shown also is the range of free-corrosion potentials for the unpolarized coupons. Though the ranges of potentials look similar, they are different, as indicated on the figure by the average values. The difference in the means is about 180 mV, which is sufficiently large to statistically consider the means are from two populations according to a Z-test of the means. For these results, the shift in the depolarized potential is approximately the same as the amount of polarization. In another study,(19) the effect was comparable.

CORROSION RATES

Coupons have been used historically in the laboratory to determine the corrosion rate under anticipated field conditions. They have been used similarly in the field, but with less frequency.(14,17,18,19) This is perhaps the situation because of the pre-exposure and post-post analysis needed to determine a single value for the corrosion rate by weight loss or pit depth analyses. As a result, corrosion coupons have been used more for research types of studies in the field, such as the two field tests conducted to evaluate the criteria for and the effectiveness of cathodic protection of underground pipelines.(18,19,24) On the other hand, electric resistance probes or electrochemical measurement techniques, such as LPR or E-Log I, are more convenient, can develop multiple values for corrosion rates over time, and do not require coupon extraction and post-test analysis to obtain this information. Electric resistance probes and the electrochemical measurement techniques are now being used more often to address the interest in determining corrosion rates to project growth rates of in-line inspection defects in corrosion integrity programs.

General Corrosion Rates

The general corrosion rate is determined by weight loss corrosion coupons, electric resistance probes, LPR measurements, and E-Log I measurement.

Weight Loss Coupons

The criteria-related potential and polarization measurements from one field study(18) using corrosion coupons was shown in Figure 6. In that same study, the corrosion coupons were used to relate the criteria measures to the general and maximum pitting corrosion rates. The general corrosion rate *CR* was determined by weight loss of the coupon, using the difference between the initial and final weight, the specimen dimensions, the steel density, and the time of exposure. The expression for the general corrosion rate is

$$CR = \frac{\Delta W}{\rho A t}, \quad (1)$$

where

ΔW = weight loss
ρ = steel density
A = surface area
t = time of exposure.

The maximum pitting rate was determined by dividing the coupon surface into nine areas of approximately 10 cm² and measuring the five deepest pits in each 10 cm² area, from which the deepest pit was determined and the rate calculated by the maximum pit depth divided by the time of exposure.

Figure 9 shows the general and maximum pitting rate as a function of the instant-off potential measured on each coupon exposed to the 1,000 ohm-cm soil for up to about four years. The data are plotted as a function of the logarithm of the corrosion rate to show the range more clearly; a trend line representing the regression line for the data is shown also. The data illustrate that the general corrosion rate is less than 1 mpy (25 µm/y) at polarized potentials more negative than –850 mV ($Cu/CuSO_4$). However, the maximum pitting rates are between about 1 and 10 mpy (25 µm/y and 250 µm/y) for polarized potentials more negative than –850 mV ($Cu/CuSO_4$). The reason for this has been discussed in an earlier paper[28]

Electric Resistance Probes

Electric resistance probes determine the corrosion rate be measuring the change in resistance of the sensing element with time. As the thin steel sensing element corrodes, it becomes thinner and its resistance increases with time. By plotting the relative resistance readings measured with a special resistance bridge with time, the corrosion rate can be determined using the sensing element parameters as

$$CR = K\frac{\Delta R}{\Delta t}, \quad (2)$$

where

K = sensing element constant
ΔR = change in resistance reading over Δt
Δt = change in time.

More modern resistance measuring devices use solid state data logging and measurement capabilities that allow storage and downloading of the raw and processed data.[25]

Figure 10 shows the readings from three electric resistance probes used in the field study mentioned above. The probes are positioned at the 3, 6, and 9 o'clock positions around and connected to the pipe. One probe was at the 6 o'clock position and was not connected to the pipe. The average on-potential, instant-off potential, and polarization were –899 mV, –808 mV, and 270 mV, respectively. The unpolarized coupon had an average potential of –609 mV ($Cu/CuSO_4$). As this figure shows, the general corrosion rate was no more than a few tenths of a mpy for the protected probes, whereas the unprotected probe showed an initially high corrosion rate that decreased to values between about 0.5 and 1 mpy (12.5 and 25 µm/y).

These data indicate the probes are sensitive to corrosion whether cathodically protected or unprotected in soil environments.

LPR

Linear polarization resistance (LPR) is a standard laboratory corrosion rate measurement method now being applied in the field.(27) It involves an instrument that uses a steel coupon as the working electrode, an auxiliary electrode, and a reference electrode. The potential of the working electrode is shifted in small increments of 1 to 2 mV over a range of ±10 to ±15 mV from the free corrosion potential. The relationship between potential and current in this region is linear, and from the slope of the regression line through the data R_p, the corrosion rate is calculated. The general corrosion rate *CR* is calculated from the Stern-Geary(29) expression and Faraday's Law as

$$CR = K' i_{corr} = K' \frac{\beta_a \beta_c}{2.3(\beta_a + \beta_c) R_p}, \qquad (3)$$

where

K' = constant
β_a = anodic Tafel slope
β_c = cathodic Tafel slope
R_p = polarization resistance
= $\Delta E/\Delta I$ from linear polarization scan.

There is ample evidence in the literature to demonstrate the use of Equation 3 to calculate the corrosion rate. Field instrumentation to make these measurements is commercially available.

E-Log i

The linear relationship in the region of the free corrosion potential as described above is a special case of the more general E-Log I relationship often called an Evans or polarization diagram. The fundamental relations are illustrated in Figure 11a. Figure 11b illustrates the method to calculate the anodic current density or corrosion rate from the development and analysis of the cathodic polarization curve using field-generated data.

In the E-log I method, and external current source is applied to either an unpolarized coupon or a depolarized coupon, such as was shown in Figure 5. The current is applied in increments and held for about 5 minutes after which the instant-off potential is measured and the process repeated for an incrementally higher current. The cathodic Tafel line is drawn graphically through the appropriate data as shown. From the defining relationship for any polarized potential E_p, the net current is defined as

$$i_n = i_c - i_a, \qquad (4)$$

where

i_n = net current applied at E_p
i_c = cathodic current from the cathodic Tafel at E_p
i_a = anodic current from the anodic Tafel at E_p,

the anodic current density i_a is calculated from Equation 4 and the corresponding values of i_c and i_n. Repeating this process at several potentials, the anodic Tafel line can be generated from regression of the data. The anodic Tafel line can then be extended or anodic current densities calculated from the regression expression for the line for any polarized cathodic potential. From Faraday's Law, the corresponding corrosion rate is calculated from i_a, the coupon density, and its dimensions. This method also permits the corrosion rate at the free corrosion potential to be determined.

Figure 11c shows the resulting relationship between the general corrosion rate and the polarized potential from Figure 11b. These data can be used to relate the corrosion rate to various polarized potentials on the pipe in the same or similar environments because of the good agreement found between the two in Figures 6 and 7. In this way, the corrosion rates so determined by this method can be used to project the corrosion growth of defects found by in-line inspection on a pipe. However, the corrosion rates will be conservative. This is because the E-Log I curve in Figure 11b will shift to less negative potentials and lower currents with time, that is, with longer polarization steps, which has the resulting effect of shifting the anodic Tafel line toward lower current densities, thereby reducing the corrosion rate.

