

A Report On
Some Factors Affecting The Life of Steel
Pilings In The Texas Gulf Coast Area



By
Bob M. Gallaway
Assistant Research Engineer
Texas Transportation Institute



This Report Covers A
Co-operative Research Project Between
The Texas Highway Department
And
The Texas A. and M. College System

TEXAS TRANSPORTATION INSTITUTE

College Station, Texas

A Report

on

Some Factors Affecting the Life of Steel
Pilings in the Texas Gulf Coast Area

A Study conducted for the

TEXAS HIGHWAY DEPARTMENT

Austin, Texas

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Bob M. Gallaway
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CORROSION REPORT

Summary

This report covers a corrosion survey study as applied to underground members of highway structures of the Gulf Coastal Area of Texas, an area fifty to seventy-five miles wide extending from the Rio Grande River to the Louisiana state line.

In seeking an answer to the question of whether or not serious corrosion of plain carbon steel pilings may be expected during the service life of fifty years or more reference is made to data of the State Board of Water Engineers, the Texas Agricultural Experiment Station, the United States Geodetic Survey, the United States Department of Agriculture, Corrosion Engineers of the Gulf Coast Industries and the technical literature.

It is suggested that corrosion data be taken under the supervision of a competent Corrosion Engineer and that these data be analyzed by a Corrosion Engineer in the light of overall economy and practical application to the individual problem concerned. Among the factors to be considered are:

- a. Rainfall,
- b. Extent of organic soils, mucks and peaty materials,
- c. Concentration of soluble salts,
- d. Soil resistivity,
- e. Hydrogen ion concentration,
- f. Chemical analyses of the soil moisture,
- and g. Observation of local structures of several years of similar service.

Suggested remedial measures where severe corrosion is anticipated include:

- a. Added thickness of steel in zone of major attack,
- b. Caustic injection,
- c. Addition of extra tensile steel within the concrete in the area of severe attack,
- d. Cathodic protection,
- and e. Protective coatings.

Since field data is limited, it is suggested that accurate records be kept on corrosion surveys and that these data be made readily available to engineers in the highway field.

The theory of corrosion of steel in water and soil is given as it may apply to highway structures.

Highway District maps are included and located on these maps are water wells and test holes. A tabulation of water well data for each county under study is keyed to these maps and contains facts on soil profile and water quality. In general these wells or test holes are those located near stream crossings of existing highways.

An annotated bibliography composed of one hundred sixty-six articles from books and the technical literature make up the final section of the report. These summaries are grouped into the following seven groups:

- a. Soil Corrosion
- b. Oxidation
- c. Biochemical Corrosion
- d. Stress Corrosion

- e. Electrochemical Corrosion
- f. Hydrogen-ion Concentration
- g. Protective Coatings

Introduction and Background

The investigation reported on herein is concerned with a study of the expected life of steel pilings used under highway structures in the Texas Gulf Coast Area. Two types of pilings involving steel are in use, the H-piling and the thin wall cylinder. The thin wall cylinder is preferred for certain installations. In practice the thin wall cylinder is driven and filled with concrete and the shell acts as a part of the reinforcing steel. The wisdom of this practice has been questioned. It is believed by some that the life of plain carbon steel driven into the earth along the Coastal Fringe of Texas may be less than the desired life expectancy of fifty years and it is further thought that this life will be less than fifty years because corrosion will take place at and below the permanent water table. It is also thought that the nature and extent of the expected corrosion should be studied in order that certain precautions may be taken where excessive corrosion is anticipated.

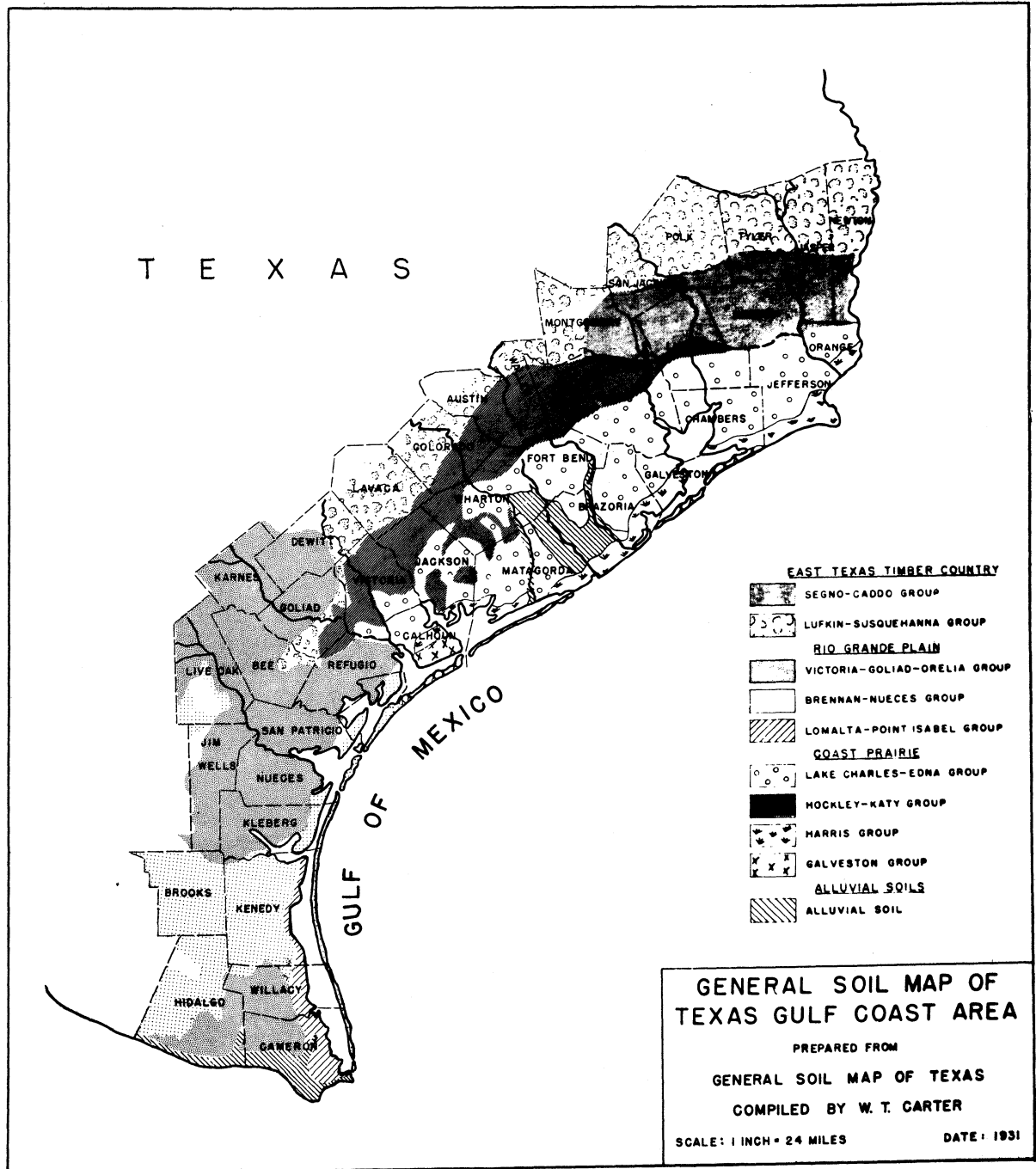
The general nature and purpose of the problem under study may be summarized as follows:

- (a) Is there danger of serious corrosion of plain carbon steel pilings below the permanent water table of the soils and mucks of the Gulf Coast Area?
- (b) What chemical and physical characteristics of the soil and soil waters, contributory to serious corrosion, exist in this area?
- (c) If serious corrosion may be expected in the Gulf Coast Area, what is the inland extent of the critical area?

The general area included in the study stretches along the Texas Gulf Coast from the Rio Grande River to the Louisiana State Line and includes soils principally of the Coast Prairies and the Rio Grande Plains. Along the larger streams are the alluvial soils. The inland extent of the coastal area studied

is shown on the map of Figure 1 taken from a study made in 1931 by W. T. Carter of the Texas Agricultural Experiment Station. In general the soils of the Texas Gulf Coast present erratic profiles within the depth involved in foundations for major highway structures.

In seeking answers to the problems previously summarized, three sources of information were utilized. A general picture of the soil stratigraphy and the chemical characteristics of the soil waters of the Gulf Coast Area was obtained from data published by the State Board of Water Engineers, the Texas Agricultural Experiment Station, the United States Geodetic Survey and the United States Department of Agriculture. A second source of information was from members of the chemical industries in the Gulf Coast Area who deal daily with the corrosion problem. The third source of data was the technical literature. The last mentioned source abounds in material on the subject of corrosion and contains an untold number of reports of experiments, surveys, bibliographies, theories and opinions.



SECTION I

CONCLUSIONS REACHED

While complete answers to the three questions posed in the Introduction can not be set down, the survey made has shown certain conclusions to be warranted.

1. Unprotected plain carbon steel pilings that are used in coastal areas and which will be subject to total and continuous immersion in sea water will have an average minimum corrosion rate of 0.005 inches per year. Corrosion rates may be much higher at the water table in areas where the water at the water table is high in soluble salts. For plain carbon steel used directly in the Gulf Waters corrosion rates of 0.02 inches per year would not be uncommon in the area of the splash zone and a rate of 0.01 inches per year at the mud line may be expected. Corrosion of unprotected plain carbon steel in such service is a very definite problem.

2. Excluding mucks and peaty materials, very little corrosion should occur for steel piling driven in ordinary soil to a point below the water table except in the zone of disturbance. The zone of disturbance will not ordinarily extend more than two or three feet below the soil-water interface.

3. Soils with resistivity measurements below 1000 ohm - centimeters are corrosive and the lower the resistivity value the higher in general will be the corrosion rate.

4. Corrosion of steel pilings under anaerobic conditions may well be promoted into a definite problem by anaerobic bacteria which act as hydrogen acceptors. The presence of sulfates and organic materials signals the probability of the existence of these bacteria.

5. High concentrations of soluble salts, particularly chlorides, are

conducive to increased corrosion rates. If inspection of existing unprotected steel of even a few years service, reveals thick loose layers of corrosion product, this will indicate continuous high corrosion rates. A thin hard adherent layer of corrosion product will, on the other hand, indicate a relatively low rate and a condition for no alarm.

6. A new underground structural steel member placed near an existing old steel structure will experience a higher rate of corrosion than if the same new structure were placed under similar conditions in a virgin location. The old member will tend to act as the cathode in the corrosion circuit although it may have acted as the anode previously.

7. Careful records should be kept regarding any corrosion surveys made.

RECOMMENDATIONS FOR THE CORROSION SURVEY

A corrosion survey should always be made where corrosion is expected and also when there is any doubt as to the existence of a corrosion problem. Prevention is quite often much more economical than repairs. To determine whether or not serious corrosion of a piling may occur the following data should be taken and carefully analyzed by a competent Corrosion Engineer in the light of overall economy and practical application to the individual problem concerned.

1. During the regular routine of foundation exploration in areas of high annual rainfall and heavy vegetative growth and in areas with a high water table and soils rich in soluble salts continuous cores should be taken to such depth as is necessary to determine the extent of organic soils, mucks or peaty materials and the concentration of soluble salts.

2. Soil resistivity measurements should be made at regular intervals in those test holes so located as to get a picture of the variation involved with due consideration for economy of taking such readings. Resistivities of 1000 ohms per centimeter or less are considered dangerous under most conditions.

3. The hydrogen ion concentration or pH should be measured. For pH readings of about 4.5 or less corrosion by hydrogen evolution may be serious. For pH readings above about 9.5 very little corrosion in soil is likely.

4. Component chemical analysis of the soil moisture should be made. Below the water table corrosion rates in the range of 0.005 inches per year may occur in waters of high chloride contents. Soils high in humic acid are also conducive to high rates of corrosion.

In the event the survey indicates that serious corrosion is likely, one of several different steps may be taken to cope with the problem.

(a). A corrosion allowance may be made in the thickness of the metal involved

(b). The soil of the immediate foundation area may be treated with caustic to increase the pH to such a point as to critically limit the corrosion rate.

(c). Tensile steel may be added in the concrete for the length of the piling where severe loss of metal may take place.

(d). Cathodic protection may be used.

(e). Certain soil conditions may allow the use of protective coatings.

Excluding mucks and peaty materials and considering driven steel such as pilings below the permanent water table in ordinary soil, very little corrosion may be expected below the zone of major disturbance. If such members are protected in some effective manner in the zone of disturbance then little danger of failure by corrosion may be expected. Under ordinary circumstances this zone of disturbance would not extend more than two or three feet below the soil-water interface.

Careful records should be kept regarding any corrosion surveys. Soil characteristics and corrosion rate records will be found useful in the future. It is reasonable to believe that there exists a direct correlation between soil type as shown in Figure I and corrosion of underground steel. The soils shown in Figure I are surface soils. The "A" horizon and sometimes a part or all of the "B" horizon are indicated but in no case are the indicated soil types delineated below a depth of six feet. Soil profiles to greater depths are shown on the county water well charts in Section IV of this report.

Other Considerations

1. Each project's corrosion considerations should be treated as a distinct and separate study in designing a pile-supported structure. An investigation of adjacent local condition is also suggested.

2. There is nothing universal about the pattern or rate of corrosion to be expected; it is subject to many variables.

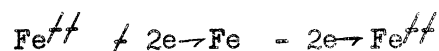
3. Provisions or measures to mitigate or eliminate corrosion should have economic justification consistent with the planned life expectancy of the structure.

4. Corrosion rates are not uniform throughout the entire length of any given piling. A definite allowance as to metal thickness should be made where protection from metal loss is to be effected with a corrosion allowance in the structure. For example, the amount of metal that may be destroyed on a given structure for a given life expectancy may be one sixteenth ($1/16$) of an inch. Under these conditions the selected structural member would be thicker by this amount.

SECTION II

NATURE AND MECHANISM OF CORROSION OFLOW CARBON STEEL

If the corrosion of metals and alloys may be defined as a process of reversion to a more stable state, then it can be said that all such corrosion involves the same typical reaction mechanisms that are basically electrochemical in nature or may be explained by the electrochemical theory. Iron ore in its natural state may be considered stable under the conditions to which it is usually subjected. On the other hand pure iron or alloys of iron which have experienced a change of state from an oxide of iron to a metal or an alloy are subject to the ravages of corrosion, for such materials are in an unstable state under the normal conditions of use. Expressed as follows in the form of the simplest chemical equation is the cycle change involved in the corrosion of iron:

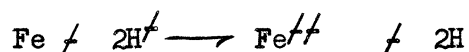


Starting at the left side of this equation Fe^{++} is usually attached to oxygen and as an oxide is stable. In the smelting process of the iron ore this oxide is reduced* to the form the useful state of iron to which man is accustomed and which appears as the second term of the equation. Corrosion or oxidation causes the metallic iron to revert to its more stable state and thus the third member of the equation comes into being. Actually this completes a cycle as is apparent from the preceding discussion and equation.

