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LITERATURE SURVEY ON UNDERGROUND PIPE LINES

THEIR CORROSION AND PROTECTION

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## INTRODUCTION

This report presents a literature survey on underground pipe lines, their corrosion, and protection. Time did not permit a complete survey; however, it is reasonably comprehensive for references published after 1930. The selection of references for this report was limited to those believed to be necessary to establish the trends of the investigations which have been conducted in the field of underground pipe-line corrosion and protection.

We have arbitrarily established eight categories for reporting the trends observed. These are:

- 1 Theory of Corrosion
- 2 Factors Affecting Corrosion
- 3 Soil Surveys; Their Value in Corrosion
- 4 Corrosion Due to Bacterial Action
- 5 Protective Coatings
- 6 Cathodic Protection
- 7 Electrolysis and Its Mitigation
- 8 The Economics of Corrosion Control.

Local conditions have a pronounced effect on corrosion and the type of protection required. As a result there is often disagreement in the literature as to the means and effectiveness of various methods of corrosion control. The various opinions are included in this report.

There are many variables affecting pipe-line corrosion which are not completely understood. As a result further investigation to determine the effect of these variables on corrosion must be conducted before there can be definite assurance that a protective measure applied will be completely satisfactory.

# LITERATURE SURVEY ON UNDERGROUND PIPE LINES

## THEIR CORROSION AND PROTECTION

### I. THEORY OF CORROSION

Corrosion of metals was once believed to be a purely chemical phenomenon. Two theories were propounded to explain the observed conditions. Larson (88), in discussing the history of corrosion, called them the carbonate theory and the peroxide theory. In the first instance, air and water containing carbon dioxide reacted to form carbonic acid. This reacted with the iron to form iron carbonate, liberating hydrogen, which combined with the free oxygen to form more water. Finally the iron carbonate reacted with the water to form iron hydroxide, releasing the carbonic acid, and allowing the cycle to be repeated. In the peroxide theory, iron, oxygen and water interacted to form iron hydroxide and hydrogen peroxide, and the reaction continued as long as oxygen remained. Neither of these theories explained satisfactorily all the factors noted in corrosion, and both have been abandoned in favor of the electrochemical theory which is accepted at present.

The electrochemical theory is based on the electromotive series and the solution potential of a metal, Uhlig (231) lists a number of factors important in the electrochemical theory of corrosion. These include contact potentials, single electrode potentials, types of cells (such as dissimilar electrolyte, differential aeration, differential salt concentration, and dissimilar temperature), electromotive series, hydrogen overvoltage, depolarization, bacterial action and oxygen concentration.

Mudd (128) defines the terms important in electrochemical theory.

The important definitions are 1 The "electrolyte" which is composed of water and dissolved chemicals. It usually is homogeneous in a true aqueous solution, but in moist soil it may vary locally as to the concentration or kind of dissolved chemical. An electrolyte will conduct electric current. 2 The "anode" which is a metal or substance in contact with the electrolyte capable of conducting electric current. With few exceptions the anode surface is oxidized or "corroded" by combining with chemicals in the electrolyte. The term "oxidation" was originally used to describe the reaction in which oxygen combined with another element, but the broader use of the term now describes the action where an atom loses electrons and becomes a positively charged ion. 3 The "cathode" which is a metal contacting the electrolyte, whose surface is not reduced but receives protection against corrosion. 4 The "conductor", which externally connects the anode and cathode to complete the circuit for current flow. Both the anode and the cathode are generally termed the electrodes.

Electrochemical cells fall into three general groups. The first is an electrolytic cell, which contains the four components listed above plus an external source of electrical energy. Such a system is responsible for stray-current electrolysis, but it is also the type of setup used in cathodic protection. The second type is the galvanic cell, consisting of dissimilar metallic electrodes in a homogeneous electrolyte. Gally (57) discusses a type met with in underground pipes, which consists of a copper line attached to an iron main. Since a potential difference of approximately one-half volt exists in such a system, there is a definite possibility of corrosion. The third cell is the concentration cell which consists of similar electrode in a nonhomogeneous electrolyte, which does not contain ions of the metal in contact with it.

The electrolyte may vary in chemical concentration or in the kind of chemicals. Generally the anode is established in the concentrated portion of the electrolyte or in the kind of chemical which combines most readily with the electrode material. Of course, it is possible that combinations of the above-listed cells may occur. A typical example might be a copper-iron couple in a soil varying greatly in chemical composition. In such a case both galvanic and concentration cells would exist.

The important factors controlling electrochemical corrosion of pipe lines have been discussed by several investigators (41, 53, 88, 101, 121, 128). Denison (41) states that an increase in the acidity of the electrolyte increases the corrosion rate because of the greater solubility of iron hydroxide in an acid medium. The author also states that carbon dioxide in high concentrations may increase the corrosion rate. Miller (121) cites some factors which are often ignored but which may play an important part in pipe line corrosion. These are the scarring or threading of the pipe surface, leading to a stress concentration of the surface, the variation of pipe sizes in dissimilar metal installations, and the influence of mill scale retained on the external surface of the pipe.

Fundamentally all such corrosion is based on two reactions. In the first the metal goes into solution, forming metallic ions. If an electrically neutral solution is to be retained, some positive ion must combine with the free electrons, this usually is the hydrogen ion. Ewing (53) denotes this as the first stage of corrosion. A buildup of hydrogen leads to polarization, which decreases the solution potential of the metal and, unless the hydrogen is removed, this leads to a greatly reduced rate of corrosion. The corrosion may continue, providing the hydrogen is removed from the metal surface. This may be brought about by: 1 the combining of the hydrogen with oxygen to form water, which

will depend on the concentration of dissolved oxygen next to the metal, the degree of aeration, the temperature, salts present, and whether the water is at rest or in motion; 2 the loss of the hydrogen by its escape as bubbles of gas, which is favored by an increase in the acidity of the electrolyte; and 3 the removal of the hydrogen through its combining with sulfide ions produced by the reduction of sulfates through bacterial action. Any such removal of hydrogen makes up the second stage of corrosion and leads to the third stage. In the third stage the ferrous ions entering the solution come down as a rust, due to oxidation of ferrous ions to ferric ions. This affects the continuation of the reaction in three possible ways. In the first case the removal of the ferrous ions from the solution allows the formation of more ions from the iron, which induces further corrosion. In the second case the rust may form a protective coating on the surface of the pipe, which serves as a means of preventing further corrosion. Finally, the oxygen supply may be limited so that the corrosion rate is decreased as the oxygen concentration is diminished. In practice this last principle is made use of in the application of deactivators, which combine with the oxygen to prevent its reacting with the hydrogen.

Logan (101) states that the potential does not determine the rate of corrosion but is the critical factor in determining whether the reaction will proceed or not. The author also lists the factors responsible for underground corrosion and to what these factors may be due. Fundamentally, soil corrosion is the same as any other form of electrochemical action. The difficulty in interpreting the results is due to the impossibility of studying the environment readily.

The important specific causes of corrosion listed by Logan (101) are as follows: 1 Differential aeration - this may be due to unequal compactness of

the backfill, unequal porosity of the soil, an uneven moisture distribution or restrictions to the movement of air or water due to buildings, roadways, or similar structures. 2 Acids and salts in the soil - these materials affect the tendency of the metals to go into solution. 3 Differences in the characteristics of the soil at different points of contact - these may affect the metal solubility or cause a concentration cell. 4 Foreign materials such as cinders, scraps of metal, or organic materials - these tend to create differences in potential. 5 Stray currents - responsible for electrolytic action. 6 Non-uniformities in the structure or conditions of the metal - while these may definitely cause a potential difference they are generally of minor importance with the possible exception of cast irons where the graphite and ferrite may react. 7 The use of a material unsuitable for a given environment - this is a frequent cause of trouble. Certain soils, due to the mineral content, may preferentially attack some metals. In such a case it is best to avoid their use. 8 Interconnection of dissimilar metals - this is a typical galvanic cell, an example being a copper pipe attached to a cast iron water main. 9 Anaerobic bacteria - the action of such bacteria is indirect. They depolarize the cathode allowing the corrosion to continue; 10 Long line currents - it is not known if such currents are the cause of or the result of corrosion. Their origin is even in doubt; they may result from one or more of several causes.

Examination of the preceding factors discloses that electrochemical corrosion is the same underground as aboveground in the field or in experimental cells. Any such action takes place in a cell composed of four parts: an anode, a cathode, an electrolyte, and a conductor.



## II. FACTORS AFFECTING CORROSION

There are a large number of general soil characteristics which have been found to affect the rate of corrosion of buried pipe. These characteristics, which will vary in importance from area to area, are: 1 Chemical, 2 Electrical, 3 Geological, 4 Biological, 5 Climatological, 6 Historical, and 7 Artificial. Larson (88) lists these factors; each of the characteristics is made up of subdivisions which are important in any consideration of corrosion. A major grouping of the various divisions is discussed by Logan (101) who divides the important properties affecting soil corrosion into chemical and physical classifications.

A detailed examination of the literature concerned with the corrosion of underground pipe lines will lead to the discovery of many apparent discrepancies in the conclusions arrived at by the various investigators. In some cases these discrepancies may exist and be due to erroneous evaluation of the data, but in the majority of instances the apparently contradictory data actually agree. This is usually due to the varying duration of the tests.

Logan (101), in his summary of the work conducted at the National Bureau of Standards, discusses the physical and chemical properties affecting underground corrosion. The occurrence of any one or even of a group of these properties does not mean that the soil is corrosive, but certain properties when present are definitely indicative of severe corrosion. Poor drainage is one of the most important factors. Others are the soluble salt content, the hydrogen ion content, the total acidity, soil resistivity, aeration, air-pore space, apparent specific gravity, water holding capacity, depth of burial,

moisture equivalent, clay content, and shrinkage. These are soil characteristics as opposed to the metal characteristics, and many are obviously interdependent. All results are based on some 36,000 specimens examined over a period of twelve years, usually at two-year intervals.

An important factor in such corrosion is the amount and type of soluble salts present. The alkali and alkaline earth metals, sodium, potassium, calcium, and magnesium when present as chlorides, sulfates, or nitrates tend to increase the corrosion rate as the percentage present in the soil increases. Carbonates or bi-carbonates act as retardants in such corrosion due to the formation of an adherent film of calcium carbonate on the cathode. However, this does not occur in the presence of an excess of chlorides or sulfates in which both calcium and magnesium carbonates are soluble. A similar reaction may occur in sulfate-rich soils if lead salts are present. In this case an insoluble film of lead sulfate protects the cathode. Such soils, high in alkali or alkaline earth chlorides or sulfates, are characterized by a low electrical resistivity, as would be suspected of such soluble salts. Several authors (36, 53, 88, 207, 209, 211, 244) are in agreement concerning the effect of soluble salts in soils.

The hydrogen ion content may have only minor significance. Logan (101) notes that the pH can vary from 4 to 9.5 without affecting the rate of corrosion, providing the electrolyte is free of soluble salts. Apparently, the controlling factor in this case is the diffusion of the oxygen to the cathode and the protectivity of the film on the cathode surface. If carbon dioxide is present in the ground water, this is no longer true. Then a pH of 5.4 is sufficient to neutralize the cathodic film, so that the rate of corrosion will increase. Due to this, the total acidity of the soil is much more important as a criterion of the rate of corrosion by natural waters than the pH. Wichers (244) considers the pH important, but considers the salt content to be even more important,

which agrees with Logan (101). Larson (88) discusses alkaline and acid soils, and states that the corrosion rate is much lower in the alkaline soils, usually due to the adherent scale or film formed on the cathode. Solov'ev (207), Solov'ev and Lubimova (210) and Rogers (168) state that alkaline soils have a higher corrosion rate than the clays or clay loams, apparently because the clays are supersaturated while the alkali soils are wetted only intermittently. The last factor may be the important one in controlling the corrosion rate, although it is also possible that the short-time tests these authors ran did not present a true picture of the corrosion rate as a function of time.

The texture of the soil actually covers a number of properties, all of which may influence the rate of corrosion. The texture will control the aeration, specific gravity, water-holding capacity, and the moisture equivalent. For example, a light-textured soil such as a sand or sandy loam will permit free circulation of moisture and gases, so that the corrosion is similar to that experienced in metals exposed to the atmosphere. A very finely textured soil such as a heavy clay will tend to retain any water, be low in oxygen, and have a high density; hence the metals in such a medium will behave as if they were submerged. The latter type of soil is most conducive to corrosion. Such characteristics as poor aeration, high moisture equivalent, high clay content, high apparent specific gravity, and high shrinkage are typical of heavy, poorly drained soils and are not independent of one another; however, such properties can be modified by the chemical characteristics. The open-textured soils usually have a high initial corrosion rate, which drops rapidly due to the formation of a layer of corrosion products forming an adherent film. This formation is promoted by the presence of a large supply of oxygen. In a poorly aerated soil the initial corrosion rate will be low, but the rate continues because the corrosion products are precipitated at some point remote from the

anodic areas. Concomitant with this limited build up of scale in a poorly aerated soil is the occurrence of pits of much greater depths than those present on pipes buried in well aerated soils. The majority of the authors (36, 78, 88, 91, 153, 213, 235) agree that dense poorly aerated soils are most corrosive. In the cases where disagreement occurs (207, 211, 244), it is due to the duration of the tests, since a short time test in a well aerated soil has a higher corrosion rate than does a poorly aerated soil. Wichers (246) is in complete disagreement with the above conclusions, but it is felt that the preponderance of the evidence is against him.

Several factors dependent on these properties are defined by Logan (101). The air-pore space is equal to the per cent volume of the soil at a definite moisture content that is occupied by air. This is an indication of the rate with which the moisture can move through the soil. Generally, a high air-pore space is indicative of a relatively noncorrosive soil. The apparent specific gravity is an index of the compactness of the soil and is dependent on the texture. The moisture equivalent is defined as the per cent of water retained by a previously saturated soil of a given weight when centrifuged at 1000 times gravity. This serves as a measure of the water retentivity of the soil. The water-holding capacity of the soil is the quantity of water retained when equilibrium is attained with the capillary and gravitational forces. Volume shrinkage is defined as a measure of the colloidal nature of the soil. It indicates the tendency of the soil to crack when dry or swell when wet. The shrinkage and swelling may cause failure of the bituminous coating or cause a differential aeration potential resulting in accelerated corrosion.

It is known that an increased depth of burial of the pipe will generally increase the long-time rate of corrosion. This is due to the decrease in aeration with depth of soil.

Some difference of opinion exists concerning the influence of the moisture content on the rate of corrosion. The general opinion held by most investigators (53, 88, 101, 210) is that the maximum corrosion rate occurs at saturation. Shepard (198) disagrees, stating that the maximum action occurs in moist, not water-saturated, soil due to the limited oxygen supply of the latter. Here again it is obvious that the author is discussing short-time corrosion.

The organic matter present in the soil is also cited (36, 53, 208, 235) as a factor which may increase the corrosivity of the soil. This organic matter may play an important role in attacking the protective coatings. Such attack occurs by peptization, emulsification, destruction by osmotic forces due to plant or animal organisms, or by electrical corrosion of the surface film or the metal.

