MIL-STD-889B
7 July 1976

SUPERSEDING
MIL-STD-889A
25 September 1969

MILITARY STANDARD

DISSIMILAR METALS

FSC MFFP

DEPARTMENT OF DEFENSE

Dissimilar Metals

MIL-STD-889

1. This Military Standard has been approved by the Department of Defense and is mandatory for use by all Departments and Agencies of the Department of Defense.

2. Recommended corrections, additions, or deletions should be addressed to Air Force Materials Laboratory, Attn: MXA, Wright-Patterson Air Force Base, Ohio 45433.

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DISSIMILAR METALS

1. SCOPE.

1.1 Purpose. This standard defines and classifies dissimilar metals, and establishes requirements for protecting coupled dissimilar metals, with attention directed to the anodic member of the couple, against corrosion.

1.1.1 Applicability. This standard is applicable to all military equipment parts, components and assemblies.

2. REFERENCED DOCUMENTS.

2.1 Issues of documents. The following documents of the issue in effect on date of invitation for bids or request for proposal, form a part of this standard to the extent specified herein.

SPECIFICATIONS

MILITARY

MIL-S-8802	Sealing Compound, Temperature-Resistant, Integral Fuel Tanks and Fuel Cell Cavities, High Adhesion

(Copies of specifications, standards, drawings, and publications required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

FSC MFFP

3. DEFINITIONS.

3.1 Dissimilar metals. This standard terms metals dissimilar when two metal specimens are in contact or otherwise electrically connected to each other in a conductive solution and generate an electric current.

3.2 Galvanic corrosion. Galvanic corrosion manifests itself in the accelerated corrosion caused to the more active metal (anode) of a dissimilar metal couple in an electrolyte solution or medium, and decreased corrosive effects on the less active metal (cathode), as compared to the corrosion of the individual metals, when not connected, in the same electrolyte environment.

3.3 Galvanic series. A galvanic series is a listing of metals and alloys based on their order and tendency to corrode independently, in a particular electrolyte solution or other environment. This tendency for dissolution or corrosion is related to the electrical potential of the metal in conductive medium. Galvanic corrosion is inherently affected by the relative position of the galvanic series of the metals constituting the couple. Metals closely positioned in the series will have electrical potentials nearer one another, whereas with greater divergence in position, greater differences in potential will prevail. Galvanic effects, i.e., corrosion of the anode will in the former condition be minimal, the latter condition will exhibit more significant corrosive effects. A galvanic series for corrosion structural metals, for sea water, is shown in Table II. A supplemental galvanic series is given in Table II.

4. GENERAL STATEMENTS. (Not Applicable)

5. DETAILED REQUIREMENTS.

5.1 Minimizing dissimilar metal corrosion.

5.1.1 When dissimilar metals are used in intimate contact, suitable protection against galvanic corrosion shall be applied. In some environments particularly with metals such as magnesium, steel, zinc, aluminum, in contact with copper, stainless steel, nickel, galvanic corrosion may be appreciable. Consequently, care should be taken to protect the anodic member by proper electrical insulation of the joint or by excluding the electrolyte if this is feasible.

5.1.2 Table I and Table II list metal in the order of their relative activity in sea water environment. The list begins with the more active (anodic) metal and procedes down to the least active (cathodic) metal of the galvanic series. A "galvanic series" applies to a particular electrolyte solution; hence for each specific solution which is expected to be encountered for actual use, a different order or series will ensue. Galvanic series relationships are useful as a guide for selecting metals to be joined, will help the selection of metals having minimal tendency to interact galvanically, or will indicate the need or degree of protection to be applied to lessen the expected potential interactions. Generally, the closer one metal is to another in the series, the more compatible they will be, i.e., the galvanic effects will be minimal; conversely, the farther one metal is from another, the greater will be the effect. In a galvanic couple, the metal higher in the series represents the anode, and will corrode preferentially in the environment.

5.1.3 Metals widely separated in the galvanic series must be protected if they are to be joined. Appropriate measure should be taken to avoid contact. This can be accomplished by applying to the cathodic member a sacrificial metal coating having a potential similar to or near that of the anodic member; by sealing to insure that the faying surfaces are water-tight; by painting or coating all surfaces to increase the resistance of electrical circuit.

