



A study of cathodic protection of underground metal structures and cathodic protection survey of pipe lines on campus of Montana State College
by Charles C Collins

A THESIS Submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering
Montana State University
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Abstract:

It is estimated that the cost of underground corrosion each year in the United States is approximately \$1,000,000,000. Practically all unprotected iron structures underground will eventually waste away. It is only since 1900 that the electrolytic nature of corrosion has become understood and any general recognition given to the corrosion problem.

Underground corrosion results from the tendency of certain metals to pass into solution as positive ions. If there exists both a metallic and electrolytic path between a pair of metallic surfaces called the anode and the cathode, then a galvanic current will probably flow. The anode wastes (rusts or corrodes) away, while the cathodic surface is protected. Galvanic currents arise on underground structures because of differences in kind or condition of metallic surfaces and surrounding soils. If there is a closed electric circuit and if there is some degree of moisture present in the soil, a current will flow underground from anode to cathode.

The prevention of corrosion consists mainly of applying a water-proof coating to an underground structure, and by lowering the potential of the pipe to a point where a current will flow from ground to the pipe. The latter is called cathodic protection. It is accomplished by impressing a voltage on the ground area through a ground bed made of scrap iron or carbon rods, with the negative terminal connected to the protected metallic surface. Cathodic protection may also be achieved by the use of magnesium anodes, which are buried in the ground after being connected to the metal structure by a length of conducting wire. The magnesium being more active, will cause a current to pass from the anode to the iron structure, which will protect the latter.

Soil resistivities and pipe-to-soil potentials are useful information for locating areas where conditions favorable to corrosion exist. A sensitive voltmeter and copper-sulfate half-cell are necessary for obtaining the potential measurements. The voltage between an underground pipe and the surrounding soil is obtained by connecting- the positive terminal of the voltmeter to the half-cell and placing the half-cell in contact with the ground. The - negative terminal of the voltmeter is connected to the pipe. Roughly, a voltmeter reading of less than 0.6 volt indicates a possibility of corrosion, and a reading between 0.6 and 0.85 volt indicates some degree of protection. A reading of more than 0.85 volt is commonly accepted as an indication of full cathodic protection to the underground iron structure at that point.

A survey of the Montana -State College campus indicates most of the underground pipe is in good condition, with a few localised areas where corrosion is taking place. A complete cathodic protection system using rectifier stations to furnish a protection voltage is considered to be rather expensive in comparison to corrosion losses taking place on the campus. A system of localized protection using magnesium anodes to furnish protection voltage in areas where corrosion is known to exist is recommended as being more economical and practical.

A STUDY OF CATHODIC PROTECTION OF UNDERGROUND METAL STRUCTURES AND
CATHODIC PROTECTION SURVEY OF PIPE LINES ON CAMPUS OF MONTANA STATE COLLEGE

By

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A THESIS

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ABSTRACT

It is estimated that the cost of underground corrosion each year in the United States is approximately \$1,000,000,000. Practically all unprotected iron structures underground will eventually waste away. It is only since 1900 that the electrolytic nature of corrosion has become understood and any general recognition given to the corrosion problem.

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INTRODUCTION

Corrosion of metallic structures causes a significant waste of national resources, the cost of which is estimated at approximately \$5,000,000,000 annually in the United States. Of this, \$1,000,000,000 is the estimated loss by corrosion of underground metallic structures. Practically all unprotected iron structures in underground locations will eventually waste away.

In 1823 Sir Humphrey Davy recognized the electrochemical nature of corrosion and upon his recommendation, zinc plates were tried on English warships for the purpose of protecting the copper on the hulls. This was probably the first cathodic protection system in history and while not successful, the fault lay with the marine growths on the ship bottoms rather than with any error in Davy's thinking. However nearly 100 years were to pass before there was any general recognition of the corrosion problem. Prior to the year 1900, accelerated corrosion was noted on some buried pipe lines near electrified street-railway tracks, and by 1910 the electrolytic nature of such corrosion was understood. With the subsequent rapid growth of buried cables, pipe lines etc., American industry became more concerned about the corrosion problem and the necessity for finding a means of control. Cathodic protection was first reported to have been used in 1922, but its effectiveness was not generally recognized until the early 1930's. Since then the use of cathodic protection as a means of reducing corrosion of underground (and underwater) metal structures has become widespread.

During this time the effectiveness of waterproof coatings for the prevention of corrosion was known, and used. For example, a bituminous coating was being applied to pipes as early as 1840 in this country by a



Fig. 1. The cost of corrosion. A 6" gas main no longer serviceable because of leaks, is being replaced by new pipe at left.

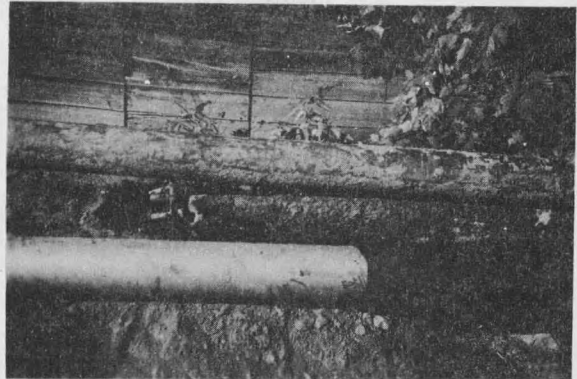


Fig. 2. Rusted pipe from project illustrated in Fig. 1, with new pipe at bottom of picture. Note waterproof wrapping (paper over asphalt) around new pipe, which is the primary means of preventing corrosion.

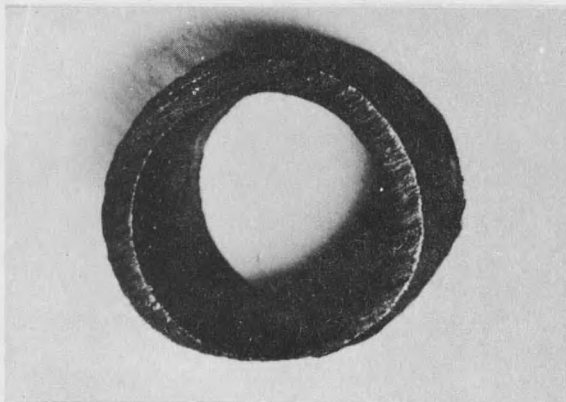


Fig. 3. Section from 1" gas line showing advanced corrosion (rusting) along lower side of pipe.

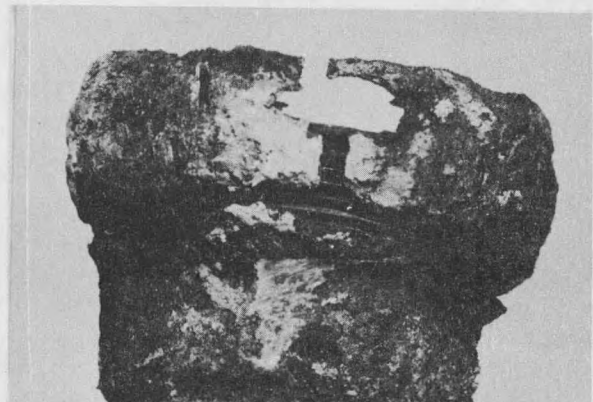


Fig. 4. 1 1/2" union corroded entirely through. Pipe and cut-off valve of same line no longer serviceable.

gentleman of the name of Angus Smith.¹ While coatings are still the primary means of extending the life of underground piping, it remained for the advent of cathodic protection to close the gap in the protection given by coatings, by providing a means for stopping corrosion at any point where a break existed in the coating. The two methods applied together, give the best economic means known today for the prevention of pipe line leaks, the inevitable result of rusting and pitting of underground metal surfaces.

¹Speller, F. N., Corrosion Causes and Prevention, New York; McGraw-Hill, 1935, p. 566.

THE ELECTROCHEMICAL NATURE OF CORROSION

From a practical standpoint the corrosion engineer is not so much concerned with the exact chemistry of corrosive action, as he is with the more immediate one of corrosion control. But to obtain an understanding of the electrical means for corrosion control it is necessary to set up a certain minimum of electrochemical theory.

If we recognize corrosion as an electrochemical phenomena, that is, by a corrosive area as being one where an electric current is flowing away from a metallic surface; then it would appear that the elimination of this corrosive tendency could be accomplished by the application of a reverse potential. This is precisely what a cathodic protection system does. Simply stated, it is an electrical circuit for applying a positive potential to the ground area adjacent to buried metal structures (or negative potential to the metal), so that any tendency for galvanic currents to flow from metal to soil will be smothered out by this reverse difference of potential applied between soil and metal. At least some degree of galvanic currents are almost certain to flow between or along bare metal surfaces underground, as the result of electrolytic action between the metal and contacting soil. As we shall see later, the metallic surfaces become electrodes in the electrolytic soil solutions, and the electrical phenomena is exactly the same as that in a wet cell.

The electrical nature of corrosion has been well established, at least as far as underground surfaces are concerned. In fact it is difficult to draw an exact dividing line between electrochemical and straight chemical reactions. The tarnishing by oxidation of metallic surfaces in air for example, has been connected with electrochemical processes, largely by the

work of C. Wagner in the early 1930's.¹ The theory developed by Wagner led to an equation to explain the tarnishing rate, and while there are observed deviations from the equation, Wagner did establish the fact that the passage of metal ions through the oxidation layer played a significant role.

A number of investigators have performed experiments which tend to establish the electrochemical nature of any corroding action occurring on a metallic surface immersed in a chemical solution. In this connection it is interesting to note that one theory suggested to explain the rusting of iron in soft water states that the iron becomes covered with a layer of magnetite (Fe_3O_4) which in turn is covered with a layer of hydrated ferric oxide $\text{Fe}(\text{OH})_3$.² But the magnetite and iron constitute a galvanic couple with iron being the anodic surface, that is; the iron is slowly carried away by a current flowing from the iron to the magnetite layer.

In order to understand the nature of the protection problem, some of the electrochemical aspects of underground corrosion will be explained. In a sense almost any chemical action can be regarded as electrochemical, since there is a transfer or displacement of electrons. However in this paper, an electrochemical action will be considered as a chemical action resulting from the flow of an electric current between spatially separated anodic and cathodic areas.

Basically, natural corrosion results from the tendency of refined metals to return to the compounds in which they exist in nature. After a metal such as iron, has been reduced and refined from its natural ores, it will have a tendency to rejoin the elements from which it was taken. An

¹Wiley, H. A., Corrosion Handbook, ed. by H. H. Uhlig, New York; Wiley & Sons, 1948, p. 16.

²Ibid., Evans, U. R., p. 7.

iron sample if placed in an electrolytic solution, will tend to pass into that solution as positive ions. This tendency is termed the solution pressure or potential, and it may be measured in an electrolyte containing its own salts, with reference to the hydrogen electrode. This forms the basis for the electromotive series, or sometimes called the electrode-potential series. The series actually represents the relative tendency of the respective metallic atoms to give up one or more valence electrons to form positive ions.

