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Standard Guide for
Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance[1]

This standard is issued under the fixed designation G82; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers the development of a galvanic series and its subsequent use as a method of predicting the effect that one metal can have upon another metal can when they are in electrical contact while immersed in an electrolyte. Suggestions for avoiding known pitfalls are included.

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* Specific precautionary statements are given in Section 5.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

G3 Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing

G15 Terminology Relating to Corrosion and Corrosion Testing (Withdrawn 2010)[3]

G16 Guide for Applying Statistics to Analysis of Corrosion Data

G71 Guide for Conducting and Evaluating Galvanic Corrosion Tests in Electrolytes

3. Terminology

3.1 Definitions of terms used in this guide are from Terminology G15.

3.2 *active*—the negative (decreasingly oxidizing) direction of electrode potential.

3.3 *corrosion potential*—the potential of a corroding surface in an electrolyte relative to a reference electrode measured under open-circuit conditions.

3.4 *galvanic corrosion*—accelerated corrosion of a metal because of an electrical contact with a more noble metal or nonmetallic conductor in a corrosive electrolyte.

3.5 *galvanic series*—a list of metals and alloys arranged according to their relative corrosion potentials in a given environment.

3.6 *noble*—the positive (increasingly oxidizing) direction of electrode potential.

3.7 *passive*—the state of the metal surface characterized by low corrosion rates in a potential region that is strongly oxidizing for the metal.

3.8 *polarization*—the change from the open-circuit electrode potential as the result of the passage of current.

4. Significance and Use

4.1 When two dissimilar metals in electrical contact are exposed to a common electrolyte, one of the metals can undergo increased corrosion while the other can show decreased corrosion. This type of accelerated corrosion is referred to as galvanic corrosion. Because galvanic corrosion can occur at a high rate, it is important that a means be available to alert the user of products or equipment that involve the use of dissimilar metal combinations in an electrolyte of the possible effects of galvanic corrosion.

4.2 One method that is used to predict the effects of galvanic corrosion is to develop a galvanic series by arranging a list of the materials of interest in order of observed corrosion potentials in the environment and conditions of interest. The metal that will suffer increased corrosion in a galvanic couple in that environment can then be predicted from the relative position of the two metals in the series.

4.3 *Types of Galvanic Series:*

4.3.1 One type of Galvanic Series lists the metals of interest in order of their corrosion potentials, starting with the most active (electronegative) and proceeding in order to the most

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[1] This guide is under the jurisdiction of ASTM Committee G01 on Corrosion of Metalsand is the direct responsibility of Subcommittee G01.11 on Electrochemical Measurements in Corrosion Testing.