Graphititis has been described by some investigators (14, 17) as the destruction of cast irons by chemical, electrochemical, or electrolytic action. The soils favoring such corrosion are heavy clays or peats saturated with moisture and high in sulfates. Later work (78) has indicated that such soils generally contain sulfate-reducing anaerobic bacteria; therefore it is probable that such corrosion is promoted by these bacteria.

Ensslin and Buschendorf (52) discuss the influence of high mineral content in the ground water, stating that the mineral water can act as an electrolyte.

One medium which must be avoided under any circumstances is cinders. Investigations (226, 235) have proven that the corrosion rate is extremely high due to the iron-carbon couple established. Cinders also aid in destroying most organic coatings.

Rogers (167) reported that oil leaking from a line into the earth is a source of corrosion, particularly if the oil is high in sulfur. The

author states that a concentration cell is established between the mill scale and the metal, resulting in localized but severe pitting of considerable depth due to the oil preventing access of oxygen to the pipe.

The soil resistivity, as determined by any of the methods covered in the instrumentation section, can be used to indicate the corrosivity of the soil; since the resistivity depends on the factors discussed previously, notably the soluble salt content, soil density, moisture content, etc. Low soil resistivities indicate a tendency toward corrosivity; however, such resistivities are more indicative in arid or semi-arid areas than in humid areas where the total acidity may be a more reliable criterion. In all such cases a variation in resistivity is much more indicative than a uniformly low value.

After considering the soil factors affecting the rate of corrosion of pipe, it is necessary to consider variations in the metal itself and how they influence corrosion. The first factor is the chemical composition of the ferrous pipe. It is the concensus that minor changes in the alloy content have little or no effect on the resistance of the pipe to corrosion (53, 78, 94, 101, 213, 247). Ewing (53) states that phosphorus renders steel slightly more resistant to corrosion. Both Denison and Romanoff (45) and Logan (94) agree that small additions of chromium, copper, or nickel may increase the corrosion resistance slightly, but generally are of no benefit. It is necessary to use high percentages of alloy if any definite benefit is to be derived. High-chromium or chromium-nickel steels of the stainless variety are very resistant to such corrosion as are the nonferrous metals in general, Ewing (53) also cites the high-silicon cast irons as being corrosion resistant.

Other factors influence the resistance of the metal to corrosion, such as threading, or scarring, or mill scale. Mill scale may protect the pipe

if it is continuous; however, a discontinuous scale accelerates the corrosion due to the galvanic couple established.

The pipe size is also a factor in the depth of pitting of the ferrous material. As the diameter increases, the maximum pit depth also increases. In this case the average maximum pit depth increases with an increase in the area in an exponential relationship  $P = b A^a$ , where P is the pit depth, A the area, and a, b are constants varying with the soil conditions. A similar relationship exists for the pit depth as a function of the duration of exposure,  $P = KT^n$ , where P is the pit depth, T the time, and K, n are constants varying with the soil.

Pitting factor, which is defined as the maximum pit depth divided by the average pit depth, can be used to indicate the influence of soil drainage. If we assign a low numerical value to a "very poor" drainage and a high numerical value to a "good" drainage, then we can plot the ratio against soil drainage and note that a linear increase occurs.

A few minor factors remain to be considered. These are the roughness and degree of oxidation of the metallic surface and the condition of the soil at the time of burial. Apparently, none of them are of major importance.

In considering the corrosion of ferrous materials, the characteristics of the metal itself are of minor importance compared to the affect of the soil conditions on the rate of corrosion. A dense soil, saturated with water, low in oxygen, high in soluble salts, and high intotal acidity will be most liable to corrode deeply the material over a period of time.

### III. SOIL SURVEYS

#### THEIR VALUE IN CORROSION CONTROL

Preliminary surveys prior to the installation of a pipe line are a necessity, if the maximum saving is to occur. It is equally true that periodic corrosion surveys must be carried out on the installed pipe line if this saving is to be retained. The preliminary survey will determine whether the pipe is to be coated, cathodically protected, or coated and cathodically protected in order to minimize loss of material due to uncontrolled leakage. Larson (88) lists a number of reasons for carrying out such surveys. These include:

1 An indication of the rate of depreciation, allowing long-term budgeting or replacement costs; 2 A determination as to whether the pipe should be repaired or junked; 3 The value of applying a protective coating or laying a bare pipe; 4 The location of areas subjected to damage by electrolysis; and 5 Effectiveness of the mitigative methods. Tietze (229) cites the case of the Phillips pipe line from Oklahoma to Kansas City, where corrosion leak data as well as pitting data were correlated with pipe-to-soil potentials determined in the corrosion surveys. Evaluation of these survey data led to a classification of severe corrosion for twenty-one per cent of the pipe length which permitted the pre-determining of ninety-three per cent of the corrosion leaks. With such information the selection of the proper protective measures is greatly simplified.

Smith (206) discusses the value of an initial survey covering the soil composition and topography. A specific example is cited covering the installation of a natural gas line. The soil through which the pipe was laid could be classified as to its corrosive characteristics, based on the survey. As a result a considerable saving occurred because the coating thickness was varied,



depending on the corrosivity of the adjacent soil. Without the survey the heaviest coating would have been applied over the entire pipe length.

Surveys can be classified into major and minor groups, depending on the purpose of the test. In general, all such surveys are divided into soil and corrosion analyses, with these major groups being broken down into the type of test, either field or laboratory. Logan (101) uses this terminology in characterizing such surveys. In the case of soil surveys carried out in the field, four methods are in general use. These consist of a determination of the soil resistivity by any one of the several methods which have been developed, such as the Shepard soil-resistivity apparatus, Wenner's four-terminal method, the electrolytic bridge, or a radio balance. A second method of conducting field tests consists of the Columbia rod with which the soil resistivity is determined, as well as the potential of the metal with respect to the soil. A third field test consists of measuring the oxidation-reduction potential of the soil as well as the pH. This method is of particular value where bacterial corrosion predominates. Finally, it is possible to determine the corrosive potential of the soil by means of a survey identifying the soil types and including such factors as topography, moisture content, and geologic formations.

Laboratory soil-survey tests can be carried out to confirm the results of field surveys or to furnish additional data. Resistivity can be determined using a simple voltmeter-ammeter installation, and measuring a soil specimen of fixed weight under a definite pressure. The hydrogen ion concentration can be determined as well as the total acidity, which is a much better method of evaluating soil corrosivity than the pH method. Two procedures have been developed for measuring the total acidity. These are Denison's, or Ewing's (101) method. The latter is slightly less accurate but less laborious and much more rapid. Another laboratory test consists of artificially inducing a current

and measuring the potential. Putnam's decomposition potential, the Williams-Corfield nipple-and-can test, or Denison's cell test (53, 88, 101) are examples of such laboratory experiments serving to correlate the behavior of the soil under artificial conditions with the actual corrosivity of the soil experienced in the field.

The corrosion survey differs from the soil survey in that it checks the actual response of pipe or test specimen to corrosion; it can be used when a line has been installed, or to determine the soil characteristics by means of test coupons. Such a survey is based on the evaluation of burial tests where the pipe, or the test coupons adjacent to the pipe, are examined over a period of time to determine either the weight loss due to corrosion or the extent of pitting. Since these tests are carried out while the samples are protected cathodically or with a coating, if such were considered necessary, the results indicate the effect of the soil on the protected pipe. It is possible to determine the approximate corrosion loss along any pipe line if some knowledge is available of the history of previous pipe lines under similar conditions.

A measurement of the potentials and currents along a pipe line by any of several methods should locate corroding areas. Care should be taken in evaluating such data because the computed value of current is less than the total value. Another source of error in long-line currents is the change due to variations in the soil moisture content or the degree of aeration. Because of these and other factors, no close correlation has been observed between electrical corrosion survey measurements and corrosion coupon data. There are also certain theoretical objections to the use of corrosion coupons, such as area, etc.

While some care must be taken in evaluating soil corrosivity tests, the results are of great value in determining the protective measures necessary.

Such tests serve to locate "hot spots" along the pipe line; however, conclusions should not be based on the results of one type of test; there should be cross checks. For example, a combination of any of the following should prove satisfactory: 1 Correlation of soil types with pit depths; 2 Correlation of corrosion with field resistivity; 3 Correlation of pit-depth with soil resistivity at some fixed moisture equivalent; and 4 Correlation of other soil-test data with pit depths. A definite correlation was found to exist between such tests and soil corrosivity. Logan (101) reported only one soil, Myatt, which was missed by all tests. Apparently with this soil pitting was due to some factor other than soil corrosivity, so a true picture was not given.

Larson (88) suggests that all soil surveys be conducted in a fixed sequence of operations to minimize the expense. If any step in the survey results in a decision to protect 75 to 80 per cent of a line, further survey expense is seldom justified, as the whole line should be protected. The author suggests that the following sequence be followed: 1 A soil survey be conducted by observation; such objects as swamps, bogs, cinders, river crossings, oil-soaked land, refuse dumps, chemical refuse, etc., should be accurately located on a map. It is important that the boundaries of all such objects be well established: 2 An historical records survey should be conducted if such information is available; the history of any lines in the locality can be checked for predicting "hot spots". Such a method is satisfactory where moderate rates of corrosion exist, but unexplainable variations or "hot spots" often occur where excessive rates of corrosion are known to exist. 3 A field survey should be conducted with resistance rods to determine the soil resistivity. Such factors as temperature, soil texture, density, amount of soluble material, or moisture content must be considered if the results are to have any meaning, because of their effect on resistivity measurements. Either Shepard or

Columbia rods are satisfactory for such a survey. 4 Laboratory tests can be carried out to determine the electrical characteristics of the soil; the normal methods consist of the nipple-and-can test, Putnam's decomposition potential, or the Denison corrosion cell. Here again a number of factors must be considered if satisfactory results are to be obtained. The moisture content, temperature, apparent specific gravity, moisture equivalent, void volume, dispersion ratio, and shrinkage should all be noted. 5 In urban areas, or where stray currents may be a problem, an electrical survey to determine their existence as well as their intensity, should be conducted. 6 The final step in such a soil survey consists of a chemical analysis. Because of the high cost, such an analysis is seldom carried out. If it is found necessary, the most important value is the total acidity.

Of equal importance is the corrosion survey carried out on existing pipe lines or on corrosion coupons to measure the extent of corrosion on these lines. Such tests portray or closely simulate the actual corrosion conditions, permitting a classification of soils as to their degree of corrosivity, based on the examination of the specimens. The scope of a corrosion survey will vary with the needs of the company, but it must be carried out periodically, not just once. The test methods usually consist of a visual examination for pitting, change in color, or similar phenomena. Such a survey classifies the action by:

- 1 The corrosive agents, such as oxygen, oxidants, waters, liquids (such as oils) brines, salts, sulfur compounds, acids, alkalis, organic matter, live vegetation roots, soil, air pollution, strains, temperature, or sun on the exposed surface;
- 2 The type of metal in the pipe or coupon; and
- 3 The appearance of the surface of the pipe or fitting (this will include the nature of the scale, pitting, graphitization, dezincification, erosion, or cracking).

Mapping is one survey method which should accompany any other survey, whether it be by the chemical, electrical, or burial method. Such a mapping survey can be conducted independently of the others, and in most cases it is an essential step preceding the installation of the pipe line. Several authors (5, 88, 141, 211, 242) have listed factors to be considered in carrying out an effective topographical survey. This should include a climatological investigation to indicate the seasonal variation in the rainfall and the degree of saturation of the soil throughout the year which will depend on the type of soil and subsoil as well as the topography of the ground. Such factors as ravines, changes in slope, benches, swamps, seepage, or other noteworthy changes in the land contour should be carefully mapped. A geological survey is also desirable since the rock formations or soil types are indicative of the corrosivity of the area. Another factor which must be considered is the biological, since both aerobic, and anaerobic bacteria in particular, are primarily responsible for the extensive corrosion occurring in certain soils. Finally it is necessary to consider the existence of certain artificial conditions such as the presence of cinder fills or street railways which cause stray currents. By considering all these factors together, it is possible to select the pipeline right-of-way and the necessary protective measures.

In conducting soil analyses certain terms are commonly used and should be defined. Some of these are: 1 Apparent specific gravity -- defined on a volume-weight basis by immersing dry lumps of soil in mercury to determine the displacement. The volume weight is calculated from the weight of mercury displaced, 2 Moisture equivalent - the moisture retained by a soil under a centrifugal force of 1000 times gravity; and 3 Disperion ratio -- arbitrarily defined as the ratio of silt and clay remaining in suspension to the total amount of silt and clay determined by mechanical analysis.

Chemical surveys are particularly desirable in some acid soils where soil-resistivity measurements lead to erroneous conclusions. However, the soil should not be selected as a criterion since some investigators have indicated that pH alone may lead to inconclusive results (66, 101, 128).

The most reliable chemical test consists of determining the total acidity of the soil by the methods of Ewing or Denison. These methods are described by Logan (101), who suggests Ewing's method for most surveys where the slight loss in accuracy is more than compensated for by the saving in time. Both methods consist of a determination of the total acidity of the soil by difference.

The redox potential is another test which has proven to be of particular benefit in bacterial soils. A redox apparatus consists of two sets of electrodes, one for measuring the soil pH and the other for determining the oxidation-reduction potential of the soil. A few methods have been developed to determine the pH of the soil colorimetrically, but none are of particular importance.

The most important method of obtaining data, which can be used to determine the amount of protection required, consists of a measurement of the electrical characteristics of the soil. The characteristics determined usually consist of the soil resistivity, or the soil potential referred to the pipe. In making any such measurements the effect of certain factors must be considered, due to the pronounced variation in resistivity or in potential which a variation in these factors may produce. Temperature is very important; as the temperature increases the resistivity decreases. A several-fold change in the resistivity is observed between measurements taken at sub-zero temperatures and those taken at 70 to 80°F. The moisture content of the soil is of even greater importance. When conducting an electrical survey, the moisture should be determined: 1 at least once daily, preferably more frequently;

2 when changes in the soil type occur; 3 following obvious changes in the moisture content; 4 after noticing actual changes in the physical aspects or coloring of a soil; and 5 following other changes discernible to an experienced surveyor. Due to a supersaturated condition which often exists in the subsoil of humid regions, electrical-resistance soil surveys are not too accurate a criterion, total acidity being more indicative of corrosivity. Such electrical-resistance soil surveys are much more indicative in arid or semi-arid regions, where the moisture content of the soil is not excessive. The soil density, which is related to the texture, affects the soil resistivity. As the density increases, the soil resistivity decreases. An excess of soluble material will result in variable and inconsistent results, probably due to the ionization of the soluble salts. Other minor variations in the test conditions or in the soil may lead to a slight variation in the results, but these are generally of little or no importance.

The three electrical methods of conducting a soil or pipe-line survey consist of line current, soil surface potential, and soil resistivity. The line-current method of survey is confined to existing pipe lines, and is equivalent to measuring the current flowing in the metallic circuit of a galvanic cell. This procedure involves four steps: 1 measuring off a desired length of pipe line on the ground surface; 2 locating the pipe at each end of this measured section with "locating bars"; 3 establishing contact to the pipe with contacting bars; and 4 measuring the potential drop between these contact points. The direction as well as the amount of the current flow can be determined. In general, measurements are repeated every 1200 to 1500 feet with 100 feet between the contact points. Since the potential amounts to a fraction of a millivolt, care must be taken in making the readings. Where lines are conducting fluctuating stray currents, two or more millivolt recorders must be operated simultaneously to detect the current loss and current gain. Where the potential source is limited to

soil-chemical action, a millivolt recorder should be connected through pipe-connection clamps on a section of line in the vicinity to record potential drops.