An electrolyte may be defined as a solute furnishing free ions in solution. Faraday investigated the conduction of electric currents in electrolytic solutions, theorized on the possibility of small particles being the "carriers," and even gave them the name ions. But it remained for Arrhenius to clarify the actual dissociation of the compound (always an electrovalent compound) into electrically charged particles, or ions. Although not all of the electrolyte may dissociate, there will be at least a partial dissociation (in a water solution) and the resulting ions will enter into the mechanics of corrosion.

As before stated any metal with corrosive properties will, when placed in an electrolytic solution, give off positive ions. These ions in turn will join negative oxygen or other ions, already present by reason of the dissociation properties of the solution. Hydrogen ions are displaced and a balance is soon reached in solution pressures and no further ions will leave the metal. Then if another piece of metal, or electrode, is placed in the solution and an outside electric potential impressed, with the positive connection to the first electrode, the transfer of ions will then be resumed and will continue until that electrode is entirely transferred to the solution, or the electric current stopped.

Another way to set up a current in an electrolytic solution is to use two dissimilar metals for electrodes. Most any two metals will do; it is only necessary that they exhibit different solution pressures by reason of their positions in the electromotive series. Then whichever electrode passes current into the solution will waste away. The process is illustrated in Fig. 5.

In the wet cell shown, zinc and copper electrodes are placed in a hydrochloric acid solution. The zinc, having a higher solution pressure, (greater negative voltage from electromotive series) will transfer positive ions into the solution. An excess of electrons will be left on the zinc plate, which may be said to be an electronegative metal when in this state. These elec-

trons are available for an outside circuit and will flow to the other electrode if a suitable connection is made between the two. At the copper plate, the electrons will join positive hydrogen ions, resulting in a layer of neutral hydrogen gas. As the hydrogen accumulates on the copper plate (polarization) additional resistance is thereby introduced into the electric circuit, and the magnitude of the current will decrease.

Inside the solution of HCl of the above cell, the hydrochloric acid dissociates. The negative Cl ions, sometimes called anions, migrate toward the zinc electrode, or anode, by virtue of the electric field through the solution. Conversely, the positive hydrogen ions, or cations, migrate toward the copper plate, or cathode. Note that the electrons flow from the

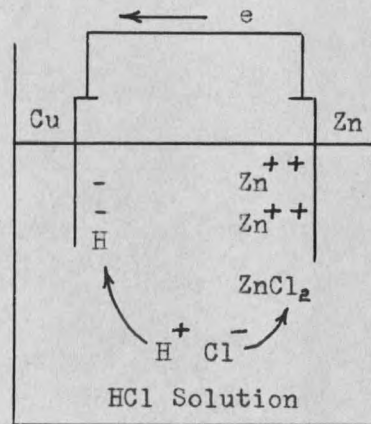


Fig. 5. Electrolytic action of copper and zinc plates immersed in an HCl solution.

zinc to copper plates in the outside circuit. The conventional current flow is in the opposite direction. An anode may be defined as the electrode which passes current into the electrolytic solution. A metal surface is called anodic when it is passing into solution by the release of positive ions. A pair of metal surfaces in an electrolyte (two dissimilar metals, or two dissimilar electrolytes must be involved) is called a galvanic cell. Electrolysis is the term given to conduction of electricity through an electrolytic solution, accompanied by a transfer of ions.

The common dry cell offers another illustration of electrochemical action. The electrolyte in this case is ammonium chloride (actually a wet solution), the zinc shell is the anode, and the carbon rod in the center is the cathode. Positive zinc ions tend to go into solution, but the action will be self limiting unless an outside electrical connection is established between the electrodes; in which case the excess of electrons on the zinc can flow over to the carbon rod where they will join NH_4^+ ions.

The above and previous illustrations are given to bring out basic corrosion theory. The actual transfer of electrons and chemical changes in many electrolytic cells become quite complex, and will show a wide variety of reactions according to the chemical constituents of the cell, current density, temperature, and ionic concentration. However it is not the purpose of this paper to give an extended treatment of electrochemical theory, but rather to apply certain fundamental facts to an understanding of corrosion processes that occur on underground metal structures. Once the nature of the corrosive action is understood, a means for controlling it will be evident.

From the theory discussed so far, the following facts are set out as being particularly important in corrosive processes. An anodic surface

corrodes, or wastes away, under the flow of an electric current. The current may be furnished by an outside source, or it may result from chemical action. In order to come from chemical action (galvanic current), it is necessary that there exist a potential unbalance somewhere within the elements of the solution or galvanic cell. In addition, there must be both a metallic and an electrolytic path between the electrode areas. The latter statement merely implies that a closed circuit must exist for the current to flow. A water solution is necessary and some water will usually enter into the chemical changes by virtue of its tendency to form hydrogen and hydroxyl ions. The most important fact from the standpoint of corrosion control is the stability of the cathodic surface, which does not enter into the chemical reaction. The last statement implies that if a metallic surface could be made cathodic, then no corrosion would occur.

A discussion of underground corrosion in relation to the electrochemical theory previously discussed, is in order. Whenever an iron structure is buried underground, there is almost a certainty that somewhere on the structure conditions will exist favorable to the creation of galvanic cell currents. The metallic structure constitutes the electrodes and the soil is an electrolyte, provided some degree of moisture is present. Almost any kind of a dissimilarity, either in the soil environment or in the metal structure, will give rise to a potential difference. For example, in Fig. 6 a potential difference is caused by the dissimilarity between the surfaces

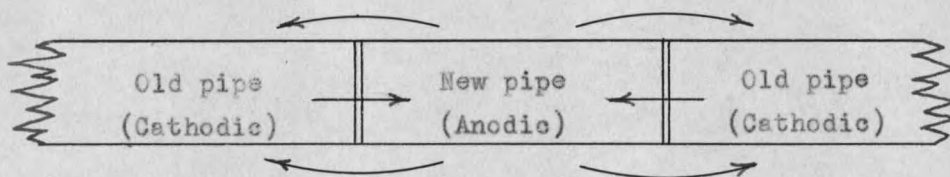


Fig. 6. Galvanic currents between old (rusted) pipe and new pipe in an underground pipe line.

of the new and old pipe. This is the same as saying that the solution pressure of the rusted steel surface is different from the new steel surface, or that the two surfaces occupy a different place in the chemical electromotive series. From the illustration, it can be seen that the current flows from the new to old pipe, and therefore, the new pipe will corrode.

Nearly all cathodic protection literature explains corrosion phenomena in the above manner, that is, by a current flow carrying the anodic surface away into solution. This is a simple explanation and easy to remember, and it will be used in the remainder of this paper after the electron theory has been given some additional attention. Actually of course, the electronic flow is opposite to the conventional current flow. In the above situation, positive iron ions from the new pipe pass off into the soil solution, leaving behind the valence electrons, which are then free to flow through the pipe to the cathodic area and join positive ions (usually hydrogen) at the pipe surface boundary. As the positive iron ions enter into chemical combination with negative ions in the electrolyte, hydrogen ions are displaced, since the overall charge of the solution must remain neutral. These hydrogen ions migrate to the cathodic surface (rusted area in this case) where, after receiving electrons they combine to form molecular hydrogen. Thus the commonly accepted explanation for galvanic corrosion is not technically correct, but it is used because of its simplicity.

Whenever two different kinds of pipe or other metal structures, are joined underground or in water, a galvanic cell is set up. Copper water pipes when connected to steel pipe, can result in corrosion to the latter. Iron, being more electronegative than copper in the potential series, will be the element which will go into solution.

Differences in the surrounding soil can also create potential differ-

ences in buried metal structures. Reference to Fig. 7 shows a typical corrosive situation caused by a difference in soil environment, the pipe being uniform through both soils. There are two conditions here that are

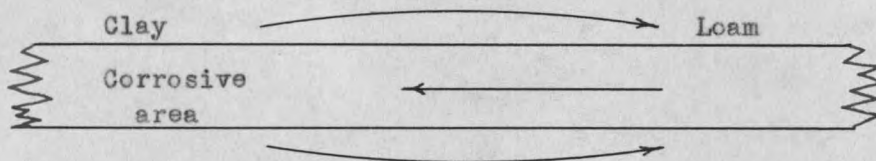


Fig. 7. Underground pipe showing path of galvanic currents caused by a difference in soil conditions.

likely to be predominant in creating a favorable environment for galvanic currents. First is the greater amount of moisture that the clay soil will hold, giving a solution into which the iron ions can pass. Second, the loam soil will drain and dry out better, allowing air to circulate around that part of the pipe. The difference in the ability of the air to get to the pipe in the two kinds of soil gives rise to a condition called differential aeration. The latter condition favors the growth of galvanic currents because the air tends to combine with the hydrogen on any cathodic section of the pipe. Retention of the hydrogen (polarization) tends to lower the magnitude of a galvanic current.

One typical corrosive situation arises from pipe being laid on hard firm ground in a trench bottom, with loose fill material being thrown around it. Air will be excluded and moisture retained at the contact between the pipe and the firm ground on the bottom side, thus creating a condition favorable to the flow of galvanic currents from the bottom of the pipe to the sides and top.

Small galvanic cells can cause pits in a steel surface. Such cells are the result of impurities in the metal, or scratches and nicks on the surface,

exposing fresh metal which will readily corrode. On an underground pipe there is usually a combination of local galvanic cell action along with longer line currents between different sections of the pipe.

Stray ground currents, if they pass through an underground structure, will set up a corrosive area at whatever point they pass from metal to soil. They will sometimes cause a considerable amount of corrosion and can be difficult to deal with.

In setting up a visual picture of galvanic currents and corrosion phenomena on a buried metal system, it should not be assumed that it is a static situation, where steady currents flow in a constant direction. Nor can we always point to a certain location and say that corrosion will, or will not occur there. For example, connections between copper and steel pipes will cause trouble in some locations and not in others. Perhaps the most certain aspect of underground corrosion (and electrochemical phenomena in general) is the variability in observed results. Chemical changes in the soil, changes in temperature and moisture, as well as polarization effects, all influence the rate (and sometimes, direction and location) of corroding currents. The resulting products of electrochemical decomposition may either promote or decrease the rate of corrosion. An oxide or other chemical coating formed close to iron may increase the resistance of the pipe-to-soil boundary, sufficient to nearly stop further corrosion. Or again, a loose non-adherent coating may actually promote corrosion by acting as a second electrode of a galvanic cell. This characteristic of variability will account for the frequent use of qualifying terms in this paper.