Pitting Corrosion Rates

The field studies[18,24] described previously serve as an example of the type of corrosion information that can be developed from coupons. Details of the coupon and field test facilities have been described in Figures 1, and some of the criteria-related results on Figures 6 through 8. As part of that same study, weight-loss measurements were made on the coupons to determine the general corrosion rate, and pit depth measurements were made to determine the average and maximum pitting rate. For purposes of pitting analysis, the coupon surface was subdivided into nine equal areas of 10 cm^2 and the five deepest pits were measured in each sub area. The average and maximum pit depths were determined and used for analysis purposes. A statistical-analysis approach was used because pitting corrosion is a random process that is well described by statistical treatments.[30]

Other studies on the maximum pitting rate of unprotected materials(i.e., without cathodic protection) in soil environments have determined that the pit depth increases in a non-linear manner according to a power-law or parabolic relationship[31,32,33] as

$$D = At^n , \qquad (5)$$

where D = maximum pit depth
A = constant
t = time
n = constant (fraction).

The present study demonstrated that the same analytical relationship in Equation 5 also holds for cathodically protected steel. Thus, by removing coupons serially in time and plotting the maximum pit depth as a function of time on a log-log basis, the constants A and n can be determined by linear regression.

Most often the maximum pitting rate R is calculated by dividing the maximum pit depth D by time t of exposure as

$$R = \frac{D}{t}. \qquad (6)$$

However, the actual rate **R** is found by differentiating Equation 5 with respect to time to obtain

$$\mathbf{R} = \frac{D}{t} n = Rn. \qquad (7)$$

Thus, since the constant *n* is a fraction typically between 0.3 and 0.6,[18,31] the actual maximum pitting rate will be typically 30 to 60 percent lower than the rate determined simply by dividing the maximum pit depth observed by the time of exposure.

The results of pitting corrosion rate measurement are shown in Figure 9. It is possible, however, to take the analysis beyond this point to permit other predictions. These have been described, in part, elsewhere.

The constants *A* and *n* uniquely determine the pitting characteristics for the environment and the cathodic-protection level applied. These values can then be used in conjunction with extreme-value statistical analysis to estimate the deepest pit expected on the pipeline with various degrees of coating effectiveness, and the time for the deepest pit to penetrate the pipe wall if the protection and environmental conditions continue to prevail. Because of the time dependence of the pitting rates, and, therefore, the general rates, there is an impact on the time dependence of the criteria for cathodic protection. This has been discussed in other papers by the author and will not be repeated here.[28,34]

SUMMARY

There has been renewed interest in the use of coupons to monitor the level of cathodic protection on buried pipelines in more recent times. In the past and more recently, they have been used in areas where conventional monitoring methods may not be adequate to accurately assess the level of protection. However, the resurgence in interest has been prompted, in part, by the need to correct for IR drop in the -850 mV polarized potential criterion and the 100 mV polarization criterion. With increasing use of in-line inspection as a supplemental means of assessing the effectiveness of coating and cathodic protection systems, coupons are being used also to develop corrosion rate information to estimate growth of defects for future maintenance and in-line inspection scheduling. This review on the use of coupons has shown the following:

- Coupons have been traditionally used to determine the local level of protection on a pipe to which they are connected, to assess satisfactory operation of the cathodic protection system, and to quantitatively assess the level of protection by determining the corrosion rates for the level of protection

- There are a considerable variety of coupon designs that have been developed and used over the years, but there is no consistency in either the size, shape, and orientation of the coupon, or the placement of the reference electrode for measuring the coupon potential

- Although the size (area) of the coupon is usually selected to represent the largest known or assumed holiday in the coating on the pipe, and these sizes typically range for about

0.1 cm² to 100 cm², the size and shape of the coupon have little effect on the potential achieved on the coupon over an extended period of time greater than a few months

- Over a broad range of soil resistivities, protection levels, and coupon sizes, shapes, and positions around the pipe, the instant-off potential of the coupon can be expected to assume the local instant-off potential of the pipe to which it is connected

- The level of polarization on the coupon is not likely to assume that locally on the pipe to which it is connected because of differences in the depolarized potentials of the coupon and pipe

- The on-potential of the coupon with the current flowing and the IR voltage drop determined when the current is interrupted may or may not be the same as that on the pipeline locally, because the relative resistance and geometry of, and current to, the pipe and coupon can be different

- The depolarized potential of the coupon and pipe will decrease in magnitude with time and polarization, with the depolarized potential decreasing approximately in direct proportion to the amount of polarization,

- Although traditionally used to monitor the level of protection, coupons have been used more recently to determine the associated general corrosion rate or pitting corrosion rate

- The general corrosion rate can be determined by weight loss of a corrosion coupon, the resistance change of an electric resistance probe, the linear polarization resistance (LPR) method, or the E-log I analysis method

- The LPR method is used to determine the general corrosion rate of only unpolarized coupons at their free-corrosion potential, whereas weigh-loss coupons and electric-resistance probes can be used to determine the general corrosion rate either at a polarized potential or the free-corrosion potential, but while the E-Log I method is applied to unpolarized coupons, it predicts the corrosion rate for a range of polarized potentials and the free-corrosion potential

- The maximum pitting corrosion rates can be characterized from pit depth measurements made on cathodically protected coupons excavated serially in time

- As a result of the parabolic non-linear time dependence of the maximum pitting rates, the actual maximum pitting rate will be about 30 to 60 percent of the rate calculated by simply dividing the observed maximum pit depth by the time of exposure, but neither one of these rates will become zero in time or with higher levels of applied protection

- Additional analysis of maximum pitting rates at various protection levels have been carried out using extreme-value analysis to estimate the maximum pit depth on a pipeline to which the coupons were attached, and the time for the pit growth to perforate the pipeline

- As a consequence of the non-linear time dependence of the maximum pitting rate, the minimum polarized potential and polarization requirements for protection to various assumed tolerance pitting rates can be estimated.

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Table 1. Some Characteristics of Coupons Cited in the Literature.