The soil-surface-potential method of survey consists of determining the potential between pipe and soil by connecting one side of a voltmeter to the electrolyte surface through a "half-cell" electrode, generally copper sulfate, and connecting the other side to the selected electrode, the pipe line in this case. The procedure consists of making two successive measurements, the first with the half-cell contact near the anode and the second with it near the cathode, the difference between the indicated potentials being a measure of the potential drop between the two contact points. These surface-potential measurements can be made with more accuracy and in less time than line-current or pipe-to-soil potential measurements. Since these measurements are of greater magnitude than line-current values, the errors are minimized. It is possible to make a series of surface measurements at consecutive 100-foot intervals over several miles of line in the same time that is required for line-current measurements to be taken at 1000 to 1500-foot intervals, and the shorter intervals give much more detailed information.

Many methods have been developed for the measurement of the soil-resistivity. Such instruments as the Shepard-cane earth-resistivity meter, or the four-electrode earth-resistivity "megger" are typical and can be used where measurements are to be made at various depths without excavation. Any such values indicate the average of the resistivity from the surface to a depth equal to the distance the electrodes are spaced, which is usually 4, 8, 16, and 32 feet. This allows a measurement of the sub-strata to be made. Similar measurements can be made using a small direct-current generator or battery



and a vacuum-tube voltmeter. Some radio-frequency units have been developed for use in low-resistivity soils, but they are not completely dependable (128).

Schlumberger, Schlumberger, and Leonardon (181) developed a soil resistivity method using recording potentiometers and nonpolarizable electrodes, which was said to be more reliable than the Shepard test or the four-electrode "megger" method of McCollum and Logan (114). Detailed descriptions of various types of electrical instruments and their application to the study of pipe-line corrosion have been given by several authors (141, 146, 148, 149, 165, 169, 194, 197, 238, 249). The laboratory equipment needed for measuring the electrical characteristics of the soils has been developed by Darnielle (37), Denison (40), Denison and Darnielle (42), and Putnam (159), who describe the equipment used, the method of conducting the tests, as well as their accuracy.

Results indicated that a definite correlation existed between the resistivity of the soil and its corrosiveness. Low resistivities are indicative of high corrosiveness, and ranges of resistivity values have been suggested as a criterion of the corrosivity of the soil. The ranges consist of 6000-10,000 ohm-cm for low corrosivity soils, 4500-6000 ohm-cm for good soils, 2000-4500 ohm-cm for fair soils, and 0-2000 ohm-cm for soils which are very corrosive. These values should not be accepted as completely indicative, since the acidity or alkalinity of the soil, as well as the amount of soluble materials present may cause a pronounced shift in the soil corrosivity.

In conducting any electrical survey it is important to realize that there are several sources of error which will render the results invalid unless compensated for. Pearson (151) and Mudd (128) enumerate several such sources of error and suggest methods of eliminating them. A typical source is a poor contact between the soil rod and the pipe metal due to dull contact points, allowing foreign material to penetrate between the pipe and the point. The

obvious remedy is to keep the points sharp. Inequalities in temperature between the two contact bars may cause a thermoelectric potential to be developed, leading to an error in the potential reading. It is always good practice to protect the bars from the sun to prevent such occurrences. The contact bars must be held properly during measurements because a piezo-electric potential can be developed due to the stressed metal. Proper holding of the bars plus repeating the tests until three equal readings are obtained will correct this error. In making the soil-surface contact it is necessary to remove the dry top layer to insure a satisfactory contact with moist soil. Potential-gradient errors can be eliminated by making contact directly above the pipe. The copper-sulfate half-cell electrodes often are slightly different; it is therefore advisable to alternate the cells to eliminate this error. Another source of error may be introduced by magnetic storms, which result in a fluctuating potential. It is best to suspend operations during such disturbances. In taking readings with a potentiometer the relationship of the external to the internal resistance must be considered. For example, if the external resistance is equal to the internal resistance, a 50 per cent error in the reading results. Lack of temperature compensation may also be a source of error. The use of Ayreton shunts improves this temperature compensation and makes the damping slightly less critical. Either switches or contacts of brass, bronze, or copper are sources of error in humid climates due to the presence of corrosion products. All instruments should be transported in a dry box and should be checked regularly. The installation of "wiping" contacts of silver for field use is an excellent means of eliminating the corrosion problem due to any variation in the points such as would occur with bronze or copper. The practice of pouring water on the ground to insure a suitable contact should be discouraged due to the error introduced by the electro-kinetic potential of the water flowing into the earth; it is best to dig down to moist soil to eliminate the earth contact source of error.

There is one other type of survey which can be conducted after the line is installed. This survey consists of the correlation of corrosion-pit or weight-loss data with the type of soil and the other factors affecting soil corrosivity such as terrain, humidity, or bacterial content. Numerous surveys have been conducted (43, 93, 101, 103, 119, 182, 189, 190, 242), the most important being that at the National Bureau of Standards. Logan and Koenig (103) discuss a typical survey conducted by the Magnolia Pipe Line Company in which the three deepest pits were measured on each joint of a 25-mile section of pipe line. Soil samples were taken to determine the soil type, and the soil corrosivity was determined independently by eight different methods. The soil corrosivities determined by these methods were compared with the observed values of the pit depths in the soils. It was found that the dispersion of pit depths was large, and no tests of a single sample of soil would reliably predict the maximum pit depth which might occur adjacent to the point where the soil was sampled. The results indicated that a soil survey will determine the average corrosivity of the soil, but no one test was found to be best for all types of soil. The eight methods checked against the pit-depth measurements were:

- 1 Shepard's method of measuring soil resistivity;
- 2 Moisture equivalence;
- 3 Soil acidity;
- 4 Acidity-resistivity;
- 5 Columbia rod;
- 6 Putnam's method;
- 7 William's Corfield nipple and can test; and
- 8 Denison electrolytic cell test.

Logan (93, 101) summarized the National Bureau of Standards Soil Corrosion data, based on some 33,000 specimens, and discussed its engineering significance. The results indicated that any data obtained from corrosion coupons must be evaluated carefully, due to the errors inherent in the use of such small specimens. Logan lists a number of factors affecting the size, number, and depth of pits such as: 1 The maximum pit depth on any area will, on

the average, be less than the maximum pit depth on a larger area exposed to the same conditions. 2 Pits usually change in depth more slowly as they become older, but this varies for different soils, particularly when bacteria are present. For any particular soil condition the rate of penetration must be included with the effect of area and of time; and 3 The relative depths of the pits in two materials, or the same material exposed in two soils, may differ for different periods of exposure or for different exposed areas.

The pit depth measurements have been used as a criterion for the rate of corrosion of the metals in any particular soil. Several authors (93, 101, 157) have suggested empirical equations relating pit depth and time, and using the maximum pit depth at any time as the criterion of corrosion.

In conducting any such tests based on pit depth or weight loss of pipe or corrosion coupons it is necessary to clean the specimens before testing. Alte (1) and Keeling (83) describe various methods of cleaning these specimens, such as hot aqueous ammonium citrate or cathodic cleansing.

After collecting the data it is necessary to analyze it properly if it is to be of any value. In the case of pit depth measurements, an analysis of the frequency, distribution, depth, and area of the pits should be made. This will be sufficient to evaluate the pitting index, which is defined as the depth of the deepest pit to the average depth of penetration. This index is directly related to the ratio of uncorroded to corroded area, giving an indication of the rate of corrosion of the pipe with time. An analysis should also be conducted before the pipe line is installed using data obtained from topographical or electrical surveys. This analysis will determine the advisability of applying a protecting coating or installing cathodic units. Such a decision should be made then because it is much more expensive to apply protective measures after the pipe has been installed than it is to do so while laying the pipe line.

#### IV. CORROSION DUE TO BACTERIAL ACTION

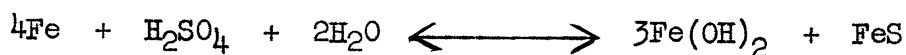
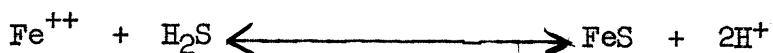
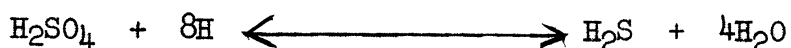
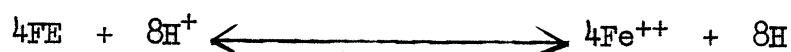
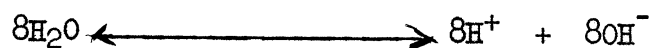
Hadley (67) estimates that between 10 and 20 per cent of all pipe replaced has failed because of bacterial action. Work in the Netherlands (132), England (166, 237), and Russia (161, 162) confirms this and clearly indicates that a soil survey must consider not two, but three factors. The biological characteristics (161, 162) must be considered as well as the physical and chemical characteristics of the soil.

Corrosion can be due either to aerobic or anaerobic bacteria as noted by several authors (166, 236, 237). However, pipe corrosion in soil is generally limited to anaerobic action, and vibrio desulphuricans is responsible for most of the soil corrosion due to bacteria. Nitrate-reducing and methane-generating bacteria are also known, but apparently they do not cause large-scale corrosion.

The sulfate-reducing bacteria are most prevalent in moist locations such as peat bogs, water basins, marshes, or dense soils saturated with water and free of oxygen (67). Heavy clays are their favorite habitat. While the presence of moisture and the absence of oxygen are the most important factors, there are several others. The soil must contain organic material, sulfur or sulfates, calcium and magnesium salts (80), and have a pH of 5.5 to 8 (175) for maximum growth. The pH is very important; at a pH of 9 growth decreases sharply and at a pH of 10 to 11 ceases altogether. However, this high pH does not destroy the bacteria; it only causes incubation, and growth recurs when a pH of 7 to 8 is reached.

Attack by the sulfate-reducing bacteria is principally limited to cast irons or low-alloy steels. Neither copper, copper alloys, nor austenitic steels are attacked. Both zinc and lead are attacked to a limited extent. Graphititis, or graphitic corrosion, of cast iron occurs only in the presence of these bacteria, although the attack is chemical in nature and is favored by the strong electrochemical action between the iron and the graphite.

Bacterial attack of iron or steel differs markedly from normal galvanic corrosion in that the rate of corrosion remains the same or increases with time, while normal galvanic corrosion decreases with time. This is due to the cathodic depolarization caused by the bacteria. Chemically, this is represented by the following reactions:



Hydrogen sulfide is formed in all such reactions, and its presence is used to confirm the presence of the bacteria in the soil.

The redox potential, i.e., the oxidation-reduction potential (215, 216), can be used to determine the degree of attack once it is known that bacteria are present. Redox potential readings on the soil can be grouped in the following general classes:

less than 100 mv	severe corrosion
100 - 200 mv	moderate corrosion
200 - 400 mv	slight corrosion
greater than 400 mv	no corrosion

A much more general agreement has been noted between soil corrosion and redox potential ( $E_h$ ) than between soil corrosion and pH.

While the major action of the bacteria is to cause depolarization, Rogers (166) reports that the bacteria might mitigate or accelerate corrosion by producing acids or alkalis. The organic sulfur compounds formed also accelerate the pitting action, so much so that corrosion may continue long after bacterial action has ceased.

Several protective methods have been applied, generally with limited success. Cathodic protection has been suggested, but at least two authors (4, 67), are dubious of its success on theoretical grounds. Alloying with copper has also been suggested, but it has not met with success (22). Aeration of the soil should be successful, but the results have been uncertain, possibly due to the difficulty of effectively aerating the soil. The most favorable procedure is coating. Obviously the coating must be moisture resistant, free from porosity, and resist attack by the bacteria. The latter has been ignored in many cases, particularly in selecting wrappings for the coating. As a result action was accelerated due to the organic matter which served as food for the bacteria. Asbestos, wax, and cellulose, either as a paper or a felt, are all attacked. Therefore, it is now customary to omit wrappings even when they are coated with asphalt or coal tar.

An examination of the literature reveals that there is a great deal of work to be done in the future. Such factors as the metabolism, the effect of essential or toxic gases, pH, bacterial count, or the redox potential must be investigated thoroughly before there will be any assurance that bacteria are no longer a problem in pipe-line corrosion.

## V. PROTECTIVE COATINGS

The coating of underground pipe lines has been used as a protective measure for nearly a century, and the present trend is toward coating a larger percentage of such pipe before installation. Kelly (84) estimated that approximately 50 per cent of the 425,600 miles of pipe underground in 1944 was coated, and 80 per cent of the coated pipe was protected by coal-tar enamels. In citing these data the author quotes one of the important factors leading to coating, that of increased value of the pipe used. Such coated pipe is estimated to be worth 35 to 50 per cent more. Coal-tar enamels had been used most extensively in the water works industry up to 1944, the time when these data were published. It was estimated that 95 per cent of coated water-works installations were protected by coal tar. A similar trend was noted in the protection of gas lines. Since 1934 95 per cent of the protected lines installed were coated with coal-tar enamels.

It is obvious that the value of coating was realized, but there was no adequate means of comparison prior to the extensive coating surveys conducted under the joint auspices of the National Bureau of Standards, the American Gas Association, and the American Petroleum Institute. These studies, combined with the independent work of other investigators, led to a determination of the properties making up an ideal pipe coating. Such an ideal coating, combining all these properties does not exist at the present, but it was possible to eliminate many coatings which were definitely unsatisfactory as well as to select the coatings which most nearly met with the specifications of the theoretical ideal. Several investigators (32, 38, 62, 88, 129, 180, 200, 213, 227) have listed the properties of such a nonmetallic coating. A compilation of these



properties follows: 1 The coating must be chemically inert. This includes resistance to water or soil acids, alkalis, organic matter (such as vegetation or humus), soil bacteria, or insects. Similarly it must be insoluble in hydrocarbons, since many pipe lines carry petroleum or petroleum products. 2 The coating must adhere tenaciously to the pipe and initially be in intimate unbroken contact with the surface. 3 The coating must be highly resistant to moisture absorption. To fulfill this condition the coating must be free from capillary pores which would permit the penetration of moisture to the metal surface. 4 The dielectric should be sufficiently high initially, and there should be no pronounced decrease in the electrical resistance with time. 5 The coating should be capable of resisting the soil stresses. This will include resistance to deformation or to cracking under pressure. 6 It should be thermally stable. There should be no excessive flow when exposed to summer temperatures or cracking at low temperatures. In general, to meet this specification it must be completely hard, yet flexible between -40 and 300°F. 7 The coating should be sufficiently strong to prevent the penetration of stones, wires, or other materials after laying, and to be unaffected by ordinary handling conditions prior to burial. 8 The material should neither disintegrate with age nor be absorbed by the soil. 9 The coating should have a high thermal conductivity. 10 The thickness should be sufficient to insure protection (greater than 0.010 inch) but not excessive, due to cost considerations. 11 The coating must be easily applied, preferably without heat or primer coat, and it must be quick setting and fast drying after application. 12 It must afford permanent protection at a reasonable cost. 13 It is desirable that a history of the use of the material over a period of time be known prior to application.