The resulting compounds of corrosion vary widely, depending on the metals involved, kind and concentration of soil chemicals, temperature and current density. In general, the metal of the underground structure returns

to a more stable (or lower energy) form, such as an oxide, sulphide, carbonate, etc. In the case of iron, the end product is usually rust, even if it is not always the initial decomposition material. An anodic area on an iron surface will pass into the soil, exhibiting a valence of two in the process (explained by the presence of two valence electrons in the outer, or fourth shell), to probably form ferrous hydroxide ($\text{Fe}(\text{OH})_2$), which in turn is joined by oxygen and hydrogen atoms from moisture present to form the porous ferric hydroxide ($\text{Fe}(\text{OH})_3$). Generally, electrolytic action tends to coat the metal with a chemical compound that reduces the rate of corrosion but does not stop it. It is fortunate that this tendency exists, otherwise underground corrosion would be a far more serious problem than it is.

The underground corrosion of iron is the main concern of this paper since it is one of the most important corrosion problems in the country as a whole and is the main corrosion problem on the Bozeman campus. No reference has been made to corrosion above ground, which represents an even larger loss to industry, since it is beyond the scope of this paper. Corrosion of buried lead-sheathed cables is sometimes encountered where the lead is in the proximity of more active metals. Certain metals such as chromium, copper, and gold show a minimum tendency to corrode. It is known that this resistance to corrosion is linked up with the formation of an extremely thin (sometimes only a few atoms thick) and tenacious oxide coating. While iron will assume an oxide coating, the ferrous hydroxide, which usually forms next to the metal, is soluble and unstable, which perhaps accounts for the fact it does not furnish a good protective coating.

THE PREVENTION OF CORROSION

Referring to the summary of some basic facts from electrochemical theory on page 12 and 13, it will be recognized that two methods of controlling corrosion are readily apparent. First, since moisture is necessary for conducting a galvanic current, we need only to exclude it from the buried structure. Second, if moisture cannot be entirely excluded, then causing the buried structure to assume a cathodic state would prevent corrosion. These are the two primary methods used in controlling or mitigating the effects of underground corrosion.

The application of an insulating, waterproof coating on any buried metal is the most basic method of corrosion control. However, no known coating will give permanent protection at a reasonable cost, and furthermore, it is seldom possible to lay the metal structure in the ground without causing at least some damage to the coating. The latter necessitates a second line of defense against corrosion. Electrochemical theory tells us that if a positive potential can be applied to the ground, causing a current to pass from the ground to the buried metal (causing the metal to assume a cathodic state), no corrosion would occur. The latter process can be carried out and as before stated, is called cathodic protection. Of course if the entire buried structure is to be made a cathode we will need to supply an anode, but that can be done by arranging a ground bed of scrap iron or carbon rods.

The application of a ground-to-pipe potential of around 0.28 volt has been found to effectively stop corrosion on a buried iron or steel structure.¹ This counter-voltage not only stops the long line galvanic currents,

¹National Association of Corrosion Engineers, Report of Correlating Committee on Cathodic Protection, Houston, Texas, 1951, p. 14.

but smothers out the local cell action also. When no galvanic currents can flow corrosion ceases, and this fact furnishes proof of the electrochemical nature of underground corrosion.

There are a few basic facts about cathodic protection that should be set up at this time. First, a cathodic protection system is not an adequate substitute for a waterproof coating over extensive underground structures. Current requirements are excessive on bare surfaces, making cathodic protection expensive on uncoated pipe lines. It is sometimes applied to uncoated lines to bring corrosion under at least a partial degree of control, but the application of cathodic protection to coated lines is much more economical. The cathodic protection has been found necessary to protect a pipe at points where the coating has been damaged or has deteriorated with age. Since the coating is an effective insulator for the low voltages involved, current requirements will be very low, as it will flow into the pipe only at the points where breaks exist in the coating. Backing up a good coating on an underground pipe line with a cathodic protection system is the most effective means now known of preserving the line.

EQUIPMENT USED FOR CATHODIC PROTECTION STUDY

To give a further understanding of corrosion of buried metal structures and their protection by electrical means, the equipment used and some laboratory experiments will be described. It was found that most of the current literature on cathodic protection did not go into the simple essentials concerning its practical application. For instance, polarities on test circuits to measure pipe-to-ground potentials were not clear from articles on the subject, and there was little information as to kind of equipment to use, or how to use the equipment in making tests. It was therefore desirable to set up simulated models in the laboratory and outdoors, in order to study corrosion currents under controlled conditions. It was at this point that considerable help was received from Mr. Carl Davis of the Montana Power Company.

The first problem was to obtain the necessary equipment for taking measurements on laboratory tests, and later for the campus survey. Although large engineering firms that engage in cathodic protection service have quite elaborate apparatus, a small amount of equipment was considered adequate for the purposes of this particular study.

The first piece of equipment which will be considered is the so called "half-cell," commonly employed in cathodic protection surveys, for obtaining a stable ground contact. If a metallic contact is made with the ground, a surface contact potential will exist, the magnitude of which will depend on the kind of metal, ground moisture and salts, etc. In short, the potential introduced into the measuring circuit will never be accurately known.

The half-cell constructed for this study was made from a copper tube about eight inches long. A wooden plug inserted in the lower end of the tube and moistened with a copper-sulfate solution, is the ground contact.

The particular cell, illustrated in Fig. 8, is patterned after the type used by the Montana Power Company. The tube is partly filled with water, and copper-sulfate crystals are added to produce a saturated solution. The wooden plug should be made from a porous type of wood and cut slightly small because the moisture will cause it to swell. The grain should be lengthwise so the solution can soak through. A length of about $5/8$ inch was found satisfactory. A rubber boot should be arranged to slip over the lower end of the half-cell, so the wooden plug will remain moist when not in use. In the field, the half-cell is used to connect the voltmeter to ground when making

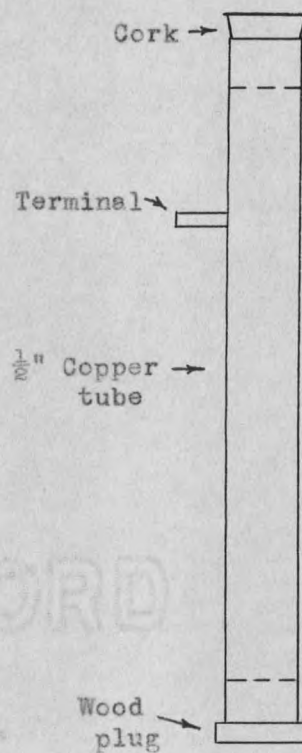


Fig. 8. Copper-sulfate half-cell.

potential measurements between buried metallic surfaces and ground. Its advantage lies in the fact that the contact potentials introduced by the half-cell are fairly stable, being around 0.5 volt.

The next item of equipment needed was a low range d-c voltmeter of high sensitivity. In taking a pipe-to-soil potential measurement, the voltmeter is connected between the pipe and the half-cell, with the latter constituting the ground connection. Since the ground resistance is ordinarily rather high, the meter current will cause a voltage drop through the ground, and the error can be appreciable if a meter of low sensitivity is used. In cathodic protection work, a voltmeter of 100,000 ohms per volt with a center-zero scale is considered desirable. The expense of such a

meter would not be justified for the project described in this paper. The meters at the engineering laboratory were checked over and a Simpson multi-meter (model 260) appeared to be the most desirable. The instrument was portable, fairly rugged and moderately sensitive. The lowest voltage range was 2.5 volts, which was satisfactory, and the lack of a center-zero scale was not deemed serious. The inclusion of milliamperere and ohm ranges in the same instrument was convenient, since both would be used at times. The sensitivity of 20,000 ohms per volt (50,000 ohms on the 2.5 volt range) was not up to cathodic protection standards, but the accuracy would be fair if ground resistance values were not excessive. The Simpson meter No. 939 was selected for this work.

The 2.5 volt and 10 m.a. ranges were checked against standard laboratory meters and found to be quite accurate for a meter of this class. The zero adjustment was set so the 2.5 volt range was correct at 0.85 volt (the standard criterion for cathodic protection). Tests were made to verify the manufacturer's sensitivity rating of 20,000 ohms per volt. The tests indicated 50,000 ohms resistance on the 2.5 volt d-c scale within ± 100 ohms. The resistance tests were made both on an impedance bridge and wheatstone bridge, the latter giving better accuracy.

A means of compensating for the resistance drop in the ground caused by the meter current, called the two-reading method, consists of bridging the voltmeter with a resistance approximately equal to that of the voltmeter. When a voltage reading is taken across a high resistance circuit, two readings are taken; with and without the shunt circuit connected across the voltmeter. The difference between the two readings is added to the higher reading. Although the two-reading method does not give an exact voltage reading, it does improve the accuracy of the meter for cathodic

protection work. The mathematical analysis of the voltmeter circuit for the two-reading method is given in the appendix.

Fig. 9 shows in the most simple manner, the voltmeter connections for measuring pipe-to-soil potentials. The meter will read

a voltage which primarily represents: (a) the electrochemical film potential on the surface of the pipe, (b) the contact potential of the ground lead from the voltmeter, and (c) the voltage drop in the ground, between the pipe and ground lead. Assuming a soil resistance between pipe and ground lead of 10,000 ohms, then using the Simpson voltmeter with an internal resistance of 50,000 ohms, let us assume a reading of 0.7 volt. The voltmeter requires a current of 1.4×10^{-5} amperes for the particular reading. Multiplying 1.4×10^{-5} by 10,000 gives a voltage drop through the ground resistance of 0.14 volt. The latter figure constitutes an error which could be significant in cathodic protection work.

Fig. 10 illustrates a typical situation on an underground pipe where galvanic currents are flowing due to differences in soil, pipe surface, and moisture conditions. In a cathodic protection survey it is necessary to determine whether conditions favorable to corrosion exist and at what points in the system they exist. Part of the survey will consist of obtaining pipe-to-soil potentials at various points, because they will be indicative of areas where current may be flowing into or out of the pipe, and of course, the direction of these currents between pipe and soil are the key to the corrosion problem. In Fig. 10, the voltmeter has been connected to the

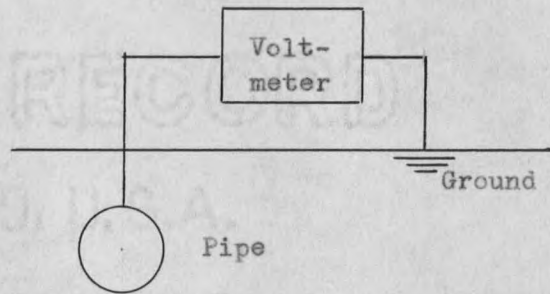


Fig. 9. Voltmeter connections for measuring pipe-to-ground potential.