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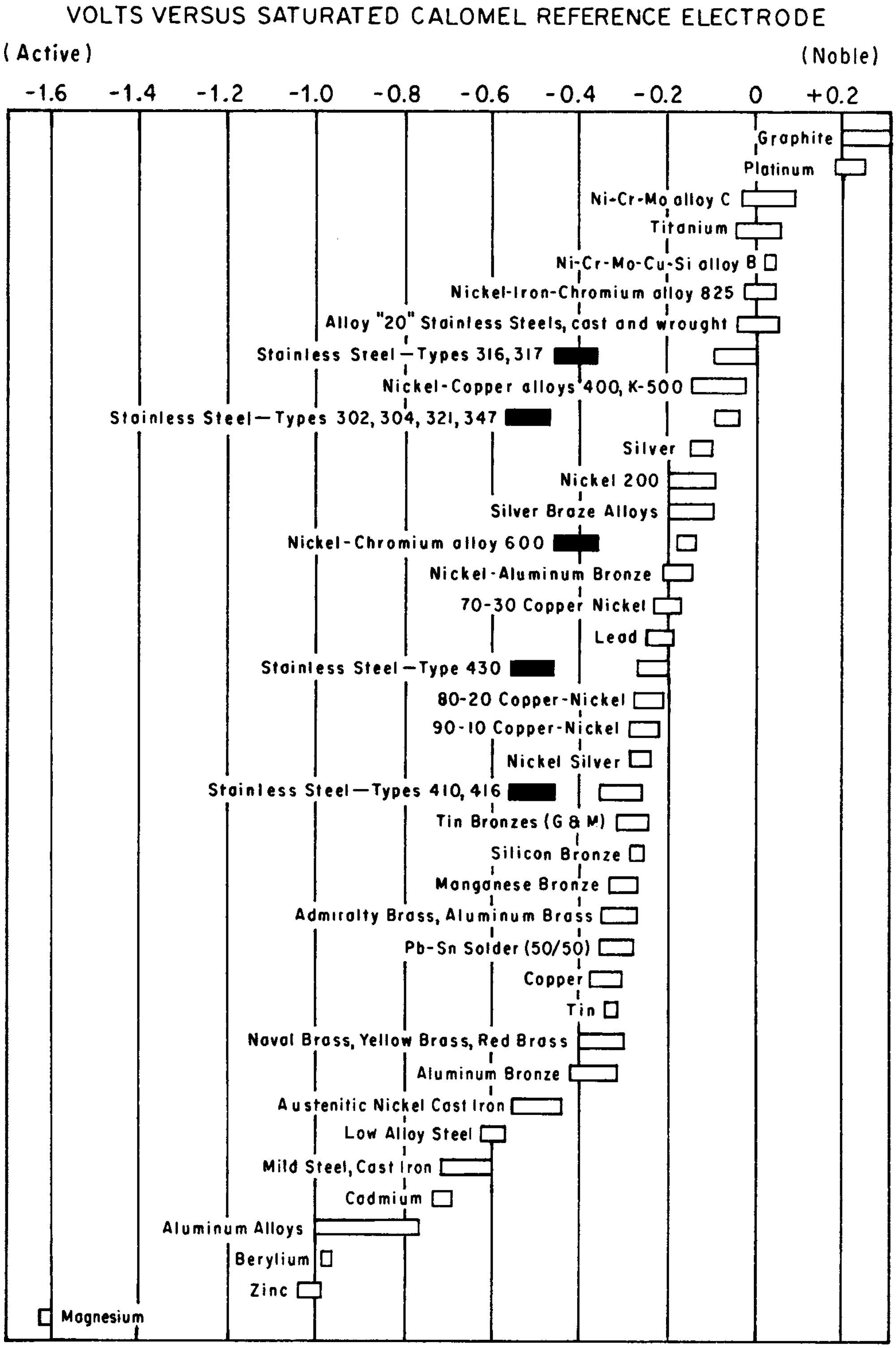
[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

noble (electropositive). The potentials themselves (versus an appropriate reference half-cell) are listed so that the potential difference between metals in the series can be determined. This type of Galvanic Series has been put in graphical form as a series of bars displaying the range of potentials exhibited by the metal listed opposite each bar. Such a series is illustrated in Fig. 1.



NOTE 1—Dark boxes indicate active behavior of active-passive alloys.

FIG. 1 Galvanic Series of Various Metals in Flowing Seawater at 2.4 to 4.0 m/s for 5 to 15 Days at 5 to 30°C (Redrawn from Original) (see Footnote 5)

4.3.2 The second type of galvanic series is similar to the first in that it lists the metals of interest in order of their corrosion potentials. The actual potentials themselves are not specified, however. Thus, only the relative position of materials in the series is known and not the magnitude of their potential difference. Such a series is shown in Fig. 2.

4.4 *Use of a Galvanic Series:*

4.4.1 Generally, upon coupling two metals in the Galvanic Series, the more active (electronegative) metal will have a tendency to undergo increased corrosion while the more noble (electropositive) metal will have a tendency to undergo reduced corrosion.

4.4.2 Usually, the further apart two metals are in the series, and thus the greater the potential difference between them, the greater is the driving force for galvanic corrosion. All other factors being equal, and subject to the precautions in Section 5, this increased driving force frequently, although not always, results in a greater degree of galvanic corrosion.