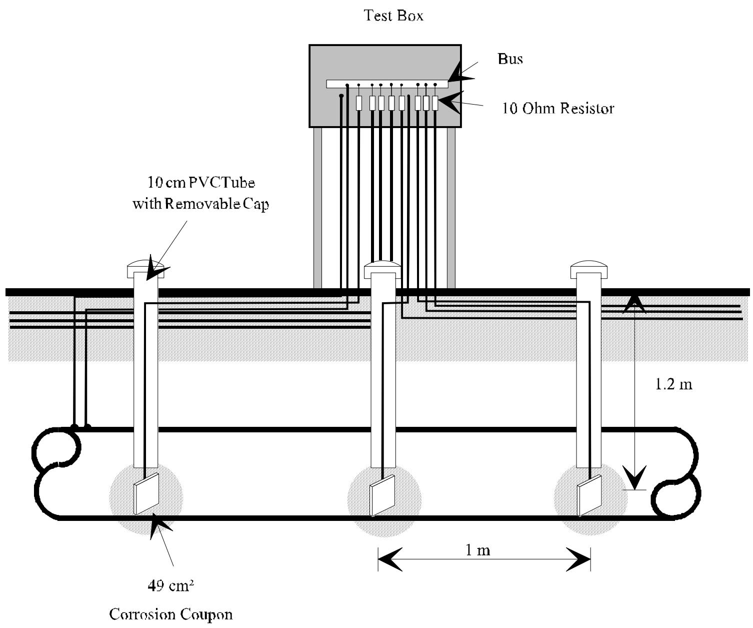
No.	Shape	Area, cm²	Measurement Purpose	Reference Electrode Location[a]	Current Interruption Method	Investigator	Reference
1	Flat, circular	10 & 30	Potential	Permanent, internal	Physical disconnect	von Baeckmann, et. al.	8,9,10
3	Flat, circular	1,10,100	Potential	Permanent, internal	Physical disconnect	Polak, et. al.	11,12
1	Flat, circular	0.1, 1, 10, 50, 500	Potential	Permanent buried, external	Electronic	Kasahara, et. al.	14,15
1	Flat, circular	100, 1000	Potential	Permanent, internal	Physical disconnect	Martin	16
1	Cylindrical	1 to 122	Potential	Temporary, at grade	Electronic	Woudstra	13
2	Cylindrical	9	Potential	Temporary, in soil tube	Physical disconnect	Thompson and Lawson	4,23
2	Cylindrical	40	Potential	Temporary, internal	Physical disconnect	Stears, et. al.	6,21,22
1	Cylindrical	18	Potential, corrosion rate	Temporary, at grade; in soil tube	Physical disconnect	Barlo	19
1	Flat, rectangular	5	Potential, corrosion rate	Temporary, in soil tube	Physical disconnect	Barlo	5,18,24
1	Flat, square	49	Potential, corrosion rate	Temporary, in soil tube	Physical disconnect	Barlo	18,24

(a) Permanent means the reference electrode is an integral part of the coupon design.
Temporary mean the reference electrode is movable and put in place only for the measurement.
In Soil Tube means the reference electrode was placed in a tube of soil that connects to the soil near the coupon.
At Grade means the reference electrode was placed at the earth surface near or above the coupon.

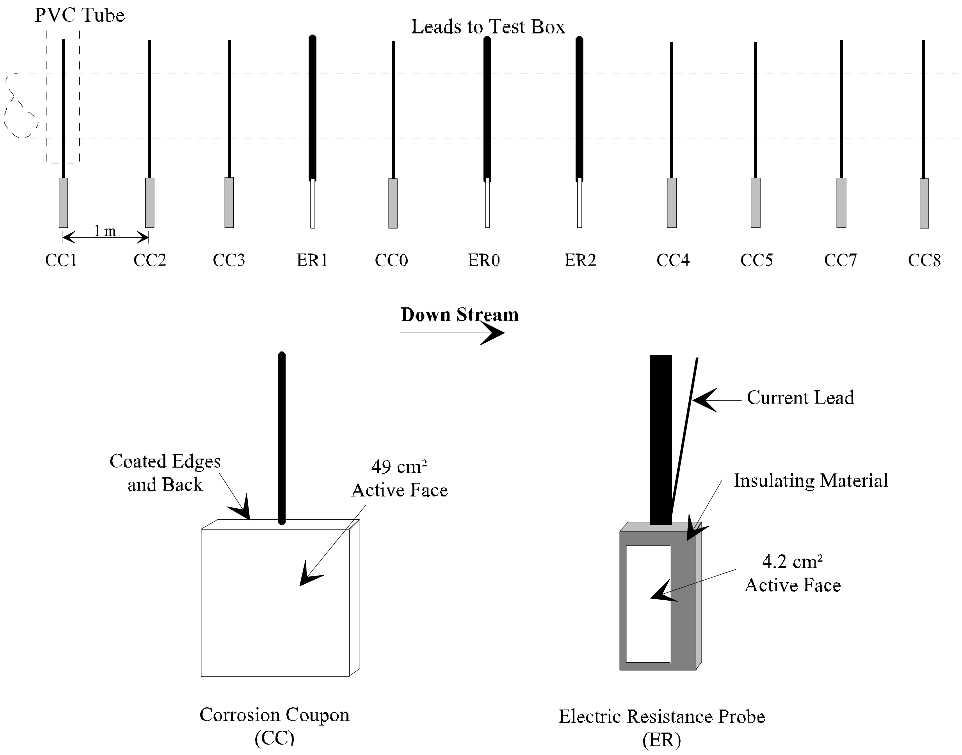
Table 2. Summary of Some Coupon Physical Features from the GERG Survey[3]
(The percentage of companies using each coupon feature is shown)

Area, cm²	Angle[a]	Reference Electrode Location	Pipe-Coupon Distance, cm
≤10 cm² -- *52%* >10 cm², ≤100 cm² -- *32%* >100 cm² -- *16%*	0° -- *21%* 30° -- *5%* 45° -- *42%* 90° -- *32%*	None -- *33%* External -- *24%* Internal -- *42%*	≤10 cm² -- *19%* >10 cm, ≤ 50 cm -- *69%* >50 cm -- *12%*

(a) 0° - coupon face parallel to the ground surface and facing downward
90° - coupon face perpendicular to the ground surface.

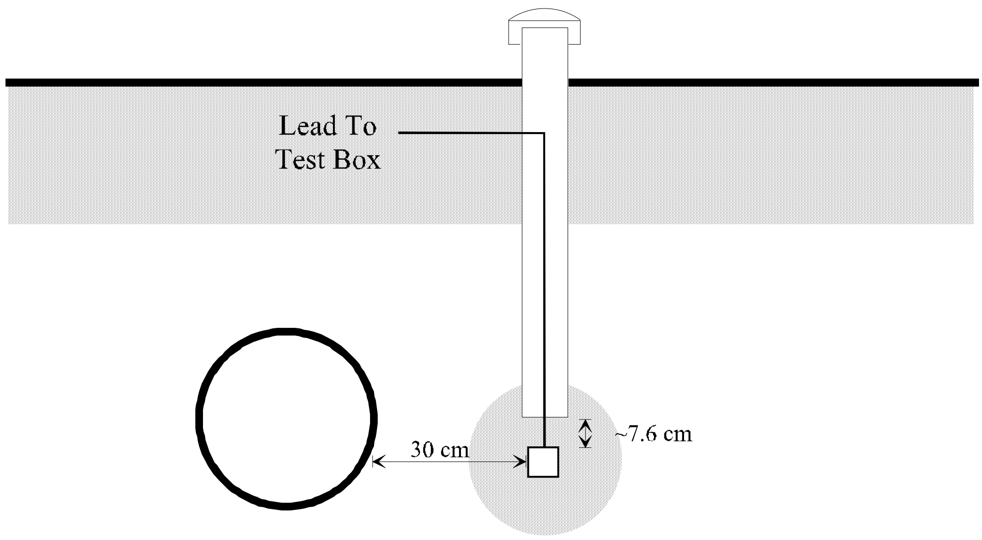


a. Test bed with corrosion coupons.



b. Corrosion coupons.