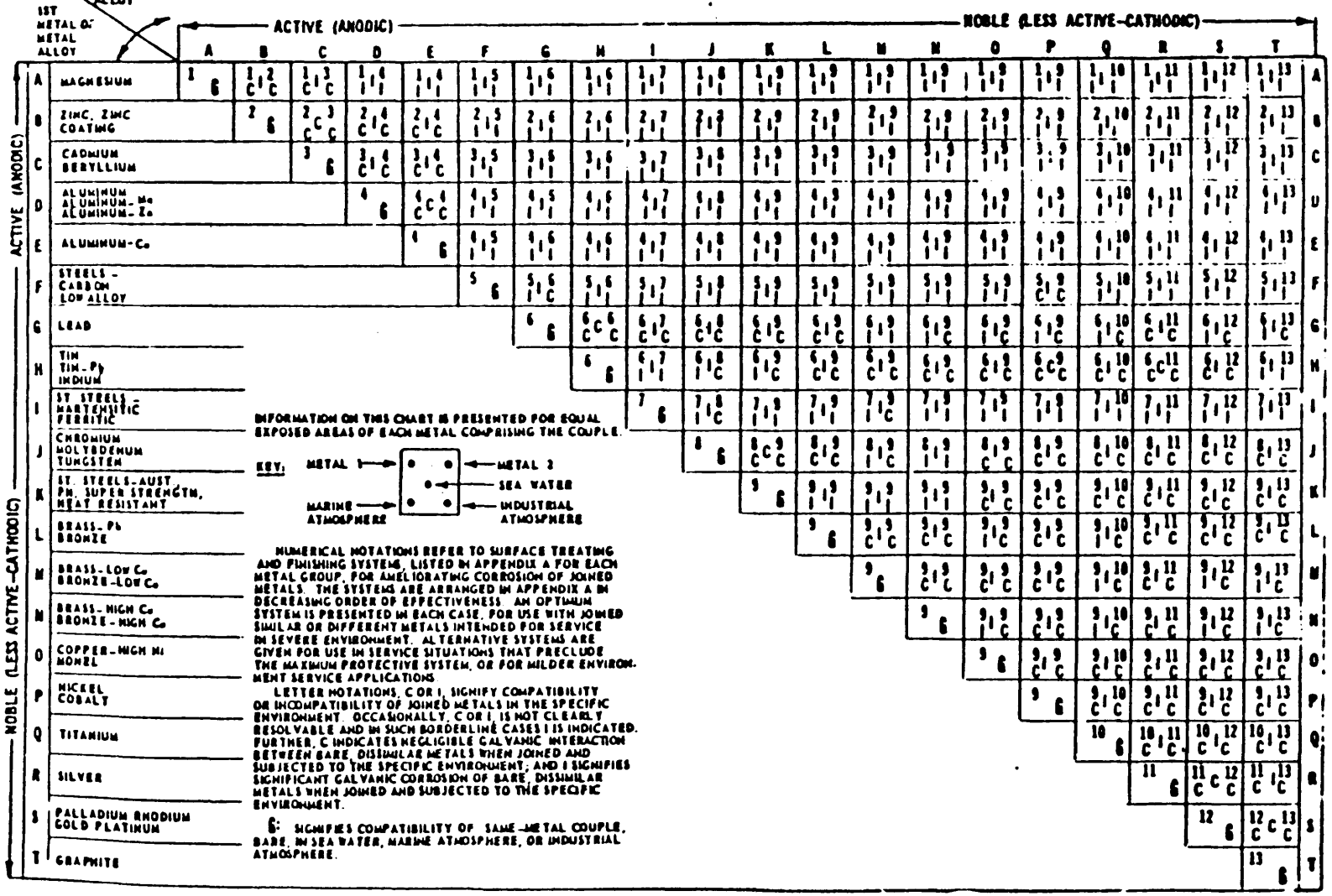
5.1.4 A small anodic area relative to the cathodic area should be avoided. The same metal or more noble (cathodic) metals should be utilized for small fasteners, and bolts. The larger is the relative anode area, the lower the galvanic current density on the anode, the lesser the attack. The galvanic corrosion effect may be considered as inverse to the anode-cathode area ratio.

5.1.5 Metals exposed to sea water environments shall be corrosion and stress-corrosion resistant or shall be processed to resist corrosion and stress-corrosion. Irrespective of the metals involved, all exposed edges should be sealed with a suitable sealant material conforming to MIL-S-8802. When non-compatible materials are joined, an interposing material compatible with each shall be used.

5.1.6 Materials other than true metals, i.e., non-metallic materials, which must be joined to metals, should be considered as metallic materials, unless there is supporting evidence to the contrary. If these materials are essentially free of corrosive agents (salts), free of

TABLE 1.

GUIDE TO USE OF JOINED STRUCTURAL METALS AND ALLOYS AND PROTECTIVE SYSTEMS FOR SERVICE IN SEA WATER, MARINE ATMOSPHERE AND INDUSTRIAL ATMOSPHERE



INFORMATION ON THIS CHART IS PRESENTED FOR EQUAL EXPOSED AREAS OF EACH METAL COMPRISING THE COUPLE.

NUMERICAL NOTATIONS REFER TO SURFACE TREATING AND FINISHING SYSTEMS, LISTED IN APPENDIX A FOR EACH METAL GROUP, FOR AMELIORATING CORROSION OF JOINED METALS. THE SYSTEMS ARE ARRANGED IN APPENDIX A IN DECREASING ORDER OF EFFECTIVENESS. AN OPTIMUM SYSTEM IS PRESENTED IN EACH CASE, FOR USE WITH JOINED SIMILAR OR DIFFERENT METALS INTENDED FOR SERVICE IN SEVERE ENVIRONMENT. ALTERNATIVE SYSTEMS ARE GIVEN FOR USE IN SERVICE SITUATIONS THAT PRECLUDE THE MAXIMUM PROTECTIVE SYSTEM, OR FOR MILDER ENVIRONMENT SERVICE APPLICATIONS.