ACTIVE END	Magnesium
(–)	Magnesium Alloys
↑	Zinc
	Galvanized Steel
	Aluminum 1100
	Aluminum 6053
	Alclad
	Cadmium
	Aluminum 2024 (4.5 Cu, 1.5 Mg, 0.6 Mn)
	Mild Steel
	Wrought Iron
	Cast Iron
	13 % Chromium Stainless Steel
	Type 410 (Active)
	18-8 Stainless Steel
	Type 304 (Active)
	18-12-3 Stainless Steel
	Type 316 (Active)
	Lead-Tin Solders
	Lead
	Tin
	Muntz Metal
	Manganese Bronze
	Naval Brass
	Nickel (Active)
	76 Ni-16 Cr-7 Fe alloy (Active)
	60 Ni-30 Mo-6 Fe-1 Mn
	Yellow Brass
	Admirality Brass
	Aluminum Brass
	Red Brass
	Copper
	Silicon Bronze
	70:30 Cupro Nickel
	G-Bronze
	M-Bronze
	Silver Solder
	Nickel (Passive)
	76 Ni-16 Cr-7 Fe
	Alloy (Passive)
	67 Ni-33 Cu Alloy (Monel)
	13 % Chromium Stainless Steel
	Type 410 (Passive)
	Titanium
	18-8 Stainless Steel
	Type 304 (Passive)
	18-12-3 Stainless Steel
↓	Type 316 (Passive)
(+)	Silver
NOBLE or	Graphite
PASSIVE END	Gold
	Platinum

FIG. 2 Galvanic Series of Various Metals Exposed to Seawater (see Footnote 3)

5. Precautions in the Use of a Galvanic Series

5.1 The galvanic series should not be confused with the electromotive force series, which, although of a similar appearance to the galvanic series, is based on standard electrodepotentials of elements and not on corrosion potentials of metals. The electromotive force series should not be used for galvanic corrosion prediction.

5.2 Each series is specific to the environment for which it was compiled. For example, a series developed in a flowing ambient temperature seawater should not be used to predict the performance of galvanic couples in fresh water or in heated seawater.

5.3 Corrosion potentials can change with time and the environment. These changes can affect the potential difference between the metals of interest and, in some cases, can reverse relative positions. It is thus imperative that the series used for the prediction be obtained under similar conditions of exposure duration and electrolyte composition as the situation being predicted.

5.4 Galvanic corrosion can occur between two identical materials in different environments. The galvanic series generated herein cannot be applied to this situation.

5.5 Use of a galvanic series provides qualitative prediction of galvanic corrosion. It should not be used for quantitative predictions of galvanic corrosion rate. A more precise determination of the effect of galvanic coupling can be obtained by the measurement of the corrosion currents involved as outlined in Guide G71.[4,5]

5.6 Some published Galvanic Series, such as those in Fig. 1[6] and Fig. 2, consider the possibility of there being more than one potential range for the same material, depending on whether the material is in the active or the passive state. Knowledge of conditions affecting passivity of these materials is necessary to determine which potential range to use in a particular application.

5.7 Galvanic corrosion behavior is affected by many factors besides corrosion potentials. These factors must also be considered in judging the performance of a galvanic couple. They include, but are not limited to, the following:

5.7.1 Anode-to-cathode area ratio,

5.7.2 Electrolyte conductivity,

5.7.3 Distance between coupled metals,

5.7.4 Shielding of metal surfaces by marine growth, sediments, and so forth,

5.7.5 Localized electrolyte concentration changes in shielded areas, and

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[4] Brasunas, A., Editor, *NACE Basic Corrosion Course*, Chapter 3, NACE, Houston, TX, 1970.

[5] Baboian, R., "Electrochemical Techniques for Predicting Galvanic Corrosion," *Galvanic and Pitting Corrosion-Field and Laboratory Studies*, *ASTM STP 576*, Am. Soc. Testing Mats., 1976, pp. 5–19.

[6] LaQue, F. L., *Marine Corrosion, Causes and Prevention*, John Wiley and Sons, New York, NY, 1975.

5.7.6 Polarization characteristics of the metals involved.

5.8 Some materials that are subject to chemical attack in alkaline solutions may suffer increased attack when made the cathode in a galvanic couple due to generation of hydroxyl ions by the cathodic reaction. Use of a galvanic series will not predict this behavior.