While many of the characteristics are to be desired, certain ones are essential. For satisfactory use over a period of time the moisture absorption

must be at a minimum and resistance to soil stress must be sufficient. Likewise the coating must not be attacked rapidly by any of the soil constituents, and the cost must not be excessive.

The mechanism of failure of the bituminous coatings has been discussed by several authors (3, 9, 13, 89). Beckman et al. (13) consider the chief mechanism leading to pipe failure to be penetration of the coating by moisture by way of imperfections approximately 0.10 mm in radius. The authors state that the direct diffusion of water vapor may also be a significant factor; electro-osmosis accompanied by the diffusion of the electrolyte was not considered to be important. Beck (9) stresses the fact that the insulating properties of the coatings cannot be used as a basis for conclusions as their efficacy as a protective coating agent. A coating with poor insulating properties may form a series of adsorption layers on the metallic surface acting as a protective coating. Another theory is advanced by Anderson and Wright (3), who believe that both oxygen and water penetrate the coating by molecular diffusion. The authors also state that a macroscopically intact coating should exclude the electrolyte. Levin (89) considered a number of factors which determine the protectivity of the coating. These include porosity, resistance to diffusion, the dependence of water solubility on temperature, viscosity, character of the emulsion formed by water and the coating, the amount of water emulsified by the coating, the charge of the aqueous layer, the ability of the layer to passivate metal, the emulsification velocity of water with the coating, and the relationship between the surface tension of the metal, the aqueous phase, and the oily phase. Levin (89) believes that porous coatings have no protective value at the pores, and a nonporous coating may have a hydrous phase formed under the coat by means of the factors discussed above. The author concludes that the protectivity of a coating is proportional to the square of the thickness.

Many coatings have been tested in the hope that one having the ideal properties would be discovered. Such surveys have been in four categories.

These are the study of metallic, bituminous, nonbituminous-nonmetallic coatings, and studies conducted with shields and reinforcements which were constructed to protect the coating against soil stress.

Several metallic coatings have been investigated at the National Bureau of Standards. Work by Logan (97) and Logan and Ewing (102) with zinc, lead, tin-coated copper, and mill scale, indicated that zinc was the only metallic coating of those studied having satisfactory protective properties. In such a case the protection was a function of the coating thickness. Zinc coatings were found to be of limited value in cities where electrolysis or galvanic action was particularly severe. Lead was definitely unsatisfactory. Its use was limited a few soils. Due to the position of lead in the electromotive series, unlike zinc, it accelerates corrosion after being pierced. Tin-coated copper behaves in a similar fashion. Here again corrosion is accelerated after the coating has been penetrated. Mill scale is not satisfactory because it is not continuous. A continuous coating of mill scale is protective but any uncoated areas lead to a galvanic couple between metal and scale, which causes corrosion. A calorized coating of aluminum renders the pipe more resistant to corrosion, but it does not prevent pitting. Logan (101) concluded that zinc was the only satisfactory metallic coating among those tested, and it must not be used in poorly drained acid soils high in salts, where the coat is attacked very rapidly. The most effective use of zinc seems to be limited to underwater protection. Mundt et al. (130) concluded that zinc was very effective in preventing such corrosion, their findings being based on five-year underwater tests conducted at the Panama Canal. This confirms the results of Senatoroff (196), who found that pipe subjected to a double-dip galvanizing proved to be very satisfactory when used across streams and sloughs.

The bituminous coatings as a class are the most important protective media. The important classes of bituminous coatings consist of the asphalt

enamels, the coal-tar enamels, the greases or waxes, and the mastics, consisting of an asphalt or coal-tar base plus an inert binder.

The asphalt coatings have been extensively investigated in the Netherlands (154, 250), where blown asphaltic bitumens have been preferred. Carriere (26) also suggests such blown asphalts for coatings. Wichers (245) and Scherer and Mudd (180) discuss the asphaltic bitumens and conclude that their principal fault is excessive porosity. An interesting application of the asphalts is noted by Negreev (131), who cites a 50 per cent clay and fifty per cent asphalt mixture as a good protective material. Of the large group of coatings tested under the joint auspices of the National Bureau of Standards and the American Petroleum Institute, Scott (186) concluded that asphalts and coal-tar enamels were best. Asphalts are resistant to relatively high temperatures, but they are attacked by oil.

The asphalt enamels are extensively used as coating material. Larson (88) lists a number of the properties of such materials: they tend to flow at high temperatures but are relatively unaffected at low temperatures; the bond is often unsatisfactory; it is necessary to protect with shields or reinforcements under soil stress; they are sometimes porous but do not absorb too much moisture; the dielectric strength is adequate; and they are attacked by aerobic and anaerobic bacteria.

The tar-base enamels have been used more than any other coating material. Larson (88) lists some of the properties of these products. They are easy to apply; resist high temperatures; the bond will vary with the method of application; optimum thickness is  $3/64$  to  $1/16$  inch; a shield is required for protection against soil stress; moisture absorption is low; dehydration is slight; the dielectric is high; and they can be applied using slings or revolving the pipe. One advantage over the asphalts is their insolubility in

petroleum products. Disadvantages cited by Scherer and Mudd (180) and Wichers (245) are the severe distortion and the low-temperature brittleness. A typical installation in which the coating consisted of coal-tar enamel was the long line from Corpus Christi, Texas, to Kentucky. Thayer (225) states that this line was protected by coal-tar enamel over a primer coat; two layers of enamel plus two wrappers covered with wooden slats were used at all river crossings. Initial surveys indicated that satisfactory results were being obtained with this means of protection. Goodwin (64) suggests the use of coal-tar enamel plus glass matting as a shield against soil stress. The matting impedes the flow of the enamel and protects against the soil stress, while it resists chemical attack.

Grease or wax coatings are satisfactory only if an effective shield is available to serve as a protection against soil stress and to prevent the penetration of excessive moisture. Hiskey (72) found such coatings satisfactory in conditions varying from swamp to desert. The author stressed the need of a good wrapper coated with a saturated hydrocarbon to prevent deterioration. Mudd (128) concluded that the major fault of grease coatings was their permeability to moisture or oil, which might lead to serious failure. One possible means of protecting the coating is to use a cellulose membrane as suggested by Logan (100). The principal difficulty met with in such a method is the susceptibility of such materials to bacterial attack. The chief advantage of such coatings is their relative ease of application, since it is possible to apply greases while cold.

The mastics are generally considered to be the most effective bituminous protective coating material (62, 99, 128, 195). Scott (195) cites a case where Somastic (trade name for one of these products) was still in good condition after ten years. These materials consist of some inert material

such as sand, gravel, or asbestos, plus an asphalt or coal-tar base. The asphalt base materials have good properties, but they dissolve in oil. There is no such difficulty in the coal-tar base mastics, but a great deal of developmental work must be done on the coal-tar materials before they are definitely satisfactory. The two principal difficulties with these materials are cost and method of application. Since the mastics are patented, cost is a definite factor, and the mastics must be mill-applied by means of special equipment. Generally, the coatings are  $3/8$  inch or greater in thickness. One fault is their attack by marine animals in brackish water (180).

The nonbituminous-nonmetallic coatings include a great variety of materials, but, with the exception of concrete, their use is not widespread. Many of the plastics or vitreous enamels are still in the experimental stage. Present data indicate that some of them may prove to be very satisfactory in time.

Concrete has been used for nearly a century, but its use as a purely protective coating has been generally abandoned due to a number of factors such as cracking or checking with age and temperature or moisture variations, its high cost, and the lack of recovery of the pipe (62). Ewing (53) states that such coatings are generally good, but a coating greater than one inch in thickness is required, and a soil high in soluble salts may disintegrate the concrete. The author notes the use of asbestos cements developed in Europe and believes they have some possibilities.

Larson (88) states that cases are known where concrete has protected pipes for up to 75 years, while most coatings are good for approximately ten years. The author lists the properties of concrete coatings. These consist of a fair bond, a thickness of  $1/4$  to  $1/2$  inch, resistance to soil stress, high porosity, low dielectric, no effect due to freezing, and deterioration due to soluble salts or acid soils. Larson (88) states that pipes can be coated by the use of molds, wrapping, or a cement gun. An interesting use of concrete

is discussed by Kerr (85) who notes the use of a thick concrete coating on pipes carrying oil or gas through swamps or across rivers where the concrete supplies a negative buoyancy and a permanent corrosion resistance. For such an application a 1 1/4-inch coating is suggested.

The asbestos cements are discussed by Dumas (50) and Rocca (164). Dumas (50) describes a coating of cement and asbestos applied as a wet sheeting on pipes in Australia, which was still satisfactory after five years exposure. Rocca (164) discusses the patented asbestos cement known as "Dalmine" which has proven to be excellent. Goodwin (64) disagrees with the majority of investigators. He states that concrete is ineffective and uneconomical in general in sands or sandy soils, where concrete is most stable. An analysis of the conclusions indicate that concrete is satisfactory insofar as protecting the metal is concerned but is undesirable from a cost standpoint.

Other nonbituminous-nonmetallic coatings consist of plastics, which often yield variable results due to soil decay, vitreous enamels (the most important in this group) natural and synthetic rubbers, and organic or inorganic paints.

Plastics such as bakelite, koroseal, and the phenol-aldehydes have been used for coatings, generally with limited success. Four-year tests on these materials conducted at the National Bureau of Standards indicated that most of these materials have a very short life. An interesting method of application of bakelite as a pipe coating is noted by Chernyavskii (27) and Moore (125). The authors suggest the bonding of the bakelite onto the pipe by polymerization due to heating. Moore (125) suggests the use of induction heating for this purpose. The rubbers have offered good resistance to corrosion except when the coating is injured, or at the unprotected ends. A thick coating of

China-wood oil was found to prevent pitting in all soils (101). Paints, either organic or inorganic were definitely unsatisfactory.

The best materials in this group are the porcelain or vitreous enamels. Gill (62) suggests that these materials should prove to be satisfactory, providing the pinholes could be eliminated. Larson (88) lists the properties of these vitreous enamels. They consist of an excellent bond, slight water absorption with some initial porosity, high-dielectric strength, high-temperature resistance, low-impact resistance, high-abrasion resistance, no soil absorption, high-chemical resistance, resistance to soil stress, and a relatively thin coating (about 1/32 inch) required. Such coatings must be mill-applied. The overall properties of these materials are very satisfactory but their cost tends to be high.

Due to the lack of resistance of most coatings to soil stress, it is necessary to use a soil shield or a reinforcement. If a bituminous coating is applied to the fabric, the protection is known as a reinforcement; if the fabric is exposed directly to the soil, it is known as a shield. The bituminous coating is often necessary due to the destruction of the fabric by organic materials present in the soil, particularly in mucks. To be effective as a shield Larson (88) suggests the following properties: some tensile strength, soft and pliable initially but hard after application, a good bond, low porosity, and resistance to bacterial action. Generally such shields lack the last two properties. Many materials have been used for these shields. They include Kraft papers, cellophane, asbestos, wood veneer, organic wrappers, cements, glass matting, and inorganic or metallic wrappers of foils of copper, aluminum, or iron. Asbestos or glass seem to be the best due to resistance to soil action. There exists a definite need for lighter soil-stress shields for use with traveling-type coating machines, and considerable research along this line could be



carried out. These coatings are hand-applied or machine-applied by saddle or rotary ditch machines. At present no completely satisfactory shield is available (64).

The extensive surveys conducted by the National Bureau of Standards, the American Gas Association, and the American Petroleum Institute indicated definitely that certain proprietary coatings were useless. The studies also evaluated the engineering characteristics of various coatings as well as the actual behavior of the coatings when applied to a pipe and examined over a period of time. This work was carried out by Logan, Ewing, and Scott, who enumerated the properties of the coatings in a series of publications (53, 92, 95, 96, 101, 172, 185, 187, 191). These coating characteristics can be summarized as follows:

- 1 no coating entirely prevents corrosion under all conditions;
- 2 coal-tar-base materials are more stable and waterproof than asphalt-base materials, but good coatings can be made from either;
- 3 machine-applied coatings are superior to similar hand-applied coatings (hand application in the field is not considered advisable);
- 4 organic reinforcement in a coating is a weakness, especially if the bitumen is an asphalt (any coating not affording some degree of protection in poorly drained soils should not be applied);
- 5 the resistance of the coating is variable from material to material, and the resistance may decrease appreciably with time;
- 6 cold unreinforced coatings are inferior to the thicker, hot-applied reinforced coatings;
- 7 zinc chromate or baked-on red or blue leads are satisfactory as an undercoat primer (they reduce corrosion but do not afford adequate protection);
- 8 there are fewer pits under a thick coating than under a thin one;
- 9 the pit depth may be greater under a thick coating than under a thin one;
- 10 a cement-sand layer over an emulsion coating is insufficient to prevent serious pitting;
- 11 shields or reinforcements should be permanent and sufficiently rigid to distribute the soil stress and pressure to

prevent flow of the coating material; 12 thickness is an important factor in coating construction; 13 a coating should be rigid enough to withstand pressures over a long period of time and elastic enough to withstand stresses due to pipe movement or temperature change--it is difficult to get both. 14 a mildly corrosive soil may require no coating unless the leak cost is abnormally high; 15 the economics of any problem should be considered; 16 with metallic coatings the important factors are the coating thickness and the potential of the coat and the base metal; 17 in insulating coatings, failures are due to faulty application, injuries, pinholes, decay, or soil-stress distortion; 18 a simple paint or dip coat is inadequate as a protective coating against corrosion; 19 shields prevent soil stress--wood shields may rot but still serve the purpose; cellulose products are attacked by soil bacteria; asbestos felts are practically unaffected, (which is also true of coal-tar-saturated fabrics), tidal marshes are least destructive to organic wrappers while mucks are the most destructive; metal foils may be satisfactory, but they have been used only in experimental installations; 20 no essential difference in properties is noted between equivalent cost coatings; 21 a higher resistance is obtained with machine-applied coatings than with hand-applied coatings; 22 coating performance is controlled by soil conditions, shrinkage, soil density, and soil stress; 23 coal-tar-base coatings are more affected by soil stress, temperature changes, or shocks than are asphalt coatings; 24 the minimum coating thickness and therefore the most economical, is 1/16 inch; 25 shielding gives an economic advantage greater than the cost; 26 care in handling and laying of coated pipe definitely affects the life of the coating.

An analysis of the results obtained in the coating tests indicates that all coatings have a limited life, and a careful analysis of the corrosion conditions is necessary in order to determine if it is economically feasible to apply a protective coating.