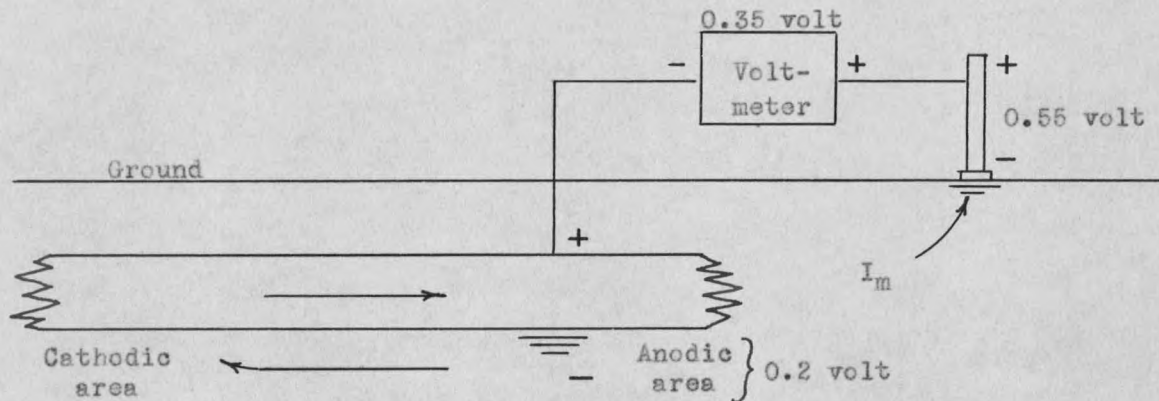


Fig. 10. Circuit diagram of a typical field test for measuring a pipe-to-soil potential, using copper-sulfate half-cell as ground terminal of voltmeter.

pipe at an anodic (corrosive) area, where current is flowing from the pipe. Assume a pipe contact potential of 0.2 volt, that is, the pipe has a higher voltage than the surrounding soil. If the potential of the sulfate half-cell is 0.55 volt, then the voltmeter will read 0.35 volt. Note that the entire voltmeter circuit corresponds to a wet cell, with the ground soil and copper sulfate solution being the electrolyte.

In cathodic protection practice a voltmeter reading taken under conditions similar to those in Fig. 10, would usually be recorded as a negative quantity, or as -0.35 volt. It is a question of whether we want a pipe-to-soil potential, or soil-to-pipe potential. Since it is customary to refer to the potential as a pipe-to-soil measurement, then reference to the polarities in Fig. 10 will show that the voltage should be expressed as a negative quantity when considered from the voltmeter and half-cell side of the circuit. The negative concept here also fits in with the basic principle of cathodic protection, namely: the pipe should be negative with respect to ground in order that a protective current may flow from ground to pipe.

A test circuit was set up in the laboratory as shown in Fig. 11 for the purpose of determining the optimum resistance to use in parallel with the voltmeter, for the application of the two-reading method. The Simpson multi-meter, set on the 2.5 volt d-c scale, was connected into the test circuit. For the first trial R_p was set at 48,000 ohms. Pipe-surface film and half-cell potentials were represented by a dry cell (1.55 volts).

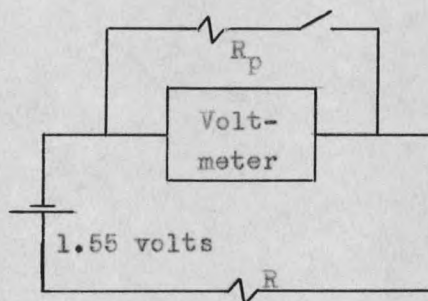


Fig. 11. Test circuit to determine correct value for parallel resistance R_p , used in the two-reading method.

The direct meter reading was 1.5 volts and with the shunt circuit closed the reading was 1.45 volts. Adding the difference of 0.05 volt to the first reading gave 1.55 volts, the correct result. A lower voltage was tried and results were equally good. Further tests indicated a negligible error for ground resistance values up to 5,000 ohms. A second series of tests using 41,000 ohms for R_p indicated that the value of the shunt resistance was not critical.

After further testing, a parallel meter resistance R_p of 40,000 ohms was chosen. This resistance gave a slight overcompensation with ground resistances under 1,500 ohms, but was quite accurate over the range between 1,500 and 7,000 ohms. With a 10,000 ohm ground resistance R , the following results were obtained:

<u>Voltage on test circuit</u>	<u>Error, using two-reading method.</u>
1.5	4%
1.0	3%
0.5	0%

A small 40,000 ohm resistor of $\frac{1}{2}$ watt rating was mounted inside a push-button switch, which in turn was taped on the meter. The leads from the switch were soldered across the meter leads. This arrangement gave a convenient means of obtaining the second voltmeter reading and did not interfere with the use of the meter as an ammeter or ohmmeter.

The remaining piece of equipment was a fibre tube for obtaining ground resistivity measurements. The particular tube was cut three centimeters long and measured 2.7 cm. inside diameter. To obtain a ground resistivity measurement a soil sample is packed firmly in the tube, then a resistance measurement is made between a pair of metal plates held tightly against the ends of the soil sample. The ohmmeter leads should be reversed for a second reading so that any difference between the contact potentials of the metal plates can be averaged out. Readings should be taken quickly as polarization effects almost immediately set up an increase of apparent resistance. The resistivity in ohms per cubic centimeter can be calculated from

$$R = k \frac{l}{A}, \quad \text{or } k = \frac{A}{l} R = \frac{5.62}{3} R = 1.87R.$$

There is special equipment made for measuring ground resistivities which is faster to use and probably more accurate. But it is considered that the above method will give sufficient accuracy for the study and survey described in this paper.

EXPERIMENTS

Some experiments were set up to study corrosion currents, and the effect of cathodic protection voltages. A pair of steel rods and a copper rod were driven in the ground at several locations and voltages observed. Between the steel and copper rod there was always a difference of potential of around 0.3 to 0.4 volt. There was also a difference of potential between the steel rods, but generally less than 0.05 volt. These tests established the fact that a pair of metal electrodes in the ground are almost certain to show a difference of voltage, even when the electrodes are of the same metal. In the latter case variations in contact pressures and ground moisture will account for the potential difference. From the standpoint of corrosion, all that is needed is a closed circuit. Figures 6 and 7 showed how a closed circuit can exist on an underground pipe.

To try out the equipment and observe the effect of a cathodic protection voltage under controlled conditions, a model situation was set up as shown in Fig. 12.

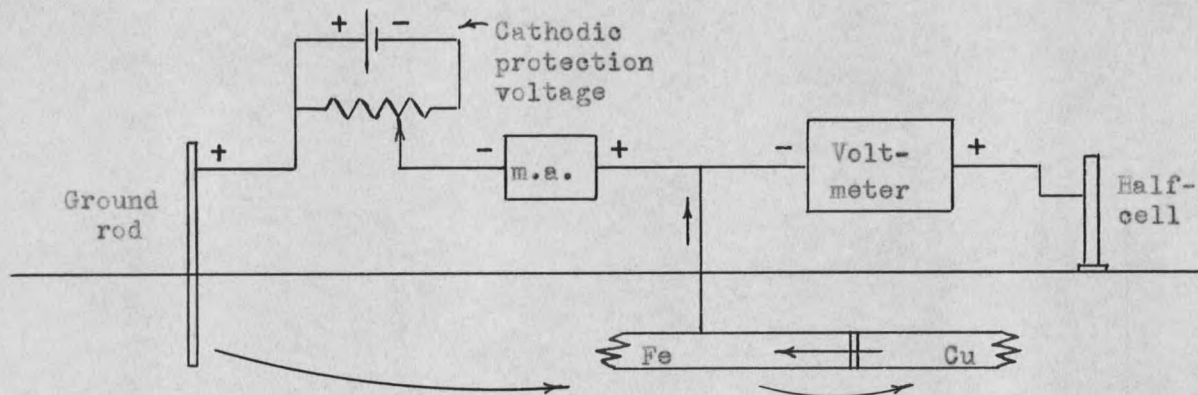


Fig. 12. Circuit for duplicating underground corrosion currents and cathodic protection system. Voltmeter is connected in the usual manner for obtaining pipe-to-soil potentials in the field. Corrosion current flows from iron to copper, which can be stopped by the over-riding cathodic protection voltage. Arrows show directions of current flow.

An iron and copper bar were bolted together and buried a few inches in the ground outside the engineering laboratory. A galvanic current flowed from the iron through ground to the copper. A voltage-divider circuit was arranged to provide a variable voltage for cathodic protection. Note that the voltmeter reads both the iron surface film potential and half-cell potential. The results are recorded in Table I.

Table I. Current and Voltage Readings in Test Cathodic Protection System.

<u>Cathodic Protection Voltage</u>	<u>Cathodic Protection Current m.a.</u>	<u>Iron-to-Soil Potential Through CuSO₄ Half-cell</u>
0.0	0.00	-0.49
0.2	0.42	-0.63
0.4	1.10	-0.73
0.6	1.50	-0.81
0.8	2.00	-0.89
1.0	2.40	-0.97

All iron-to-soil potentials in Table I include a correction factor of 0.03 volt, which represents the difference observed between the voltages in the two-reading method. Note that the cathodic protection current and the test voltages do not follow a proportional relationship with the protection voltage. Such a non-linear relationship is typical of electrochemical actions.

Another experiment was set up similar to the above, using a different type of soil which was placed in a box so the experiment could be performed in the laboratory. Enough water was sprinkled on the soil to make it moderately damp, and a copper plate and two steel plates were inserted in the

soil. The purpose of this experiment was to study the actual galvanic current flowing out of an iron anode and the effect of different cathodic protection voltages. This was not done in the previous experiment because the micro-ammeter necessary to measure these currents, introduces considerable resistance into the circuit, and it was desired to make that experiment representative of field conditions. The circuit diagram is set up in Fig. 13, and Table II shows the results as the cathodic protection voltage is varied from zero to one volt.