5.9 A more detailed discussion of the theory of galvanic corrosion prediction is presented in Appendix X1 and in ASTM STP 576.[5]

6. Development of a Galvanic Series

6.1 The development of a Galvanic Series may be divided into several steps. First is the selection of the environment and conditions of interest. During the exposures, the environment and conditions should be as close as possible to service conditions. A list of environmental factors and conditions that could affect open-circuit potentials follows. This is not intended to be a complete listing, but it should serve as a guide to the types of factors that require consideration:

6.1.1 Temperature,

6.1.2 Flow velocity, and

6.1.3 Electrolyte composition:

6.1.3.1 Dissolved oxygen,

6.1.3.2 Salinity,

6.1.3.3 Heavy-metal ions,

6.1.3.4 Organic matter, including bacteria and marine growth,

6.1.3.5 Soluble corrosion products,

6.1.3.6 pH,

6.1.3.7 Conductivity,

6.1.3.8 Corrodents not part of the original environment (for example, de-icing salts, fertilizers, and industrial effluents), and

6.1.3.9 Waterline effects.

6.2 The metals of interest are to be obtained and prepared for exposure. The processing and surface condition of these metals should be as close as possible to the expected condition of the metals used in service. A list of factors that could affect the potentials of the metals follows. This is not intended to be a complete listing, but it should serve as a guide to the types of factors that require consideration:

6.2.1 Bulk composition,

6.2.2 Casting or wrought processing method,

6.2.3 Heat treatment, and

6.2.4 Surface condition:

6.2.4.1 Mill finish,

6.2.4.2 Degree of cold-work from surface preparation,

6.2.4.3 Corrosion product films,

6.2.4.4 Prior electrochemical history-passive versus active, and

6.2.4.5 Pits or shielded (crevice) areas.

6.3 Panels of the materials of interest should have electrical wires attached, with the attachment points protected from the electrolyte by coating of an appropriate nonconductive material or by the panels being mounted such that the point of electrical connection is not in contact with the electrolyte. A reference half-cell, which is stable in the environment of interest over the anticipated duration of exposure, should be selected. During exposure of the panels, their corrosion potential relative to the reference half-cell will be measured periodically, using a voltmeter.

6.3.1 The size of the panels, wire connections, and voltmeter input resistance should be selected to preclude errors caused by polarization of the panel material, any voltage drop in the wire, and polarization of the reference half-cell during the potential measurement procedure.

6.3.2 Exposure duration should be sufficiently long to be indicative of the anticipated service condition.

6.3.3 Potentials should be measured frequently enough to provide good indications of potential variability during exposure, as well as systematic potential shifts that may occur.

6.3.4 If the intent is to simulate long-term service, the potential readings should show no systematic variation over the latter portion of the exposures which would preclude the accurate extrapolation of the data to the service times of interest.

6.4 Information relevant to selecting environment and materials, as well as to the mounting of specimens and taking data, may be found in Practice G71.

7. Report

7.1 The report concerning the development of the galvanic series should include as much detailed information as possible, such as the following:

7.1.1 The metallurgical history of the metals tested, including the factors listed in 6.2,

7.1.2 The size, shape, and surface preparation of panels before exposure, and the method used to hold the panels,

7.1.3 The environment and conditions, including those items listed in 6.1,

7.1.4 The equipment and procedure used for potential measurements,

7.1.5 The exposure duration and potential measurement frequency,

7.1.6 The condition of panels after exposure, and type of corrosion, and

7.1.7 A listing of the materials arranged in order of average or steady-state corrosion potential over the time of interest. This list should follow the guidelines set forth in Practice G3.

7.1.7.1 The measured corrosion potential for each material may be listed beside that material in the form of an average or steady-state value with or without a standard deviation or other error band as calculated by procedures in Practice G16, or in the form of a total range of potentials. This information may be plotted in bar graph form.

7.1.7.2 The final listing or graph should contain an indication of the noble and active directions, and sufficient information about the conditions under which the series was obtained to prevent misuse of the series for other environments and conditions.

8. Keywords

8.1 active; corrosion potential; galvanic corrosion; Galvanic Series; noble; passive

APPENDIX

(Nonmandatory Information)

X1. THEORY OF GALVANIC CORROSION

X1.1 The difference in electrochemical potential between two or more dissimilar metals in electrical contact and in the same electrolyte causes electron flow between them. Attack of the more noble metal or metals is usually decreased, and corrosion of the more active metal is usually increased.

X1.2 Under the influence of galvanic coupling, appreciable polarization of the metals may occur, which may produce a protective film on the metal surface or which may cause breakdown of an already existing protective film. This effect is commonly observed with stainless steel. Thus, an overall characterization of each metal in the galvanic couple is necessary to evaluate the behavior of the metals in a particular corrosive environment.