An important factor in determining the life of the protective coating is the preliminary preparation of the pipe surface. A satisfactory job may increase the coating life due to uniform adherence of coating to pipe as well as removing residual moisture or mill scale, which may initiate corrosion under the coating. Larson (88) lists a number of the methods used in the preparation of such pipe surfaces. These consist of pickling, mechanical cleaning such as chipping or wirebrushing, sandblasting, shotblasting, heating, or washing with solvents. Mudd (128) considers the most important factor to be the removal of moisture and loose foreign material in order to secure an effective bond between the coating and the pipe. Scherer and Mudd (180) discuss the use of special pipe cleaners such as the rotary-head traveling cleaner, which they favor over all others. Mudd (129) describes in considerable detail the methods of cleaning the pipe surface and removing the residual moisture. The author prefers mechanical methods such as rotary knives or cutters, or blasting with sand or grit, to flame cleaning, because of the high operating cost, inflammable hazards, and localized pipe stresses occurring in the latter. It is suggested that high-frequency induction heating may be preferable. To remove the moisture, sandblasting or the application of a primer coat serving to crystallize the water is suggested. Chemical dehydrants may also be used.

Liebman (90) discusses the factors which determine the extent of the surface preparation of the pipe prior to coating. These are: 1 the wetting strength or wetting depth of the coating, 2 the wetting time of the coating, 3 surface tension of the coating, 4 adhesion characteristics, and 5 bonding characteristics.

A survey of the cleaning methods is given in TP-6G of the NACE (32), in which the standard methods of surface preparation are surveyed, such as: weathering; wire brushing; flaming; blast cleaning by the open dry, closed

recirculating, or wet systems; chemical cleaning by pickling or electrolytic pickling; roller roughing; surface cleaning with solvents, alkaline compounds, acids, or emulsions; and surface conversion. The report also suggests that the removal of residual sand or dust is advisable before coating.

After the pipe has been properly cleaned, the primer, coating, and shield or reinforcement must be applied. Here again improper methods will materially decrease the coating life. Three possible coating procedures can be followed, depending on the type of coating, facilities available, and the cost analysis. Ewing (53) discusses the three types. These are mill coating, yard coating, or field coating. Mill coating requires extensive equipment, but for mastic-type coatings it is the accepted procedure. Either a dip or wrap method is used. In yard application, trough or machine methods are used; in the field a rolling rig, Gardiner coater, or the sling method is standard. Primer is applied with a sprayer or a brush. The shield is generally applied immediately after the coating, using the same equipment. Ewing (53) also discusses the methods used in the application of a concrete coating such as the wood trough, cement gun, removable steel forms, Kraner process (where the pipe is rotated while a ribbon of concrete is fed onto the pipe), or extrusion machines.

Huddleston (77) also suggests certain procedures, such as coating the ends first and insulating the pipes at points of contact to prevent galvanic corrosion and to minimize the protection cost of any cathodic units.

A pipe can be prepared perfectly and coated without error, but faulty handling can injure it so severely when it is being laid that the coating may prove to be of little or no value. To prevent this, adequate inspection and testing procedures are necessary according to Parker (143). Such an inspection should cover: 1 pipe handling, cleaning, and priming; 2 enamel application;

3 felt and reinforcement application; 4 handling of the coated pipe; 5 coating of the field joints; 6 Holiday inspection; 7 Holiday patching; and 8 lowering and backfilling.

The necessity for these visual or electronic inspections is graphically portrayed by Cramer (34), who discusses an installation using a coating consisting of hot wax, a dielectric wrapper, more wax, and a Kraft paper wrapping. A detailed analysis of the faults was conducted after the pipe was installed, in which it was found that 32.2 per cent of all faults determined with a Holiday tester were due to poor inspection of the pipe, skid marks, bruises, walking on the pipe, coating bruises, crossing another pipe, or shovel marks. Another 33.7 per cent was due to inadequate coating. Further, 27.1 per cent was due to drips, welds, lugs, services, gates, bonds, or laps occurring during the welding or coupling of the pipe.

To check the coatings, several methods are available. Typical methods are visual inspection or the use of an electronic Holiday detector. These are the most important, but several other tests have been developed, such as a chemical test depending on a color change from potassium ferricyanide, which reacts with the iron exposed at pinholes, giving a characteristic color. Another test, which has generally been superseded by the electronic Holiday detector, is made with the faultometer, using an ignition coil as a spark source to locate pinholes. Pfeiffer (154) and Larson (88) discuss various tests used to determine the best material before coating. The authors suggest such tests as ring and ball, viscosity, melting point, flow, brittleness, moisture absorption, impact, shear, softening point, or burial. These tests are excellent in determining if a material meets the coating specifications, or in selecting the best coating material from a series of bitumens. A general survey of these test methods

is also given by several authors (33, 56, 86, 88, 154). In conjunction with such tests Dorsey (49) suggests a simple method of checking insulating couplings, using a direct current source and a magnetic compass.

The electronic Holiday detector is discussed by several authors (79, 101, 147, 150, 218, 228). Such a unit can be operated by two men who can cover four to six miles per day by walking above the buried pipe line. The unit consists of an alternating-current source plus a microphone hummer for picking up coating faults by a change in the pulse. This method is satisfactory for locating isolated holes, the end of coatings, or the pipe line, and for determining the coating conductivity and the current density. The unit develops a current flow between pipe and earth with the current returning through holes in the coating or as a charging current between the pipe and the ground; a current leakage indicates a Holiday. It must be emphasized that such an inspection does not insure a 100 per cent coating job, and other faults also exist in the equipment. The detector may also damage the coating if too high a voltage is applied. The method is not satisfactory for detecting potential sources of trouble such as improper pipe cleaning, a wet pipe when the primer was added, too thick a primer film, or a primer film which was not dry when the coating was applied. It is suggested that the minimum voltage capable of detecting the Holidays be used, and the unit should not be used for determining the coating thickness, nor for testing hand-brushed hot applications.

Beck (9, 10) has conducted a series of tests in which the coated pipes underwent vibrational stresses, with or without a superposed electric current, in an attempt to duplicate the vibrational stresses due to heavy traffic. The author's results indicate that asphalt or coal-tar enamels are unsatisfactory. The only coating behaving well consisted of a grease bandage.

The superposing of an electric current accelerated the failure. These studies were conducted in the period from 1930 to 1933, and the results are such as to indicate that more consideration should be given to the selection of the proper coating in cities, where the pipes are subjected to electrolytic currents, excessive galvanic action, or to vibrational stresses.

Before coating a pipe line, it is advisable to investigate the economics of the system. In many cases coating may not be indicated. Scott (188) enumerates the factors to be considered in the selection of a coating and its application. These factors include: 1 the coating cost; 2 coating life; 3 pipe-line cost; 4 maintenance and reconditioning cost; 5 interest rates; 6 revenue loss due to service interruption; 7 damages; 8 salvage value of the pipe; and 9 service life of the pipe. Some other factors must be considered after these have been satisfactorily evaluated: 1 it must be realized that the proper application of a coating is essential; 2 the existence of soil stress must be recognized and the problem of its existence corrected for; 3 coatings should be classified to permit the proper selection of the one that best fills the existing conditions; 4 methods for forecasting the future behavior of the pipe and coating must be developed; 5 a better understanding of the pitting phenomena permits the selection of a proper coating.

By considering the factors determining the selection of the proper coating, it may be found that a bare pipe is the most economical. Failure to recognize this possibility has led and will lead to expenditures for a coating which was not required.

## VI. CATHODIC PROTECTION

Whether a pipe line should be protected by coating, whether thick-walled pipe should be used, or whether cathodic units should be installed must be decided on the basis of an economic balance. Doremus et al. (48) state that cathodic protection must be based on the answers to these four questions: 1 is complete cathodic protection desired, with indefinite extension of the pipe life and a high salvage value, 2 is partial cathodic protection satisfactory, with some extension of pipe life and a lower salvage value, 3 can the line be reconditioned, resulting in lower costs for the cathodic protection, 4 is some combination of these best. Obviously, the engineering problem is to find the method giving the desired degree of protection at a minimum cost without spending too much for the engineering. Generally it will be found that complete protection is much too expensive. It is usually possible to get 80 to 90 per cent protection, using 10 to 20 per cent of the current, at 15 to 20 per cent of the installation cost necessary, if the line were to be completely protected. For general protection, an electrical survey determining the current density, potential, or current-potential must be made. If the protection is to be limited to corrosive areas, the survey will be based on a study of the leak records, a soil resistivity survey, or line-current measurements to determine the major points of polarity change. Several factors must be considered in conducting such a survey. If the pipe is coated, the voltage applied must be limited, to prevent damage to the coating. There is also a limit to the current drained, based on the pipe size, completeness and effectiveness of the coating, and the soil resistivity. Care must be taken in determining the total requirements for



protection. The selection of a cathodic unit on the basis of low current output is fallacious, since it has been proven that current economy and dollar economy often are not synonymous.

Engineering analyses indicate that a large number of small electrical drains is generally better than a small number of large electrical drains. The first system theoretically offers more complete protection than the second. However, such factors as coating and soil resistivity must be considered.

Several factors which influence the protective system to be applied are listed by various authors (21, 98, 118, 136). Logan (98) noted that a protective current always causes alkali to accumulate on the cathode; this acts as a protection against anaerobic bacteria, but destroys the coating bond. The metal potential with respect to the reference electrode is no criterion of the corrosion rate; this has been widely misinterpreted. A better method is the use of a log current density-potential curve. The protection criterion is a current density which exceeds the protective value for the pipe line. This appears on the plot as a straight line with a negative slope.

McLeod (118) lists further factors, such as the pipe area, which will determine the total current required. The availability of power as well as the existence of a right-of-way for locating the ground beds at suitable sites must also be considered. Any foreign pipe lines or similar structures must be taken into account, since they may be a source of interference in a cathodic installation. This is of particular importance on gas lines in urban areas, since the gas mains are interconnected with the water system in most residences, necessitating protection of both systems by the gas company, which is much too expensive for one utility to undertake, the installation of insulating couplings, or a sharing of the expenses by the utilities, to their mutual benefit.

Brown and Mears (21) attack the problem from an electrochemical viewpoint. The authors list eight factors which are important in insuring complete protection. These are: 1 the cathode areas must be polarized to a potential equal to or greater than the open circuit potential of the anodes; 2 the cathode must be polarized to the open circuit potential of the anodes where the cathodic polarization is large compared with the resistance drop; 3 if the cathodic polarization is small compared with the resistance drop the cathode must be polarized to a potential more anodic than the open circuit potential of the anodes; 4 the total current depends on the current required to polarize to a potential equal to or greater than the open circuit potential of the anode; 5 protection depends on the position of the auxiliary anode relative to the position of the local anodes and cathodes; 6 the less the potential drop between the auxiliary anode and the local cathodes, the less current is required; 7 special attack or inhibition may be produced by the products of electrolysis resulting from the application of a cathodic current; 8 special attack on surfaces which are made cathodic may be beneficial if the type of attack is also altered. These factors are based on an electrochemical analysis of the operation, and their application may yield protection, but at an excessive cost.

Olson (136) considers some of the factors listed previously, plus several others, in establishing an adequate basis for the solution of the problem dealing with the control of stray currents from such cathodic-protection installations. This is very important, since the procurement of adequate protection of one system, which results in excessive damage to another system, is poor economy. The author lists the following items which serve as a basis for solution of this problem: 1 it is impossible to protect cathodically a metallic underground structure without affecting to some extent the electrical condition of other underground structures in the vicinity; 2 after a cathodic-protection

installation is placed in service it is impractical, if not impossible, to make adjustments between the protected and unprotected lines, which will reestablish the original conditions in every respect at all points on the protected lines; 3 the unprotected lines are adversely affected only when cathodic protection causes current to flow from the lines to the soil at any point; 4 it follows from 3 that, in order to prove that a corrosive condition has been established by the cathodic installation, it is necessary to detect a flow of current from some point on the unprotected line to soil, which is caused by the operation of the cathodic unit; 5 an objectionable condition exists when a voltage is established across the junction of an unprotected line and earth by virtue of a cathodic installation on another line when that voltage is in such a direction as to cause a tendency for current to discharge from the pipe; 6 corrosion coupons for such an installation are of questionable value due to the potential from coupon to pipe.

In conducting the preparatory survey prior to installing a cathodic unit, Logan (101) suggests three possible criteria that can be used. These criteria are: 1 the current density; 2 pipe-to-soil potential, and 3 a current-potential curve. Of these, the current density is the least satisfactory because it must be calculated over a large area, where the current is not uniform, and no simple way of determining the current density is known. In addition, the values change with time; as a result it is not a safe criterion.

In determining the pipe-to-soil potential, a voltmeter is used in conjunction with a copper sulfate half cell or a steel electrode. It is assumed that the pipe is neither charging nor discharging when the reading is 0.54 volt, and adequate protection may be based on the lowering of the voltage to -0.80 to -0.85 volt with respect to the copper sulfate cell. In general, this has proven to be satisfactory, but there are several objections to this criterion. The

potential may vary from point to point with respect to a remote electrode, or the total potential in the pipe may change with time. An increase in the oxygen content of the soil will raise the potential while an increase in the alkaline content decreases the potential. Another source of error may result from the IR drop caused by a current flowing to or from the pipe. Due to these sources of error some engineers use a criterion of protection which assumes that the pipe is protected if the potential is lowered 0.3 volt. One obvious fault in this is that it assumes a pipe, whether corroding or not, must still be protected.

Current-potential curves are the most adequate criterion for cathodic protection.

A null circuit such as developed by Pearson and Hadley (101) is generally used to determine the pipe-to-copper-sulfate cell potential and the impressed current. Due to the equipment required for field tests, the method is not used as extensively as the results warrant. In some cases pipe-to-soil potential surveys indicate the same current requirements for protection as the current-potential method, but the opposite is often true. Logan (101) cites an example in which the experimental results based on pipe-to-soil potential measurements indicated that from 18 to 30 amperes were required to lower the potential 0.3 volt. Current-potential curves indicated that only three amperes were required.

Several authors (55, 104, 122, 123, 124, 170, 241) list the same criterion of -0.80 to -0.85 volt as indicating protection of the pipe line, together with a number of suggestions for obtaining readings having a minimum of error. The effect of seasonal variations on the protective potential should be considered. In the wet season the criterion is -0.80 volt, but this should be less in the dry season. A potential of -0.68 volt is suggested then. The

protective voltages will also depend on the metal in the structure, the soil corrosivity, or the location of the ground bed in relation to the anodic and cathodic areas. Cathodic areas may require a lower potential than is true in anodic areas.

After the electrical measurements have been made it is necessary to analyze the data mathematically. Attenuation equations have been applied by several authors (48, 60, 68, 140, 155, 156, 171, 192, 203, 214) to the problem of cathodic protection. Numerous assumptions are necessary in applying these equations to cathodic protection, such as: 1 uniform pipe section and conductivity (this is satisfactory on welded or screwed-on lines, but not on those equipped with Dresser-type coupling); 2 the soil is of uniform resistivity (while this is not true, fluctuations do not cause too serious an error); 3 the leakage resistance is constant (this is a function of the soil resistivity which must not be too variable); 4 an infinite line length (this is not valid near insulation); and 5 there is a polarization variation.

Pope (155,156) developed the attenuation equations, and listed a series of equation illustrating such effects as: 1 the presence of a leaky coating of the pipes; 2 variations of the soil resistivity; 3 changes in the longitudinal conductivity of the structures; 4 any change in diameter of the structures; 5 a change in the distance to the anode; and 6 a change in the degree of separation of the structures. The equations were based on the maximum interference current, maximum rate of current loss, and the length of exposure to corrosion. Standring (214) extended the work of Pope (155) in determining the attenuation effects over an infinite length of pipe. The equations are derived and the method of application of the data is denoted.