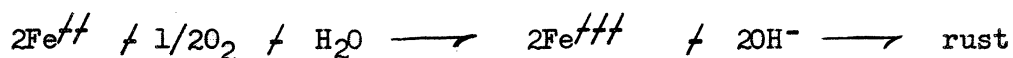
There are many variables which affect the rate of this reversion to a more stable state. Looking further into the primary chemical reactions that

*By definition reduction is the gain of electrons. In passing from an oxide to the metallic state, Fe^{++} gains two electrons, negative charges, and thus becomes metallic iron.

take place in the presence of moisture one may write the following equation:



In order that this reaction may proceed the two atoms of hydrogen are removed either by forming water, gaseous hydrogen or by entering a biochemical reaction involving hydrogen. If the hydrogen film is not removed, then for all practical purposes, corrosion ceases. In practice oxygen and water are quite often present in some form and the primary reaction may proceed as follows:



Actual corrosion seldom appears to be so simple and in reality is not because many complex problems exist in the actual corrosion processes. It is the effect of the numerous variables which complicates the problem.

According to Speller¹ the following facts regarding the corrosion of iron have been definitely established:

1. "At normal temperatures iron will not corrode appreciably in the absence of moisture.
2. The presence of oxygen is usually essential for serious corrosion to take place in ordinary water at room temperature. Dissolved oxygen alone will greatly accelerate corrosion in acid, neutral, or slightly alkaline water. In natural waters, the rate of corrosion is almost directly proportional to oxygen concentration if other factors do not change.
3. Corrosion in acid solutions tends to be much more rapid than in neutral solutions, and the latter is more rapid than in alkaline solutions.
4. Hydrogen gas is usually evolved from the surface of the metal during corrosion in acid solutions and in concentrated solutions of alkalies; in nearly neutral solutions the evolution is usually very much less and may not be appreciable.

¹ Speller, F. N., Corrosion Causes and Prevention 3d Edition

5. The products of corrosion consist, mainly, of black or green ferrous hydroxide next to the metal, and reddish-brown ferric hydroxide (rust) which forms the outer layer, with graded mixtures of the two in between. When iron corrodes in the atmosphere, the amount of ferrous rust produced is small, but when formed underwater the corrosion products often contain a large proportion of ferrous iron.
6. In natural water, the precipitated rust usually carries down some compounds containing lime, magnesia, and silica, together with other insoluble material from the water. These substances have considerable influence on the structure and density of the rust coating on the metal surface.¹ A loose, nonadherent coating under ordinary conditions may accelerate locally the rate of corrosion; a uniformly dense and adherent coating may form an effective barrier and reduce the rate very considerably.
7. Surface films, sometimes invisible, often play an important part in controlling the rate and distribution of corrosion. These films have been made visible by separation from some metals and have been shown to raise the potential of these metals and make them more resistant in certain environments. In fact, the superior resistance of metals like high chromium steel and aluminum, for example, is undoubtedly due largely to the formation of such films.
8. In most cases the initial rate of corrosion is much greater than the rate after a short period of time. This is particularly noticeable in film-forming solutions, such as the alkalies or chromates.

¹ The term "coating" is used here to designate a more or less continuous layer of solid matter on the surface of a metal. The term "film" is used to indicate a very thin liquid or solid coating, usually a reaction product under 2,000 Å in thickness.

9. Corrosion at normal temperature often increases with increase of concentration in dilute solutions of many neutral salts, particularly chlorides, but decreases again in more concentrated solutions, other things being equal.

10. In natural waters the rate of corrosion generally tends to increase with increase in velocity of motion of the water over the metal surface, with some exceptions where the film-forming tendency predominates.

11. Dissimilarity in the chemical composition of metals in contact with each other in an electrically conducting solution sets up a difference in potential (precisely as in the galvanic cell) and thus accelerates corrosion locally. In corroding metals these variations in potential are found between a metal and other reactive materials, or between different metals in contact. This action is accompanied by an electric current which flows through the solution from anode to cathode,¹ i.e., from the more corrodible to the less corrodible metal in this particular solution.

¹ In any cell in which electrolysis may go on, the cathode is the pole at which hydrogen or metal ions are plated out; the anode is the pole at which the metal ions enter the solution. For instance, the statement that iron is anodic to copper means that when pieces of iron and copper, in external electrical contact, are immersed in a conducting solution, the iron will act as anode and tend to go into solution as positively charged particles (iron ions), and the copper will act as cathode and attract to itself negative ions from the solution. The terms are always relative; for instance, an area may be anodic with respect to a second area but cathodic with respect to a third. The terms "anodic" and "cathodic" are used throughout this writing in place of electropositive and electronegative because these are not always used in the same sense. In corrosion of ferrous metals in contact with a solution, iron is usually dissolving at anodic areas and hydrogen ions are discharging simultaneously at cathodic areas.

12. Variation in the composition or concentration of a solution in contact with a metal may also cause a current to flow through the solution from anodic to cathodic areas. For instance, parts which are shielded from oxygen are anodic to aerated areas. The current flowing with corrosion has been measured and found proportional to the corrosion. This fact has led to a satisfactory explanation of pitting.

13. Composition of ordinary iron or steel, within the common variations found commercially, has little effect on corrosion underwater or underground, but it often has a marked effect on atmospheric and acid corrosion. From the standpoint of corrosion, the homogeneity of iron is not so important as external conditions. This, however, is a very important factor in the case of some other metals such as magnesium.

14. The condition of the metal surface in submerged corrosion may not effect the total corrosion, although it may have a marked tendency to localize the action. Corrosion of iron is rarely uniform over its entire surface. The distribution of attack usually determines the useful life of metal structures in corrosive environments.

15. The smaller the anodic areas in relation to the associated cathodic areas, the greater is the rate of penetration of corrosion at the anodic points. The polarity of a certain area sometimes reverses during the progress of natural corrosion.

16. Biological organisms, particularly anaerobic bacteria, often exert a marked accelerating influence on the electrochemical processes of corrosion.

Considerable experimental work has been done, and, for that matter, is still going on in an effort to evaluate the effect of these variables. Many

volumes have been written on corrosion with the motivating force directed in general toward a solution of the basic problem of reducing the rate at which corrosion occurs. This rate is a function of the variables involved in the corrosion of steel underground, and it is not, in general, an impossible task to separate these variables sufficiently to effect at least a partial solution of the problem. Such a solution is possible in most soil corrosion problems because there is nearly always a variable which alone is responsible for the existing rate of metal loss. That is not to say that in most such corrosion problems there is only one variable, far from that. Specifically, in any reaction be it chemical, electrochemical or biochemical that involves more than one step such as in the corrosion of steel, the overall rate of reaction is determined by some single reaction within the chain of reactions that make up the corrosion process. Quite often this "weak link" in the chain offers a point of entry which may lead to a solution.

An evaluation of the effect of these variables in the corrosion process should be made when dealing with a corrosion problem. In bridge piling work the type of metal is generally fixed; ASTM A-7 is usually specified. The effect of the lack of chemical and/or physical surface homogeneity will be discussed later. The environmental factors, however, are more numerous and much more complex. A list of the factors which vary with environment are, according to Speller, as follows:

- (a). "Hydrogen-ion concentration (pH) in the solution.
- (b). Influence of oxygen in solution adjacent to the metal.
- (c). Specific nature, concentration, and distribution of other ions in solution.

- (d). Rate of flow of the solution in contact with the metal.
- (e). Ability of environment to form a protective deposit on the metal.
- (f). Temperature.
- (g). Static or cycle stresses.
- (h). Contact between dissimilar metals or other materials as affecting localized corrosion."

Anaerobic sulfate-reducing bacteria should also be considered among the environmental factors affecting the rate of corrosion of steel. The work of numerous investigators points out the wide spread distribution and tremendous damage done by these bacteria.

A limited discussion of each of the factors listed above is desirable and shall be undertaken. A more comprehensive appraisal of these items has been made by the many investigators in the field of corrosion; so a series of abstracts from selected articles published in the literature is included and will be found in Section V of this report.

pH or Hydrogen Ion Concentration

The definition of pH may be given as a measure of acidity or alkalinity of a solution or mixture. Actually this is an over simplification of the term which in equation form is as follows:

$$\text{pH} = \log \frac{1}{(\text{H}^+) \text{ per liter}}$$

which states that pH is the logarithm to the base 10 of the reciprocal of the gram ionic hydrogen equivalents per liter. Pure water has an H^+ ion concentration of 10^{-7} moles per liter which is equivalent to pH 7.0 and is therefore said to be neutral since the H^+ and the OH^- ions are in balance. If the H^+ ions outnumber the OH^- ions, the solution has a pH of less than 7.0 and is considered acid; whereas, if the solution has more OH^- ions than H^+ ions, its pH is greater than 7.0 and it is considered basic.

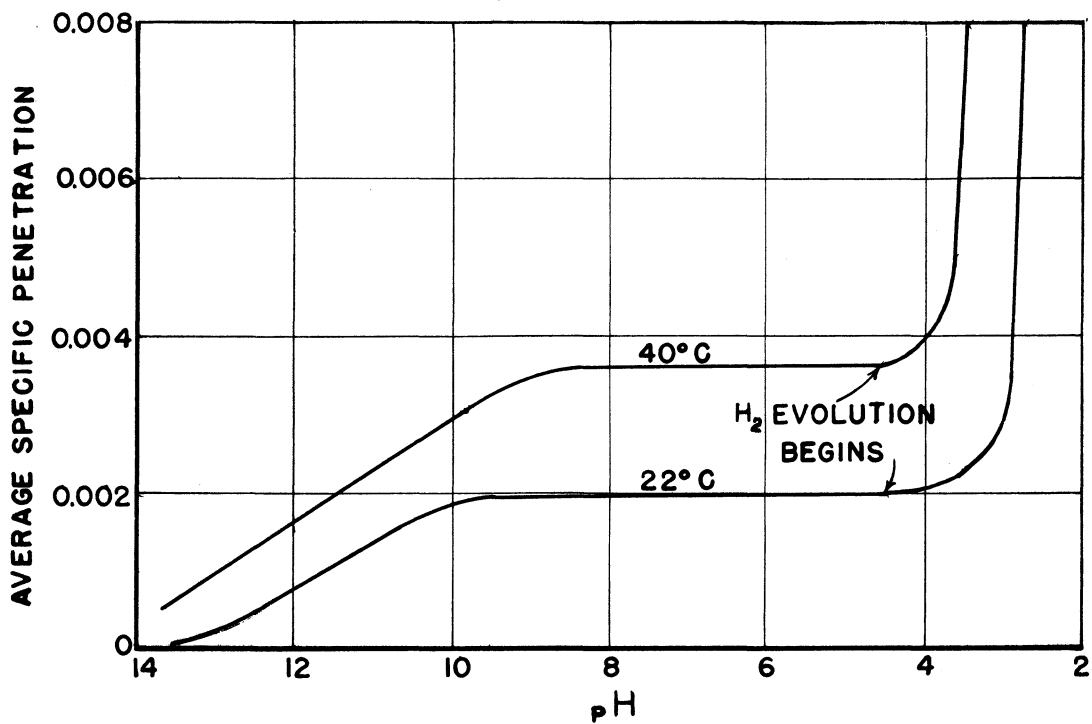


FIGURE 2. VARIATION OF STEEL CORROSION WITH ACIDITY.

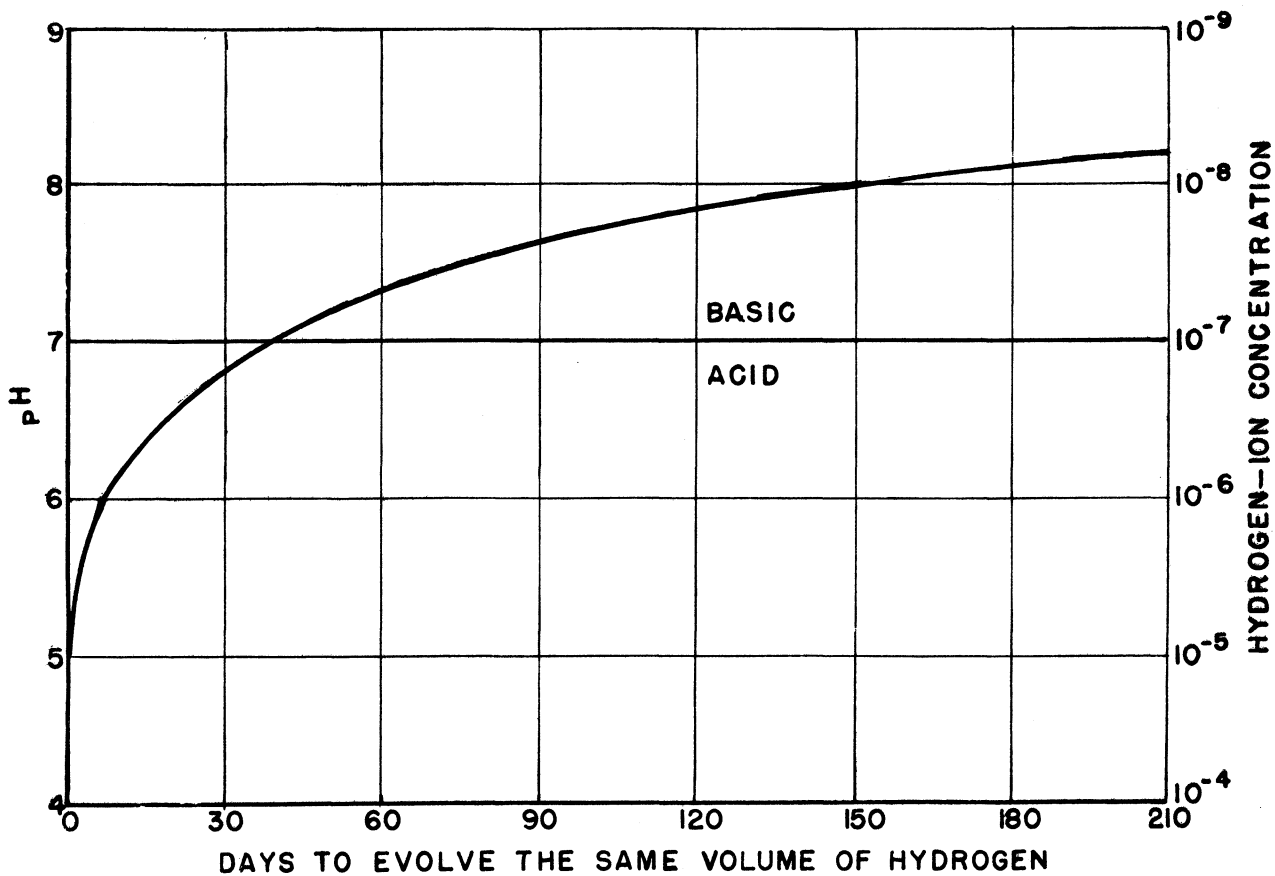


FIGURE 3. RELATION BETWEEN ACIDITY AND EVOLUTION OF HYDROGEN.