X1.3 Galvanic corrosion of metals can be treated by application of the mixed potential theory first described by Wagner and Traud.[7] The theory is based on two simple hypotheses: (*1*) any electrochemical reaction can be divided into two or more oxidation or reduction reactions, and (*2*) there can be no net accumulation of electrical charge during an electrochemical reaction.

X1.4 Under the simplest circumstance, metallic corrosion would involve only two reactions, oxidation and reduction. The corrosion of iron in sulfuric acid (H_2SO_4) involves the anodic dissolution of iron and the evolution of hydrogen. This is demonstrated by the polarization curves for iron in 0.52 N H_2SO_4 in Fig. X1.1. The first hypothesis of the mixed potential theory is satisfied if one considers that each reaction has its own reversible potential and polarization parameters. The second hypothesis, that the total rate of oxidation equals the total rate of reduction, is only satisfied at the intersection E_{corr}, the corrosion of *mixed* potential. At this point the rate of iron dissolution is equal to the rate of hydrogen evolution. The potential is so displaced from the equilibrium potential that the reverse reactions occur at a negligible rate and do not influence the corrosion rate.

X1.5 In Fig. X1.1, the data indicate that iron will corrode at a rate of about 0.4 mA/cm^2 and will exhibit a potential of about −0.52 V versus the saturated calomel electrode (SCE).

X1.6 When two different corroding metals are coupled electrically in the same electrolyte, both metals are polarized so that each corrodes at a new rate. Fig. X1.1 shows the corrosion potentials and polarization parameters for uncoupled Metals A and B. Metal A is more noble than Metal B in that the equilibrium potential is less negative. When the mixed potential theory is applied to the individual reactions (A/A^+, H_2/H^+, B/B^+, H_2/H^+), the uncoupled corrosion rates are $i_{corr,A}$ for Metal A and $i_{corr,B}$ for Metal B. When equal areas of Metals A and B are coupled, the resultant mixed potential of the system $E_{corr,AB}$ is at the intersection where the total oxidation rate equals the total reduction rate. The rate of oxidation of the individual coupled metals is such that Metal A corrodes at a reduced rate $i'_{corr,A}$ and Metal B corrodes at an increased rate $i'_{corr,B}$.

X1.7 The information required to predict the corrosion behavior of galvanically coupled Metals A and B is shown in Fig. X1.2. In addition to the anodic polarization curves for Metals A and B, it is necessary to measure either the cathodic polarization curves for these metals or the mixed potential of the galvanic couple ($E_{corr,AB}$) under actual environmental conditions, because the nature of the cathodic reactions can have a marked influence on the mixed potential. The two electrodes are not always polarized equally (mixed control), and the coupled potential can shift to either a more negative (cathodic control) or positive (anodic control) direction, as shown in Fig. X1.3. In this figure the current i_{AB} is the galvanic current which can be measured by a zero resistance ammeter.

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[7] Wagner, C., and Traud, W., *Z. Elektrochem*, Vol 44, 1938, p. 391.