LETTER NOTATIONS, C OR I, SIGNIFY COMPATIBILITY OR INCOMPATIBILITY OF JOINED METALS IN THE SPECIFIC ENVIRONMENT. OCCASIONALLY, C OR I, IS NOT CLEARLY RESOLVABLE AND IN SUCH BORDERLINE CASES I IS INDICATED. FURTHER, C INDICATES NEGLIGIBLE GALVANIC INTERACTION BETWEEN BARE, DISSIMILAR METALS WHEN JOINED AND SUBJECTED TO THE SPECIFIC ENVIRONMENT; AND I SIGNIFIES SIGNIFICANT GALVANIC CORROSION OF BARE, DISSIMILAR METALS WHEN JOINED AND SUBJECTED TO THE SPECIFIC ENVIRONMENT.

6: SIGNIFIES COMPATIBILITY OF SAME-METAL COUPLE, BARE, IN SEA WATER, MARINE ATMOSPHERE, OR INDUSTRIAL ATMOSPHERE.

TABLE II. Galvanic series of selected metals in seawater.

Active (Anodic)

Magnesium (Mg)
Mg Alloy AZ-31B
Mg Alloy HK-31A
Zinc (pl. hot-dip, die cast)
Beryllium (hot pressed)
Aluminum (Al) 7072 cl. on 7075
Al alloy 2014-T3
Al alloy 1160-H14
Al alloy 7079-T6
Cadmium (pl.)
Uranium (depl.)
Al alloy 218 (die cast)
Al alloy 5052-0
Al alloy 5052-H12
Al alloy 7151-T6
Al alloy 5456-0, H353
Al alloy 5052-H32
Al alloy 1100-0
Al alloy 3003-H25
Al alloy 6061-T6
Al alloy 7071-T6
Al alloy A360 (die cast)
Al alloy 7075-T6
Al alloy 1100-H14
Al alloy 6061-0
Indium
Al alloy 2014-0
Al alloy 2024-T4
Al alloy 5052-H16
Tin (pl.)
Stainless steel 430 (active)
Lead
Steel 1010
Iron, cast
Stainless steel 410 (active)
Copper (pl.)
Nickel (pl.)
Chromium (pl.)
Tantalium
Stainless steel 350 (active)
Stainless steel 310 (active)
Stainless steel 301 (active)
Stainless steel 304 (active)
Stainless steel 430 (passive)
Stainless steel 410 (passive)
Stainless steel 17-7 pH (active)
Tungsten
Niobium (Columbium) 1% Zr
Brass, yellow, 268
Uranium (depl.) 8% Mo.
Brass, Naval, 464
Yellow brass
Muntz metal 280
Brass (pl.)
Nickel-silver (18% Ag)
Stainless steel 316L (active)
Bronze 220
Everdur 655
Copper 110
Red brass
Stainless steel 347 (active)
Molybdenum, Comm pure
Copper-Nickel 7151
Admiralty brass
Stainless steel 202 (active)
Bronze, phosphor 534 (B-1)
Stainless steel 202 (active)
Monel
Stainless steel 201 (active)
Steel alloy Carpenter 20 (active)
Stainless steel 321 (active)
Stainless steel 316 (active)
Stainless steel 309 (passive)
Stainless steel 17-7 pH (passive)

TABLE II (Continued)

Stainless steel 304 (passive)
Stainless steel 301 (passive)
Stainless steel 321 (passive)
Stainless steel 201 (passive)
Stainless steel 286 (active)
Stainless steel 316L (passive)
Steel alloy AM355 (active)
Stainless steel 202 (active)
Steel alloy, Carpenter 20 (passive)
Steel alloy AM350 (passive)
Steel alloy 286 (passive)
Titanium 5Al, 2.5 Sn.
Titanium 13V, 11Cr, 3Al. (annealed)
Titanium 6Al, 4V (h.t + aged)
Titanium 6 Al, 4V (annealed)
Titanium 8Mm.
Titanium 3 Al, 13V, 11Cr (h.t + aged)
Titanium 75A
Stainless steel 350 (passive)
Graphite

Noble (Less Active-Cathodic)

acid or alkaline materials (neutral pH), and free of carbon or metallic particles, not subject to biodeterioration or will not support fungal growth, and do not absorb or wick water, then these may be considered non-metallics suitable for joining to metals. Many materials classed non-metallic will initiate corrosion of metals to which they are joined, e.g., cellulosic reinforced plastics, carbon or metal loaded resin materials, asbestos-cement composites.