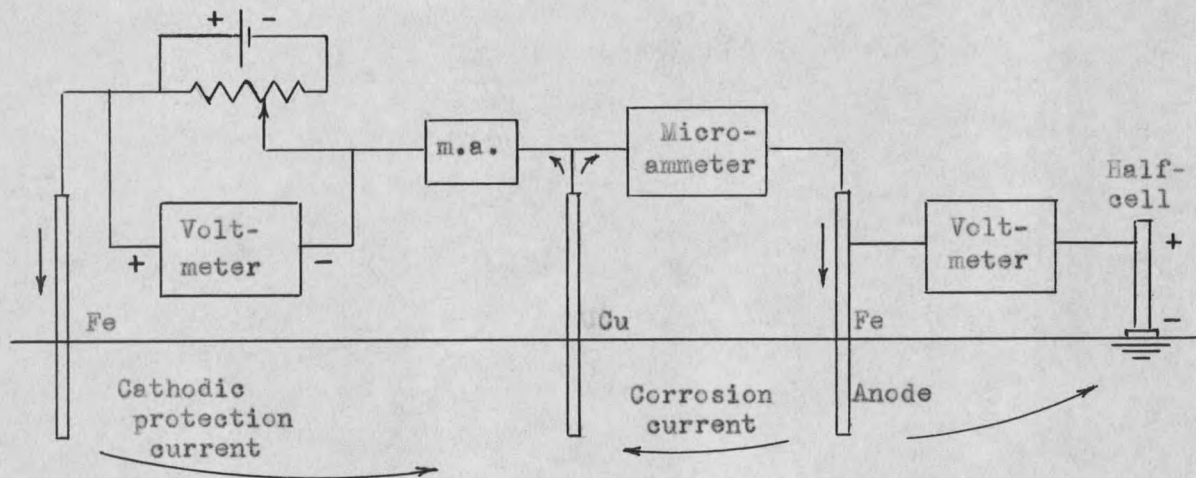


Fig. 13. Circuit diagram of cathodic protection experiment to show magnitude of galvanic current flowing from an iron anode. Arrows indicate the various current directions before sufficient counter-voltage was applied to stop the underground current from leaving anode. Open circuit voltage between copper and iron, 0.6 volt.

The most important fact brought out in the experiment is the decrease of current leaving the iron anode underground, as the cathodic protection voltage is increased. Note also that with a cathodic protection voltage of 0.63 the current flow from the anode is stopped completely. That is the ideal level for a cathodic protection system, but cannot be achieved in an actual system (except at a few points) because of voltage drops along the protected structure.

Table II. Currents and Voltages in Laboratory Cathodic Protection Test.

Cathodic Protection Voltage	Cathodic Protection Current m.a.	Current through Iron Anode to Ground Micro-amps	Iron-to-soil Potential Through CuSO ₄ Half-cell
0.0	0.00	310	-0.62
0.1	0.24	180	-0.70
0.2	0.30	150	-0.72
0.3	0.40	110	-0.75
0.4	0.45	80	-0.77
0.5	0.52	50	-0.79
0.6	0.60	15	-0.81
0.63	0.64	0	-0.82
0.70	0.70	-25	-0.84
0.8	0.78	-58	-0.86
1.0	0.92	-140	-0.92

Another fact brought out in the experiment is that total protection was achieved at the point where potential between pipe and soil as measured through the half-cell, was 0.82 volt. This gives a criterion by which to estimate whether full protection has been reached in field surveys. Actually 0.82 volts falls inside the theoretical range at which galvanic currents should be stopped from an iron surface (0.812 to 0.831).¹ In field practice, the criterion is commonly set at 0.85 volt to include a safety factor. Another criterion sometimes used is to apply the necessary cathodic protection voltage (or current) to raise the static ground-to-

¹National Association of Corrosion Engineers, Report of Correlating Committee on Cathodic Protection, Houston, Texas, 1951, p. 14.

pipe potential by 0.3 volt.

The iron-to-soil potential readings in Table II include an average correction factor of 0.02 volt. An approximate check can be made by using equation (6) from page 3 of appendix. The ground resistance in voltmeter circuit is expressed by

$$R = \frac{R_{V1} R_{V2} (V_{13} - V_{13}')}{V_{13}' R_{V1} - V_{13} R_{V2}}$$

where R_{V1} is voltmeter resistance, R_{V2} is resistance of voltmeter and shunt in parallel, V_{13} is voltmeter reading without shunt resistance, and V_{13}' is voltmeter reading with shunt resistance connected in circuit.

$$R = \frac{50,000(22,222) (0.77 - 0.75)}{0.75(50,000) - 0.77(22,222)} = 1,093 \text{ ohms}$$

The voltmeter uses $\frac{0.77}{50,000}$ amperes at a voltage reading of 0.77.

Multiplying ground resistance by the meter current gives a voltage drop of 0.017 volt. This corresponds to the 0.02 correction factor actually used.

It is of interest to check the current requirement per unit area for complete protection of the iron surface. The area of the iron plate underground was approximately 6 sq. in. Full cathodic protection was achieved with a current of 0.62 m.a., which amounts to 15 m.a./sq.ft., a rather high figure. In practice it usually requires from one to 20 m.a./sq.ft. to protect a bare iron surface with 2 to 3 m.a./sq.ft. being perhaps an average range.

Some further laboratory tests were run to establish the nature of corrosion. One test involved two soil samples placed in the same jar with a nail inserted in each soil. The nails were connected electrically through a microammeter. The initial current was 30 microamperes but by the second day was down to four microamperes. After this the current direction

would change occasionally, particularly at times when water was added to maintain the soil moisture content, reversing later as the soil dried out. After about two months the nails were removed, with both showing surface rust.

In another test two nails were placed in a beaker of tap water and a voltage impressed on them until the portion of the anodic nail below water line was completely corroded away. The water in the beaker was allowed to dry by atmospheric evaporation. The remaining sediment was found to be magnetic, which would mean that at least part of the material was magnetite, (Fe_3O_4). The material was weighed and the calculated weight of iron (assuming the material to be magnetite) was compared to the loss of weight in the nail. The calculated weight of iron (8.0 grams) was too much in comparison to the loss of weight in the nail (7.4 grams). On the other hand, if the material in the beaker was all ferric hydroxide ($\text{Fe}(\text{OH})_3$), the calculated weight of iron would be too small. It was concluded then that the material was some of each, in fact calculations indicated 74 percent magnetite and 28 percent ferric hydroxide.

The above explanation assumes the presence of only two compounds of iron with oxygen and water. It is quite possible that there are also present other hydrated forms of ferric oxide, but the above calculations probably do not contain any serious error. Ferrous hydroxide for example, tends to oxidize to the ferric form. Ordinary rust is considered to be mainly ferric hydroxide.

CATHODIC PROTECTION SYSTEMS

A cathodic protection system may be of the impressed current type, or the galvanic anode type. The impressed current type uses a d-c voltage to cause the underground metal structure to assume a lower potential level than the ground. The positive lead is connected to a ground bed consisting of scrap iron, carbon or graphite rods; and the negative lead is connected to the system to be protected. If scrap iron is used, the iron will corrode away at the rate of about 20 pounds per ampere year. It is a case of sacrificing the scrap iron to protect the underground system.

In the application of cathodic protection, a survey is first made in which the entire underground system to be protected is given a close study and mapped out. A record is made of structure-to-ground potentials, ground resistivity measurements, and possibly soil analyses. Areas showing high structure-to-ground potentials, low soil resistivities, or high chemical content, are more likely to be corrosive.

To interpret the record of potential measurements between the metal structure and ground, in the case of iron a guide often used is to consider a potential measurement (through copper-sulfate half-cell) less than 0.6 in magnitude as being indicative of a current flow out of the iron surface, while between 0.6 and 0.85 is considered to be a range over which current might flow out of the iron but corrosion is not apt to be serious. A reading of 0.85 volt or more indicates of course, a current flow into the iron surface, which is thereby protected. However in general, the record of potentials and ground resistivity measurements must be taken as a guide and not as an absolute indicator of corrosive locations. It must be noted that no known method will accurately predict where and to what extent corrosion will occur.

Before applying cathodic protection it is necessary to electrically isolate the system to be protected. This not only provides an economical application of electricity by keeping it on a given system; but stray current from a cathodic protection system may cause corrosion on foreign lines by taking ground paths between different structures. A second requirement is that of bonding the system to be protected until it is electrically continuous. While insulated joints on an unprotected system may reduce current flow through the structure, they will increase corrosion on a protected system because the current will tend to follow a ground path around any insulated point, causing corrosion wherever current leaves the metal surface.

Well designed ground beds are essential to the efficient operation of a cathodic protection system. They should be buried below the frost line, and the resistance between ground bed and soil must be low. A backfill of fine coke (coke breeze) is frequently used, both to lower the resistance to earth and to increase the life of the ground bed. The ground bed should be located in a low resistance ground area and the location should permit, as much as possible, an even current distribution over the protected underground structure.

The size, number, and location of rectifier stations must be planned with respect to suitable location of ground beds, and distance each rectifier unit will furnish protective current. Sources of electric power may sometimes influence the location of stations also. Raising the voltage output to increase the area of protective coverage can be carried only to a certain point. An excessive potential applied to a pipe for example, will result in a wasteful use of current, and if the pipe is coated, hydrogen may form under the coating causing the bond to weaken between

coating and pipe. Voltages for cathodic protection are low, usually under twenty volts. For long coated pipe lines, each rectifier station may serve up to 20 miles of pipe, or more.

Calculation of current requirements and comparison with similar cathodic protection systems often helps in the overall design. Because of the variables, computations may be difficult, and actual tests are preferred when possible. Tests are made by using a portable d-c voltage source and temporary ground beds. After a test voltage is applied, structure-to-soil potential measurements are taken to determine how far a protective level of voltage extends.

When the rectifier stations, or other sources of direct current are connected to the underground system and ground beds, the voltage at each station must be adjusted until a suitable level of protection is achieved. This can be determined by taking half-cell potential readings at different locations on the protected structure. The current requirements will probably change for a time, and several weeks may elapse before the operation becomes fairly stable. However, ground beds deteriorate, soil conditions change and chemical changes are likely to occur on and near the metal surfaces of the ground bed, all of which influence the operation of the cathodic protection system. For such reasons, it is necessary to make periodic checks on current output and potential readings if the system is to maintain its efficiency.

The photographs on page 36 show a cathodic protection unit on the Montana Power Company gas transmission pipe line near Cut Bank, Montana. In Fig. 14 the distribution transformer near top of the pole reduces voltage for the rectifier in cabinet near base of pole. The positive output lead, about half way up the left side of pole, goes to the ground bed.

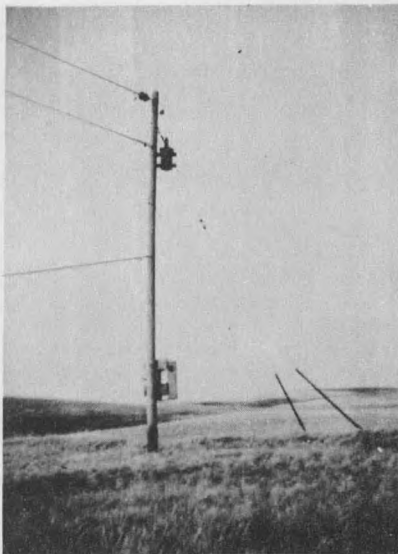


Fig. 14. Cathodic protection station on Montana Power Co. gas transmission line near Cut Bank, Montana.