The pH range within which the corrosion of steel occurs includes the acid condition and also the basic condition from 7.0⁴ to about 9.5. The conditions creating or maintaining the pH within this very wide band may vary considerably. As a general rule the corrosion of steel proceeds more rapidly with increasing acidity as is indicated in Figure 2. There are exceptions to this as in many other "rules of corrosion", for steel may be corroded at a rapid rate under certain conditions while the pH is rather close to 7.0. The explanation of this is to be found in the work of previous investigators whose findings indicate that total acidity, ionized plus unionized acid as determined by titration, is more important than hydrogen ion concentration in determining corrosion rate. An interesting relationship between pH and rate of evolution of hydrogen is shown in Figure 3.

INFLUENCE OF OXYGEN NEAR THE METAL SURFACE

The availability of oxygen to the corroding surface is a most important factor in determining the corrosion rate of steel in natural waters. The solubility of oxygen in the corroding solution is also a factor and under certain conditions for underground members of fixed location, oxygen solubility would be of prime importance. In the Texas Gulf Coast Area the rate of movement of underground water is low and it is quite possible that diffusion would be more important than water movement in making the oxygen available to the surface in question. Temperature effects are fixed since the ground temperature a short distance below the surface level remains essentially the same all the time. Where oxygen depolarization is the controlling mechanism of corrosion, the rate of corrosion is a direct function of the rate at which the oxygen arrives at the corroding surface. Oxygen may, under certain conditions, serve as a film repair agent. It has been shown by experiment that an increase in oxygen availability will decrease the probability of attack and increase the intensity. The corrosion will be stifled if the ferrous ions are precipitated near the corroding surface;

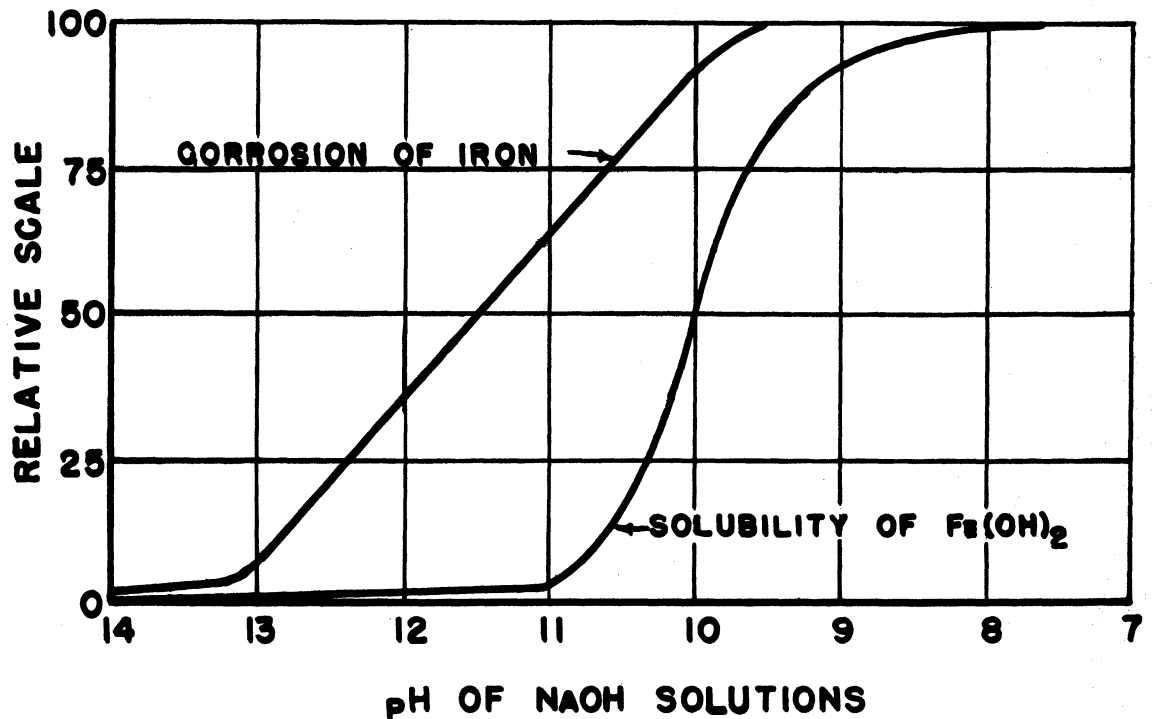


FIGURE 4 RELATIVE CORROSION AND SOLUBILITY RATES IN SODIUM HYDROXIDE SOLUTIONS.

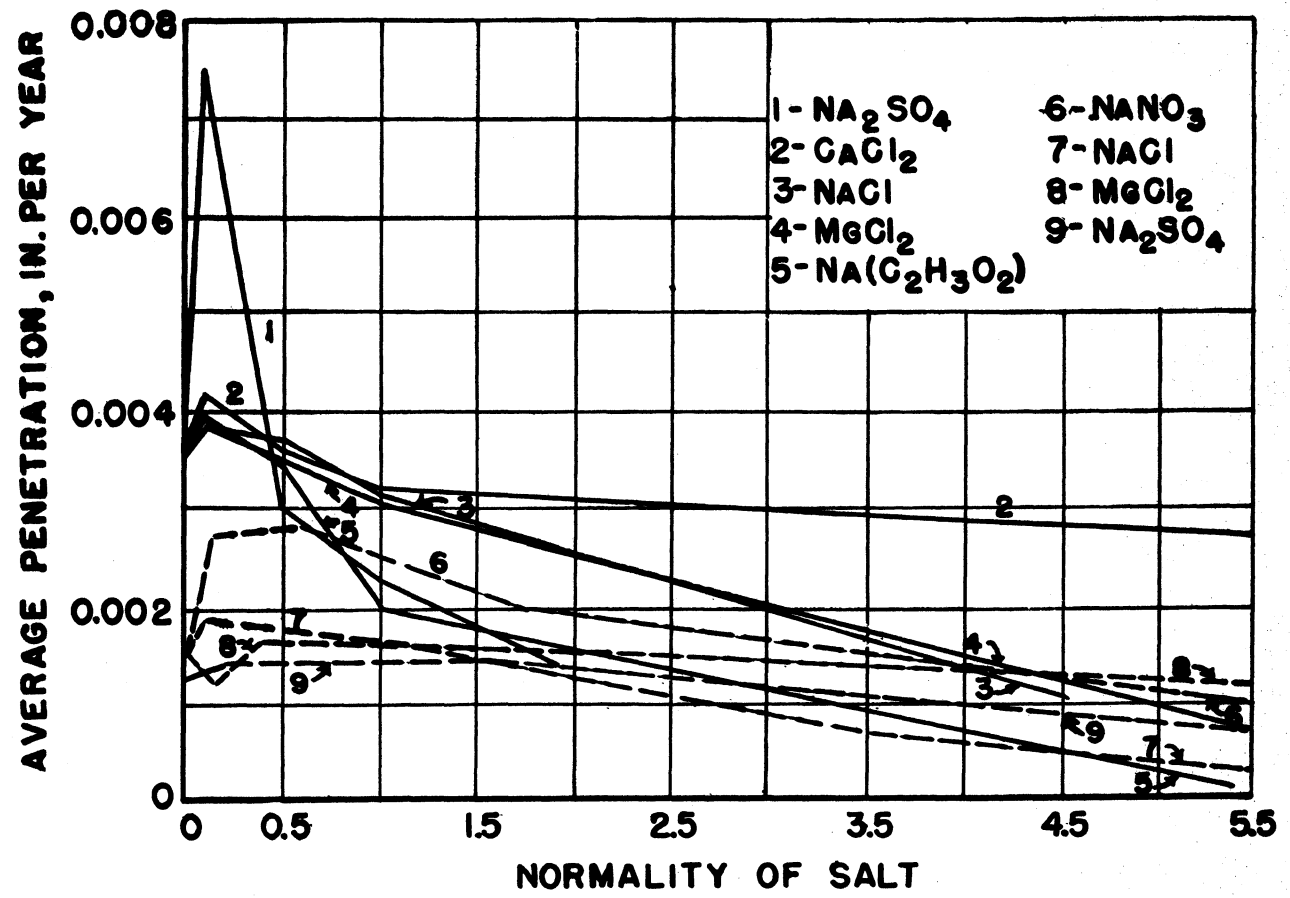


FIGURE 5. EFFECT OF VARYING SALT CONCENTRATION ON CORROSION RATES.

whereas, if the solid formation forms further out from the steel surface then it serves as a shield under which further corrosion takes place. The work of Bengough and Lee indicates corrosion in stagnant sea water is due to evolution of hydrogen for at least half of the loss.

SPECIFIC NATURE, CONCENTRATION AND DISTRIBUTION OF OTHER IONS IN SOLUTION

Among other things the corrosion rate of steel in soil is a function of the conductivity of the soil moisture, but it must be remembered that pure water is a very poor conductor. The conductivity of a soil-water mixture is therefore highly dependent upon the nature and concentration of ions other than those produced in the ionization of water. Rather extensive research was carried out by Whitman and co-workers on the rate of corrosion and the solubility of ferrous hydroxide in salts of varying concentration. An example is shown in Figure 4. The nature of the corrosion products is also of considerable importance. In general Bengough found that chloride ions tend to break down the protective coating formed by the corrosion products and possibly acts as peptizing agents on the films formed in the corrosion process. Chloride ions therefore interfere with inhibitors often to the extent of making it very difficult and sometimes impossible to protect steel by inhibition in the presence of these ions. Carbonates and silica deposits are laid down purposely in cathodic protection work to shorten the time required to set up the initial protective barrier.*

Analyses of waters from wells drilled in the Gulf Coast Area for drinking water and irrigation purpose show various amounts of sulfates, chloride and other ions. The reader is referred to a later section of this report which includes tabulations of water analyses of many water wells along the Texas Gulf Coast. Many of these waters are high in chloride ions indicating that corrosion inhibition promoted by use of an inhibitor or other similar barrier would be less likely in such an environment.

* Private communication with Atlantic Laboratories, Dallas, Texas.

Excessive amounts of chloride ions may produce an unfavorable atmosphere for steel protected by chromates. The effect of varying salt concentration on the rate of corrosion is shown in Figure 5.

RATE OF FLOW OF SOLUTION IN CONTACT WITH METAL

In general the rate of flow of ground water is of minor consequence in its effect on corrosion rate of steel underground; however, the very slight thermal movement of waters in mucks of low density may well be a factor in helping to promote bacterial growth which may easily form a step in the corrosion process. A steel member protected from the mud, say, with concrete and subject to an atmosphere in very short supply of oxygen from the mud-water interface downward may fail from corrosion in which sulfate-reducing bacteria act indirectly as hydrogen acceptors. The diffusion of oxygen under such conditions would be promoted by thermal currents and since only a very low oxygen concentration is thought to be required this could mean the difference necessary.

ABILITY OF ENVIRONMENT TO FORM A PROTECTIVE DEPOSIT ON THE METAL

In the primary electrochemical reaction of corrosion where the iron enters the solution as Fe^{++} and hydrogen is plated out on the metal surface, environmental conditions may be such as to remove practically none of this hydrogen. If such conditions exist, then this hydrogen film acts as a barrier to further corrosion. Such a condition may exist when the formation pressure of the hydrogen is low, low enough to greatly limit the evolution of bubbles of sufficient size to overcome the interfacial bond between the bubble and the metal. A steel piling driven into the earth and extending below the permanent water table would be protected under such conditions provided this film remains undisturbed. This film may, however, be periodically broken by lateral deflection of the member. And, too, certain bacteria may enter the corrosion reaction chain and act to depolarize the steel surface and to thus allow corrosion to continue. Hedges' work points out the importance of the chemical characteristics of films formed

as these characteristics affect the rate of attack on the metal. The work of Whitman, Russell and Davis presents the curve shown in Figure 4 giving the solubility of $\text{Fe}(\text{OH})_2$ in an alkaline solution. It is evident from this information that corrosion rates may be changed by the degree of alkalinity of the environmental solution. That is, the protective film may be helped or hindered depending on the solubility of the corrosion products in the solution.

TEMPERATURE

The temperature, as is commonly known, affects the rate of a chemical reaction. An increase in the temperature is usually accompanied by an increase in the corrosion rate. Corrosion of submerged steel under natural conditions in sea water is an indirect exception to this general rule. Measurement of corrosion rates of steel submerged in seawater are nearly the same the world over. The rate of penetration is approximately 0.005 inches per year (ipy). The increase in corrosion rate expected in warmer waters over that in cold waters is offset by other factors. Earth temperatures decrease with increase in depth to a certain point dependent upon the location. Measurements made in Brazos County show the temperature* to become constant at a depth of twenty to twenty-five feet. The measured temperature in this depth range fell between 70 and 75°F. Of course, higher temperatures exist at a depth of several hundred feet, but such depths are not involved in this study.

STATIC OR CYCLIC STRESS

As previously mentioned lateral deflection of a steel piling may cause an increase in the corrosion rate by breaking the protective film. At the metal surface an area of steel under residual stress is anodic to an unstressed area of the same member and when subjected to a corrosive atmosphere is likely to

* From unpublished research data of Prof. L.A. DuBose of A. & M. College of Texas on seasonal variations of earth temperatures under buildings.

corrode rather rapidly. Oil well tubing manufactured with an upset at the threaded end has been observed to corrode quite rapidly near this upset. It is believed by some authorities that residual stress is the causative agent. Cyclic bending may also be a contributing factor, since the point of attack is near a stiff section of the tube string.

CONTACT BETWEEN DISSIMILAR METALS OR OTHER MATERIALS AS AFFECTING CORROSION

There is little likelihood that dissimilar metals would be involved in bridge pilings. It is possible, however, in splicing operations, that the weld metal would be different from the base metal. This may give rise to localized corrosion. The effect of solution conductivity on such combinations is shown in Figure 6.

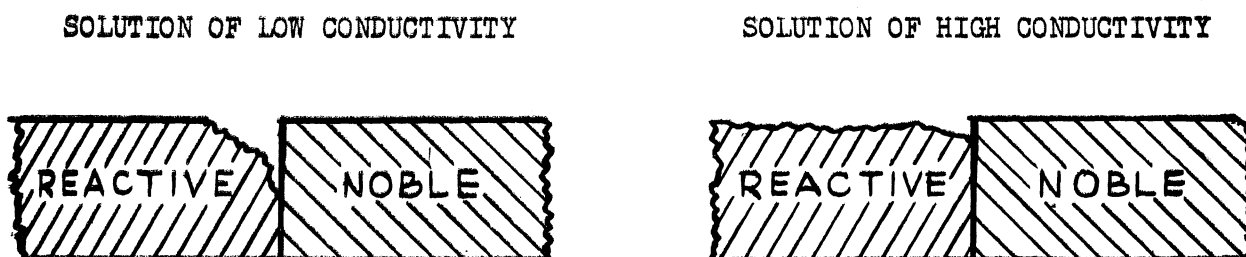


Figure 6.

