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MIL-STD-889C
22 August 2016
SUPERSEDING
MIL-STD-889B
7 July 1976

DEPARTMENT OF DEFENSE

STANDARD PRACTICE

DISSIMILAR METALS



AMSC N/A

AREA MFFP

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FOREWORD

1. This standard is approved for use by all Departments and Agencies of the Department of Defense.

2. Comments, suggestions, or questions on this document should be addressed to: Commander, Naval Air Warfare Center Aircraft Division, Code 4.1.2, Mail Stop 120-3, Route 547, Joint Base-MDL, NJ 08733-5100, or emailed to michael.sikora@navy.mil. Since contact information can change, you may want to verify the currency of this address information using the ASSIST Online database at https://assist.dla.mil.

3. For guidance on the technical content of this document, contact Commander, Naval Air Warfare Center, Aircraft Division, (Code 4.3), 48066 Shaw Road, 2188 Patuxent River, MD 20670.

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1. SCOPE

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

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

2. APPLICABLE DOCUMENTS

2.1 General. The documents listed in this section are specified in sections 3, 4, and 5 of this standard. This section does not include documents cited in other sections of this specification or recommended for additional information or as examples. While every effort has been made to ensure the completeness of this list, document users are cautioned that they must meet all specified requirements of documents cited in sections 3, 4, and 5 of this standard, whether or not they are listed.

2.2 Government documents.

2.2.1 Specifications. The following specification forms a part of this document to the extent specified herein. Unless otherwise specified, the issue of this document is the one cited in the solicitation or contract.

DEPARTMENT OF DEFENSE SPECIFICATION

MIL-PRF-81733	-	Sealing and Coating Compound, Corrosion Inhibitive

(Copies of these documents are available online at https://assist.dla.mil.)

2.3 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

SOCIETY OF AUTOMOTIVE ENGINEERS (SAE) INTERNATIONAL

SAE AMS-S-8802	-	Sealing Compound, Temperate-Resistant, Integral Fuel Tanks and Fuel Cell Cavities, High Adhesion
SAE AMS3265	-	Sealing Compound, Polysulfide (T) Rubber, Fuel Resistant, Nonchromated Corrosion Inhibiting for Intermittent Use to 360 °F (182 °C)
SAE AMS3269	-	Sealing Compound, Polysulfide (T) Synthetic Rubber for Integral Fuel Tank and Fuel Cell Cavities High Strength, for Intermittent Use to 360 °F (182 °C) (Stabilized Type)
SAE AMS3276	-	Sealing Compound, Integral Fuel Tanks and General Purpose, Intermittent Use to 360 °F (182 °C)

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SAE AMS3277	-	Sealing Compound, Polythioether Rubber, Fast Curing for Integral Fuel Tanks and General Purpose, Intermittent Use to 360 °F (182 °C)
SAE AMS3281	-	Sealing Compound, Polysulfide (T) Synthetic Rubber for Integral Fuel Tank and Fuel Cell Cavities Low Density (1.20 to 1.35 sp gr), for Intermittent Use to 360 °F (182 °C)

(Copies of these documents are available online at http://www.sae.org.)

2.4 Order of precedence. Unless otherwise noted herein or in the contract, in the event of a conflict between the text of this document and the references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. DEFINITIONS

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

3.2 Galvanic corrosion. Galvanic corrosion manifests itself in the accelerated corrosion of 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 a conductive medium. Galvanic corrosion is inherently affected by the relative position in 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. Use Table I as a guide in determining the relative compatibility of dissimilar metal combinations. A galvanic series for metals in sea water is shown in Table II. Compatibility does not indicate a complete freedom from galvanic action. Galvanic effects, i.e., the degree of corrosion of the anode is influenced by the difference of the metals in the galvanic series, kinetic factors such as polarization effects, the electrolytic environment, and the physical arrangement of the metals. Refer to Appendix B for additional information.

4. GENERAL REQUIREMENTS (Not Applicable)

5. DETAILED REQUIREMENTS

5.1 Minimizing dissimilar metal corrosion. When dissimilar metals are used in intimate contact, protection against galvanic corrosion shall be applied. In some environments galvanic corrosion may be appreciable, particularly with metals such as magnesium, steel, zinc, and aluminum (anodes), in contact with copper, stainless steel, and nickel (cathodes). For non-

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continuously immersed couples, to protect the anodic member, the design shall incorporate electrical insulation of the joint or must include methods to exclude the electrolyte. Material compatibility through simulation (such as ASTM B117 or other approved method) must be demonstrated. If found to be non-compatible, the methods for galvanic protection noted below must be considered.