Figure 1. Flat, Square and Rectangular Corrosion Coupons Used for Criteria and Corrosion Rate Measurements [After Barlo[18,24]]



c. Side view of corrosion coupons.

Figure 1 (Continued). Flat, Square and Rectangular Corrosion Coupons Used for Criteria and Corrosion Rate Measurements [After Barlo[18,24]]

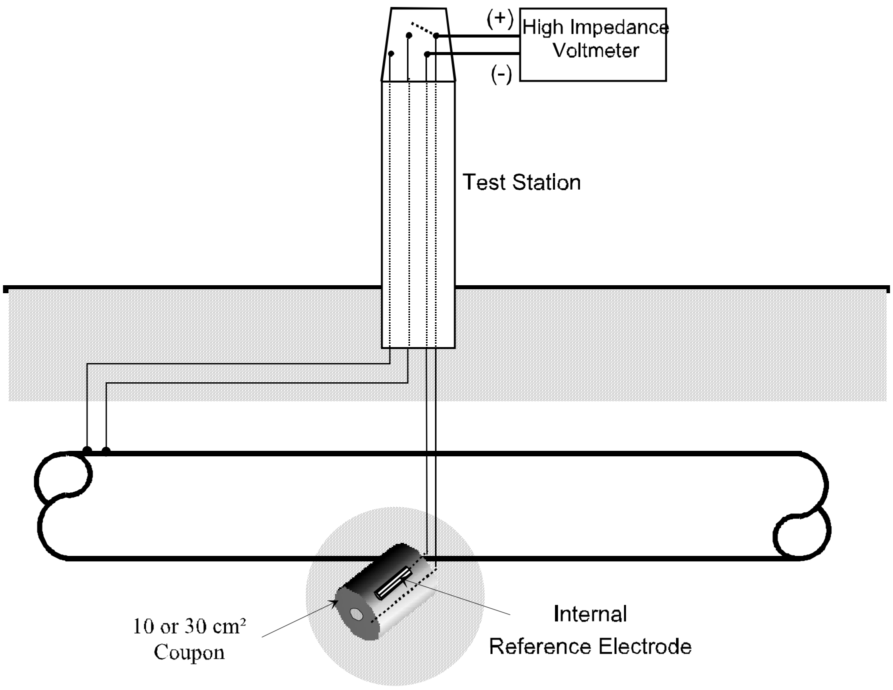


Figure 2. Flat, Circular Coupon Used for Criteria Measurements [After von Baeckmann et. al. [3,8,9,10]]

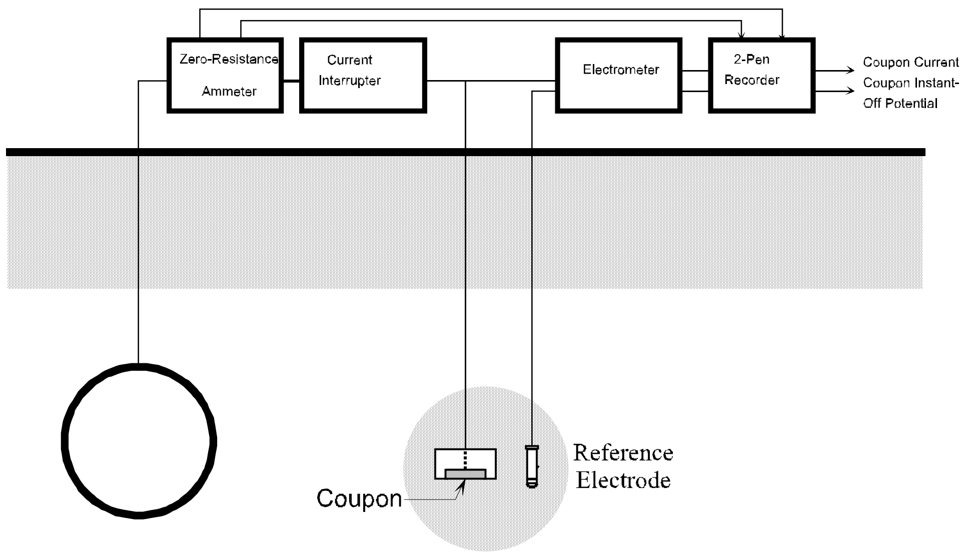


Figure 3. Flat, Circular Coupon Used for Criteria Measurements [After Kasahara[14,15]]

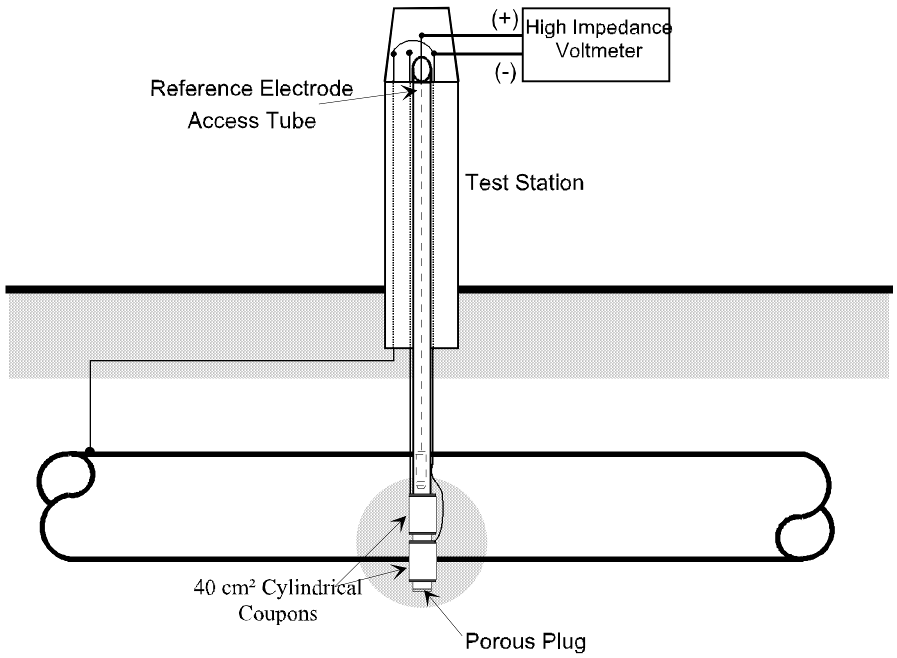


Figure 4. Cylindrical, Tube Coupons Used for Criteria Measurements [After Stears et. al.[6,21,22]]