Effect of Solution
Conductivity

Corrosion at such a junction would also be promoted as a result of welding operations by leaving the slag on the weld. This band of slag would act as a cathode or more noble metal and the adjacent exposed metal as an anode where the loss would very likely occur. It is therefore, advisable to carefully and completely remove the slag at such junctures. Breaks in the mill scale of hot rolled steel are often points of concentrated attack.

Tree roots in contact with the steel would promote corrosion. Of course, these would be a problem only in certain areas and to limit depths or under

special conditions (e.i. roots may catch under the end of the piling and be carried down several feet below normal depths before the root is cut or broken and left lodged near the piling surface). The danger involved would be of minor consequence.

ANAEROBIC SULFATE-REDUCING BACTERIA

Although some authorities contend that a type or types of bacteria are not agents in the production of crude petroleum, these investigators do claim that sulfate-reducing bacteria reduce sulfates to sulfides and may thus account for the presence of H_2S in many crude oils and the evolution of H_2S in swamps. The presence of these sulfate-reducing bacteria is reported all over the world and at depths from a few feet to many thousands of feet. Khur* in Holland has done extensive research on sulfate-reducing bacteria in connection with corrosion of steel and cast iron. Starkey and Wight in this country report the widespread distribution of the species spirillum sporovibros desulfurican. These and many other authorities have proved experimentally that these bacteria act as depolarizing agents in the corrosion process.

Starkey and Wight in their very extensive and quite thorough research on "Anaerobic Corrosion of Iron in Soil" published in 1945 by the American Gas Association suggest the use of oxidation-reduction potential measurements (redox potential measurements) as a rapid electrical means of evaluating the corrosion intensity of the soil particularly in marsh lands.

* The translation of Khur's paper was effected by Sgt. Peter Groot of the Royal Netherlands Air Force with technical assistance by William G. Bradley and U. Grant Whitehouse of the Dept. of Oceanography, Texas A. and M. College. The author is grateful to these individuals. This article contains an international bibliography on this subject.

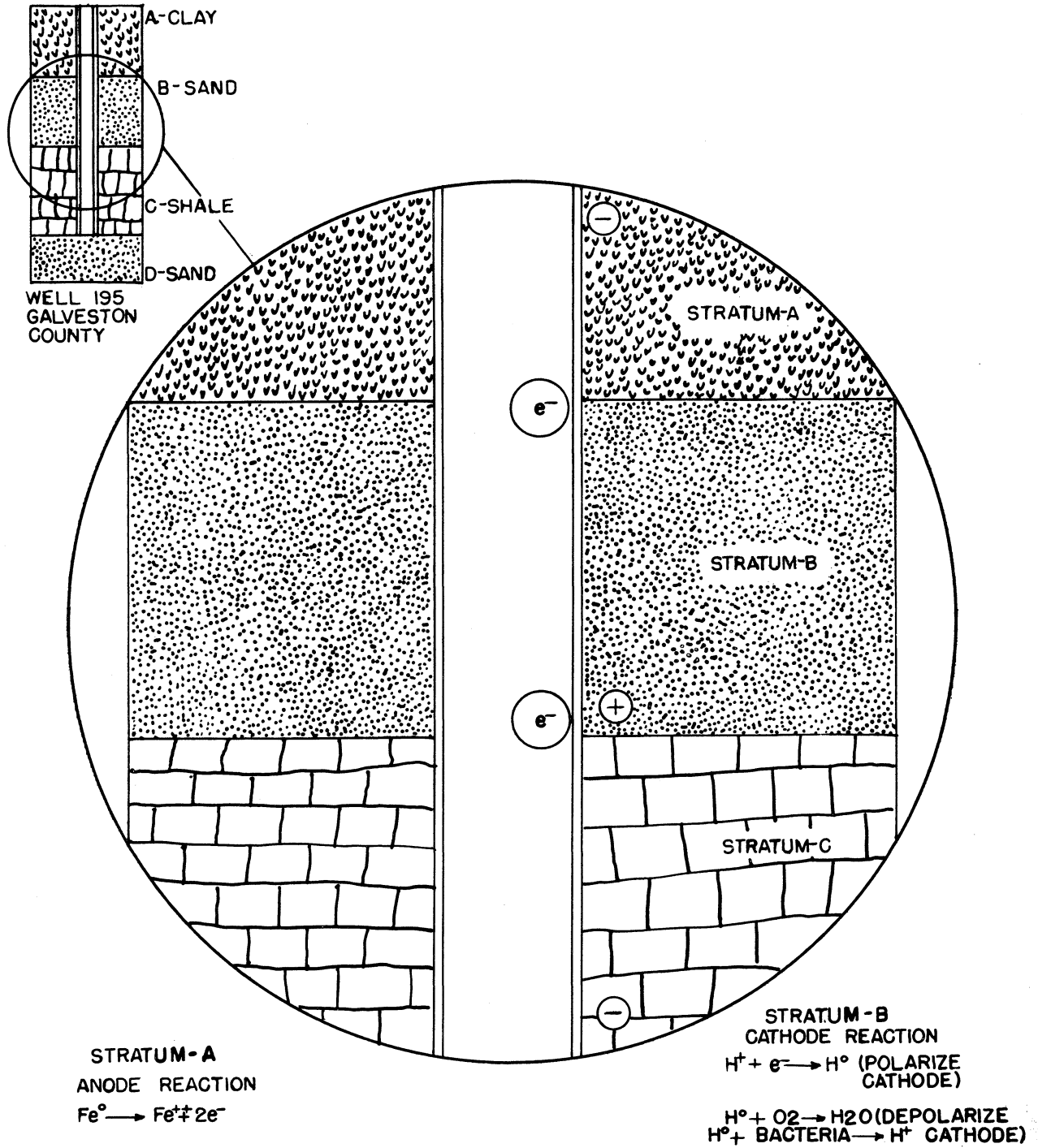


FIGURE 7. ELECTROCHEMICAL CORROSION OF STEEL PILING

As for protection Speller recommends coatings and or cathodic protection. High pH effected by caustic injection is also feasible.

An example of electrochemical corrosion of a steel piling is shown in Figure 7. Stratum B is assumed to be the cathode and strata A and C the anodes. Sulfate-reducing bacteria may act as hydrogen acceptors and thus promote corrosion in such a soil profile. Stratum B may also contain a high concentration of organic matter the decomposition of which could account for the oxygen supply necessary to depolarize the cathode.

SECTION III

CORROSION PREVENTION AND CONTROL BY GULF COAST INDUSTRIES

Many millions of dollars are being invested in the vast chemical empire developing along the Texas Gulf Coast and with this growth has come the problem of corrosion control and prevention, a problem that has received increasing attention in the last ten years principally for economic reasons. The writer reasoned that the corrosion engineers of these industries might possibly be willing to furnish information of value to the problem of corrosion of steel pilings of highway structures in this area. With this view in mind the writer visited various individuals who deal with corrosion problems and discussed the many phases of corrosion and corrosion control. The following resulting information is presented not as the solution to the problem at hand but as background information that should be helpful in the solution of a particular problem concerning highway structures.

Magnolia Petroleum Refinery of Beaumont* has been concerned with corrosion control for more than twenty-five years and have taken volumes of data on corrosion. In recent years soil resistivity measurements taken in the area from Port Neches, Texas to the Refinery at Beaumont, Texas along and near the Neches River show reading from as low as 200 ohms per centimeter to about 1200 ohms per centimeter in the clays of this area. Soils with resistivities measuring 100 ohms per centimeter are considered very corrosive. Control is effected with coatings and/or cathodic protection.

The California Company** of New Orleans, Louisiana reports no corrosion that may be attributed directly or indirectly to bacteria in the muds of the

* Private communication from Mr. George Debney, Chief Engineer of Magnolia Petroleum Refinery, Beaumont, Texas

** Private communication from Mr. C. P. Besse of the California Company of New Orleans, Louisiana

floor of the Gulf of Mexico along and near the Louisiana Coast Area. This finding is not in agreement with the data of other Corrosion Engineers of the area. Steel used in the form of columns and piling is protected in the zone of maximum attack (the tidal zone) with an 18 gage monel wrapping. This means of protection is now being replaced by some concerns with a corrosion allowance, that is, an additional thickness of base metal.

The average analysis of 77 samples of sea water is presented in the following table as a courtesy of the Corps of Engineers, District Engineer, New Orleans, Louisiana.

Table I

Average Analysis of 77 Samples of Sea Water Parts per Million of Salts
and Their Composite Radicals*

| | Na | K | Ca | Mg | SO ₄ | Cl | Br | CO ₃ | Total |
|--------------------------------|--------|-----|-----|------|-----------------|-------|----|-----------------|--------|
| NaCl | 10,705 | | | | | 16510 | | | 27,215 |
| MgCl ₂ | | | | 973 | | 2834 | | | 3,807 |
| MgSO ₄ | | | | 335 | 1323 | | | | 1,658 |
| CaSO ₄ | | | 371 | | 889 | | | | 1,260 |
| K ₂ SO ₄ | | 387 | | | 476 | | | | 863 |
| MgBr ₂ | | | | 10 | | | 66 | | 76 |
| CaCO ₃ | | | 28 | | | | | 42 | 70 |
| Total | 10,705 | 387 | 399 | 1318 | 2688 | 19344 | 66 | 42 | 34,949 |

Pilings along the coast subject to total water immersion (i.e., below the water table) may be subject to such waters. Corrosion rates in the neighborhood

* The data of Table I was furnished by courtesy of the Corps of Engineers, U.S. Army Office of the District Engineer, New Orleans District, New Orleans 9, Louisiana

of 0.005 ipy would not be considered uncommon for bare low carbon steel. The freshwater-water table is being lowered in highly industrialized areas of the Gulf Coast Area and as this takes place a salt water wedge is moving in from the Gulf of Mexico. This could cause an increase in corrosion rates in an area of low elevation that may now appear only slightly corrosive.

Protection of steel platforms used as protective barriers around producing oil wells in the saltwater bays near Corpus Christi, Texas* is effected in a dual manner. Vinyl Plastic coatings and cathodic protection utilizing magnesium anodes are used.

A typical installation is shown in Figure 8. The color difference at the water line is vinyl plastic, not rust. Protection is still complete after five years of service. Measurements were made by Atlantic Engineers of the corrosion rate of plain steel coupons electrically connected and positioned vertically in the salt water of the Copano-Aransas Bay Area north and east of Corpus Christi, Texas. The variation in loss of metal from the mud line to the splash zone is shown in Figure 9. As may be noted the loss in inches penetration per year (ipy) is considerably higher than some other reported average figures particularly for the completely submerged zone. This difference may be attributed to a difference in environment and the time factor.

Through the courtesy of Mr. T. O. Foster, Jr., District Engineer of Texas Highway Department District No. 16 at Corpus Christi, Texas a number of pictures were made of the repair and improvement of the Nueces Bay Causeway pile bents. The vertical members of these bents suffered considerable loss of exposed steel in the tide and splash zone. These pilings are thin steel cylinders driven about 70 to 90 feet and filled with reinforced concrete. The exposed column segment is

* This information was obtained by private communication courtesy of Mr. Howard E. Greenwell of Atlantic Refinery Laboratories, Dallas, Texas.

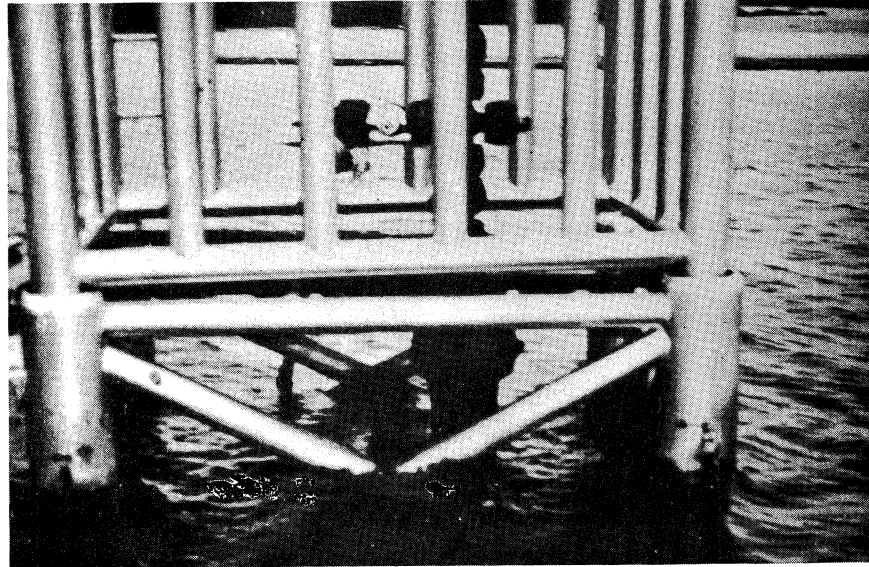


Figure 8. Protective barrier around oil well in salt water; color difference at water line is a rust preventive coating of vinyl plastic.

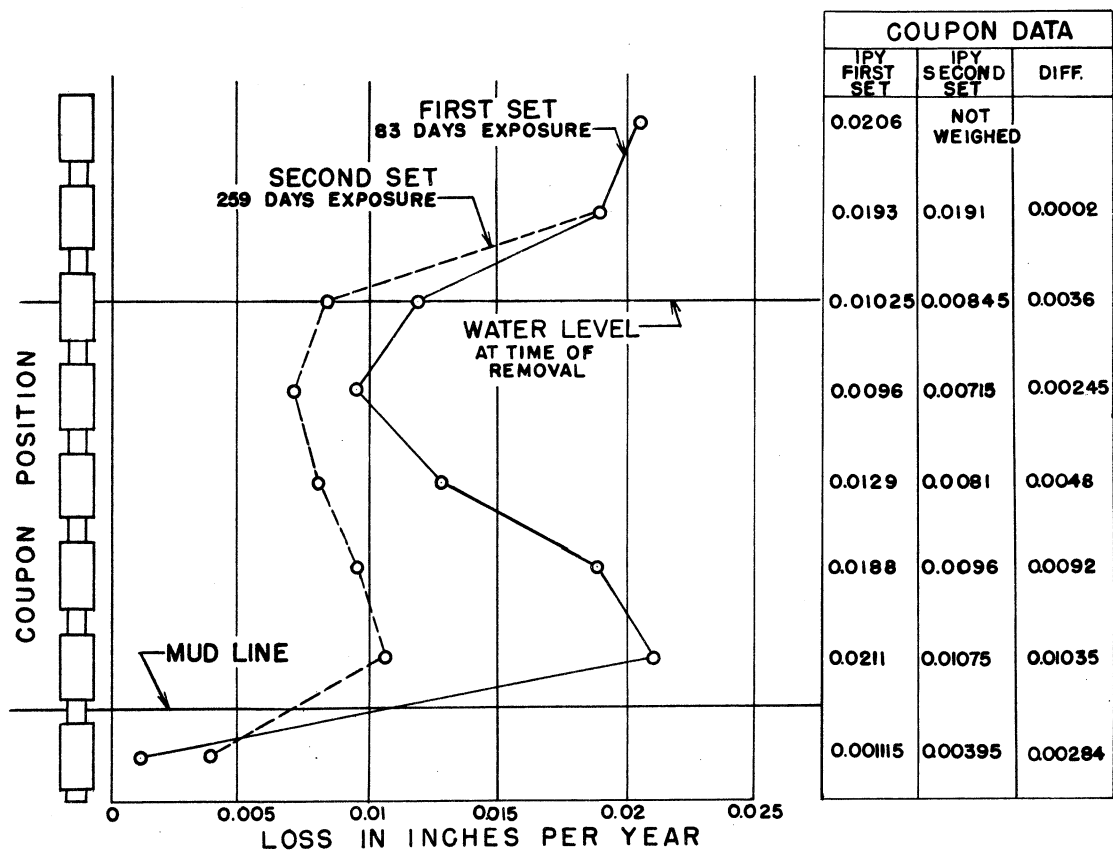


FIGURE 9. VARIATION IN LOSS OF METAL FROM THE MUD LINE TO THE SPLASH ZONE IN COPANO BAY.

fluted Mayari R steel about 0.25 inches thick which is also filled with reinforced concrete. No corrosion protection was provided on this steel at the time the bridge was constructed in 1949. Bethlehem Steel Company reports in their literature and from their tests that Mayari R steel is more resistant to corrosion than ASTM A-7. The fact that these unprotected columns have suffered considerable corrosion to date at the tide and splash zone is not to disprove Bethlehem's claims for no direct comparison as to service, shape and environment was made with ASTM A-7. Protective measures were carried out more for improved appearance than from any fear of development of structural weakness.