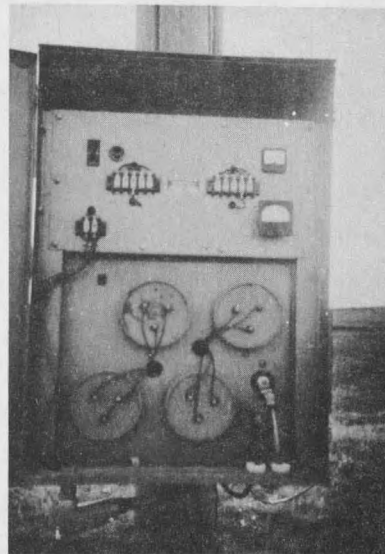


Fig. 15. G-E rectifier unit with cover open. Output at time of picture was 15 amperes at 17.5 volts.



Fig. 16. Ground bed of cathodic protection station shown in Fig. 14. Rectifier cabinet on pole in distance.

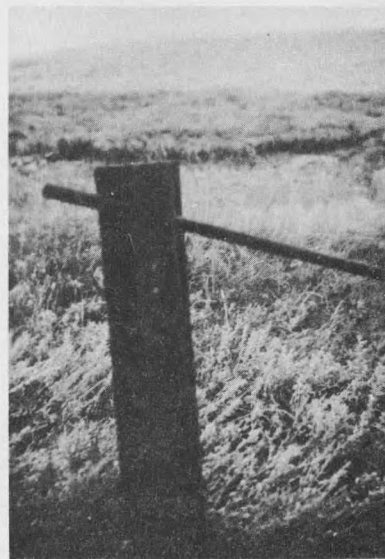


Fig. 17. One of steel rails in ground bed. Rod at top is welded bonding connection between the rails.

Fig. 16 shows the ground bed for the cathodic protection unit of Fig. 14. Barely showing through the surrounding grass, are several steel rails and a steel bonding rod connecting the rails together. The rails are set vertically into the ground and the bonding rod is welded to each rail forming an electrically continuous ground bed. The bed extends for approximately 100 yards, and is a Y shape. The Montana Power Company is at the present time favoring the use of discarded pipe for ground beds. The pipe is buried in a horizontal position. The lead-in wire and its connection to the pipe must be insulated, otherwise that portion of the wire buried in the ground would corrode away just like the ground bed.

The location of the above cathodic protection unit has been chosen with reference to the location of the gas line, the availability of electric power, and nearness to a suitable area for a ground bed. The particular ground bed lies in a low area where drainage is poor, but soil moisture conditions favor a low resistance contact between the scrap iron and ground, the latter being essential to the efficient operation of the system.

The use of galvanic anodes is another means of applying a protective current, and is often economical on small underground systems, or on larger systems where protection is only needed in occasional areas called "hot spots." Aluminum, zinc, and magnesium are all more active than iron (more negative in the electromotive series) but magnesium is generally preferred because of its higher voltage and more dependable operation. The magnesium acts as a sacrificial anode when connected to the buried structure by a conducting wire. Current will flow from the magnesium to the iron structure by the ground path. The magnesium-to-ground potential as measured through a half-cell is about -1.5 volts and is quite stable.

Magnesium anodes made especially for cathodic protection work can be

obtained. They may be purchased with 10 feet of wire attached. They are made in various weights, but the 9, 17 and 32 pound sizes are the more common. In most soils it will be found desirable to surround the magnesium anode with a backfill material to provide a lower resistance, as well as a more homogeneous ground contact. One type of backfill is made from powdered bentonite and gypsum, hydrated ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Each pound of magnesium will furnish 500 ampere-hours of current.

The use of magnesium anodes is quite simple. An anode is connected to the underground structure by a conducting wire, then buried in the ground, preferable below frost line. The wire only needs to be buried deep enough to avoid damage, and it does not need to be insulated, since it is on the protected side of the circuit. Insulated wire is ordinarily used though, to reduce the current drain on the anode. No elaborate survey is generally necessary; they can be installed by untrained help, and they require no maintenance other than replacement. Soil resistivity measurements are useful in estimating an optimum size of anode to use. A life expectancy of ten years is the usual basis on which estimates are made. Tables are available which give a recommended spacing between anodes according to size of pipe and ground resistivity.

It should be again stated that cathodic protection is not to be considered as a primary means for prevention of underground corrosion, except in special cases. Sound corrosion engineering should take into consideration all possible economic means for extending the life of underground metallic structures. Adequate drainage of areas where steel structures are located is a most effective way of getting at a basic cause of corrosion. If possible, metallic structures should not be located in areas where waste products have been disposed of. Trash and general waste items

left over from construction jobs should not be used as backfill on pipe lines. Ashes and cinders are most likely to cause acute corrosion problems. The use of different kinds of metals in adjacent structures should be avoided, if possible. It has been previously stated in this paper that insulating joints can sometimes reduce currents flowing through an underground structure, but if cathodic protection is contemplated, then an electrically continuous system is necessary.

CATHODIC PROTECTION SURVEY OF MONTANA STATE COLLEGE CAMPUS

The survey of the college campus was made to determine the kind and extent of a cathodic protection system that might be set up. The need for at least some protection was already established since some pipe replacements have been made. Trouble occurred primarily on gas pipe lines and only in a few areas. Corrosion has not been a serious problem on the campus, but it was considered desirable to make a survey for the purpose of determining to what extent corrosion was taking place and recommending means of reducing corrosion in the future.

The system of underground piping on the campus consists of steam, gas and water pipes, the latter including a system of lawn sprinkling pipes. Together it makes a fair concentration of underground pipes going in different directions under most of the campus.

The steam pipes are not considered a problem since they are already covered with heat insulation. The water mains are cast iron and no trouble has been experienced with them. The gas lines on the campus are ordinary wrought iron; they are owned by the college and are insulated from the Montana Power Company mains. The gas lines are welded together, making them electrically continuous. Most of the gas lines are bare but present practice is to use a coated pipe on any new installations. The water mains on the campus are not insulated from the city system. Joints on the water mains are of different types; some are insulating while others give an uncertain degree of electrical contact. Resistance checks were made between the fire hydrants at Hamilton and Lewis halls, and from Lewis Hall to the fire hydrant at the southeast corner of the agriculture building, giving 1.5 and 3.0 ohms respectively. The measurements indicate fair conductivity at joints along those particular runs of water pipe. A few

checks between faucets on sprinkler system showed negligible resistance. There is some degree of bonding between the water and gas lines at the gas hot-water heaters in housing areas.

During the summer of 1956 a number of trenches were excavated over the campus, giving an opportunity to make observations on underground piping at a number of different points. Pipe-to-soil potential measurements were made and condition of any exposed lines noted. In general it can be said that corrosion was mild. Most voltage readings ran between -0.5 and -0.67 volt, a range over which it can be said that corrosion can exist, but is not likely to be severe. Nearly all the pipe exposed was in good condition, with only superficial rust in scattered areas. One pipe in front of the Student Union building was badly rusted, but this could have been due to the proximity of a copper pipe which crossed within five feet. Another pipe near the northwest corner of the heating plant was badly rusted. This pipe was exposed by a trench running at right angles and a section had been cut out of the pipe to make a free pathway along the trench. The pipe-to-soil potential was -0.5 volt. Of more significance was a voltage of 0.4 volt between the two ends of the pipe. A check with the milliammeter showed 0.22 m.a. There are ashes and cinders in some of the soil around the heating plant area, which would account for corrosive conditions. In general the soil on the campus gives no evidence of being especially corrosive. It is common practice to join copper water lines to steel lines in the housing areas, with no trouble having been experienced, which is further indication of the mild nature of the soil.

Soil resistivities over the campus ran from 2,500 to 9,000 ohms per cubic centimeter. In this part of the country, soil resistances averaging this high are not apt to show acute corrosion problems.

Actual observations along with soil resistivity measurements indicates that some of the area around Montana and Hamilton halls, the heating plant, and some points in the housing area at the northwest corner of the campus might be places of possible corrosion. It should be noted however, that time did not permit a complete survey of soil resistivity measurements.

The problem of isolation and bonding the underground piping system on the campus would be expensive. There are three connections to the city water system that would need insulating joints. The largest expense would probably be the installation of bonds between each length of pipe on the water mains. Such bonds should be brazed or welded to the pipes, and to the joint itself if separate from the pipes. In addition, a number of bonds should be installed between steam, gas and water systems, to reduce stray currents from passing between different parts of the underground system through a ground path. Such currents can occur at a point where for example, a gas and water line cross within a few feet of each other. If a difference of potential exists between the two lines, say due to a difference in resistance between this location and the point where the connection is made to the rectifier station, then a current may pass between the gas and water lines, corroding the particular surface where the current leaves for the ground path.

After bonding and isolating, rectifier units would need to be set up at various points to furnish a d-c voltage, if it were decided to use an impressed current system. Mr. Davis of the Montana Power Company estimated that four or five rectifier stations would probably be needed. The reason for this number is that most of the gas and water pipe is bare, and protection would not extend very far from each unit unless an excessive voltage was used. The actual location of the stations could be decided on

after trial tests.