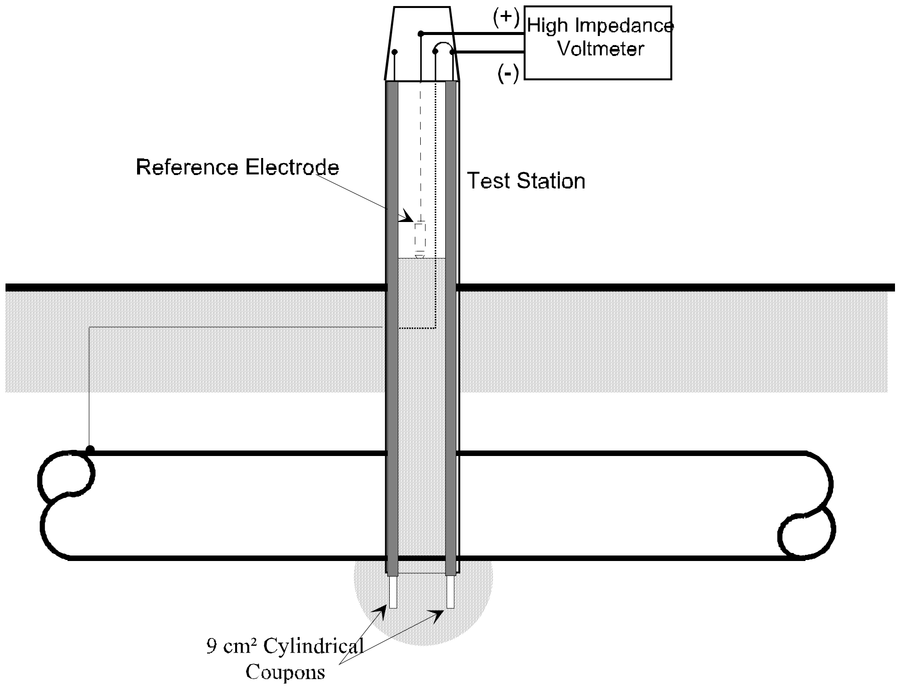
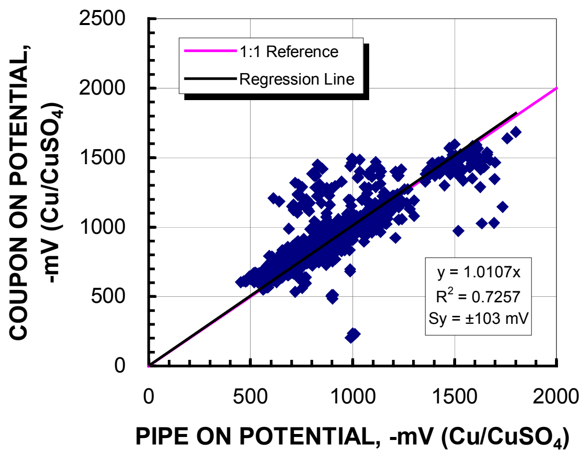
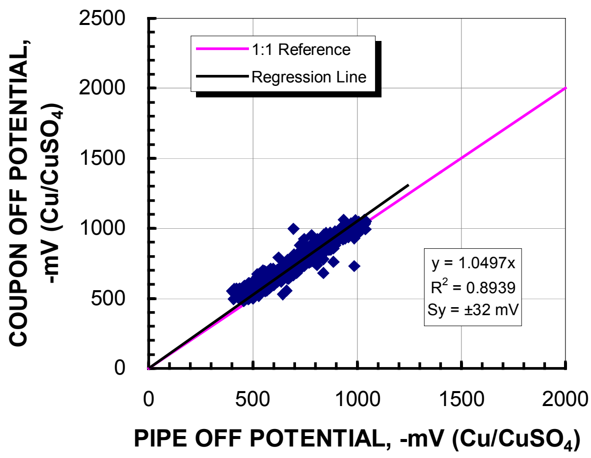


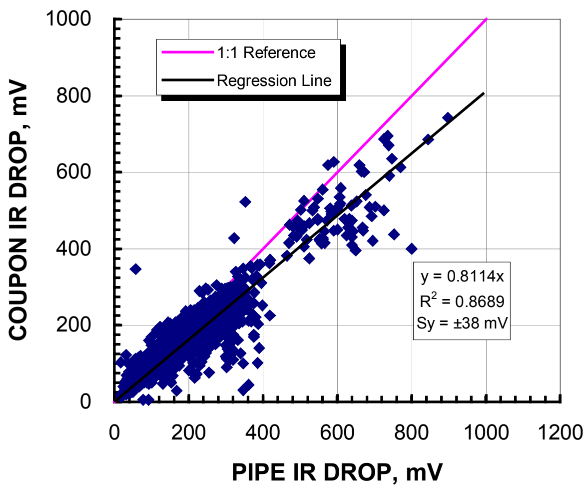
Figure 5. Cylindrical, Rod Coupons Used for Criteria Measurements [After Thompson and Lawson[6,23]]



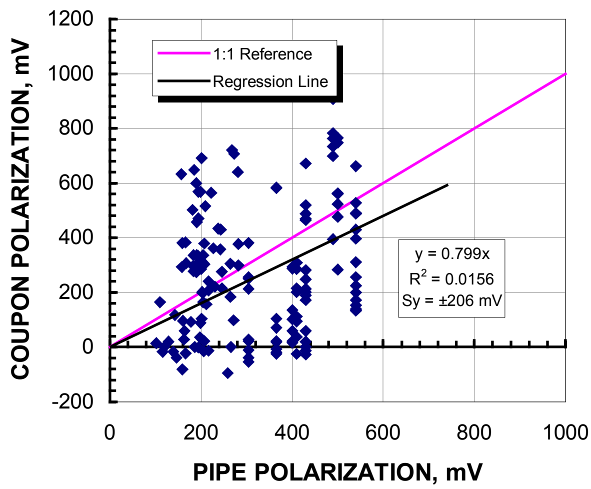
a. On potential.



b. Off potential.

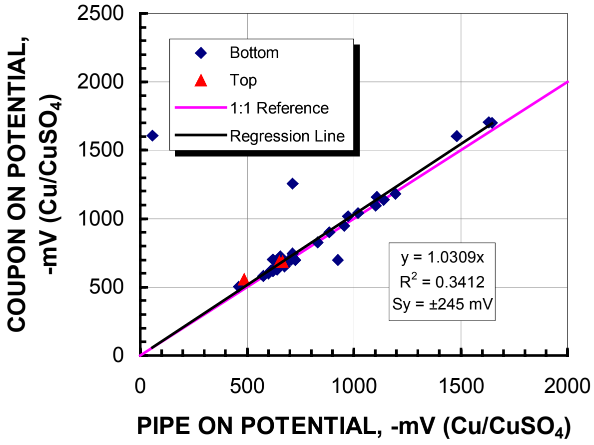


c. IR drop.