It can be positively stated, however, that from the viewpoint of minimum corrosion these columns should be smooth and round and not fluted.

A general view of the corroded pilings is shown in Figure 10. Considerable marine growth is in evidence near the water surface. Under the circumstances this marine growth and the corrosion products present a barrier which reduces the corrosion rate. The affect of the "shape factor" is clearly evident in Figures 11 and 12. In Figure 11 a vertical line of fracture in the corrosion product coating is shown immediately above the clamp bolt. Close inspection of a similar piling in the foreground of Figure 12 shows evidence of an increased rate of corrosion at the line of intersection of the concave planes making up the flutes of the piling. Rusting is in evidence just above the reinforced concrete jacket; note the dark areas. At least two affects of the "shape factor" cause an increase in the corrosion rate at the point in question. The affect of Poisson's ratio and the affect of film fracture are considered the accelerators in this case. In this particular instance the prevailing wind adds still another corrosion acceleration factor for the section above the tidal zone.



Figure 10. General view of corroded pilings showing marine growth and corrosion product at water line.



Figure 11. Bay side view of corroded piling at a point 6' above the water line showing rust fracture line at flute intersections.

A general view of the reinforced concrete jackets on the pilings may be seen in Figure 13. The concrete in the forms of the foreground was only a few hours old when this picture was taken. Further in the background the forms are in various states of removal. All of these jackets are at the same elevation and are about five inches thick and six feet long, some four feet above the water line and two feet below. Where by chance this jacket does not extend into the mud at least one foot and particularly where there is metal exposed to the water below the concrete jacket and above the mud line corrosion of this metal may be expected to increase*. A specific example of this rapid rate is shown in Figure 14. A review of Figure 9 bears out this statement.

Leendert de Witte and Fred J. Radd of Continental Oil Company presented a paper at the Fall Meeting of the Petroleum Branch American Institute of Mining and Metallurgical Engineers in October of 1954 in which was discussed the subject of "Corrosion of Oil Well Casing by Earth Currents" (to be published in Journal of Petroleum Technology). Pertinent points of this paper are: (a). Observed casing currents are mainly due to electrochemical potentials of the type in evidence on spontaneous potential curves of electrical logs and form a plausible cause for many cases of external casing corrosion, where the corrosion cannot be explained by metallurgical anomalies in the pipe. (b). Current patterns predicted from electric log spontaneous potential curves check closely with measured current profiles in the salt mud area of Kansas. (c). In completely anaerobic systems hydrogen over potentials will reduce the rate of current flow unless the hydrogen is removed. Sulfate-reducing bacteria are suggested as depolarizers.

* Daremus, E. P. and Doremus, G. L., "Cathodic Protection of Fourteen Offshore Drilling Platforms" Corrosion Vol. 6, No. 7, (1950) p 216-224.

Private communication with David M. Updegraff, Chief Research Microbiologist for Magnolia Petroleum Field Research Laboratories in Dallas, Texas, revealed that his company, like most other major oil companies of the United States, is actively pursuing research in the field of petroleum microbiology and he recognizes, among many other things, the important part played by sulfate-reducing bacteria in the corrosion of iron and steel.

Corrosion Engineer C.P. Dillon of Carbon and Carbide Chemical Company of Texas City, Texas, suggested that there was considerable difference in the so called "industrial atmospheres", and that the critical relative humidity is also a major factor in atmosphere corrosion. The direction of the prevailing wind is considered of major import in atmospheric corrosion by this authority. The writer observed and photographed an example of this difference on the pile bents of the Nueces Bay Causeway. The thickness of the corrosion products on the side of the column facing the prevailing wind may be seen in Figure 11. The lee side above the splash zone of this and all other columns of this bridge had accumulated less than one-sixteenth of an inch thickness of corrosion product.

In a recent conference with R. C. Buchan, Chemical Engineer for Humble Oil Company, Houston, Texas, the subject of cathodic protection for the foundation pilings of typical bridge foundations in the Gulf Coast Area was discussed. The particular cases in point were the foundation pilings of the Old and Lost River Bridge and the San Jacinto River Bridge on State Highway 73. Two suggestions were made regarding these particular installations. Caustic injection in the soil area at each nest of pilings was suggested as a means of raising the pH of the soil to such point that very little corrosion would occur.

Extention of concrete cover over the steel to a point not less than thirty inches below the mud-water interface was also suggested. A cost estimate was not made on cathodic protection for these installations but the writer's conclusion drawn from the conversation is that cathodic protection of these particular installations is neither warranted nor economically practical. On the other hand cathodic protection of the submerged segments of the pile bents of the Nueces Bay Causeway might well have been a more economical partial solution to that corrosion problem particularly if such measures had been taken initially.

Limited information on corrosion of oil well tubing and oil well casing was obtained through the courtesy of the Phillips Petroleum Company Field Engineer located near the Capano Bay Field east of the Woodsboro, Texas. Photographs were made of what is termed ringworm corrosion* of upset oil well tubing. This type of corrosion is believed to be promoted by residual stresses in the tube. Casing corrosion is not uncommon in this area but such corrosion usually occurs at depths much greater than would be encountered in pilings for highway structures. Records indicate perforation of casing walls by corrosion in 7 to 14 years of service for this area. It is the author's opinion that the complete story as to depths at which severe corrosion occurs was not obtained. Exposing such data is not in the best interest of parties concerned. The amount of this loss that may occur on the soil side of the casing is not generally known but recent studies indicate that about 75 percent of the total casing corrosion is external.

A paper co-authored by J. D. Sudbury, J. A. Landers and D. A. Shock of Continental Oil Company and entitled "External Casing Corrosion Control" was

* See Speller p. 571

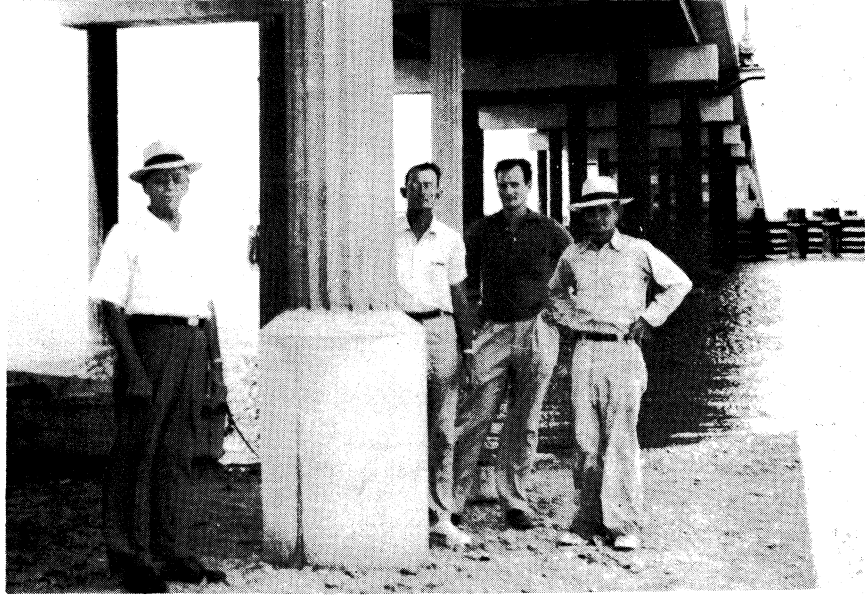


Figure 12. Repaired pier in foreground showing accelerated corrosion at flute intersections just above concrete jacket.

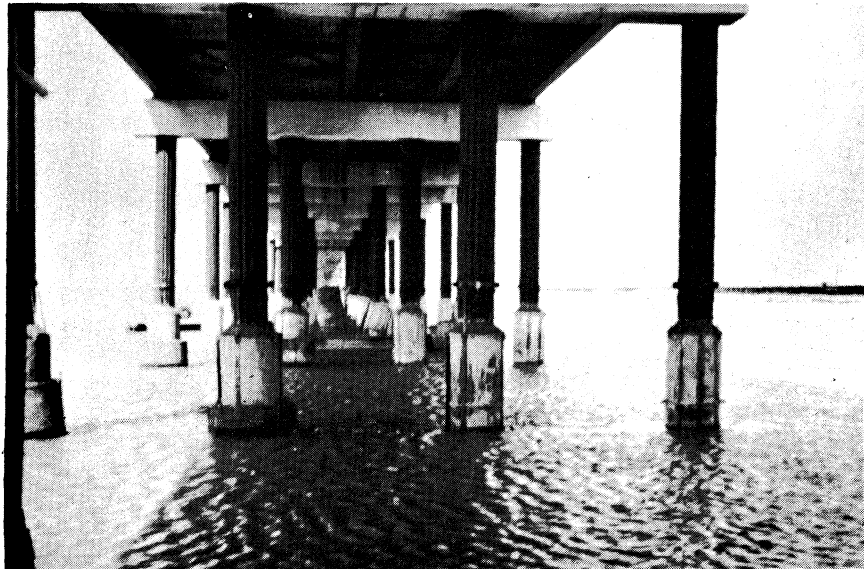


Figure 13. General view of reinforced concrete jackets.



Figure 14. Structure removed from salt water showing excessive corrosion of member in foreground; this member was located at the mud-water interface.

presented at the October 1954 Meeting of the National Association of Corrosion Engineers, which paper is to be published, probably in the Journal of Petroleum Technology. The following points are presented as a summary of this paper

- (a) Estimated annual cost of oil and gas well casing corrosion is over \$20,000,000.
- (b) Hydrogen depolarization of the cathodic areas of a casing is effected by oxygen or certain bacteria.
- (c) Oxygen is present in many formations to depths as great as 1500 feet.
- (d) It was shown that the rate at which the current enters or leaves the pipe is the important item and not the direction of the current flow in the pipe.
- (e) Cathodic protection appears to be an effective economical means of protecting oil well casings provided certain minor difficulties are overcome.

SECTION IV
WATER ANALYSIS AND DRILLERS' LOGS
OF COASTAL WATER WELLS

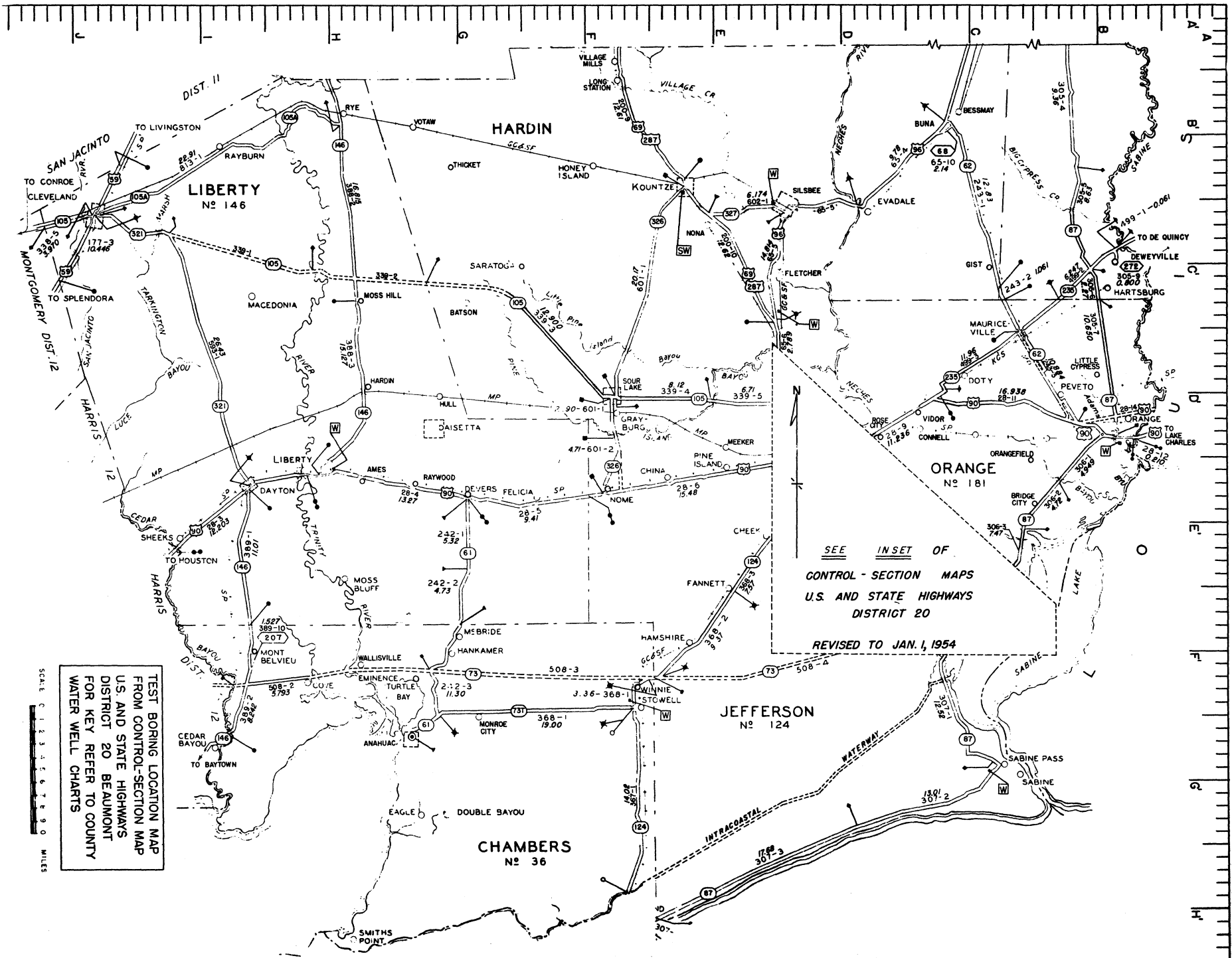
This section of the report presents a number of analyses of water from wells drilled along the Texas Gulf Coast and drillers' logs of some of these wells. Included also are data from test holes drilled in this area by the Works Progress Administration under the direction of Department of Agriculture.