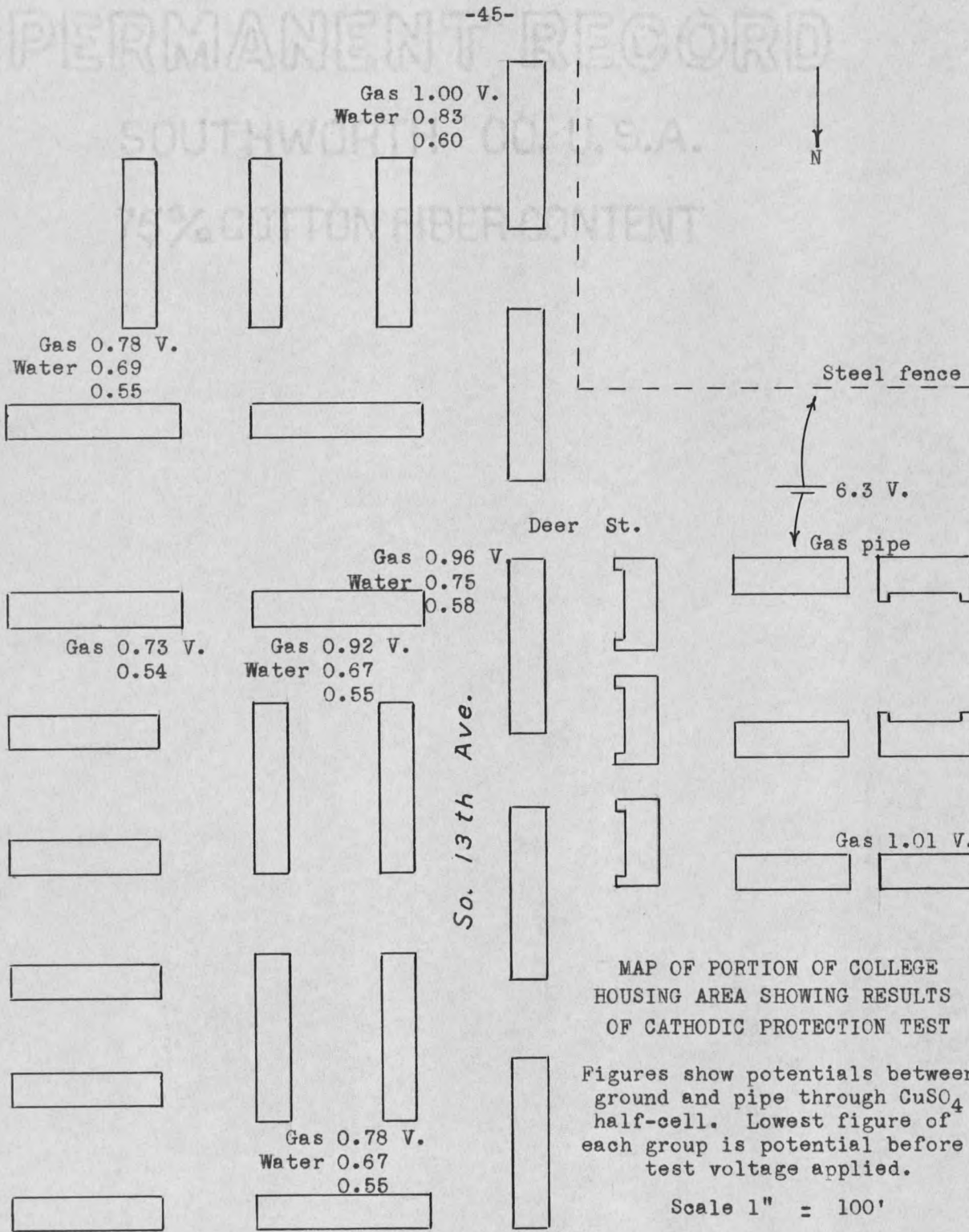
The above information is given relative to the possible installation of a cathodic protection system on the campus, using rectifier units and ground beds. This is not to say it is necessarily the best system, but the information is given by way of showing what would be required and the difficulties involved. No cost study was made, but \$15,000 is given as an estimate.

TRIAL RUN OF IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

A trial run of an impressed-current system of protection was made at the new housing area from a point on Deer street. Initially, two tests were run near Montana Hall using a steel rod driven in the ground, and another test was made near the engineering laboratory using a similar ground. A car battery was the voltage source. The results from these tests were poor. On the latter test a current of 90 m.a. was recorded, with the protective level not extending over fifty feet any direction. A second ground rod was driven and the current went up to 125 m.a., which indicated that lack of a suitable ground bed might be the reason for the low test current.

The next location for a test was chosen on Deer street primarily because of the proximity of a steel fence which might give a good ground. The test was set up at apartment No. 1403, running a connection from the steel fence to positive side of a car battery. A length of wire was run from the negative terminal to the water pipe going into the apartment. The current measured from 390 to 442 m.a. during the period of the test. However, a suitable level of cathodic protection was still not achieved.

On another day while the ground was still slightly damp from a recent rain the test was repeated, using the fence as a ground bed, and connecting the negative battery terminal to the gas line at apartment 1403. This time a current of 4.7 amperes was recorded, and it was found that a suitable level of protection extended over a large portion of the housing area. Pipe-to-soil potentials ran from -0.6 at the fire hydrant on Elk street, to -1.2 volts in the area adjacent to the test. Before the test the potential range ran from -0.41 to -0.62 in the same area. The map on page 45 shows results of the test over a portion of the test area.



MAP OF PORTION OF COLLEGE HOUSING AREA SHOWING RESULTS OF CATHODIC PROTECTION TEST

Figures show potentials between ground and pipe through CuSO_4 half-cell. Lowest figure of each group is potential before test voltage applied.

Scale 1" = 100'

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The potential measurements are shown on the map without the negative sign, to save space. It will be noted that a difference exists between potential measurements made on gas and on water pipes, at each location. Gas and water pipes were generally not over five feet apart, and potential measurements were the same before test voltage was applied (given by lowest figure at each location on map). No entirely satisfactory explanation has been found for this but two possible factors are: poor electrical contact at some of the water-pipe joints and the screw-on type couplings used on the gas lines around the gas meters; and a difference in the water and gas pipes used in service lines. The water pipes for example, were probably galvanized when first installed. However, the water pipes entered the ground underneath buildings, so no visual check could be made on the condition of the galvanized coating at the present time. Tests made with an ohmmeter showed some resistance in the gas lines around meters.

The above tests demonstrated the importance of an adequate ground, even for a trial run. The tests also showed the need for good electrical continuity in the protected structure. The cathodic protection level obtained in the final test at the new housing area tended to back up the estimate of Mr. Davis of the Montana Power Company, that four or five rectifier stations might be required for complete campus protection. Also, it should be mentioned that both the above test and the laboratory tests described previously in this paper, confirmed the variable nature of electrochemical action underground.

RECOMMENDATIONS

The magnesium anode type of cathodic protection is recommended for the Montana State College campus, as being the most economical, as well as most practical choice. Considering the fact that corrosion has not been an acute problem on the campus, that the corrosion which has been encountered has been limited to certain areas; it is believed that the expense of the rectifier system would not be justified.

Magnesium anodes offer a convenient means of protection over restricted areas. Anodes could be placed in the few areas where corrosion has been experienced. After that the only additional coverage would be at any point where corrosion might show up in the future.

For the first installations, the Dow type 17-D3 (17 lb. anode), Galvo-Pak magnesium anode, or one of a similar type, is recommended. The particular anode comes packed in a backfill contained in a cloth sack, and with ten feet of wire attached. One supply house currently quotes a price of \$12.81 plus freight, on the above anode and \$11.81 in quantities greater than 11. Anodes of the above type are generally sold only in multiples of two, since they are shipped in waterproof containers which hold two anodes.

For an initial estimate of the length of bare pipe each anode will protect, use 60 ft. for 6", 90 ft. for 4", and 150 ft. for 2" pipe. Recommendations as to type, weight, and spacing of anodes should be modified in the future according to experience gained. Also, it is important that a record be kept of the date, weight, type, and location of each anode that is placed in the ground.

APPENDIX

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A METHOD FOR ADAPTING A VOLTMETER OF MODERATE SENSITIVITY TO CATHODIC PROTECTION MEASUREMENTS¹

The following analysis is based on the magazine article by Hayward and Wainwright, set out in the footnote on this page. However, the material of that article has been modified to better suit the conditions of this paper, and it has also been specifically directed toward the Simpson Model 260 multi-meter with a sensitivity of 20,000 ohms/volt on the d-c scales. While the method described will improve the accuracy of any voltmeter on low-energy measurements, for cathodic protection purposes the above meter probably represents the minimum sensitivity that is practical.

The circuit diagram which illustrates the situation when obtaining a potential measurement between pipe and ground is shown in Fig. 1.

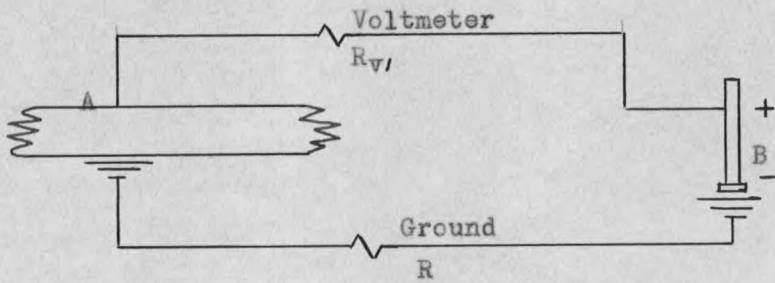


Fig. 1. Voltmeter circuit for measuring pipe-to-soil potential through half-cell.

The voltmeter is indicated by its resistance R_v , A is the surface film potential at the pipe, B is the half-cell potential, and R is the ground resistance. The circuit is further modified in Fig. 2, by adding a parallel resistance R_p around the voltmeter. The pipe and half-cell are replaced by voltage sources.

¹Hayward, H.N. and Wainwright, R. M., "Low-Energy Measurement Problems in Cathodic Protection," Electrical Engineering, vol. 71, March, 1952, pp. 276-278.

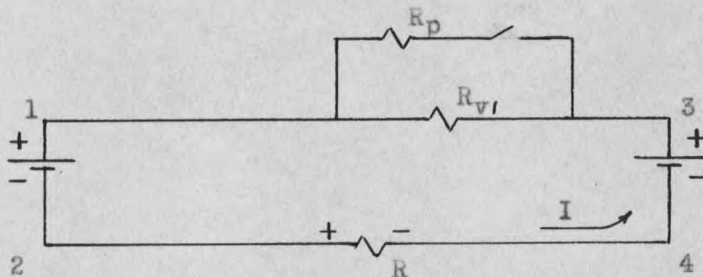


Fig. 2. Equivalent circuit for the voltmeter and half-cell shown in Fig. 1.

The algebraic addition of potentials from the equivalent circuit is

$$V_{13} = IR_{V1} = -E_{12} - IR + E_{34}. \quad (1)$$

The voltage 13, recorded by the voltmeter, is not the pipe-to-soil voltage E_{12} that is wanted. V_{13} includes the ground resistance drop and the half-cell potential E_{34} . But the latter can be given a known value, or since it is fairly stable, we can cause our reference values to include the half-cell voltage and thereby disregard its actual magnitude. But the ground resistance drop is a variable which can cause a significant error.

$$\text{From equation (1)} \quad E_{34} - E_{12} = I(R_{V1} + R) \quad (2)$$

Dividing (1) by (2)

$$\frac{V_{13}}{E_{34} - E_{12}} = \frac{IR_{V1}}{I(R_{V1} + R)} = \frac{R_{V1}}{R_{V1} + R} \quad \text{and} \quad V_{13} = \frac{(E_{34} - E_{12})R_{V1}}{R_{V1} + R} \quad (3)$$

Similarly, when the switch to R_p is closed

$$V_{13}' = IR_{V2} = \frac{(E_{34} - E_{12})R_{V2}}{R_{V2} + R} \quad (4)$$

Where V_{13}' is the voltmeter reading when the switch to R_p is closed

$$\text{and } R_{V2} = \frac{R_p R_{V1}}{R_p + R_{V1}}.$$

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Dividing the two voltmeter readings

$$\frac{V_{13}}{V_{13}'} = \frac{\frac{(E_{34} - E_{12})R_{V1}}{R_{V1} + R}}{\frac{(E_{34} - E_{12})R_{V2}}{R_{V2} + R}} = \frac{R_{V1}(R_{V2} + R)}{R_{V2}(R_{V1} + R)} = \frac{R_{V1}R_{V2} + R_{V1}R}{R_{V1}R_{V2} + R_{V2}R} \quad (5)$$