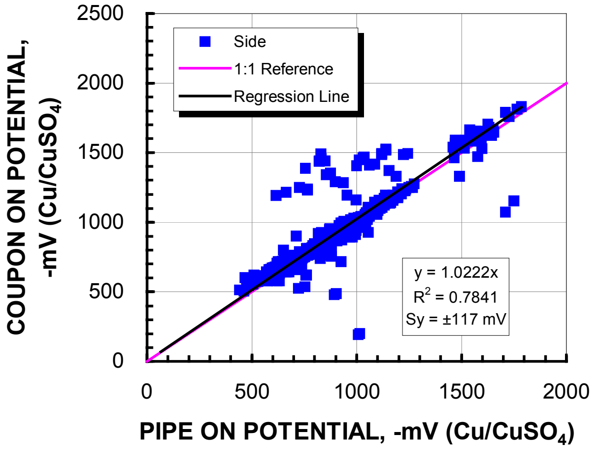


d. Polarization

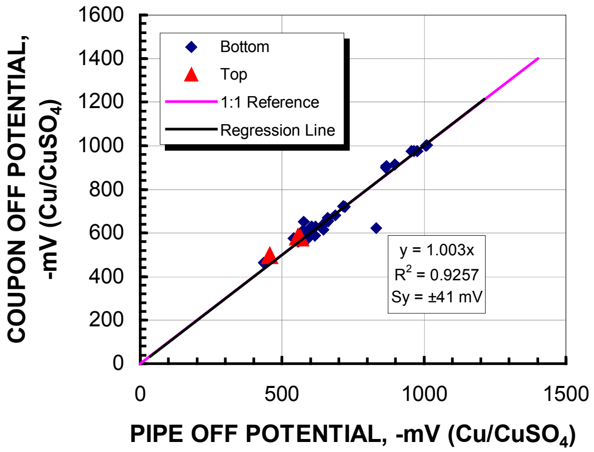
Figure 6. Pipe and Coupon Criteria-Related Parameters Correlation[24]



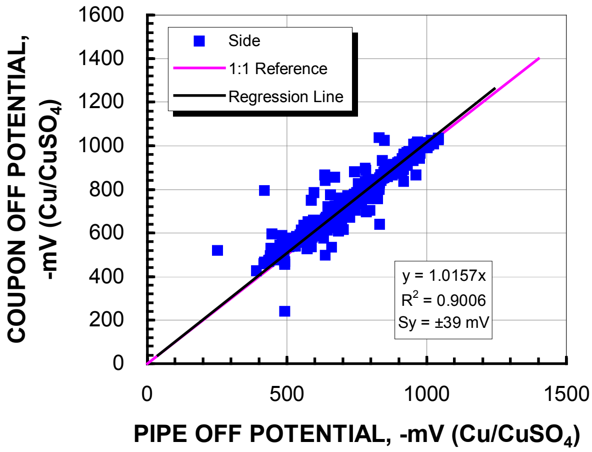
a. On potential; top and bottom.



b. On potential; side.

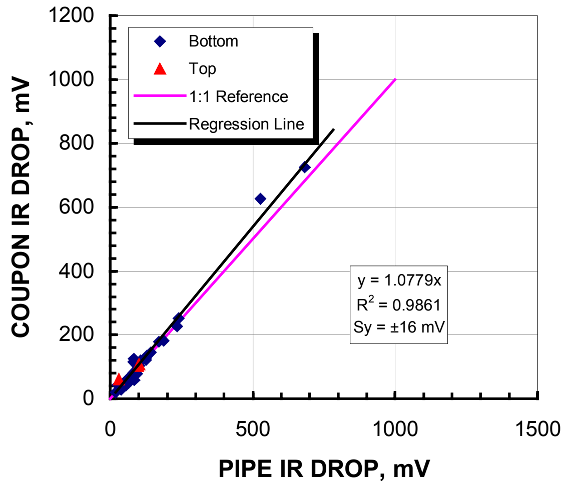


c. Off potential; top and bottom.

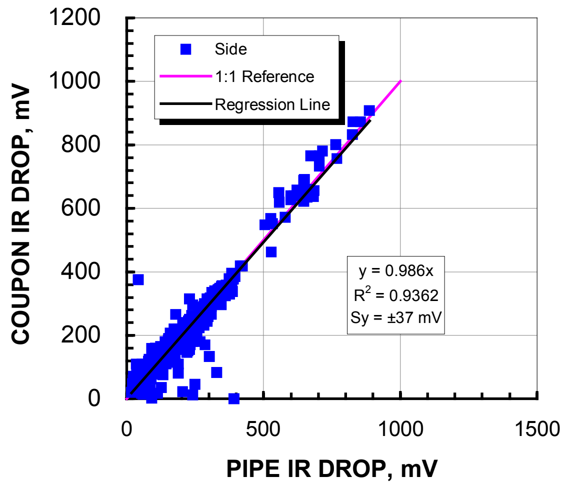


d. Off potential; side.

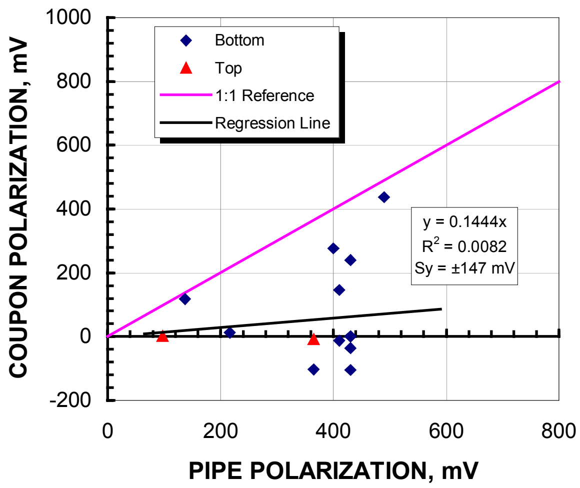
Figure 7. Effect of Coupon Position Around the Pipe[24]



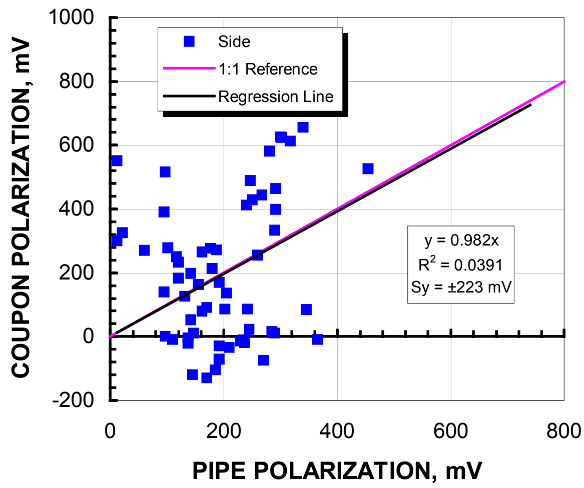
e. IR drop; top and bottom.



f. IR drop; side.



g. Polarization; top and bottom.



h. Polarization; side.