An extensive survey of the field of cathodic protection was published under the joint auspices of the Electrochemical Society and the National

Association of Corrosion Engineers. This symposium is entitled "Cathodic Protection" (221). The symposium covers the electrochemical principles of cathodic protection as well as several papers on survey procedures, including the methods and the equipment to be used. The material was similar to that covered in the corrosion and soils survey section of this report, but a great deal more detailed. Some interesting points were discussed by Sheppard(221), who states that the earth's magnetic field and the Aurora Borealis both can be a disturbing source of error in making measurements of pipe-line currents due to other sources. However, neither is felt to be an important source of corrosion. The author also notes that aerobic and anaerobic bacterial corrosion may occur adjacent to one another, resulting in extremely severe corrosion because of a concentration couple established between the two soil sections due to a difference in oxygen concentrations. The symposium covers other facets of cathodic protection such as the use of rectifiers or wind-driven generators, as well as anodes and ground beds; the greatest number of papers were concerned with galvanic protection, using dissimilar metal anodes of zinc, aluminum, and magnesium. Here, too, the material is similar to that discussed in this report but the individual papers are more detailed.

Mudd (128) discusses corrosion control by cathodic means. The size of the installation is governed by the amount of current required to develop a pipe-to-soil potential of  $-0.85$  volt referred to a copper sulfate electrode. For cathodic protection, as differentiated from galvanic protection, an external source of direct current is required. This can be supplied by using rectifiers of the contact type such as copper, copper oxide, or selenium units; thermo-ionic rectifiers such as the Ignatron, or the metallic vapor unit, where voltages in excess of 30 volts are required, may also be used. Bonner (19) describes the construction, electrical characteristics, efficiency, voltage

regulation, and circuits of selenium units having a range from less than one ampere to 540 kilowatts in a single installation. A similar description of the characteristics of copper-copper oxide rectifiers is given by Burton and Hamann (23), who also compare selenium and copper-copper oxide rectifiers. The authors conclude that selenium units are best where limited space and light weight are factors, as well as for situations requiring a high voltage and low current. The copper-copper oxide units are preferred for intermittent short-period use, for low voltages and high currents, or for long life. These units are more stable; there were cases of units having lives in excess of twelve years.

Other sources of direct current were cited by Mudd (128), such as motor-generator sets, engine-driven generators, wind-driven generators, or thermocouple units. All such units are subject to certain inherent faults. It is essential that the maintenance should not be excessive, which limits the use of certain types. Motor-generator sets suffer in this respect, plus having a low efficiency. A similar problem arises with engine-driven generators, for which automobile engines are usually used. The wind-driven generators have a minor maintenance problem, but no protection is given by the unit if there is no wind, and excessive wind may actually accelerate the corrosion due to loosening the corrosion products. It is possible that thermocouples might prove satisfactory, but such units are still in the experimental stages.

Several authors have discussed specific cathodic units, and the results obtained from their installation. Dean (39) describes rectifiers on the Bonita pipe line. The history notes many leaks in the period 1914 to 1932, even after application of a gunite coating in 1927. An asphalt coating was applied in 1932, but 1500 pipe failures occurred in the period 1932 to 1943. After the cathodic unit was installed the number of leaks dropped to 104 in 16 months as compared to a predicted number of 314, based on an extrapolation of the leak-record curve.

Rogness (174) noted the same effect on a 28-inch riveted-steel pipe line. A high leak history indicated that the coating was not satisfactory and rectifier units were installed, which decreased the number of leaks. The author noted that constant maintenance of the cathodic units was necessary.

Huddleston (75) describes a rectifier cathodic unit used to protect a 24-inch gas line, which was rapidly deteriorating due to bacterial corrosion. Prior to the installation, the leak rate was one every 10 to 15 days. After installation pinhole leaks were virtually eliminated over a 62-month period.

A similar problem existed in New Orleans, where the extremely corrosive soil required special measures. Trouard (230) describes the protective system, which consisted of a coating plus a cathodic installation. By maintaining certain conditions there has not been a failure or a leak in 20 years. The precautions observed consisted of 1 keeping a reasonably good coating on the mains; 2 maintaining the system so that it was electrically continuous and free from accidental electrical contact with other sub-surface utilities; 3 maintaining a potential of -0.85 volt with respect to a copper sulfate half cell; 4 the cathodic protection device was maintained in continuous operation; 5 many small rather than a few large units were used for the installation in order to prevent cathodic interference. Backfills with a high gypsum content were very satisfactory. The current output was checked on a monthly basis to insure optimum performance. Obviously, these precautions were worth the extra time and expense, since the complete prevention of leaks eliminated the maintenance problems which must be faced in patching a pipe line.

Schreiner (184) describes a protective system applied to a gas line in Ohio. The line was 40 years old, bare, and equipped with mechanical couplings. Selenium rectifiers were used to supply the direct current; the anodes consisted



of 150-foot sections of scrap pipe in a ground bed consisting of alternate layers of rock salt and soil. Based on the leak rate, a definite saving occurred due to the cathodic protection.

After a system is selected it is necessary to connect the elements of the cathodic protective unit and to insure satisfactory electrical bonds. Negligence in this respect will lead to unsatisfactory results. Mudd (128) lists a number of precautions which should be observed if the unit is to operate properly. The author suggests that all underground cables and connections be large enough to prevent an abnormal voltage drop. Such cables should be placed underground, since it is less expensive than an overhead system and theft is prevented. Areas near the connectors should be insulated to withstand exposure to the moisture and the soil. The most satisfactory installation consists of a 600-volt copper cable overlaid with a layer of rubber as insulation plus a sheathing of nonhygroscopic synthetic rubber. The connections should have a low resistance and remain tight. Bolts can be protected by applying a one-inch layer of bitumen enamel. It is suggested that shunts be applied at all such connections to allow current measurements to be made. A similar system can be used to protect crossing lines from corrosion. The current flow is determined and a satisfactory bond wire installed so that no change in potential exists between the two pipes.

One further precaution often taken is to sectionalize the current flow by means of insulators. Certain precautions must be taken with such insulators if a concentrated current is to be prevented from flowing from section to section around the insulator. It is customary to apply a protective coating immediately adjacent to the insulator extending for at least 50 pipe diameters along the pipe. It is necessary to insulate pump stations from the main pipe

lines if rapid deterioration of the buried station piping is to be prevented since such piping might be anodic to the main lines.

Ewing (55) discusses several methods of electrical bonding suitable for cathodic units. Soldering and brazing are less satisfactory than welding due to the lower strength of the bond and the difficulty in cleaning the joints. In brazing, too low a temperature gives poor joints while too high a temperature may produce cracks in the steel. It is better practice to braze the copper wire to a steel terminal and then weld the terminal to the pipe. This is considered to be the best practice, since any attempt to weld the copper wire to the pipe requires a large welding current and skilled welders. Even so the pipe may be weakened, and such welding produces toxic gases. After the junction has been made, a moisture-proof coating should be applied to prevent corrosion from causing a bond failure.

Scott (193) has derived the relationships controlling the size of the drainage bond and the current passing between the pipes. These relationships may be used to test the efficiencies of insulated flanges, or to indicate when sufficient protection has been applied.

McElhatton (117) discusses the factors serving as a basis for selecting a bond, as well as suggesting types of bonds which are suitable. Such bonds should have a very low resistance; they should not fail during the life of the pipe; and the cost should not be excessive.

Another important factor in maintaining cathodic installations at maximum efficiency is the proper preparation of anode ground beds after selecting the best location for these beds. Soil conditions determine the selection of the ground bed site. An area having a low electrical resistivity is most desirable since the resistivity affects the power requirements. If such an area is not available, the local soil resistivity can be lowered by the addition of

chemicals to the backfill. For example, a 1000 to 15,00-pound cast-iron anode would require 600 to 800 pounds of crushed gypsum plus 200 to 300 pounds of salt. Another requirement in such an area is an adequate supply of water in the soil to insure a uniform soil resistivity.

Mudd (128) discusses ground-bed installations and the factors controlling their selection. In any soil of a given resistivity several factors act as a basis for such an installation. These factors are the size, shape, disposition, depth of insertion, and number of anodes, all of which must be considered in determining the current requirements. Ground beds display certain characteristics: an increase in the soil contact surface is accompanied by an increase in the total current, but the current density decreases logarithmically. Either vertical or horizontal anodes are used. An advantage of horizontal anodes is the fact that the soil resistivity profile is not an important factor. It is possible to select the soil layer having the lowest resistivity to which it is practicable to excavate.

It is also possible to use a multiple anode system, since such a system increases the total current, but adjacent anodes reciprocally reduce the current-transmission ability of the others. It is also possible to increase the total current by increasing the anode spacing. The advantage of such an installation is its ability to introduce more current into the system. In an installation having high current requirements, a single anode system would not be satisfactory due to the current limitations.

Another factor in selecting a system is the anode material. The selection usually depends on cost, and the material loss per ampere per year. Three materials are in common use at present. These are mild steel pipes which lose 15 to 20 pounds per ampere per year, cast iron scrap which loses 2 to 20

pounds per ampere per year, and carbon or graphite which loses from 0 to 2 pounds per ampere per year. The carbon anodes are still being tested to determine their characteristics.

Schneider (183) summarizes the factors influencing corrosion, such as: 1 local action; 2 long-line currents; 3 stray currents; 4 crystal structure of the steel; 5 slag inclusions; 6 differences in soil or solution; 7 differences in aeration. The author also discusses the factors responsible for the long-line currents. He considers that different soils, a variable moisture content, differences in chemical concentration or degree of aeration, as well as dissimilar metals were responsible for these currents. In considering mitigative measures the relative advantages of horizontal and vertical anodes are compared. A horizontal anode is believed to be advantageous for the following reasons: 1 the entire length of the anode is active; 2 it is possible to place large pipes serving as anodes in machine-dug trenches; 3 the anodes can be placed in comparatively shallow soil; 4 examination is easier; 5 such anodes do not interfere with farming or similar activities. These advantages are balanced by certain disadvantages, such as the following: 1 in cities it is not possible to bury them in parks or under streets or under most private property; and 2 horizontal anodes are not satisfactory in marshes due to the pumping and cribbing required. These disadvantages of the horizontal anodes are overcome by using vertical ones, where the ease of installation, in soils free from stones or in swamps, plus the ability to install them in restricted quarters, leads to their use. However, vertical anodes suffer from several faults. They are difficult to install in shallow ground, the moisture content varies along the anode throughout the year, they are difficult to examine, and it is necessary to purchase the land in cultivated areas since the electrodes usually extend above ground. A fluctuation of moisture

content along the pipe results in a nonuniform corrosion rate, which can be partially compensated for by tack welding a copper cable along the anode.

Resistivity is usually accepted as the criterion for locating ground beds. Good (63) stresses the importance of properly locating the anode systems to insure adequate protection. The accepted procedure consists of determining the resistance from anode to earth, pipe to earth, resistance of the wire and pipe to direct current and the soil resistivity. The author also discusses the relative efficiencies of various anode configurations and gives graphical methods for determining the most economical anode length.

Shepard and Graeser (199) conducted a detailed study on ground beds and anode configurations in which anodes of various materials, varying in dimensions and in geometrical shape, were installed vertically and horizontally in different ground beds. Equations were developed covering the resistance of a hemisphere to a remote ground and the resistance of horizontal or vertical pipes to ground.

Graphite anodes were tested for underground use, while various materials were examined to determine their ability to protect underwater structures. Platinum electrodes were found to be satisfactory in limited-size installations. The study (199) also determines the factors to be considered in protecting underwater structures. These factors consist of: 1 protective coating, 2 corrosiveness of the water, 3 current density, 4 injury to the paint coating, 5 resistivity of the water, 6 anode materials, and 7 anode configuration.

Several investigations were conducted to determine the characteristics of graphite anodes (30, 46, 51, 134, 139). Palmquist (139) lists the factors important for maximum economy, which indicate that graphite anodes are preferable. These factors are: 1 long life, 2 resistance to electrochemical attack, 3 low cost, 4 ability to handle relatively large currents, 5 a relatively constant

contact resistance with soil and water, 6 conditions which do not promote an accumulation of reaction products on the anode surface, and, 7 absence of self-passivation. In selecting the backfill a choice can be made among calcined and sized, petroleum coke, metallurgical coke, or a mixture of graphite particles and alkalizing materials. The author reports that the last is best. The backfill requirements are a function of the anode size, and, to some extent, of the anode placement, whether horizontal or vertical.

Dorcas (46) compares graphite anodes to steel, iron, or dissimilar metals, and discusses the size, methods of connection, and savings resulting from their use. Generally, such anodes are about 80 inches long and 2, 4, or 6 inches in diameter. A detailed description of the method of connecting the anodes to the conductor is given; No. 6 copper cable is suggested for the conductor.

The author (46), in discussing the possibility of lower costs, states that the initial graphite anode cost is generally the same as scrap iron, but the groundbed material is more expensive; this is compensated for in a lower carrying and installation cost and a much longer life.

Work by Emerson (51) on two graphite-anode groundbed installations in dry lake beds indicates that electrical resistivity cannot be accepted as the sole criterion in selecting the locations. These two installations were made in soils of similar resistivity; however, one soil consisted of a fine dense clay which prevented the escape of the gases generated. These gases caused the adjacent soil to dry out, resulting in a pronounced increase in the soil resistance, and the installation was a failure. The problem was solved by backfilling with coke breeze, which allowed the gases to escape.

Oliver and Palmquist (134) state that carbonaceous-type backfills are valuable because of the lowering of anode-to-soil resistance, the transfer of

the electrochemical attack from the anode to the backfill, prolonging the anode life, and the existence of a greater current-carrying capacity without materially reducing the anode life. The addition of lime to the backfill is also suggested, because such an addition decreases the rate of electrochemical attack, lowers the oxygen discharge potential, increases the moisture retention, and improves the uniformity of the carbonaceous backfill.

Committee TP-3 (30) of the National Association of Corrosion Engineers conducted experiments with various backfills and anodes to determine their properties. Backfills, other than soil, are recommended because of their lower resistance. Such backfills increase the anode life, allow greater current capacities per anode, reduce the effect of gas blocking, and tend to make the anodes function more uniformly. A comparison of the anode performances indicated that graphite has a longer life than carbon, but both carbon and graphite should have a longer service life than steel at comparable current densities. Theoretically, steel anodes have a voltage advantage, but the tests did not confirm this. Apparently the actual life of a steel anode is much less than the theoretical, due to the increased voltage requirements in excess of the theoretical. It was also found that the anode attack varies directly with the current density. The committee is checking the advantage of mixing lime with carbon or graphite in the backfills, as well as attempting to determine whether the lower resistance of gypsum and soil backfills as compared with a natural soil backfill, compensates for the apparent increase in anode attack. The results of these investigations will be published in a future report.

Ball (6) has discussed the various methods of locating and installing ground beds. The author suggests the use of a "megger" rather than the direct-current methods, the alternating-current ammeter-voltmeter system, or Shepard

rods. He suggests that the pipes used for anodes be perforated and risers installed, extending to the surface, so that salt can be washed into the pipes and allowed to seep into the soil.