5.1.7 Where magnesium is one of the metals involved in the dissimilar metal combination or where stainless steel is used in contact with itself, it is required that the edges of the joint be adequately sealed to prevent excess galvanic or crevice attack. Where it is not required that the material be electrically contacted, then a non-metallic insulating gasketing material may be used.

5.1.8 If the environment to which the couple is to be exposed is highly aggressive, it is advisable to employ maximum protective measures, otherwise some compromise in the protective system could be allowed. In any event, maximum protective systems always should be employed when magnesium is one of the metals involved, whether or not the combination is to serve in an electrical conducting system.

5.2 Precautions and methods for joining. Where it becomes necessary that relatively incompatible metals must be assembled, the following precautions and joining methods are provided for alleviation of galvanic corrosion.

a. Select materials which are indicated to be more compatible in accordance with the galvanic series; design metal couples so that the area of the cathode is smaller (appreciably) than the area of the anodic metal. For example, bolts or screws of stainless steel for fastening aluminum sheet, but not the reverse. Interpose a compatible metallic gasket or washer between the dissimilar metals prior to fastening; or plate the cathodic member with a metal compatible to the anode. These are applicable to couples which are to serve as an electrical connection.

b. Interpose a non-absorbing, inert gasketing material or washer between the dissimilar materials prior to connecting them. This is applicable to couples which are not to serve as electrical conductors.

c. Seal all faying edges to preclude the entrance of liquids.

d. Apply corrosion-inhibiting pastes or compounds under heads of screws or bolts inserted into dissimilar metal surfaces whether or not the fasteners had been previously plated or otherwise treated. In some instances, it may be feasible to apply an organic coating to the faying surfaces prior to assembly. This would be applicable to joints which are not required to be electrically conductive.

e. Where practicable or where it will not interfere with the proposed use of the assembly, the external joint should be coated externally with an effective paint system.

f. Welded or brazed dissimilar metal assemblies should be coated with a paint system or other suitable protective coatings to at least 1/3 inch beyond the heat affected zone.

g. In so called protective environments (usually referred to as humidity-controlled) caution should be applied to dissimilar metal combination treatments. If the assumption is made that no corrosion will occur because humidity control will be maintained, the stringent requirements would be unnecessary. It must be recognized that humidity and moisture controlled environments can be assured only by hermatically sealed compartments or containers in which the moisture vapor content has been adequately reduced, so as to preclude condensation of water at the lowest temperature expected to be encountered in the actual surface of the item. If humidity and condensate control cannot be maintained or is uncertain (frequently this is so) then dissimilar metal contacts should be treated as if protection were required against the worst environment.

6. APPENDICES.

6.1 Appendix A. Lists priority protective treatments and systems for each metal or alloy. This listing should be consulted for the selection of systems to be applied in the joining of dissimilar metals. The surface finishes provided in the sublistings under each metal give the optimum first, and others in descending order of preference. Environmental conditions to which the couple is expected to be subjected in service must be taken into account. Assurance should be established that lesser protective systems if selected, will fulfill the need. Considerations must be given to these factors: service conditions, electrical

requirements, design requirements, minimization of maintenance and cost. Costs should not compromise the level of protection desired. Specific reviews of proposed protective systems for dissimilar metal couples should be performed by the procuring agency, and authorization of the agency for the use of the selected systems is required prior to their introduction or adoption.

6.2 Appendix B. The principal factors that are involved in the phenomenon of galvanic corrosion are explained.

CUSTODIANS:
Army - EL
Navy - AS
Air Force - 11

REVIEW ACTIVITIES:
Army - MU
Navy - EC, OS
Air Force - 13, 17, 99

USER ACTIVITIES:
Army - MR
Navy - None
Air Force - None

PREPARING ACTIVITY:
Air Force - 11

PROJECT NUMBER: MFFP-0113

APPENDIX A

RECOMMENDED TREATMENTS IN ORDER OF PROTECTIVE EFFECTIVENESS

10. GENERAL

10.1 Scope. This appendix lists protective systems for each metal or alloy with optimum treatments listed first, and others in descending order of preference.

10.2 Application. Each listing is presented as a guide only each application must be reviewed considering service conditions, design requirements and maintenance costs.

20. REFERENCE DOCUMENTS

SPECIFICATIONS

FEDERAL

QQ-P-416	Plating Cadmium (Electrodeposited)
TT-C-490	Cleaning Method And Pretreatment of Ferrous Surfaces For Organic Coatings

MILITARY

MIL-M-3171	Magnesium Alloy, Anodic Treatment of
MIL-C-5541	Chemical Conversion Coatings On Aluminum And Aluminum Alloys
MIL-C-8514	Coating Compound, Metal Pretreatment, Resin-acid (Asg)
MIL-A-8625	Anodic Coatings, For Aluminum And Aluminum Alloys
MIL-C-8837	Coating, Cadmium (Vacuum Deposited)
MIL-P-15328	Primer (Wash), Pretreatment, Blue (Formula No. 117-B For Metals)
MIL-P-16232	Phosphate Coating, Heavy, Manganese Or Zinz Base (For Ferrous Metals)
MIL-C-17711	Coatings Chromate, For Zinc Alloy Castings And Hot-dip Galvanized Surfaces
MIL-C-26074	Coating, Electroless Nickel, Requirements For