Figure 7 (Continued). Effect of Coupon Position Around the Pipe[24]

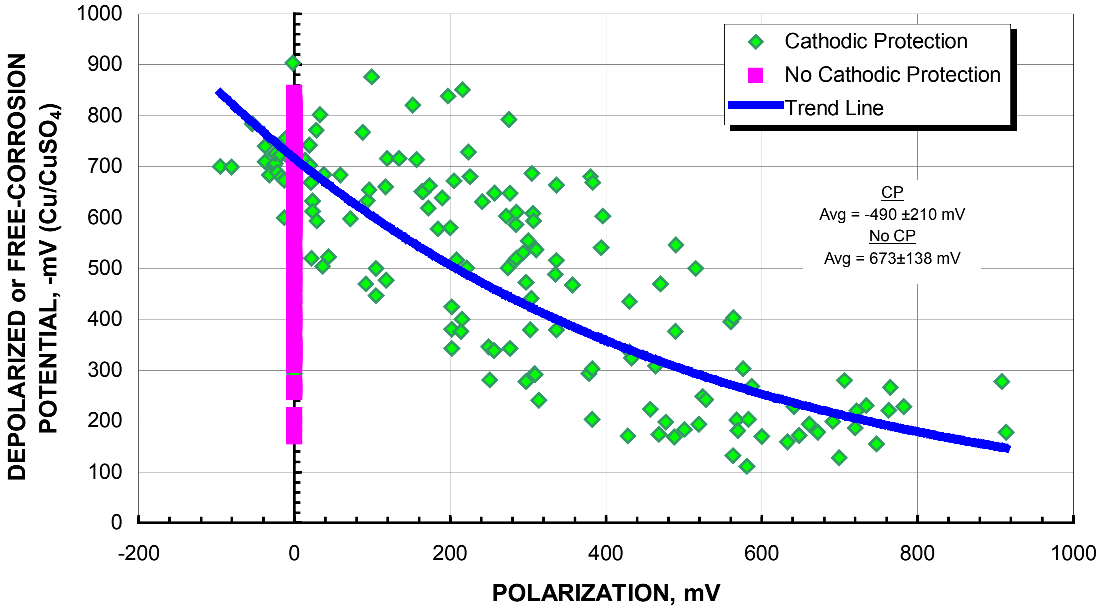


Figure 8. Effect of Polarization on the Depolarized Potential(24)

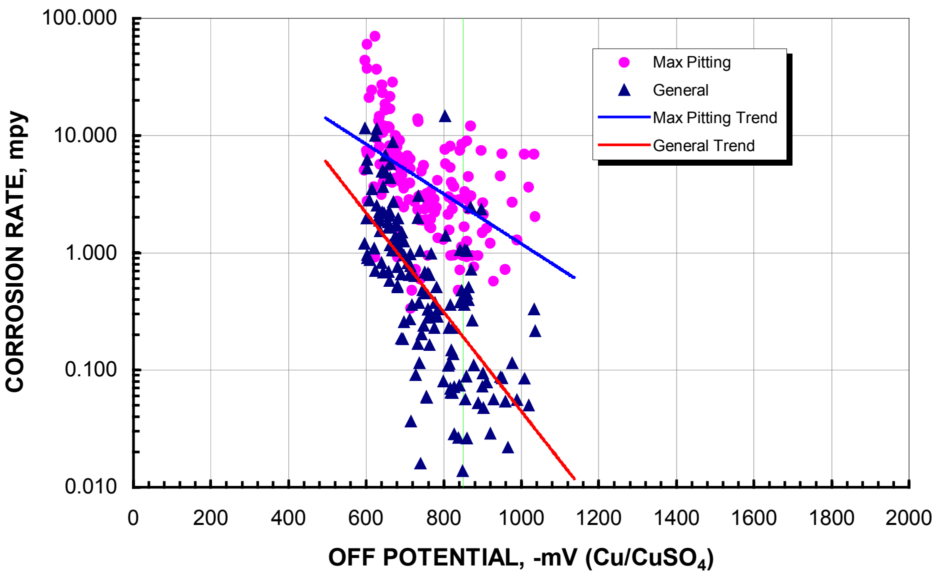
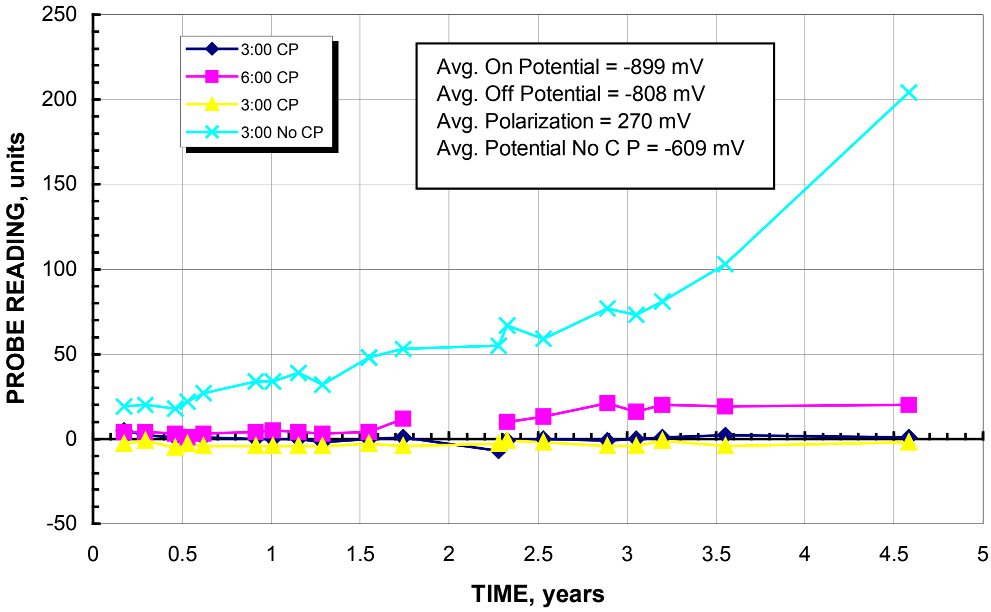
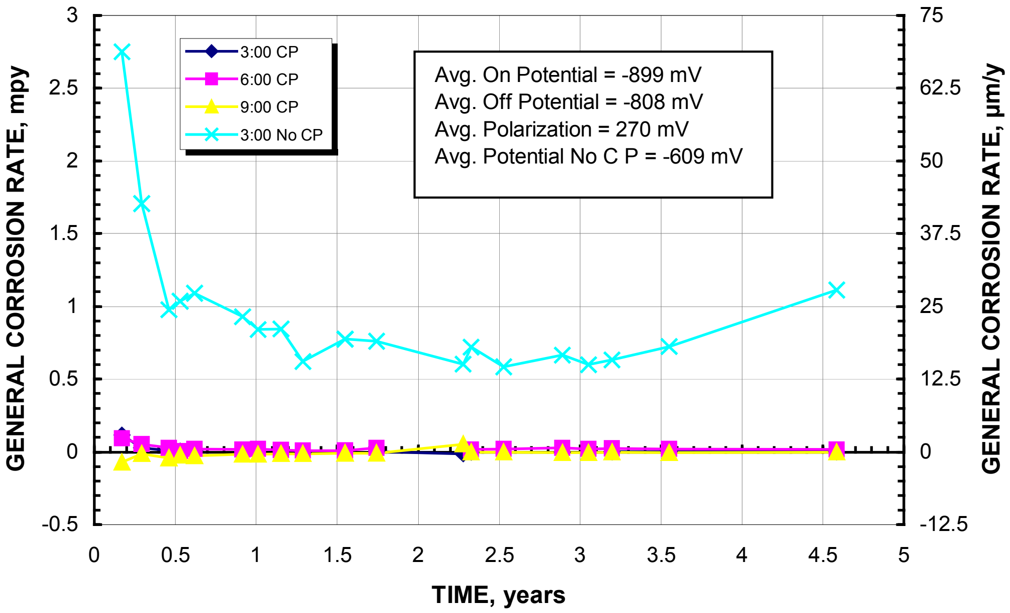