Marx (107) describes the addition of calcium sulfate or calcium chloride to a backfill. The specific installation consisted of T-rails placed vertically with 100 pounds of salt added for each rail. It was found that the soil resistance without the salt was 3.75 ohms, permitting a current of eight amperes per rail. Addition of the salt reduced the resistance to 2.14 ohms and increased the current capacity to fourteen amperes.

Statham (217) describes a specific groundbed installation, which proved to be quite satisfactory. A series of ditches four feet deep was dug parallel to, and in excess of 250 feet from the line. Drill cables plus junk pipe were used as the anode, and cables were attached to link the anodes to the rectifiers. This installation proved to be relatively inexpensive.

Mudd (128) discusses the distribution of cathodic units with respect to the pipe line. The author lists the following: 1 trial groundbed installations should be prepared at distances of 300 to 400 feet from the line, using a single anode, and attaching portable generators to determine the point at which there is neither under- nor over-protection; 2 results will vary greatly, depending on the condition of the pipe and the soil resistivity; an uncoated pipe may require 40 ampere units every 750 feet while a single ampere unit can protect up to 45 miles of mastic-coated line; 3 half-cell measurements must indicate a definite current flow from soil to pipe along the section to be protected.

Stegner (219) has analyzed cathodic and galvanic protective systems and has discussed the advantages and disadvantages of both. Large current requirements are best supplied by rectifier units; galvanic protection is necessary where no power is available; however, this situation seldom arises.



Right-of-ways or easements are also a problem with cathodic installations because the initial pipe-line easement will not cover rectifier installations, which must be made several hundred feet from the pipe line. This is no problem with a galvanic unit since it is installed on the same right-of-way. Accessibility may be a problem, too. Rectifier units are usually located near crossings or roads which are readily accessible, and a long section of line is protected with one unit. Since galvanic anodes must be installed along the right-of-way at relatively short intervals, the transportation problem is much more serious. If there are foreign systems causing interference, cathodic protection may prove to be quite a problem, since bonds must be installed to prevent accelerated corrosion of either system. Due to the low voltage, cross-bonding, and interconnection used in galvanic systems, this is no problem. Galvanic units are excellent for use in cities where the availability of sites, as well as the size of rectifiers, constitutes a problem. With any system requiring an external source of power maintenance and checking difficulties exist. Any rectifier installation must be checked regularly to determine whether the performance is unchanged. With a galvanic system no voltage or current checks are required after installation, providing the system is well designed and no contacts with foreign installations occur, or if the lead wires remain undisturbed. Both systems have their particular applications, so no rule-of-thumb applies. It is necessary to study each layout to select the proper system.

Peabody and Woody (144) describe the protective measures taken on an installation covering 236 cities and towns, and including 5200 miles of pipe lines. Cathodic units were installed in 1941, and resulted in almost complete protection. Both rectifiers and galvanic anodes were used, and the authors discuss the installations, including the composition of the backfills. Various coatings were used, notably greases and enamels. The grease coatings cost

approximately one cent a foot less than the enamel coatings, but the cathodic installations or grease-protected lines were more expensive. Cathodic installation costs on a grease-coated line were \$3.72 per mile of 3-inch-equivalent pipe per year while an enamel-coated pipe could be protected for \$1.17 per mile of 3-inch-equivalent pipe per year. The authors suggest that the pipes be insulated at the meters and consider that it is best to install the cathodes when the pipe is laid. The report is very extensive, covering material, labor, installation, and engineering costs as well as the means of protecting the pipe and the characteristics of the protective units.

Logan (101) has compared the properties of the metals commonly used for galvanic anodes and believes that aluminum, magnesium, and zinc are all satisfactory. Aluminum was found to be good, but it should not be used in alkaline soils; magnesium was generally satisfactory, as was zinc; however, the latter did have certain limitations. The low potential of zinc limits its use to low resistance soils; the anodes are subjected to local or galvanic corrosion; they occasionally develop high-resistance corrosion products; and anodes containing some impurity are subject to a reversal of potential.

Mudd (128) also discusses some of the characteristics of galvanic anodes. One important factor is that it is possible to locate the anodes close to the pipe, since the potential is low. The author found that zinc was effective due to the low rate of soil action. This was further favored by the use of a gypsum backfill. Magnesium was also satisfactory, but the actual current developed was far below the theoretical due to the local soil action.

Mears and Brown (120) investigated the reactions of magnesium, aluminum, and zinc in various solutions of sodium chloride, sodium sulfate, sodium chromate, sodium hydroxide, ammonium hydroxide, calcium hydroxide, barium hydroxide, hydrochloric acid, and nitric acid. The authors also investigated the effect of alloying the anodes. It was found that the addition of zinc to

aluminum raised the potential in neutral solutions but had no effect in alkaline solutions. The aluminum alloys in general had very high potentials in alkaline soils, resulting in excessive dissolution of the anodes. Theoretically aluminum is the best material of the three, based on ampere-hours per pound. A comparison indicates that aluminum will deliver 1352, magnesium 997, and zinc 372 ampere-hours per pound. The actual current delivered under operating conditions is a great deal less than this, but aluminum appears to be the least expensive, based on the relative cost per ampere-year.

Reid and Horst (160) and Horst, Reid and Verink (73) discussed the general problem of corrosion control by magnesium, and aluminum anodes. They listed factors controlling the magnitude of the current and the anode efficiency. The magnitude of the current is controlled by: 1 the presence of stray currents, 2 availability of cheap electrical power, 3 geometrical configuration of the structure to be protected, and 4 the potential hazards to life and property in the event of failure of the structure. An increased efficiency can be obtained by using chemical backfills, which provide a low-resistivity local environment for the anode, minimizes the anodic polarization and the tendency to form high resistance films on the anode, influences favorably the anode potential, and reduces the local corrosion of the anode. The same protection criterion is used for these installations, -0.85 volt with respect to a copper sulfate half cell. The authors also discuss the various types and sizes of anodes. They suggest that these be buried to a depth of approximately six feet or deep enough to be in a permanently moist soil. It is suggested that the connecting wires to the anodes should be soldered, welded, or brazed to ensure a satisfactory contact.

Laboratory tests were conducted by Hoxeng, Verink, and Brown (74) with aluminum anodes to determine the suitability of aluminum for use, as well as the best type of backfill for these anodes. A wet type of backfill, made

alkaline by a lime or salt addition, plus some mercury salts, was found to give a very low anode-to-soil resistance and a much higher anode potential. These are also available in packaged form, which consists of the anode encased in a cement-like material acting as the groundbed. This insures a backfill which is uniform and of the proper composition, reduces the technical supervision of installation, avoids wastage of materials, permits anode installations in swamps or marshy ground, reduces the installation time, and permits the use of production equipment. The best of these anodes consists of aluminum containing one per cent zinc encased in a cement of magnesium oxychloride. On a relative cost basis, with aluminum expressed as unity, magnesium anodes sell at \$1.62 and zinc at \$1.81 in carload lots, which makes aluminum anodes desirable from the standpoint of cost.

Doremus et al. (48) also compare the various galvanic anodes and conclude that zinc has too low a potential for severe conditions; aluminum polarizes too rapidly, but this can be prevented by a special chemical backfill; however, the driving potential is still low. Magnesium is believed to be best due to its high driving potential, freedom from polarization, ability to attract and hold moisture, and decreased resistance in the vicinity of the anode. The current per mile is controlled by the size and the spacing and number of anodes, and these variables depend on the pipe size, type and condition of coating, condition of the pipe surface, soil resistivity, interference due to crosslines, etc.

Various investigators (70, 163) conducted extensive tests with magnesium anodes in an attempt to determine the most effective alloy and backfill. The stability and effectiveness of the anodes was found to depend on the amount of rainfall, temperature, and anode design. The best alloy consisted of six per cent aluminum, three per cent zinc, and the remainder magnesium. A semi-fluid groundbed was found to be most effective, and it was found to be best

to vary the backfill composition from high resistance soil to low resistance soil. Three parts of Aquagel plus one part of gypsum was found best in low-resistance soils, while a groundbed consisting of two parts of Aquagel, one part of gypsum, and one part of anhydrous sodium sulfate was best in high resistance soils.

Several authors (81, 133, 142, 152) have discussed the factors to be considered in determining the best type of magnesium-anode installation. The composition, backfill, and current density will determine the life and efficiency of the anodes. It is suggested that the anodes be installed approximately ten feet from a pipe line, using an auger to facilitate installation. The anode-to-anode distance may vary from 50 feet to several miles, depending on the current requirements.

Another type of anode has been developed, which is discussed by Peifer (152). This consists of a magnesium ribbon buried above the pipe line by plowing it into the earth or laying it in the same ditch. This is tied to the pipe every 1000 feet by brazing a steel wire to the pipe. Little is known as to the efficiency of such installations at present.

Parker (142) lists the factors to be considered for maximum operating efficiency. These consist of: 1 use the right amount of magnesium (if necessary tailor it to fit in the field); 2 distribute it properly: full protection without too much overprotection is best but not to a degree that increases installation costs excessively; 3 install it correctly with the current output regulated for a known and uniform life, and with proper facilities for necessary inspection and maintenance; 4 inspect the finished job. Verify the actual establishment of protective potentials; know the anticipated life of the anodes and keep up with the status of the project by frequent instrumental surveys.

Following these suggestions should eliminate a great deal of the guesswork which often occurs in such installations.

Specific cases have been discussed by several authors (69, 179, 204, 205, 241, 243). Hart and Osborn (69) cite the use of magnesium for the cathodic protection of the Katy pipe line. The authors note a current efficiency of 50 per cent with a bentonite-plus-gypsum backfill and an alloy of six per cent aluminum, three per cent zinc, remainder magnesium. Anode placement was based on an assumed life of ten years with a current demand of one milliamperere per square foot of bare pipe in high-resistance soils, and three milliamperes per square foot of bare pipe in low-resistance soils. The total cost of protection was \$11.67 per ampere-year.

Smith et al. (205) discuss the internal and external corrosion experience on Shell's product pipe lines, where magnesium anodes were installed to reduce the leak frequency. This frequency dropped from eleven per year to none in a short time. The authors suggest such installations at road crossings, where they have been found to be more satisfactory than casings. Another suggestion is to have separable leads or a junction box on the anodes to facilitate checking, which need be done at semiannual intervals only. The authors cite a 1950 cost estimate of \$1,500,000, for reconditioning and coating 320 miles of pipe. Galvanic protection would require 4000 anodes having a six-year life and costing \$10,000. The interest on \$1,500,000 at four per cent per year would be \$60,000 resulting in a net saving of \$50,000 per year, plus no interruption in line service. Obviously it would be to the advantage of any company contemplating reconditioning to carry out such an economic balance.

Smith (204) discussed a magnesium anode installation at the Dow Chemical Company, Midland, Michigan, where an initial investment of \$12,400 has resulted in a saving of \$6,500 per year. It is now customary to install

such protective units on all new lines and at all leak points. Due to this system the leak rate has dropped to one third of the previous value. These units are believed to have added three to four years to the life of the old lines. The new procedure, which is expected to increase the life of the lines appreciably, consists of using extra-heavy protection on all new lines and bonding all lines together.

An installation at the water works of Lake Jackson, Texas, is described by Wahlquist and Osborn (241). The magnesium anodes were installed to a depth of three to six feet, approximately ten feet from the pipe line. The backfill consisted of a 75 per cent bentonite, 25 per cent gypsum slurry; or a 50 per cent bentonite, 25 per cent gypsum, 25 per cent sodium sulfate slurry if the soil had a resistivity greater than 1000 ohms per cubic centimeter.

Whaley (243) describes similar installations in Iraq, where the galvanic anodes were particularly useful in isolated corrosive marshes remote from any power supply. The author suggests that strong clays with some base-exchange properties are excellent locations for the magnesium anodes.

Simpson (201) described the history of the gas distribution system in Houston, Texas. In the 1925-1930 period the pipe fittings were welded, sections of pipe had no protection, and there was no insulation against other metals. Since the soil was corrosive, pipe repair soon became expensive. The system was replaced, protecting the line with rectifiers in less congested areas and magnesium or zinc anodes for main protection and in the more congested areas. A pronounced reduction in the number of leaks occurred, indicating the effectiveness of the protection. It was concluded that zinc was effective in soils having a resistivity less than 2500 ohms per cubic centimeter and also on coated pipe. Magnesium was effective in high-resistance soils or on poorly coated pipe. The best conditions for these anodes demands a low-resistivity

soil which remains moist. An indication of the protectivity of the system can be noted by comparing the leak records before and after installations. Originally there was an average of one leak per year per 1.4 miles of 3-inch-equivalent pipe. This was reduced to one leak per year per 15.5 miles of 3-inch-equivalent pipe after cathodic protection was applied. The author notes that one of the biggest problems with such installations is not one of mechanical breakdown but one of personnel training.

The use of zinc anodes for preventing corrosion is described by various authors (20,126, 202) who cite the application of these anodes to specific installations. Brockschmidt (20) gives physical data for installations in highly corrosive river-bottom land where zinc anodes proved to be very satisfactory. High-purity zinc was necessary to prevent polarization, and some difficulty resulted from the ground water, which tended to foul the anode by forming a hard scale, reducing the efficiency.

Morgan (126) and Simpson (202) describe the protection of the Houston, Texas, gas system by these zinc anodes. The authors found that zinc was effective on poorly-coated as well as well-coated lines; they suggest that it is advisable to break up the line in convenient lengths with insulating couplings. A backfill of clay plus dehydrated gypsum was found to be most satisfactory.

The behavior of experimental installations of zinc anodes has been observed by several authors (2, 31, 44, 61, 239) in an attempt to find the operating characteristics, type of backfill, and most desirable alloy.

Anderson (2) investigated gypsum backfills, and concluded that such backfills were effective due to the formation of layers of basic zinc sulfate and zinc sulfate plus zinc carbonate, both of which allow the passage of water, insuring good conductivity. With patented backfills of bentonite plus gypsum, efficiencies as high as 90 per cent have been observed over a 5-year period.



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(31) conducted similar tests with zinc and magnesium anodes. The report covers the use of various alloys in backfills consisting of gypsum, bentonite, natural clay, etc.

Denison and Romanoff (44) investigated the performance of experimental zinc-iron couples underground. The authors concluded that more anode area was required in some soils than in others. It was found that high resistivity and high alkalinity tended to inhibit the corrosion of the zinc anodes. This could be compensated for to some extent by connecting more anodes in the circuit. The authors state that the minimum protective current, as obtained from current-potential curves for the cathodes, is of the same order of magnitude as the average current of the galvanic couple, calculated from direct measurements of current, from the loss in weight of the zinc anodes and from the loss in weight of the unconnected iron rings. Therefore, it is concluded that no more current is required for protection in the environments studied than is equivalent to the loss in weight produced by normal corrosion.

Gilbert and Corfield (61) studied the behavior of zinc-iron couples in carbonate soils and concluded that the carbonate coating formed on the anode reduced the current output to such an extent that no great advantage is gained by providing a large anode area. A pronounced variation in the potential was found from season to season. Voltages were highest in the dry season, dropping as the soil moisture content increased.