The wells selected for presentation are, in general, those wells near stream crossings of State and U. S. Highways. These data are included for general information purposes of an area in question and should be considered as rather conservative from the corrosion viewpoint. As a general picture the soils profiles are erratic and the closer to the coast the higher is the soluble salt content. The fact that an included well in a given area indicates either or both low soluble salt content and/or a uniform soil profile does not mean freedom from corrosion. Whether or not corrosion may be expected in a given area must be determined by careful analysis of corrosion data taken at the site under study.

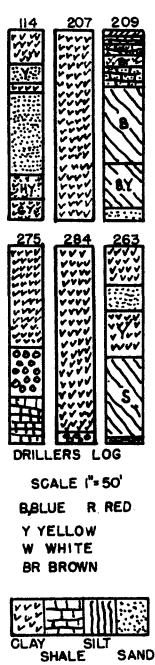
The water well data are given by counties and are tied to the District Maps by a key which appears in the second column of the tabulated data. For example, consider District No. 20 and Chambers County. The first line of data on the Chambers County tabulation deals with Well No. 30. The key to the location of this well on District No. 20 Map is H7F'3. The driller's log for Well No. 30 is drawn to the indicated scale and is shown in the upper left margin of the Chambers County Tabulation.

To locate this well (key H7F'3) proceed down the left margin of District No. 20 Map seven units below H and move across to the right to a point directly

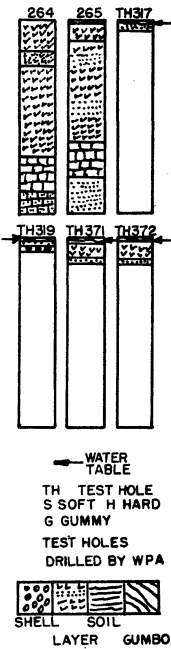
below three units to the right of F' (Indexing guide at top margin of map). The intersection of these two location lines positions Well No. 30 near the Cedar Bayou - State Highway No. 73 Crossing. Reference to given data on this well shows 432 ppm total solids for the water; the water table is at about 10 feet below ground level; the soil profile indicates mostly clay with a little shale for the 100 feet of depth shown. The depth of this well is 368 feet. It is highly probable that the total solids data for this well is of little value to the corrosion engineer but reference to Test Hole Data in the later portion of this same tabulation reveals more solids in general and a much higher quantity of sulfates. In the presence of organic matter and sulfates corrosion rates may be stepped up by sulfate reducing bacteria acting as hydrogen acceptors.



JEFFERSON COUNTY

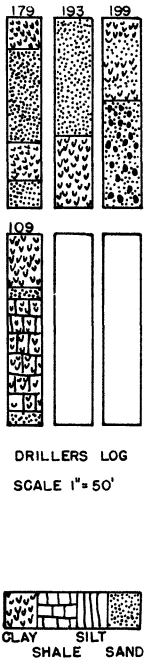


| WELL NO | KEY | DEPTH | Ca | Mg | Na+K | HCO ₃ | SO ₄ | Cl | F | NO ₃ | CaCO ₃ | TOTAL SOLIDS | |
|---------|------|-------|-------|-----|--------|------------------|-----------------|-------|-----|-----------------|-------------------|--------------|-------|
| 71 | D5C7 | 320 | 2.4 | 2.7 | 160 | 348 | 2 | 54 | 0.8 | 20 | 17 | 393 | |
| 72 | D5C7 | 315 | 6.9 | 1.8 | 176 | 375 | 1 | 69 | 0.7 | 0 | 25 | 440 | |
| 73 | D5C7 | 100 | 6.0 | 1.5 | 203 | 336 | 2 | 130 | | 10 | 21 | 509 | |
| 74 | D5C7 | 280 | 4.4 | 2.7 | 160 | 348 | 2 | 58 | | 20 | 22 | 398 | |
| 75 | D5C7 | 600 | 6.0 | 1.5 | 429 | 451 | 2 | 410 | 1.5 | | 21 | 1,072 | |
| 76 | D5C7 | 180 | 6.4 | 2.7 | 151 | 311 | 2 | 68 | 0.6 | | 27 | 384 | |
| 114 | C8D4 | 562 | | | | | | | | | | | |
| 181 | C5E7 | 254 | 2.0 | 7.5 | 542 | 519 | 2 | 590 | 0.3 | | 80 | 1,417 | |
| 207 | C5E7 | 230 | | | | | | | | | | | |
| 209 | C5E7 | 117 | 8.0 | 3.5 | 860 | 4.76 | 2 | 1,290 | 0.2 | 20 | 341 | 2,500 | |
| 280 | C5E7 | 946 | 254 | 144 | 4,330 | 250 | 2 | 7,400 | 0.4 | 20 | 1,229 | 12,300 | |
| 275 | C5E7 | 935 | | | | 294 | 2 | 3,950 | | | | 417 | |
| 284 | C5E7 | 965 | 118 | 28 | 1,945 | 323 | 3 | 3,100 | 0.4 | 20 | 413 | 15,350 | |
| 261 | B9E5 | 1,000 | | | | 339 | 2 | 850 | | | | 88 | |
| 262 | B9E5 | 20 | | | | 384 | 25 | 202 | | | | 390 | |
| 263 | B9E5 | 822 | | | | 323 | 2 | 1,340 | | | | 159 | |
| 264 | B9E5 | 549 | | | | 369 | 2 | 141 | | | | 26 | |
| 265 | B9E5 | 1,471 | 1,572 | 899 | 18,800 | 150 | 0.34 | 400 | | | | 55,900 | |
| 288 | C5E7 | 20 | 42 | 27 | 73 | 18 | 12 | 200 | 0.2 | 81 | 217 | 444 | |
| 125 | D2D8 | 45 | 105 | 14 | 82 | 470 | 25 | 61 | | | | 318 | 518 |
| 317 | D2D8 | 12 | 89 | 14 | 96 | 451 | 25 | 65 | | | | 278 | 511 |
| 319 | D2D8 | 15 | 86 | 3.0 | 280 | 512 | 311 | 144 | | | | 338 | 1,103 |
| 370 | B9E5 | 9 | | | | 561 | 25 | 72 | | | | | |
| 371 | B9E5 | 6 | 23 | 69 | 702 | 1,147 | 200 | 510 | | | | 342 | 2,068 |
| 372 | B9E5 | 5 | | | | 537 | 22 | 16 | | | | | |

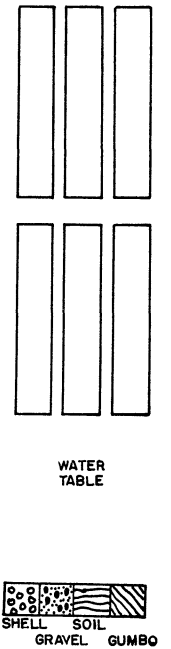


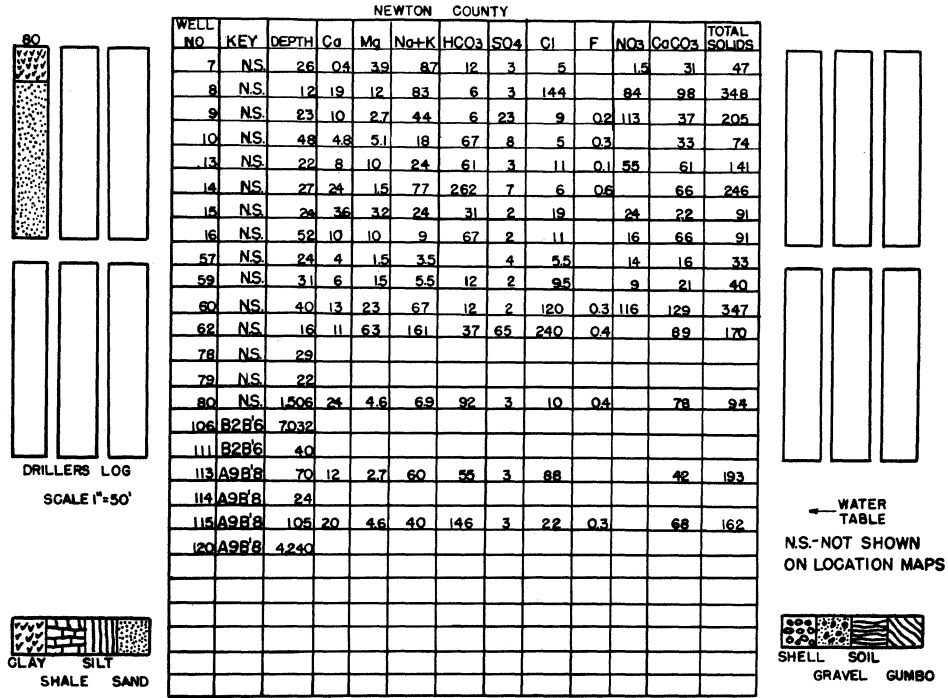
WATER WELL CHARTS FOR JEFFERSON AND LIBERTY COUNTIES - DISTRICT 20

LIBERTY COUNTY

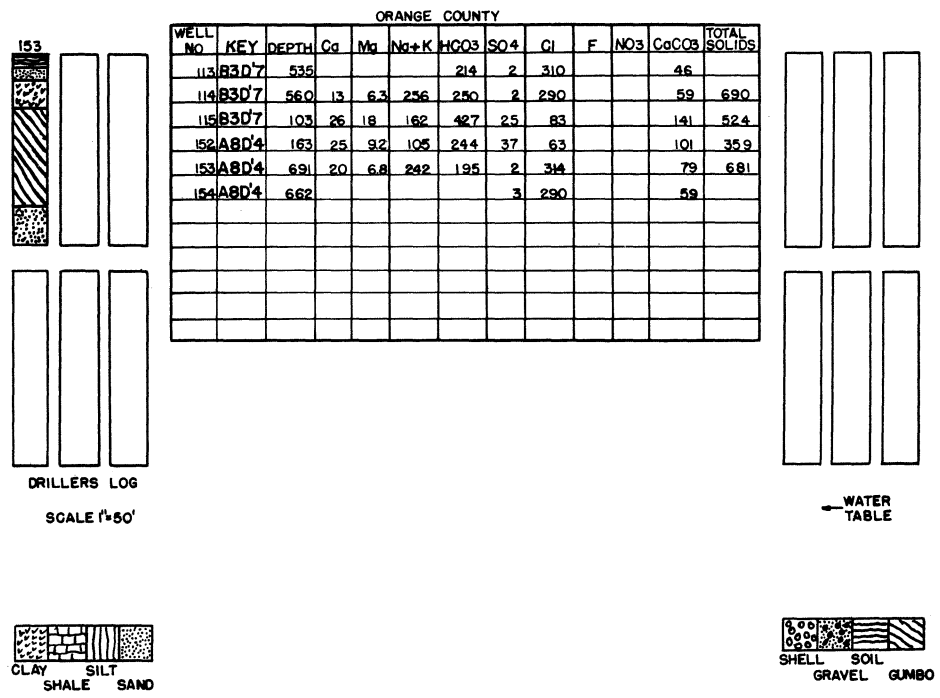


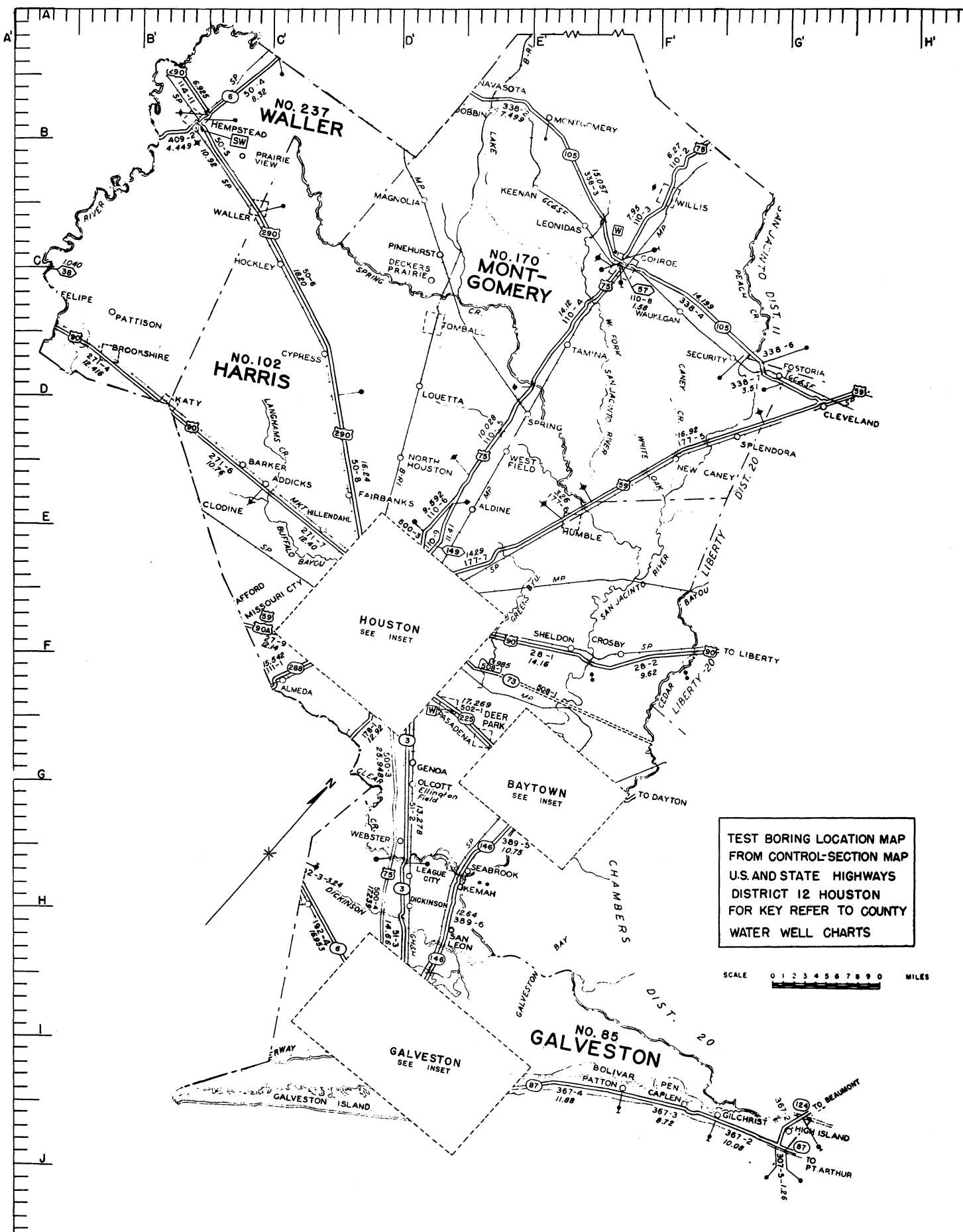
| WELL NO | KEY | DEPTH | Ca | Mg | Na K | HCO ₃ | SO ₄ | Cl | F | NO ₃ | CaCO ₃ | TOTAL SOLIDS |
|---------|------|-------|-----|-----|------|------------------|-----------------|-----|-----|-----------------|-------------------|--------------|
| 179 | H3D7 | 565 | 70 | 6.6 | 66 | 190 | 6.8 | 125 | 0.4 | 0.2 | 202 | 419 |
| 193 | H3D7 | 200 | | | | | | | | | | |
| 197 | H3D7 | 2.8 | 62 | 5.2 | 15 | 185 | 4 | 38 | | | 176 | 259 |
| 198 | H3D7 | 40 | 38 | 2.4 | 1.7 | 108 | 8 | 8 | | 0.2 | 105 | 142 |
| 199 | H3D7 | 232 | | | | | | | | | | |
| 107 | I2E2 | 175 | | | | | | | | | | |
| 118 | I2E2 | | | | | | | | | | | |
| 112 | I2E2 | 380 | 128 | 21 | 271 | 450 | 11 | 436 | | | 406 | 1,080 |
| 109 | I2E2 | 407 | | | | | | | | | | |