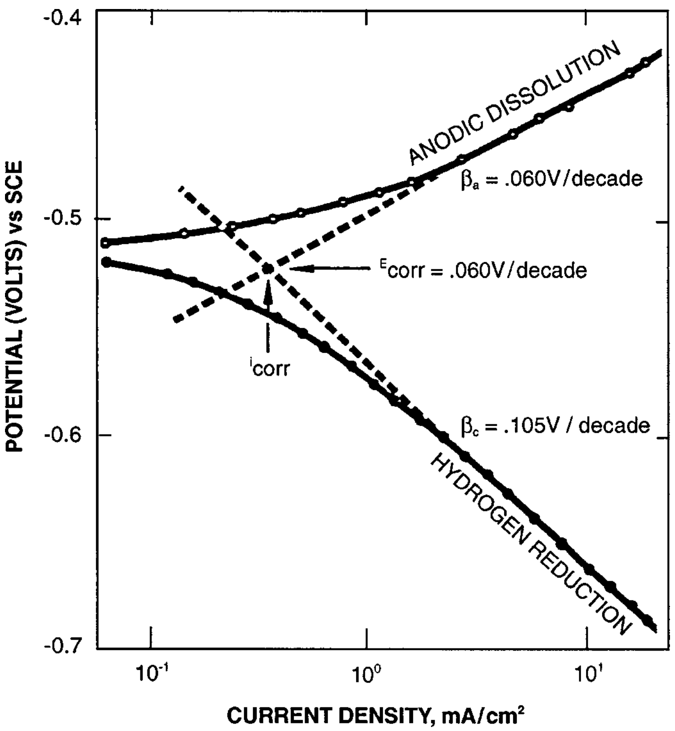

FIG. X1.1 Polarization Behavior of Iron in Deaerated 0.52 *N* Sulfuric Acid

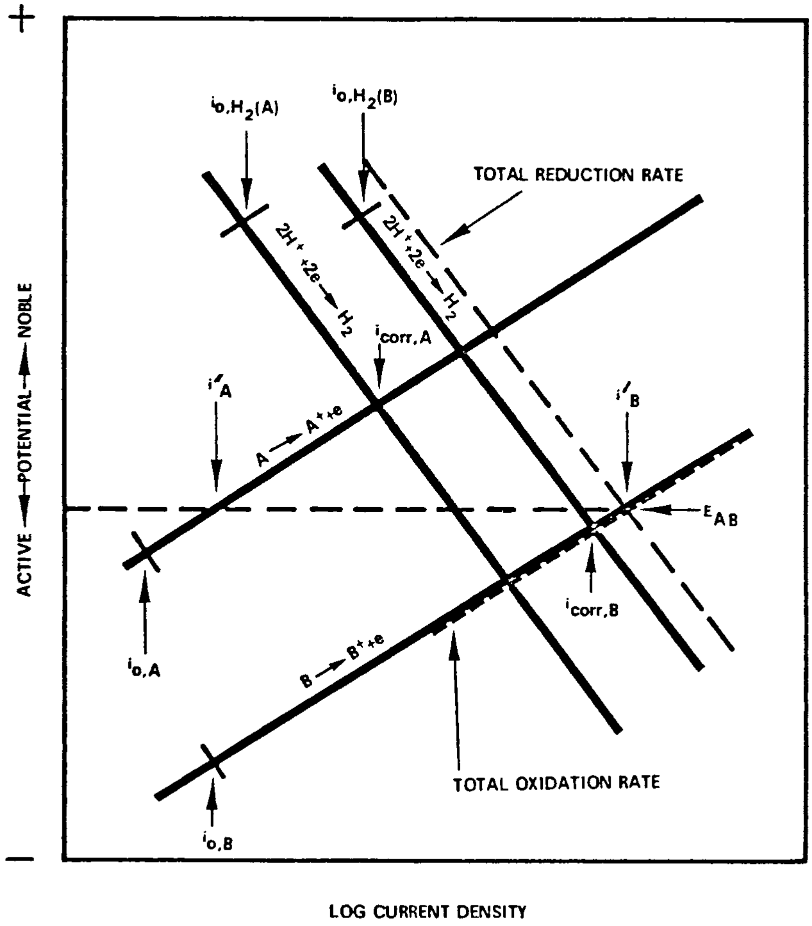

FIG. X1.2 Corrosion Behavior of Galvanically Coupled Metals A and B in the Case of Charge Transfer Control (not diffusion limited)

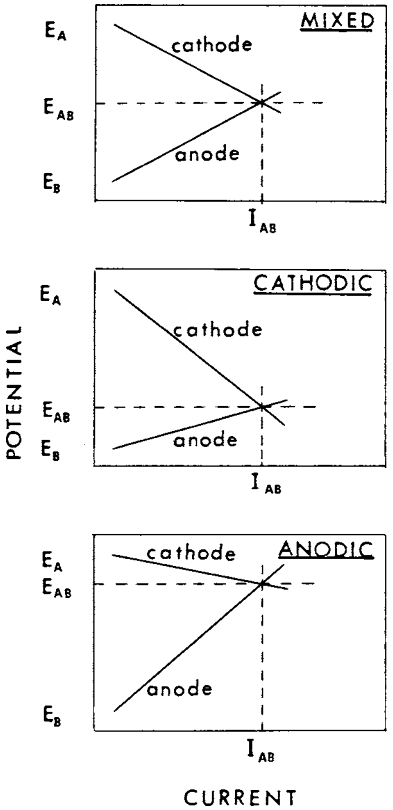

FIG. X1.3 Effects of Polarization on Metal Potential

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