Wahlquist (239) analyzed the use of zinc for cathodic protection and concluded that it was advantageous due to low cost, constant current, and minimum electrical interference. The author noted that impurities in the anodes are an important factor in their efficiency. Tests on backfills indicated that one consisting of clay and powdered gypsum was most satisfactory, while mixtures of clay and lime or clay and ammonium chloride were definitely unsatisfactory.

Another factor which must be considered is the location and selection of the anode systems installed for cathodic protection. Good (63) discusses the importance of proper location of the anode systems and gives the relative efficiency of various anode configurations. It is necessary to determine the soil resistivity and the pipe-line resistance to earth for this purpose. These methods will apply to cathodic as well as galvanic installations.

Mudd (127) discusses the factors to be considered in the locating and spacing of galvanic anodes. The proper location is determined on the basis of soil resistance and porosity, the best being a dense impervious clay. The author suggested the use of a "megger" or radio balance for this purpose. The anode should be located close to the surface and far enough from the cathode to ensure a uniform current distribution to prevent diffusion of chemicals toward the cathode. Anode spacing should be such as to allow sufficient soil area for current flow. The author tabulates results showing the effect of anode spacing; it is suggested that anodes be spaced from 30 to 50 anode diameters apart.

After analyzing the information available relevant to the installation of cathodic protection units, it is obvious that at the present the installation of these units is based on the judgment of the individual rather than on sound engineering principles. It is not possible to use laboratory tests as a control because the factors controlled in the laboratory are uncontrollable in the field. It is concluded that a great deal more work must be done before such installations can be constructed on the basis of sound engineering principles.

## VII. ELECTROLYSIS AND ITS MITIGATION

Stray currents from such sources as electric street railways or power houses are an important, though localized, source of pipe-line corrosion.

Historically, the effect of stray-current electrolysis has been known since the latter half of the nineteenth century. Initial investigations and methods of alleviating such corrosion were made in Europe. Investigations in the United States began in 1911, when the National Bureau of Standards instituted a series of studies into the cause and prevention of corrosion due to stray currents.

Fundamentally, electrolysis is due to an impressed current foreign to or remote from the location of corrosion and traveling along conductors which may or may not be the pipe line. Finally, it does travel along the pipe line and results in corrosion at the point where the currents leave the pipe. While the problem can be stated quite simply, the solution is much more difficult. Experienced electrolysis engineers are needed to install an adequate protective system and to supervise the system after it is installed. An experienced engineer is essential because a method which is perfectly satisfactory in many cases may prove to be unsatisfactory in others.

Most stray-current electrolysis is due to direct current. Thayer (224) states that less than one per cent of the damage caused by stray currents is due to alternating current. However, he does state that some corrosion may be due to alternating current but is not recognized as such. An example is cited in which the rust on a pipe adjacent to an unruined section acts as a rectifier, allowing a pulsating current to pass, which results in corrosion. Bond (18) also believed that a rectifier pulsation might cause corrosion, and

Beck (8) stated that alternating current was more dangerous than direct current because of the three possible ways in which currents may flow, namely, by contact, induction, or influence. Experiments conducted by Kalman, et al. (82) do not confirm this; the authors' results indicated that alternating current superposed on direct current had an insignificant effect at small potential differences. Extensive studies conducted by McCollum and Ahlborn (110) indicate that corrosion of iron and lead decrease as the frequency increases. With iron, a limiting frequency occurred between 15 and 60 cycles per second, beyond which value no corrosion was noted. The authors also found that sodium carbonate in the soil reduced the corrosion loss of iron subjected to an alternating current, but increased the loss of lead, possibly due to effects other than alternating current. Maximum corrosion of iron occurred when the period of alternation was in excess of two weeks. Apparently, the concensus is that alternating current is not an important factor in pipe-line corrosion in the majority of cases.

The initial step to be taken in correcting stray-current electrolysis is the institution of a complete survey using the proper instruments. Cunningham (35) suggests that such a survey should locate all subsurface structures as well as the street-railway tracks, substations, and negative feeders. In conjunction with these data, McCollum and Logan (112, 115) suggest that soil-resistivity measurements be made. They also suggest that the intensity of discharge of the current from pipe to soil be measured. In making any such measurements, it must be realized that a number of variables influence the results. McCollum and Logan (111, 112) cite a number of these variables. For example, an increase in the soil pressure increases the conductance slightly if the original pressure is low. A more important factor is the effect of the moisture content. As this content increases, provided the soil is not saturated, the conductance also increases, and the soil resistivity may vary by a factor of several hundred.

As a result, no such surveys should be made when the soil is excessively dry. The amount and kind of soluble material in the soil will also affect the resistivity. Surveys should never be conducted in very cold weather. The resistivity may be two hundred times as great at  $-18^{\circ}\text{C}$  ( $0^{\circ}\text{F}$ ) as it is at  $+18^{\circ}\text{C}$  ( $64^{\circ}\text{F}$ ). A further factor is the effect of current flow through the soil. Any such flow produces a temporary increase in the soil resistivity.

Numerous methods have been suggested for measuring the current or the soil resistivity. Of these, the earth-current meter developed at the Bureau of Standards by McCollum (115) is excellent. Kuhn (87) suggests the potential-tangent method be used after the data have been collected.

After completing the survey, it is possible to select some system which will satisfactorily protect the pipe line from corrosion. However, before considering protective systems, it is best to review the influence of various factors on corrosion. Work in Switzerland (28) and at the Bureau of Standards (111) has proven that the current density at the anode determines the corrosion efficiency, rather than the total amount of current; the lower the current density, the higher the efficiency. A higher corrosion efficiency implies a higher rate of corrosion. Moisture content also affects corrosion efficiency markedly, an increase in moisture causing an increase in corrosion efficiency. McCollum and Logan (111) state that changes in temperature, depth of burial, amount of oxygen present, voltage, and type of iron have no appreciable effect on corrosion efficiency. However, the amount of oxygen present does have a marked effect on the corrosion end products.

Mitigation practices depend on the conditions existing in each case; therefore, no general procedure will hold true. A few general practices are suggested and should prove to be of assistance in any case. Carle (24) suggested that the rails be welded in an electric street-railway system.

Generally it is good practice to bond the rails when there is a ground return rather than a two-wire system. A proper negative return is the most feasible method and may prove to be the most expensive, too. Carlson (25) cites a drainage system of 4/0 wire used to protect two cables, 22,000 feet from a power house, which were exposed for 1500 feet. Such a drainage system to the negative bus would cost more than ten thousand dollars. Some saving could be made by using No. 0 wire, as suggested by Marx (106), but the expense would still be prohibitive. Carlson (25) suggested a forced drainage system costing five hundred dollars initially, plus a power and maintenance cost of eight dollars a month. The type of cathodic installation will depend on power costs, pipe network, availability of ground, soil characteristics, and current density. In some instances, galvanic protection with zinc, magnesium, or aluminum anodes is best; in other cases, a rectifier system is preferable.

Insulating couplings may also prove of value, particularly where a maze of interlocking gas and water lines occurs. Several authors (15, 16, 65, 109, 113, 176, 178) suggest the use of these couplings. Beck (11) has investigated several types and concludes that the best condition is one using a medium-length coupling on a coated pipe. The resistance in these couplings ranges from 1000 to 10,000 ohms, and this resistance may decrease with time in certain couplings.

Bureau of Standard surveys (109, 113, 176) indicated that the best system combined an insulated line with a negative feeder. This proved to be more economical than the uninsulated system, providing the voltage connections were good. Besig (15) states that in some cases, at least, a negative return may do more harm than good.

Protective coatings have been applied to prevent corrosion due to stray currents, but many investigators believe that they are of no value.

McCullum and Peters (116) concluded that paints, dips, or wrappings were generally of no value in positive areas near the power house, and only of temporary value in negative areas. This is confirmed by Ewing (53) who states that bituminous coatings in positive electrolytic areas are likely to concentrate the electrical discharge at the imperfections in the coating, causing rapid failure of the pipe. Besig (15,16) believed that coatings combined with insulated joints and, if necessary, an external metallic shield was the best protective measure. In any event, where coatings are used, a regular maintenance and checking program must be followed.

Coatings have proven satisfactory in the case of steel imbedded in cement. Either the steel or the cement can be coated with a layer of asphalt, which apparently halts the deterioration of the cement caused by corrosion of the metal. The deterioration is marked by extensive spalling, due to the greater volume of the corrosion products. Neither sulfate cements nor cements including asphalt proved satisfactory in preventing such deterioration (29, 105).

Guillot (65) has suggested a method which might have some value. In this case, the metal is coated with a conducting envelope which is not liable to corrosion; this acts as an electronic filter. Graphitized rubber is suggested by the author.

The best protective measure appears to be a negative return, either natural or forced. From an economic standpoint, the forced drainage system is least expensive. The selection can be a galvanic system consisting of dissimilar metal anodes or a cathodic unit using some external source of power. A determination of the protection requirements should be based on the average voltage measured and not on the peak voltage.

Any such problem is the joint responsibility of the owners of the power source and the underground utilities. If it is handled as such a problem, the overall cost will be a minor item. An attempt to place the responsibility solely on one party leads to unnecessary expense and difficulty in installing protective systems (177).



## VIII. THE ECONOMICS OF CORROSION CONTROL

The estimated cost of some 500,000 miles of underground lines conveying natural gas, water, and petroleum products is 6.0 billion dollars (101). Uhlig (232) estimates that the direct costs of corrosion and prevention of corrosion of these pipe lines is in excess of 600 million dollars per year out of a total annual loss of 5.5 billions per year for all forms of corrosion and prevention. Since these figures do not include such indirect losses as escaping gas or oil, soil or water contamination by petroleum, or the burning of buildings due to escaping gas, it is obvious that the annual corrosion costs on underground pipe lines alone are staggering. A factor of increasing importance is the physical loss of metals which are becoming increasingly difficult to replace. At the present rate of depletion of these metals, it may not be a question of cost as much as it is a question of availability.

It is possible to quote savings arising from various corrosion mitigatives, but such data are meaningless under other conditions. Thayer (222) clearly indicates this in citing the conditions affecting costs, such as soil variation or coating conditions. For example, under one set of conditions twelve miles of eighteen-inch pipe was protected by one cathodic protective unit. A similar unit under different conditions protected less than one mile of twelve-inch pipe.

Some average costs have been determined which give an indication of the anticipated expenditures in the long run. Wright (251) cites costs amounting to one per cent of the initial investment on a line 28.1 miles in length. These costs covered the installation and maintenance of a cathodic unit. A more general cost survey was conducted by Speller and Chappell (212). The

authors found that the average annual unit corrosion cost amounted to three hundred and eight dollars per year per mile of pipe line. These data were based on replies to a series of questions asked of fourteen oil companies. Their annual loss was in excess of ten and one-half million dollars, and the survey definitely indicates that corrosion is the most serious problem in the petroleum industry.

Stirling (220) describes another method of denoting corrosion costs. The author cites a leak cost of one hundred and sixty dollars per leak. He stresses the indirect losses resulting from corrosion. In one line more than 90 per cent of the gas over a forty-mile length was lost due to leaks. Not only is such a loss a very serious problem, but the method used by many companies to mitigate the effects of corrosion is expensive and results in a decrease in the line capacity: this consists of using pipe of greater than average wall thickness to compensate for the loss caused by corrosion. Such a practice results in as much as a six per cent loss in carrying capacity to say nothing of the additional cost per length of pipe. These results are confirmed by Uhlig (232), who cites a saving of three hundred and thirty thousand dollars on an eight-inch pipe line installed in 1945. By reducing the wall thickness from 0.322 inch to 0.250 inch, thirty seven hundred tons less steel was required on the two hundred and twenty-five mile line. Only a fraction of this saving would be required to protect the line cathodically, so that the decrease in wall thickness would not have a deleterious effect.

In determining the most economical means of protecting an underground pipe line a large number of factors must be considered. Several authors (58, 59, 137, 138, 232) discuss these in some detail. After the survey has been conducted the following factors are of importance, based on an installed line: 1 cost of leak repairs, 2 cost of reconditioning and replacements, 3 loss of

fluid due to leakage, 4 damages, 5 loss of goodwill, 6 loss of revenue, 7 fixed charges on capital expenditure, 8 cathodic protection, and operation and maintenance costs.

Gear (59) has proposed a method which eliminates from consideration repair costs other than those directly affecting the pipe life. For uniformity all such repairs are expressed per million feet of three-inch-equivalent pipe.

The authors (58, 59, 137, 138, 232) agree that control should be instituted before leakage occurs whenever this is possible. Olson (138) concisely surveys the paramount reasons for corrosion control and concludes that the most satisfactory means of protection consists of cathodic units. Here again a number of factors must be considered if the most economical installation is to be selected. In some cases, such as on bare or poorly coated pipe, or at river crossings, in swampy areas, or other inaccessible locations where leak repair costs are prohibitive, there is no question that protective measures must be taken. However, in other locations any selection must be based on a number of factors. It is a question whether it is less expensive to: 1 repair leaks and make replacements only when necessary; 2 recondition and coat the pipe over a period of time; 3 recondition, coat, and cathodically protect the pipe; or 4 cathodically protect the pipe with no reconditioning or coating. Obviously, these questions can be answered only after an extensive survey and cost analysis has been conducted, but a great deal of money can be saved by conducting such a survey rather than assuming that any one system is best.

Gear (58) conducted an economic analysis on a pipe line which bore out the conclusions noted above. The author cited three possibilities in protecting a pipe line from corrosion. Clamp saddles and replacement joints could be installed at a cost of four thousand dollars per year; the pipe could be reconditioned, replacing sections when necessary at an initial cost of

twenty-five thousand dollars plus an annual expenditure of twenty-five hundred and seventy-five dollars; the third possibility consisted of cathodically protecting the line at an initial cost of seven thousand dollars plus sixteen hundred dollars per year for maintenance. Obviously, cathodic protection results in an appreciable saving.

Olson (138) cites costs of such cathodic protection together with the factors which must be considered in making such an installation. These factors consist of determining the amount of current required for adequate protection, the equipment necessary, the location of this equipment for maximum effectiveness, and the design giving the most economical results. The last factor will be based on the current requirements, the maintenance problem, and the uniformity of operation required. In general, the selection is made from a rectifier unit, galvanic anodes, a wind generator, or a motor generator. The last two are usually undesirable due to the maintenance problem and the nonuniformity of operation. Generally, a large installation of bare pipe requiring a high current for protection is most economically protected by a rectifier unit. For coated pipes requiring low currents the galvanic anodes are often best. For example, in highly corrosive soil requiring fifty amperes per mile a galvanic installation will cost fifteen dollars and sixty cents per ampere per year, or seventy-eight hundred dollars per mile; a rectifier will cost seven dollars and seventy cents per ampere per year or only thirty-eight hundred dollars per mile. With a coated line requiring one ampere per mile for protection the annual cost per mile of galvanic protection is eighty-seven dollars. A rectifier unit will cost one hundred and ten dollars per mile per year.

It is obvious that a number of factors must be considered in determining the least expensive means of mitigating corrosion losses. After a survey has been conducted, there remains the problem of choosing the most applicable of any group of protective measures.

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