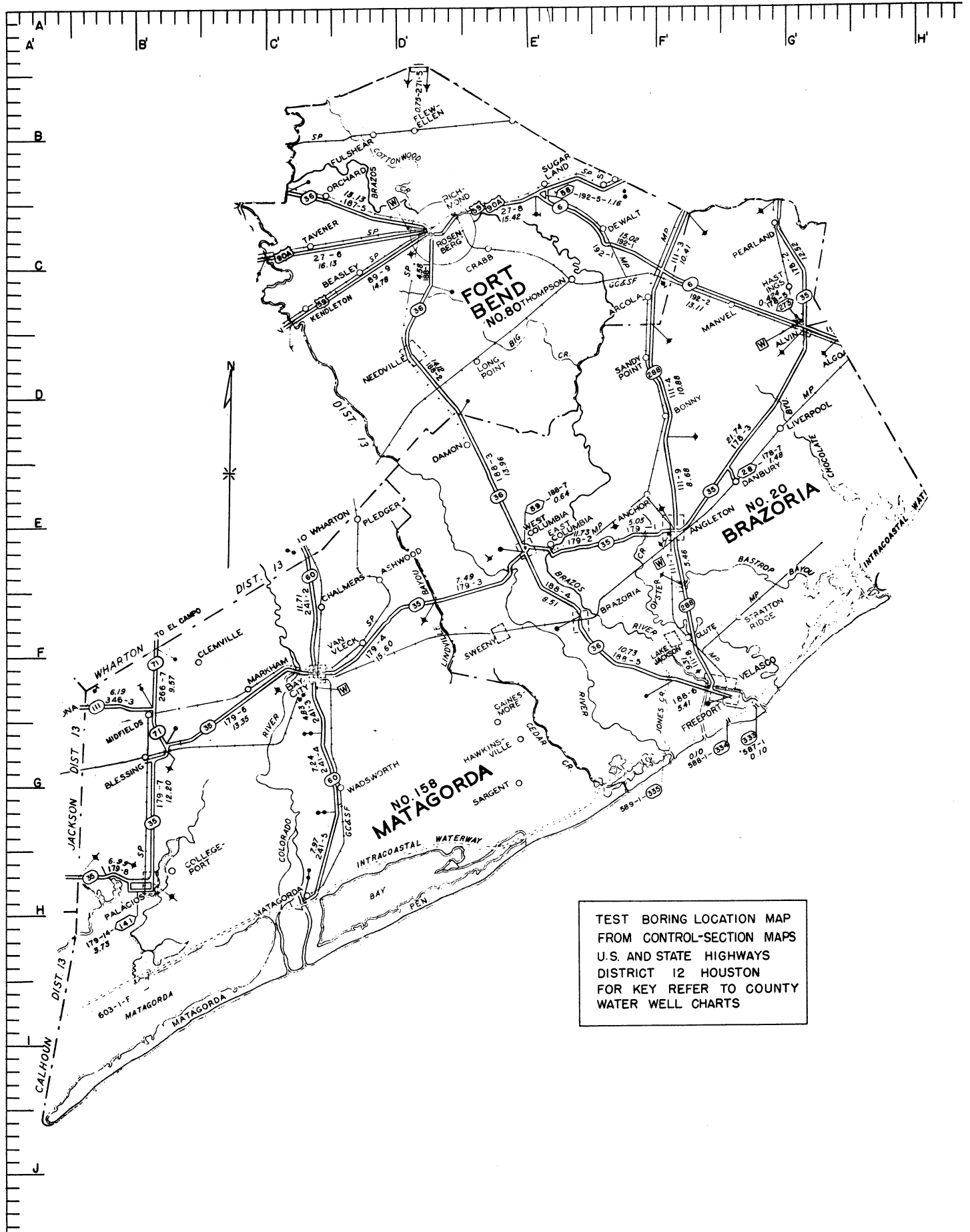
WATER WELL CHARTS FOR NEWTON AND ORANGE COUNTIES - DISTRICT 20

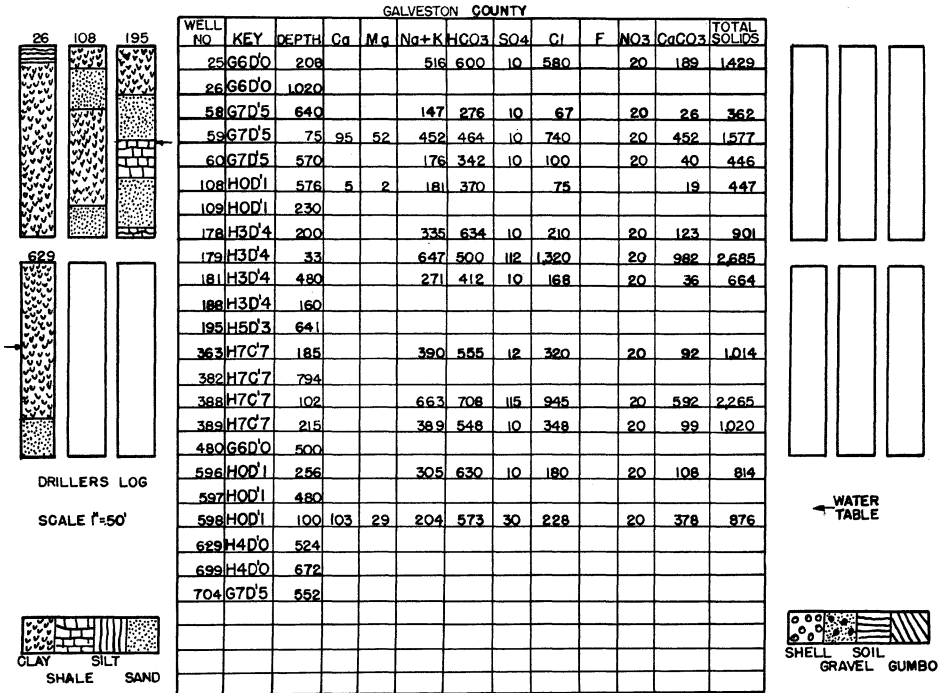




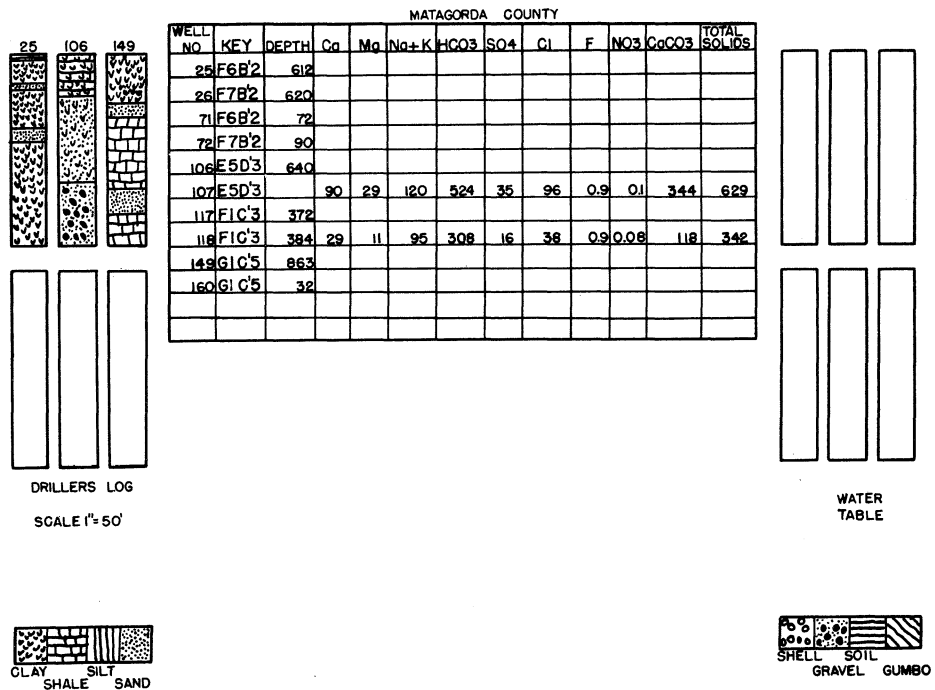
TEST BORING LOCATION MAP
 FROM CONTROL-SECTION MAP
 U.S. AND STATE HIGHWAYS
 DISTRICT 12 HOUSTON
 FOR KEY REFER TO COUNTY
 WATER WELL CHARTS