MILITARY (CON'T)

MIL-M-45202	Magnesium Alloy, Anodic Treatment of
MIL-C-81562	Coating, Cadmium And Zinc (Mechanically Deposited)
MIL-A-81801	Anodic Coatings For Zinc And Zinc Alloys

30. Recommended Treatments in Order of Protective Effectiveness

Treatments specified herein represent a decreasing order of protectiveness for the metals to which they apply. Where a choice of treatment can be exercised and long-range economics permit, the selection of treatments should be made accordingly. Specific enhancing effects can be accomplished by selecting the treatments of higher level for each metal when the metals are to be coupled and so used. Alternately, high-degree protection frequently is achieved where the optimum treatment is selected for one metal, and a second or third option is taken for the second metal. In atmospheric corrosion considerations, where costs must be taken into account, it makes much sense to select a higher-level treatment for the more active metal, and an alternate treatment for the less active metal. This choice takes into account the fact that the more active metal is likely to undergo more corrosion initially, even under mild conditions when galvanic effects would be minimal. Hence, cathodic control of corrosion, frequently useful in electrolytic solutions, virtually is inoperative under usual atmospheric exposure conditions.

30.1 Treatment for Magnesium

a. Anodic coating (MIL-M-45202) + alkali-resistant paint system or resin seal.

b. Chromate conversion coating (MIL-M-3171) + alkali-resistant paint or resin system. Alternate for general use in non-persistent wet or marine atmosphere; or anodic coating without organic system.

c. Metallic coating, electroless nickel (MIL-C-26074B) + cadmium overplating (QQ-P-416). For electrical, thermal conducting purposes, in absence of wet, saline or acidic atmospheric conditions.

d. Chromate treatment. Suitable for assured condensation and acid-free conditions.

Note: Bare magnesium shall not be used.

30.2 Treatment for Zinc and Zinc Coatings

a. Anodic coating (MIL-A-81801) + paint or resin coating system-primarily for castings.

b. Chromate conversion coating (MIL-C-17711) + paint or resin system; or anodic coating without organic system. For use in non-persistent wet or marine atmosphere. For electrical, thermal conducting purposes in mild atmospheres in absence of wet, saline or acidic conditions.

c. Chromate conversion coating without paint or resin coating system.

Note: Bare, plated zinc shall not be used in a marine environment.

30.3 Treatment for Cadmium or Beryllium

a. Chromate conversion coating (QQ-P-416, MIL-C-8837 or MIL-C-81562) + paint or resin coating system.

b. Chromate conversion coating without organic system. For use in non-persistent wet or marine atmosphere. For electrical, thermal conducting purposes in mild atmospheres in absence of wet, saline or acidic conditions. Recommended for beryllium in high temperature applications to forestall catastrophic oxidation in oxygen containing atmosphere.

30.4 Treatment for Aluminum and Aluminum Alloys

a. Anodic coating (MIL-A-8625) + paint or resin coating system.

b. Chromate conversion coating (MIL-C-5541) + paint or resin coating system; or anodic coating, sealed, with resin seal (when porous castings are used, impregnated with resin prior to surface treating and finishing).

c. Chromate conversion coating without paint or resin coating, for electrical, thermal conducting purposes in mild atmospheres in absence of saline, alkaline or acidic conditions.

d. Bare aluminum - may be used when surface treating would interfere with application, under conditions free of salinity or extended wetness, or when high corrosion resistant alloys are used. Faying edges should be sealed to prevent crevice corrosion.

30.5 Treatment for Carbon and Low Alloy Steels

a. Metallic coating (e.g., sacrifical Zn, Cd + chromate treatment, or non-sacrificial Cu, Ni) + paint coating system. For steels of strengths greater than 220 ksi metallic coatings to be applied by non-electrolytic methods; zinc or cadmium prohibited. For steels of strengths up to 220 ksi metallic coatings may be applied electrolytically, but the steel should be stress relieved before plating and hydrogen embrittlement relieved after plating.

b. Metallic coating, e.g., sacrificial Zn or Cd, with supplemental surface treatment, or non-sacrificial, e.g., Cu or Ni, without paint coating system, for direct metallic contact or for achieving least potential difference between joined metals. For metals of strengths greater than 220 ksi, metallic coating, if required, to be applied by non-electrolytic methods; zinc or cadmium prohibited.

c. Zinc phosphate conversion coating (TT-C-490) + paint coating system. Caution, if phosphate coating used on steels of strengths between 150 to 220 ksi, hydrogen relief required; stress relief required prior to phosphating and hydrogen embrittlement required after phosphating.

d. Pretreatment primer (MIL-P-15328, MIL-C-8514) + paint coating system.

e. Heavy phosphate conversion coating (MIL-P-16232) + supplemental treatment. Not for steels of strengths greater than 220 ksi.