The only unknown is R (ground resistance), but it can now be calculated. From (5) $V_{13}(R_{V1}R_{V2} + R_{V2}R) = V_{13}'(R_{V1}R_{V2} + R_{V1}R)$

$$V_{13}R_{V1}R_{V2} + V_{13}R_{V2}R = V_{13}'R_{V1}R_{V2} + V_{13}'R_{V1}R$$

$$R_{V2} < R_{V1} \quad \text{Therefore } V_{13}' < V_{13}$$

$$\text{and } R_{V1}R_{V2}(V_{13} - V_{13}') = R(V_{13}'R_{V1} - V_{13}R_{V2})$$

$$\text{then } R = \frac{R_{V1}R_{V2}(V_{13} - V_{13}')}{V_{13}'R_{V1} - V_{13}R_{V2}} \quad (6)$$

$$\text{From (3)} \quad \frac{E_{34} - E_{12}}{V_{13}} = \frac{R_{V1} + R}{R_{V1}} \quad \text{and } E_{34} - E_{12} = \frac{V_{13}(R_{V1} + R)}{R_{V1}} \quad (7)$$

$$\text{Similarly } \frac{E_{34} - E_{12}}{V_{13}'} = \frac{R_{V2} + R}{R_{V2}} \quad \text{and } E_{34} - E_{12} = \frac{V_{13}'(R_{V2} + R)}{R_{V2}}$$

Substituting value for R in (7)

$$\begin{aligned} E_{34} - E_{12} &= \frac{V_{13} \left[R_{V1} + \frac{R_{V1}R_{V2}(V_{13} - V_{13}')}{V_{13}'R_{V1} - V_{13}R_{V2}} \right]}{R_{V1}} \\ &= V_{13} \left[\frac{R_{V1}(V_{13}'R_{V1} - V_{13}R_{V2}) + R_{V1}R_{V2}(V_{13} - V_{13}')}{R_{V1}(V_{13}'R_{V1} - V_{13}R_{V2})} \right] \\ &= V_{13} \left[1 + \frac{R_{V2}(V_{13} - V_{13}')}{V_{13}'R_{V1} - V_{13}R_{V2}} \right] \quad (8) \end{aligned}$$

To simplify, choose R_p so that $R_{V2} = \frac{R_{V1}}{2}$. Then (8) becomes

$$E_{34} - E_{12} = V_{13} \left[1 + \frac{\frac{R_{V1}}{2}(V_{13} - V_{13}')}{V_{13}'R_{V1} - V_{13}\frac{R_{V1}}{2}} \right]$$

$$E_{34} - E_{12} = V_{13} \left[1 + \frac{R_{V1} (V_{13} - V_{13}')}{2R_{V1} V_{13}' - R_{V1} V_{13}} \right] = V_{13} \left[1 - \frac{V_{13} - V_{13}'}{2V_{13}' - V_{13}} \right]$$

or $E_{34} - E_{12} = V_{13} \left[1 + \frac{V_{13} - V_{13}'}{V_{13}' - (V_{13} - V_{13}')} \right]$ (8)

To further simplify, from (9) if $E_{34} - E_{12} = V_{13} + \frac{V_{13} (V_{13} - V_{13}')}{V_{13}' - (V_{13} - V_{13}')}$

Assuming $V_{13} - V_{13}'$ in denominator is a small value,

$$E_{34} - E_{12} = V_{13} + \frac{V_{13} (V_{13} - V_{13}')}{V_{13}'}$$

and if $V_{13}' \rightarrow V_{13}$

then $E_{34} - E_{12} = V_{13} + (V_{13} - V_{13}')$ (10)

Equation (10) is the basic relation that gives a method for determining the algebraic sum of pipe-to-soil and half-cell voltages. This method can be seen to require two voltmeter readings, with the difference between the two being added to the higher reading. The above relation was developed on the basis of the simplifying assumption that R_p would be chosen so $R_v = \frac{R_{V1}}{2}$, but there is no indication of how well this will work over a wide range of ground resistance values. In equation (6) make above substitution for R_{V2} .

$$R = \frac{R_{V1} \frac{R_{V1}}{2} (V_{13} - V_{13}')}{V_{13}' R_{V1} - V_{13} \frac{R_{V1}}{2}} = \frac{R_{V1} (V_{13} - V_{13}')}{V_{13}' - (V_{13} - V_{13}')}$$

Allowing $V_{13} - V_{13}'$ to disappear in the denominator, the following relation is evident

$$\frac{R}{R_{V1}} \sim \frac{V_{13} - V_{13}'}{V_{13}}$$

This indicates that as R becomes large, the difference between the two voltmeter readings will become greater. Since the above relation is not linear, there might be doubt as to the accuracy of the two-reading method when ground resistance is high in comparison to the meter resistance.

The following calculations are made to find a relation between R and the voltmeter resistance

$$E_{34} - E_{12} - V_{13} = V_{13} - V_{13}' \quad \text{From (10)}$$

$$\text{From (3) and (4)} \quad V_{13} = \frac{(E_{34} - E_{12})R_{V1}}{R_{V1} + R} \quad \text{and} \quad V_{13}' = \frac{(E_{34} - E_{12})R_{V2}}{R_{V2} + R}$$

$$\begin{aligned} E_{34} - E_{12} - V_{13} &= (E_{34} - E_{12}) - \frac{(E_{34} - E_{12})R_{V1}}{R_{V1} + R} \\ &= (E_{34} - E_{12}) \left[1 - \frac{R_{V1}}{R_{V1} + R} \right] = (E_{34} - E_{12}) \left[\frac{R}{R_{V1} + R} \right] \end{aligned} \quad (11)$$

$$\begin{aligned} \text{Also, } V_{13} - V_{13}' &= \frac{(E_{34} - E_{12})R_{V1}}{R_{V1} + R} - \frac{(E_{34} - E_{12})R_{V2}}{R_{V2} + R} \\ V_{13} - V_{13}' &= (E_{34} - E_{12}) \left[\frac{R_{V1}}{R_{V1} + R} - \frac{R_{V2}}{R_{V2} + R} \right] \\ &= (E_{34} - E_{12}) \left[\frac{R(R_{V1} - R_{V2})}{(R_{V1} + R)(R_{V2} + R)} \right] \end{aligned} \quad (12)$$

Then substituting (11) and (12) into (10),

$$(E_{34} - E_{12}) \left[\frac{R}{R_{V1} + R} \right] = (E_{34} - E_{12}) \left[\frac{R(R_{V1} - R_{V2})}{(R_{V1} + R)(R_{V2} + R)} \right]$$

$$\text{Cancelling} \quad 1 = \frac{R_{V1} - R_{V2}}{R_{V2} + R} \quad \text{and} \quad R_{V2} + R = R_{V1} - R_{V2}$$

$$2R_{V2} = R_{V1} - R \quad \text{and} \quad R_{V2} = \frac{R_{V1} - R}{2}$$

The last equation gives a clear statement as to what conditions will give a reasonably correct voltage indication, (subject to simplifying assumptions, made in developing equation 10). Obviously, to obtain a correct answer for each measurement would require a determination of R, and then an adjustment of R_{V2} (through R_p). Such a procedure would be impractical, but the above equation also indicates that if R is small compared to R_{V1} , we can set $R_{V2} = \frac{R_{V1}}{2}$.

Using the above relation, the following calculation can be made for R_p , the parallel resistance around the meter

$$R_{V2} = \frac{R_p R_{V1}}{R_p + R_{V1}} = \frac{R_{V1}}{2} \quad \text{and} \quad 2R_p R_{V1} = R_{V1} (R_p - R_{V1})$$

$$\text{or } R_p = R_{V1}$$

The calculated voltages for an actual situation can be shown, using the above relation. Fig. 3 illustrates the voltmeter circuit, using the two-reading method, where R represents the ground resistance in a cathodic protection measurement. The voltage source whose potential we wish to measure, represents the combined half-cell and iron-surface film potentials. Meter errors are not considered in the following calculations. The Simpson multi-meter has a resistance of 50,000 ohms on the 2.5 volt d-c scale.

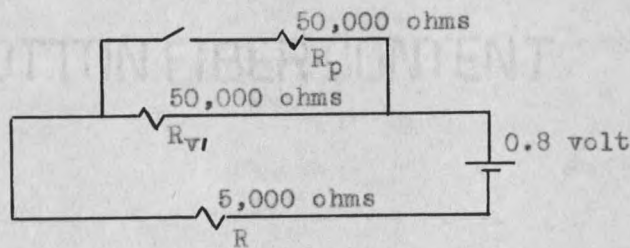


Fig. 3. Voltmeter circuit, using two-reading method, with shunt resistance made equal to the resistance of voltmeter.

For the first reading, the current in the circuit will be

$$\frac{0.8}{50,000 + 5,000} = 0.000014545 \text{ ampere}$$

The IR drops across ground resistance and meter are

$$\begin{aligned} 5,000 (0.000014545) &= 0.0727 \text{ volt} \\ 50,000 (0.000014545) &= \underline{0.7273} \text{ "} \\ &0.8000 \text{ "} \end{aligned}$$

For the second reading, with shunt resistance in the circuit, the current through the ground resistance will be

$$\frac{0.8}{25,000 + 5,000} = 0.00002667 \text{ ampere}$$

The IR drop across the meter will be $50,000(0.00002667)(\frac{1}{3}) = 0.6667$ volt. Adding the difference between the two IR drops, or meter readings ($0.7273 - 0.6667$), to the higher reading gives 0.7879 volt. Comparing the latter value to 0.8000 volt gives an error of 1.51 percent. The advantage of the two-reading method is apparent when the error in the original reading (0.7273 volt) is found to be 9.09 percent.

The above calculations indicate that the two-reading method used with the Simpson model 260 multi-meter is capable of an accuracy within about 1.5 percent on the 2.5 volt d-c scale, under the following conditions: the shunting resistance be made equal to the meter resistance and the resistance of the measured circuit be under 5,000 ohms.

Taking into account meter errors, it would be necessary to keep readings under one volt if the above accuracy was to be approximated. The particular meter had been previously adjusted to give the same reading as a laboratory standard meter at 0.85 volt. Comparison with the standard meter after the above adjustment showed very close agreement from near zero to 0.9 volt. Making allowance for meter errors and the human error in reading the meter, we could say the practical accuracy under the above conditions would probably fall within two percent. This would be about the minimum accuracy compatible with cathodic protection work, over the above range. For voltage readings higher than one volt, the particular meter will introduce slightly more error, but this would not be critical. The voltage range where the most accuracy is needed in cathodic protection

surveys is around 0.5 to one volt. The above meter will give the desired accuracy over this range, when used with the two-reading method, and provided that ground resistance values do not exceed 5,000 ohms.

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