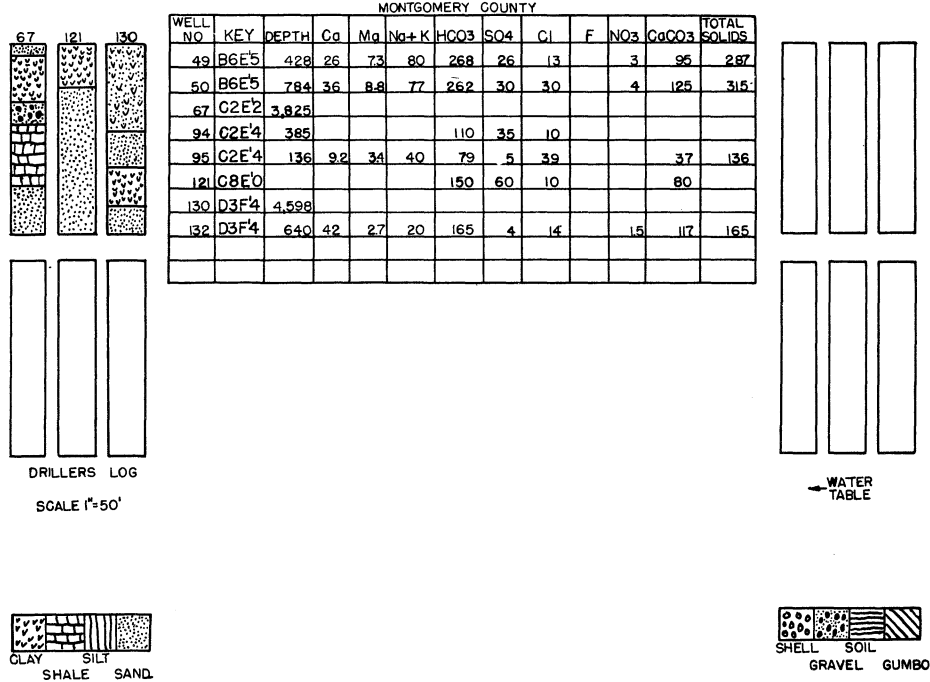
SCALE 0 1 2 3 4 5 6 7 8 9 0 MILES



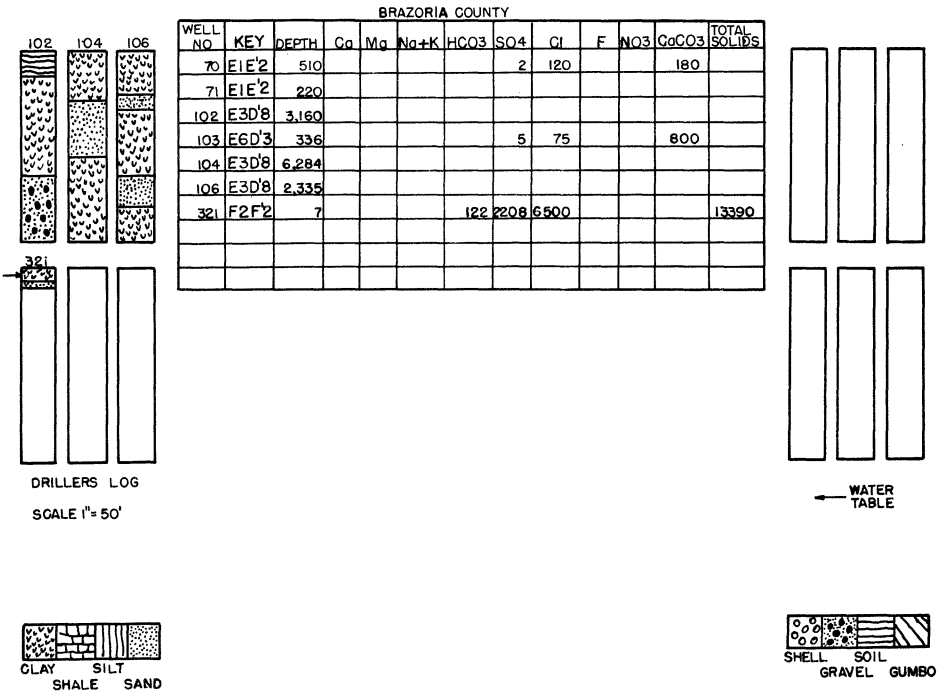


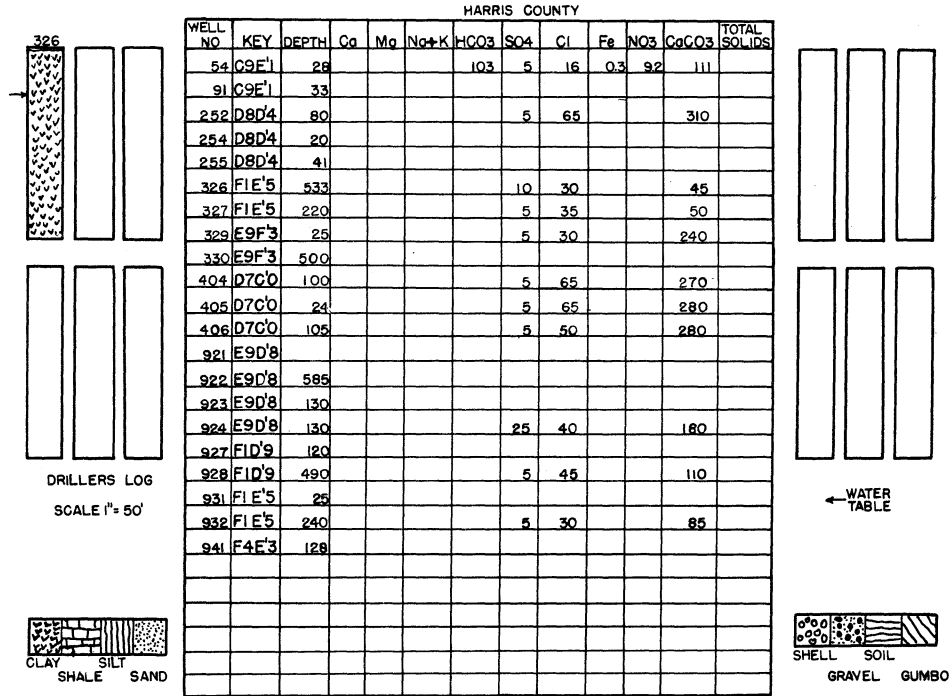
WATER WELL CHARTS FOR GALVESTON AND MATAGORDA COUNTIES - DISTRICT 12



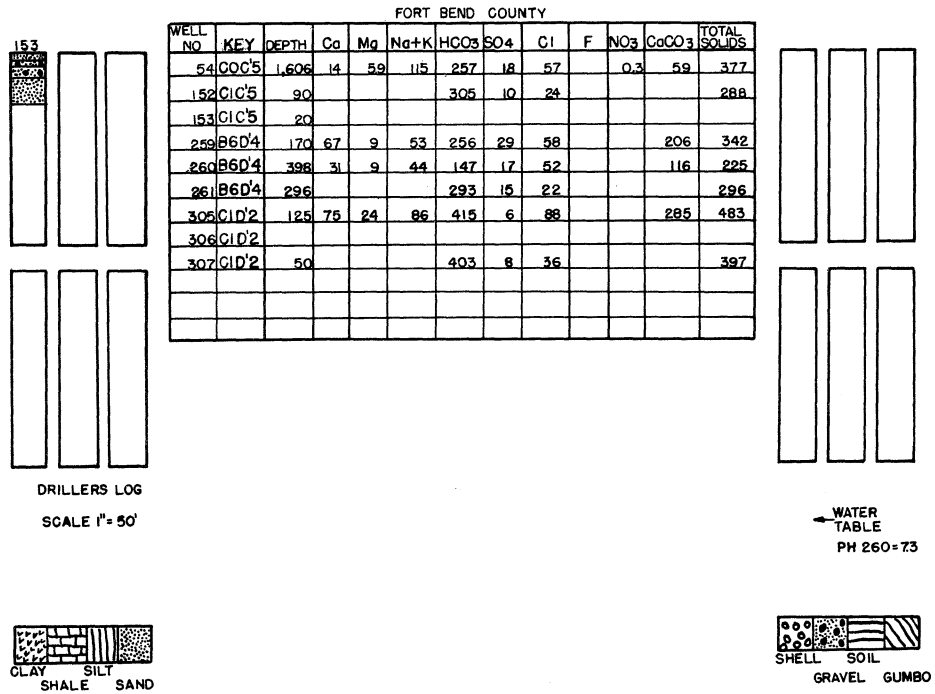


WATER WELL CHARTS FOR MONTGOMERY AND BRAZORIA COUNTIES - DISTRICT 12



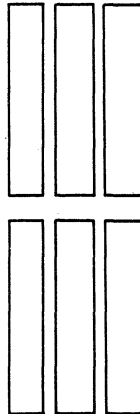


WATER WELL CHARTS FOR HARRIS AND FORT BEND COUNTIES - DISTRICT 12

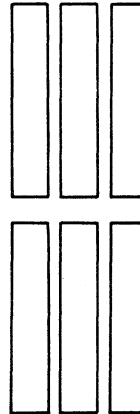


NUECES COUNTY

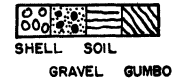
| WELL NO | KEY | DEPTH | Ca | Mg | Na+K | HCO3 | SO4 | Cl | Fe | NO3 | CaCO3 | TOTAL SOLIDS |
|---------|------|-------|----|----|-------|------|-----|-----|------|------|-------|--------------|
| 55 | E7C3 | 745 | | | | | | | | | | |
| 56 | E7C3 | 20 | | | | | | | | | | |
| 126 | F9B8 | 935 | | | 890 | 211 | 626 | 860 | | | 108 | 2,430 |
| 127 | F9B8 | 963 | | | 680 | 226 | 492 | 628 | | | 104 | 1,880 |
| 128 | F9B8 | 570 | | | 480 | 302 | 344 | 360 | | | 78 | 1,310 |
| 129 | F9B8 | 700 | | | | | | | | | | |
| 130 | F9B8 | 695 | 20 | 2 | 552 | 249 | 375 | 471 | 0.5 | | 58 | 1,571 |
| 147 | G7B3 | 712 | | | | | | | | | | |
| 148 | G7B3 | 850 | 22 | 9 | 355 | 287 | 207 | 292 | 0.3 | | 92 | 1,090 |
| 149 | G7B3 | 745 | | | | | | | | | | |
| 170 | E8D8 | 14 | | | | | | | | | | |
| 171 | E8D8 | 60 | | | | | | | | | | |
| 260 | E8D8 | 440 | | | | | | | | | | |
| 265 | E8D8 | 63 | 64 | 12 | 253.9 | 306 | 114 | 270 | 0.15 | 0.48 | 209 | 880 |



DRILLERS LOG
SCALE 1"=50'



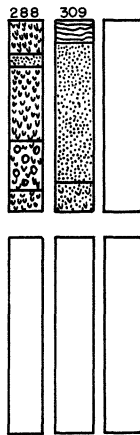
← WATER TABLE



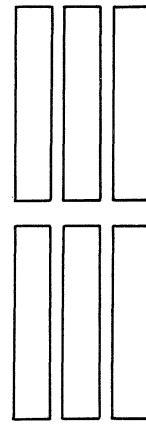
WATER WELL CHARTS FOR NUECES AND SAN PATRICO COUNTIES - DISTRICT 16

SAN PATRICIO COUNTY

| WELL NO | KEY | DEPTH | Ca | Mg | Na+K | HCO3 | SO4 | Cl | F | NO3 | CaCO3 | TOTAL SOLIDS |
|---------|------|-------|----|----|------|------|-----|-----|---|-----|-------|--------------|
| 288 | E7C3 | 1,864 | | | | | | | | | | |
| 309 | E6C3 | 6,003 | | | | | | | | | | |
| 386 | D3D4 | 345 | 7 | 4 | 299 | 378 | 67 | 215 | | 20 | 32 | 782 |

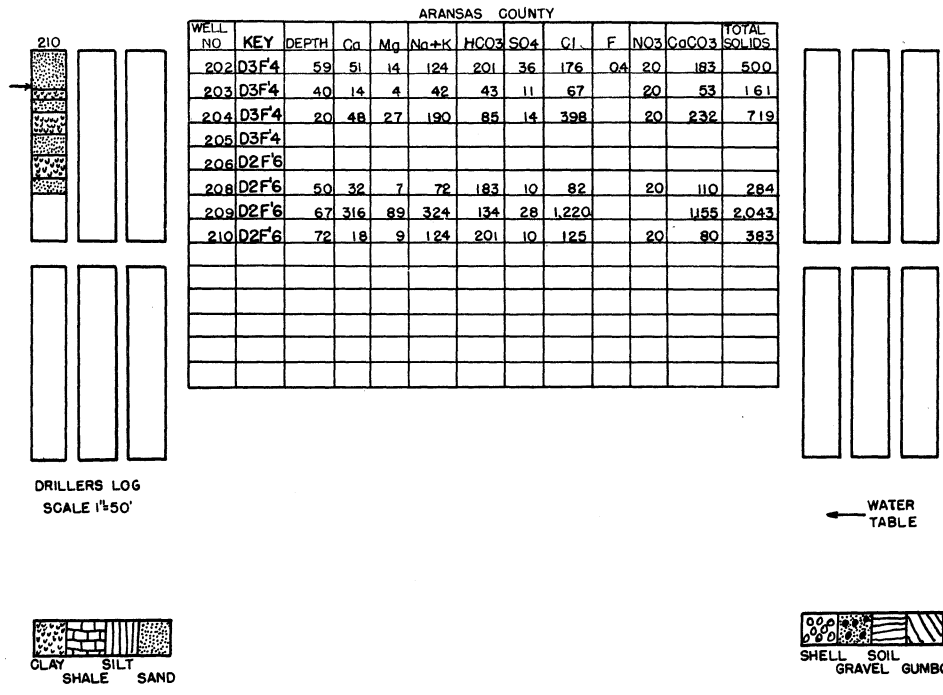


DRILLERS LOG
SCALE 1"=50'

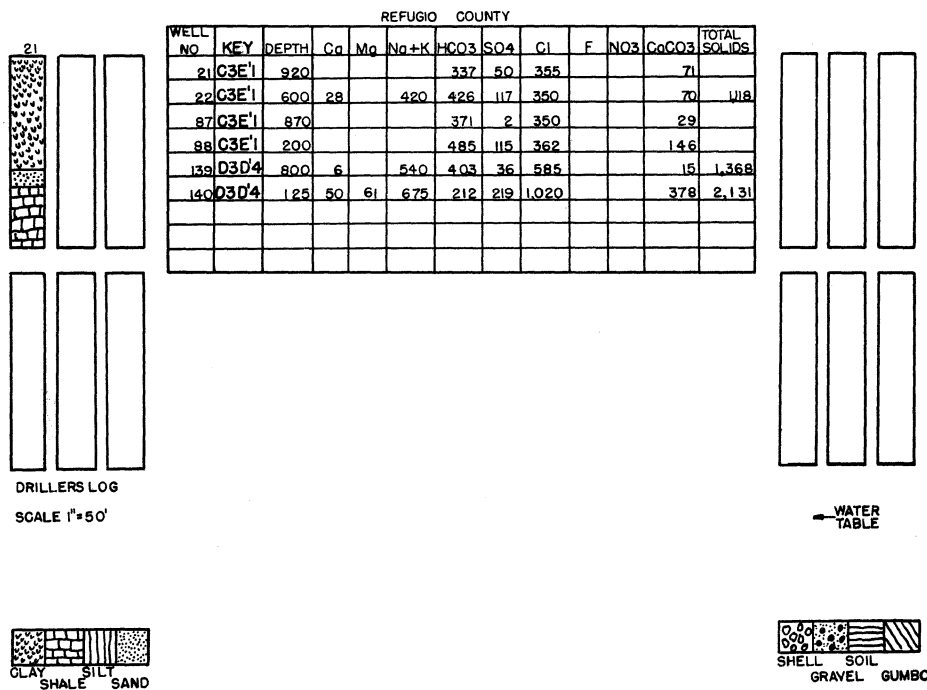


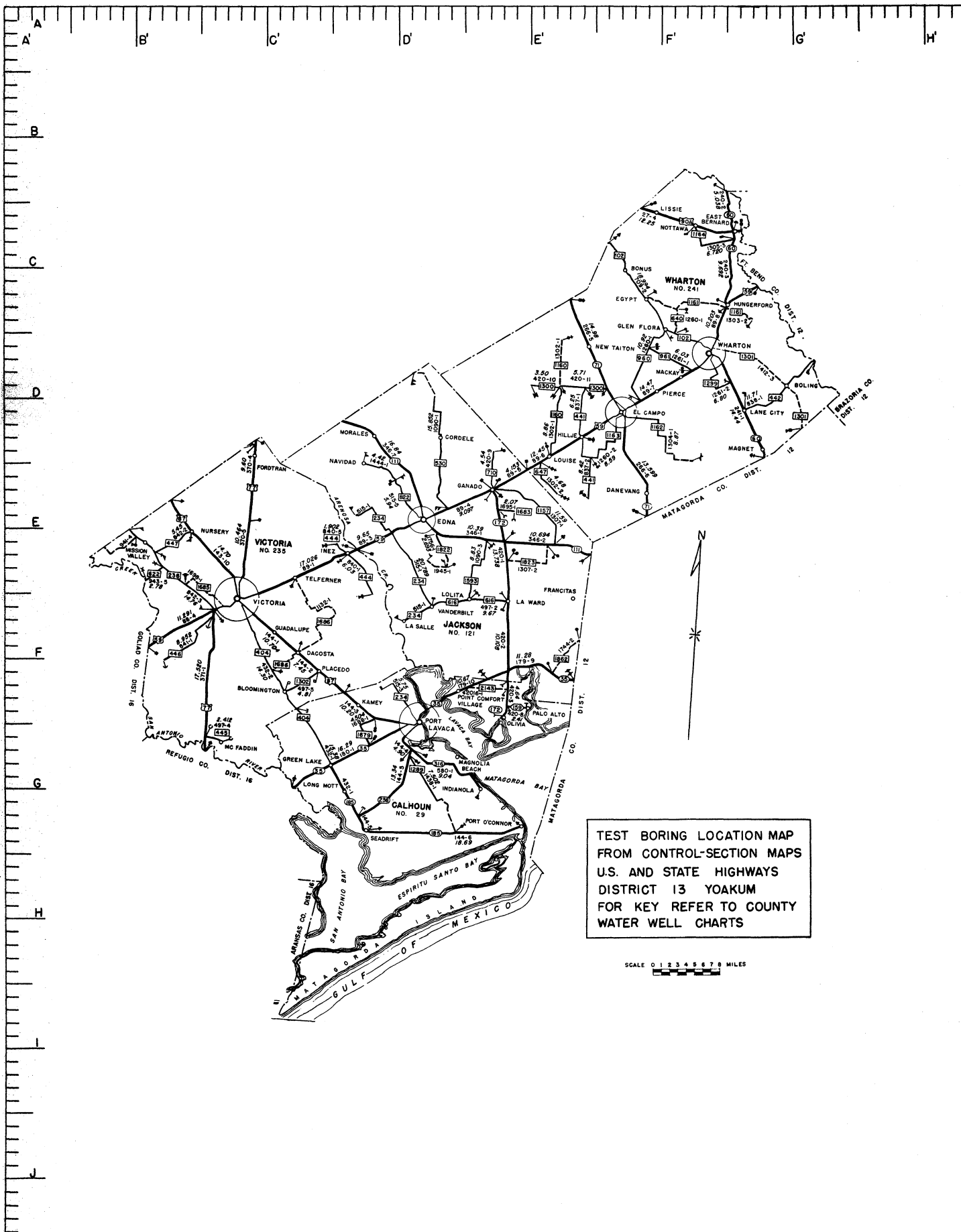
← WATER TABLE





WATER WELL CHARTS FOR ARANSAS AND REFUGIO COUNTIES - DISTRICT 16





TEST BORING LOCATION MAP
 FROM CONTROL-SECTION MAPS
 U.S. AND STATE HIGHWAYS
 DISTRICT 13 YOAKUM
 FOR KEY REFER TO COUNTY
 WATER WELL CHARTS

SCALE 0 1 2 3 4 5 6 7 8 9 MILES