Note: Bare steel not recommended.

30.6 Treatment for Lead, Tin, Solders, and Indium

Coatings of these materials applied to other metals by hot-dipping, fusing, or electroplating processes.

a. Coat with paint or resin coating system. Electroplated coatings should be "flowed" prior to applying coating system.

b. Electroplate with other metal to reduce the electropotential difference of metals being joined, where direct contact of metals required for electrical purposes.

30.7 Treatment for Steels-Carbon, Lo Alloy, Martensitic and Ferritic Stainless

Steels with chromium contents in the region of 12 percent will undergo considerable surface staining and limited rusting in corrosive environments, but on the whole are appreciably less corroded than carbon steels.

a. Paint or apply resin coating; zinc phosphate carbon steels prior to application of paint or resin coating.

b. May be electroplated, or used bare for use in non-persistent wet or marine atmosphere, and for electrical or thermal conducting purposes. Faying edges to be sealed to prevent crevice corrosion.

30.8 Treatment for Chromium (plate), Molybdenum, Tungsten

a. Paint or apply resin coating to reduce corrosion at voids in chromium plating, or staining of molybdenum or tungsten surfaces.

b. Normally may be used bare for electrical wear resistance, or thermal conducting purposes. Seal faying edges to mitigate crevice attack of metal to which joined.

30.9 Treatment for Steels Stainless-Austenitic, PH, Super Strength, Heat Resistant, Brass-Leaded, Bronze, Brass Bronze-Lo Copper, and Copper High Nickel

a. Apply metallic coating as may be required to minimize electrical potential difference between the metals to be joined and apply paint or resin coating system, primarily to diminish ion contamination from metals of this group onto more anodic metals to which they might be joined, thereby diminishing potential damage to the more anodic metal.

b. Apply metallic coating (as "a" above), use without paint or resin coating, for electrical or thermal conducting purposes. May be expedient to overcoat completed assembly with paint or resin.

c. Apply paint or resin coating system and seal faying edges.

d. Use bare and seal faying edges for electrical and thermal conducting purposes, if more anodic metals are not directly joined or in close proximity to receive rundown of surface condensate.

e. Select galvanically compatible metals required to be coupled for high temperature applications, where metallic coatings may not be useful and paint or resin coatings are impractical.

30.10 Treatment for Titanium

a. Anodize, for anti-galling and wear resistance.

b. Apply metallic coating (Cd, Zn prohibited, Ag over Ni acceptable) + paint or resin coating.

c. Apply metallic coating (Cd, Zn prohibited, Ag over Ni acceptable), seal faying edges. For electrical or thermal conducting purposes.

d. May be used bare with faying edges sealed in contact with metals other than magnesium, zinc or cadmium; for electrical or thermal conducting purposes.

30.11 Treatment for Silver

a. Silver or silver plated parts to be used as electrical, open-close contact points, plugs and receptacles should be plated over with rhodium, palladium or gold.

b. May be used in stationary components of electrical assemblies, e.g., connectors, printed circuits, but should be enveloped by sulfur-free conformal coatings.

c. Apply chromate conversion coating + corrosion inhibiting fluid film to parts of electrical plugs, receptacles, etc.

30.12 Treatment for Rhodium, Palladium, Gold, Platinum and Alloys

a. Use bare, with compound sealant at edges of dissimilar metal joint, or by enveloping dissimilar metal joint in conformal coating, where feasible.

30.13 Treatment for Graphite

a. Plate graphite to minimize electrical potential difference between graphite and metal to be joined to it. Seal faying edges to preclude corrosion at contacting surface of the metal member, if service is electrical, or apply conformal coating.

b. May be used bare in electrical or thermal conducting service, conditions permitting. Seal faying edges.

APPENDIX B

WHAT IS INVOLVED IN GALVANIC CORROSION

10. GENERAL

10.1 Scope. This appendix explains the principal factors that are involved in the phenomenon of galvanic corrosion.

10.2 Application. This appendix is tutorial only and is not contractually binding.

20. REFERENCED DOCUMENTS

Not Applicable.

30. GENERAL REQUIREMENTS

30.1 Factors influencing galvanic corrosion. Several factors can influence the kinetics of galvanic corrosion. Among these are the polarization behavior of the metals under the prevailing conditions; the areas of the anode and cathode; the electrical resistance and current; the type and concentration of the electrolyte; the pH of the electrolyte medium; the degree of aeration or motion of the electrolyte medium. Basic factors are the electrical potentials of the electrodes, current, and resistances, expressed by

$$E_c - E_a = IR_e + IR_m$$

where E_c is the potential of the cathode (as polarized); E_a the potential of the anode (as polarized); R_e the resistance of the electrolyte solution path in the galvanic circuit (internal circuit); and R_m the resistance of the electrodes (external circuit).

solution path in the galvanic circuit (internal circuit); and R_m the resistance of the electrodes (external circuit).