Figure 9. General and Pitting Corrosion Rates Comparison

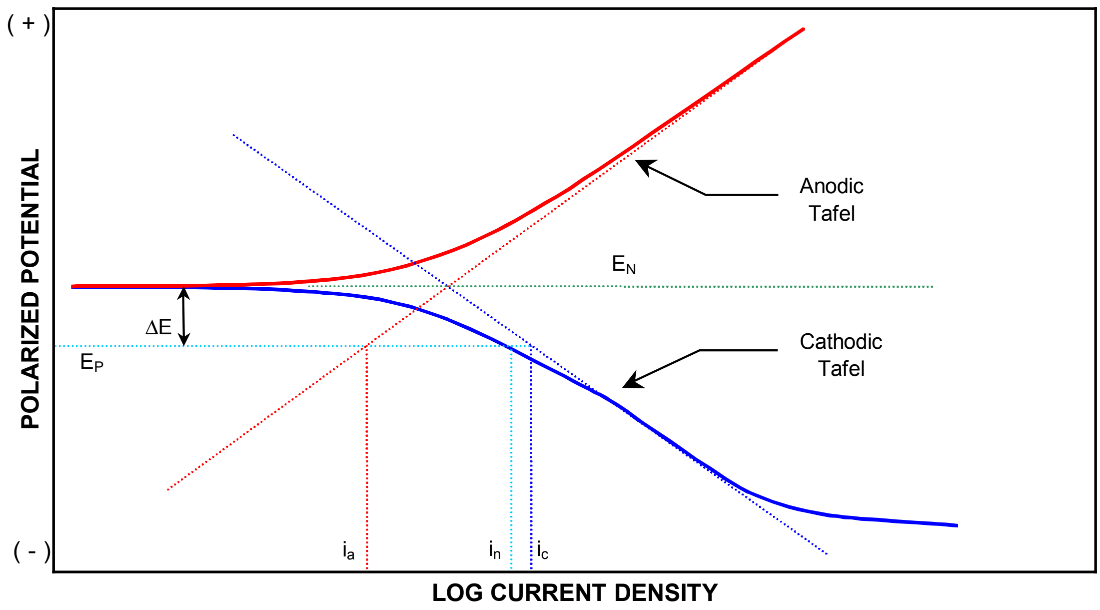


a. Reading.

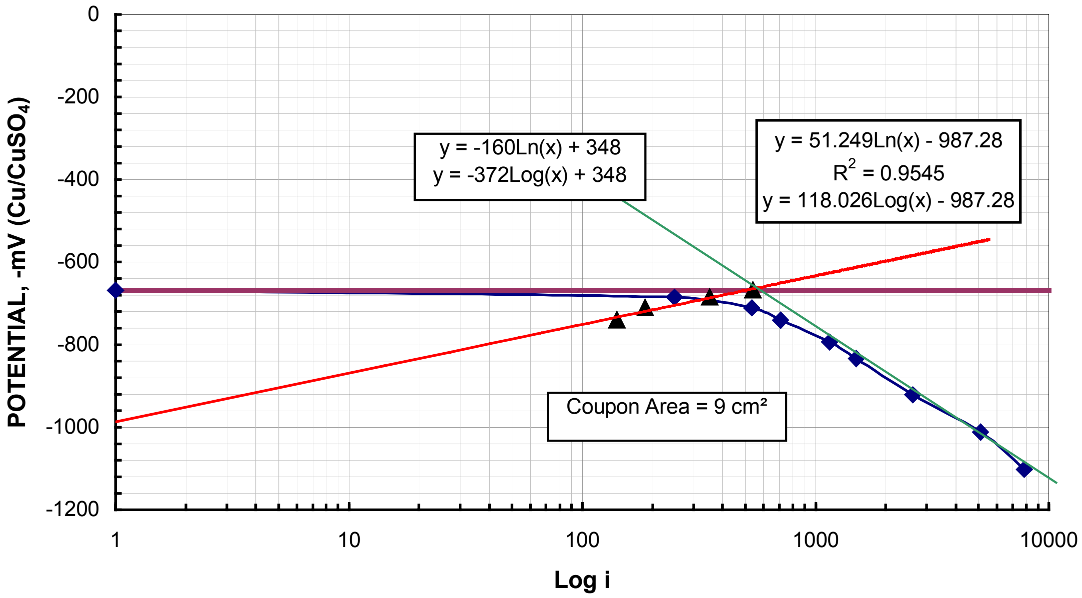


b. Corrosion rate.

Figure 10. Electric Resistance Probe Readings and Associated Corrosion Rate[24]

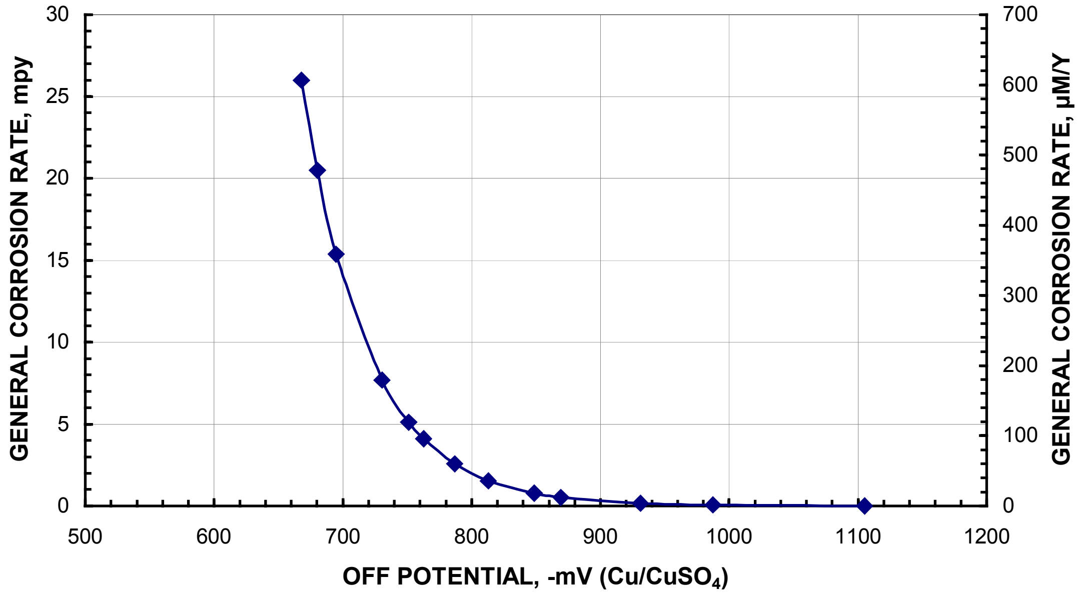


a. Basic relationships.



b. Field data analysis.

Figure 11. E – Log I Method of Determining Corrosion Rates



c. Calculated corrosion rate.

Figure 11 (Continued). E – Log I Method of Determining Corrosion Rates