30.2 Corrosive environment. In a liquid medium or electrolyte solution, of a given concentration of the electrolyte, and a specific temperature of the medium, each metal has a specific electrical potential, i.e., ability to undergo dissolution - to form metal ions with the release of electrons. In a very corrosive solution, having high conductivity and producing readily soluble corrosion products of the metal, corrosion will continue. In a limited volume of solution, where conditions more probably will develop to hamper corrosion, e.g., increase of concentration of metal ions, the corrosion may diminish with time. On the other hand, the same metal as the anode of a galvanic couple, will tend to exhibit accelerated corrosion, which can be related to a flow of current in the circuit, if the cathode is unaffected by polarization. If the electrodes polarize progressively, galvanic current flow and corrosion will subside and may actually stop. Generally, the rate of corrosion will decrease with higher concentrations of the electrolyte, or with lower temperature.

Galvanic effects may change because of different pH conditions within an electrolyte. A metal which is the anode in a neutral or acidic solution may become the cathode if the solution is made basic.

Oxygen dissolved in the electrolyte can depolarize the cathode by oxidizing absorbed hydrogen. In some cases, oxygen may be necessary to promote oxidation of the anode. Available oxygen and the rate of its diffusion therefore can increase galvanic attack.

Ions which are generated at the electrode as corrosion proceeds concentrate at or near the electrode surfaces (polarization) and impede current flow. For each of these cases, in static solutions, the corrosion action is diffusion-dependent and is under diffusion-control. Agitation of the solution will increase the reaction rate.

30.3 Conductivity of the galvanic circuit. Corrosion of a single metal in an electrolyte involves the flow of current from local anodic to local cathodic areas on the metal surface. This is termed "local cell corrosion" and is the situation of normal corrosion. Relatively small differences in potentials of local cells are the result of compositional dissimilarities on the metal surface because of different metal phases or crystal orientation, crystal imperfections segregations, grain boundaries, and other conditions. The more inhomogeneous the surface, the more susceptible it is to general attack. Dissolution of the anode relates to the galvanic current according to Faraday's law,

$$W = \frac{Ite}{F},$$

where W is the weight or quantity of metal dissolved, in grams; I the current in amperes; t the time of current flow, in seconds; e the equivalent of the anode metal (atomic weight divided by valence or charge of ions produced); F the faraday (96,500 coulombs).

Galvanic corrosion should not be confused with the corrosion of a single metal resulting from current flow in an electrolyte solution-caused by differences in oxygen content of the electrolyte solution at different surfaces of the metal, or by differences in solute ion concentration or differential aeration; and differential ion or concentration, respectively.

30.4 Potential between the anode and cathode. Standard electrode potentials of metals are of little value in establishing galvanic corrosion relationships in actual environments. The standard potential of a metal is the potential in equilibrium with a molar concentration (unit activity) of its ions. This condition is not encountered in situations of galvanic corrosion. A glavanic system is dynamic; therefore the potentials of the metals are not at equilibrium. The metals are not likely to be found in solutions of their own ions, and the reaction is not controlled solely by difference of potential. The reaction is controlled by polarization of the anode, the cathode or both, and by the resultant galvanic current flow.

From the standard electrode potentials shown in Table IA, it is seen that aluminum should behave anodically toward zinc and presumably would retard the corrosion of zinc in a usual coupled situation. That the reverse is true is readily seen from the established galvanic series of metals in sea water, Table II. It is of interest to note that in sea water, the potential difference between copper and stainless steel (passive) is small, from which one might conclude that galvanic couples of aluminum with copper or aluminum with stainless steel in sea water should result in approximately equal degree of attack on the aluminum. But this does not occur; stainless steel which can undergo some passivation in the presence of oxygen will have less galvanic effect on the aluminum, whereas copper which normally remains active will have more effect.

A galvanic series can be derived for metals in any electrolyte solution. For specific practical informational needs, the solution conditions, i.e., electrolyte concentration, pH, flow, aeration, temperature,

should be specified and maintained as closely as possible.

TABLE IA

STANDARD ELECTRODE POTENTIALS - AQUEOUS SOLUTION, IM-RESPECTIVE METAL ION, 25°C, AT EQUILIBRIUM

Metal (High purity)	Standard Electrode Potential (v)
$Magnesium^{2+}$	$^{-}2.37$
$Aluminum^{3+}$	$^{-}1.67$
$Zinc^{2+}$	$^{-}0.76$
$Chromium^{3+}$	$^{-}0.74$
$Iron^{2+}$	$^{-}0.44$
$Cadmium^{2+}$	$^{-}0.40$
Tin^{2+}	$^{-}0.14$
$Lead^{2+}$	$^{-}0.13$
$Hydrogen^{+}$	0.00
$Copper^{2+}$	$^{+}0.34$
$Silver^{+}$	$^{+}0.80$
$Mercury^{2+}$	$^{+}0.85$
$Platinum^{2+}$	$^{+}1.2$
$Gold^{+}$	$^{+}1.69$

30.5 Polarization. The polarization of electrodes in an electrolyte solution occurs because of a film of oxide or other compound or gas on the electrode surfaces. These changes reduce the potential difference relative to the open circuit potentials*2 and lessen the corrosion rate. Such changes increase the resistance of the external circuit and diminish current flow; and intensify or diminish with galvanic current, or with applied current. Electrode polarization behavior is a means by which the compatibility of coupled dissimilar metals in solution can be established. Polarization measurements can provide information as to the effects of relative areas of anode and cathode and effects of changes in potential on the corrosion.

Polarization of galvanic electrodes is illustrated in Figure 1A. When the anode, cathode, or both polarize, the control is anodic,

cathodic, or mixed, respectively. Galvanic corrosion and current flow are polarization and resistance controlled. When the electrodes do not polarize, resistance of the circuit, the solution path (R_e) and the metallic portion (Rm) control the reaction.

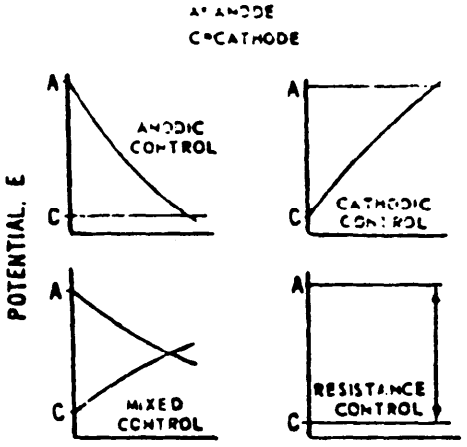


FIGURE 1A. Types of polarization and control in galvanic corrosion.

30.6 Electrode areas. Under cathodic control, corrosion of the anode is proportional to the area of the cathode. If the cathode area is two to three times the area of the anode and if the polarization is negligible, the current is generally increased by the same factor. The same relationship prevails if the anode area is decreased relative to the cathode. Decreasing the area of the cathode, in effect increasing the area of the anode, reduced the galvanic current density and diminishes corrosion of the anode so that normal corrosion becomes dominant. The situation is somewhat different in mixed control. An increase in the cathode area can have some accelerating corrosion effect but this is generally less than in the case of cathodic control, and the effect does not occur in a proportional way. Normal corrosion becomes less pronounced. In anodic control, the corrosion of the anode essentially is unaffected by the cathode area; increasing the area of the anode decreases the galvanic current.

30.7 Resistance and galvanic current. In a polarized galvanic circuit, resistance is contributed by the portion of the electrolyte between the anode and cathode (R_e, internal path) and by the films of reaction products formed on the electrode surfaces (R_m, metallic path), which impede ion exchange and reduce current flow. Therefore, the total resistance, R, of the circuit is expressed as $R = R_e + R_m$. In the polarized system, as the resistance increases, the potentials of the anode and cathode approach each other until a steady state reaction is attained. The limiting current corresponds with the intersection of the polarization curves. This is the maximum current obtainable in the system if constant conditions are maintained.

30.8 The electrolyte medium. In each liquid medium or solution (for a given concentration of the electrolyte and temperature of the medium), a metal has a specific electrical potential. In a very corrosive solution, one having high conductivity and producing readily soluble compounds of the anode of a galvanic couple, the anode will corrode uniformly. If the cathode does not polarize, the corrosion of the anode will be accelerated. However, with polarization of the electrodes, galvanic current flow and corrosion subside. Generally, for a given electrolyte solution, the rate of corrosion decreases with higher concentration of the electrolyte or with lower temperature.

In a solution containing ions that can polarize the anode, the cathode, or both, galvanic effects will be small.

Coupled dissimilar metals may exhibit different responses in the electrolyte solution because of pH changes. A metal which is the anode in a neutral or acidic solution may become the cathode if the solution is made basic. This is illustrated with magnesium-aluminum couples in dilute, neutral, or slightly acidic sodium chloride solution. With dissolution of the magnesium anode, the solution becomes alkaline, and then the aluminum is rendered anodic, a reversal of polarity. In neutral sodium chloride solution, the anode iron of an iron-copper couple becomes the cathode when the solution is altered by the addition of ammonia.

30.9 Aeration, diffusion, and agitation of solution. Oxygen dissolved in the electrolyte solution can act to depolarize the cathode by oxidizing adsorbed hydrogen. In some cases, oxygen may be necessary for oxidation of the anode. Available oxygen and the rate of its diffusion therefore can increase galvanic current. Ions which are formed at the electrodes during galvanic corrosion concentrate at or near the electrode surfaces (polarization) and impede current flow. For each of these cases in

still solutions, the galvanic action is duffusion-dependent and is under diffusion control. Agitation or movement of the solution will increase the reaction rate. If the electrode areas are not large, little difference will ensue.

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