5.1.1 Galvanic series in sea water. Table II lists metals in the order of their relative activity in a sea water environment and should be used as a reference to minimize galvanic potential when selecting metals that will be in direct contact. The list begins with the more active (anodic) metal and proceeds 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, and will help with the selection of metals having minimum 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 the effect. In a galvanic couple, the metal higher in the series represents the anode, and will corrode preferentially in the environment to the cathode which is lower in the series.

5.1.2 Large separation in galvanic series. Metals that are to be joined that are widely separated in the galvanic series shall be protected with measures to avoid contact. This shall 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 ensure that the faying surfaces are watertight; by painting or coating all surfaces to increase the resistance of the electrical circuit; or where the faying surfaces are not required to be electrically conductive by inserting a barrier or “shield” of a material which will isolate or insulate the faying surfaces. Such a shield must be inert and non-absorbing. This shield may be an organic barrier (such as sealant) to provide interference to galvanic activity, or a compatible ribbon or strip of an intermediate metal or material which will provide a barrier to both physical and galvanic corrosion. Materials and metals used as shields will be application dependent. If the protection of the galvanic couple is by paint or coating, inspection and maintenance of the paint or coating integrity is highly recommended at appropriate intervals for the application.

5.1.3 Anode to cathode area ratio. Any small anodic area relative to the cathodic area shall be avoided. The same metal or more noble (cathodic) metals shall be utilized for small fasteners and bolts.

5.1.4 Sea water environments. 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 shall be sealed with a suitable sealant material, e.g., MIL-PRF-81733, SAE AMS-S-8802, SAE AMS3265, SAE AMS3269, SAE AMS3276, SAE AMS3277, or SAE AMS3281. When non-compatible materials, i.e., those with a significant potential difference (see Tables I and II) are joined, an interposing material compatible with each shall be used.

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5.1.5 Non-metallic materials. Materials other than true metals, i.e., non-metallic materials, which must be joined to metals, shall incorporate protection schemes similar to metallic materials, unless there is supporting evidence to the contrary. If these materials are essentially free of corrosive agents (salts), free of acid or alkaline materials (neutral pH), and free of carbon or metallic particles, not subject to bio-deterioration, 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.

5.1.6 Magnesium and stainless steels. Where magnesium or a magnesium alloy 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 shall 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 gasket material may be used. The maximum protective systems shall always 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 Joining methods to prevent galvanic corrosion. Where it becomes necessary that relatively incompatible metals, i.e., those with a significant potential difference (see Table I), must be assembled in the design, as applicable to that design, the following methods shall be used to minimize or prevent galvanic corrosion.

a. Compatible materials shall be selected in accordance with the galvanic series and shall design metal couples where the area of the cathode is smaller than the area of the anode metal. For example, bolts or screws of stainless steel for fastening aluminum sheet, but not the reverse. A compatible metallic gasket or washer shall be interposed between the dissimilar metals prior to fastening; or plate the cathodic member with a metal compatible to the anode. These methods are applicable to couples that are to serve as an electrical connection.

b. A non-absorbing, inert gasketing material or washer shall be interposed between the dissimilar materials prior to connecting them. This is applicable to couples that are not to serve as electrical conductors.

c. All faying edges shall be sealed to preclude the entrance of liquids.

d. Corrosion-inhibiting pastes or compounds shall be applied under the heads of screws or bolts inserted into dissimilar metal surfaces whether or not the fasteners had been previously plated or otherwise treated in addition to applying an organic coating to the faying surfaces prior to assembly. In situations where large faying surfaces are involved it may be feasible to insert a thicker barrier such as dried adhesive or sealant material. This applies 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 shall be coated externally with an effective paint system or sealant.

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f. Welded or brazed dissimilar metal assemblies shall 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 shall be applied to dissimilar metal combination treatments, especially when considering the end-use environment of the item. 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 hermetically sealed compartments or containers in which the moisture vapor content had 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 shall be treated as if protection were required against the worst environment.

6. NOTES

(This section contains information of a general or explanatory nature which may be helpful but is not mandatory.)

6.1 Intended use. 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.

6.2 Acquisition requirements. Acquisition documents should specify the following:

a. Title, number and date of this standard.

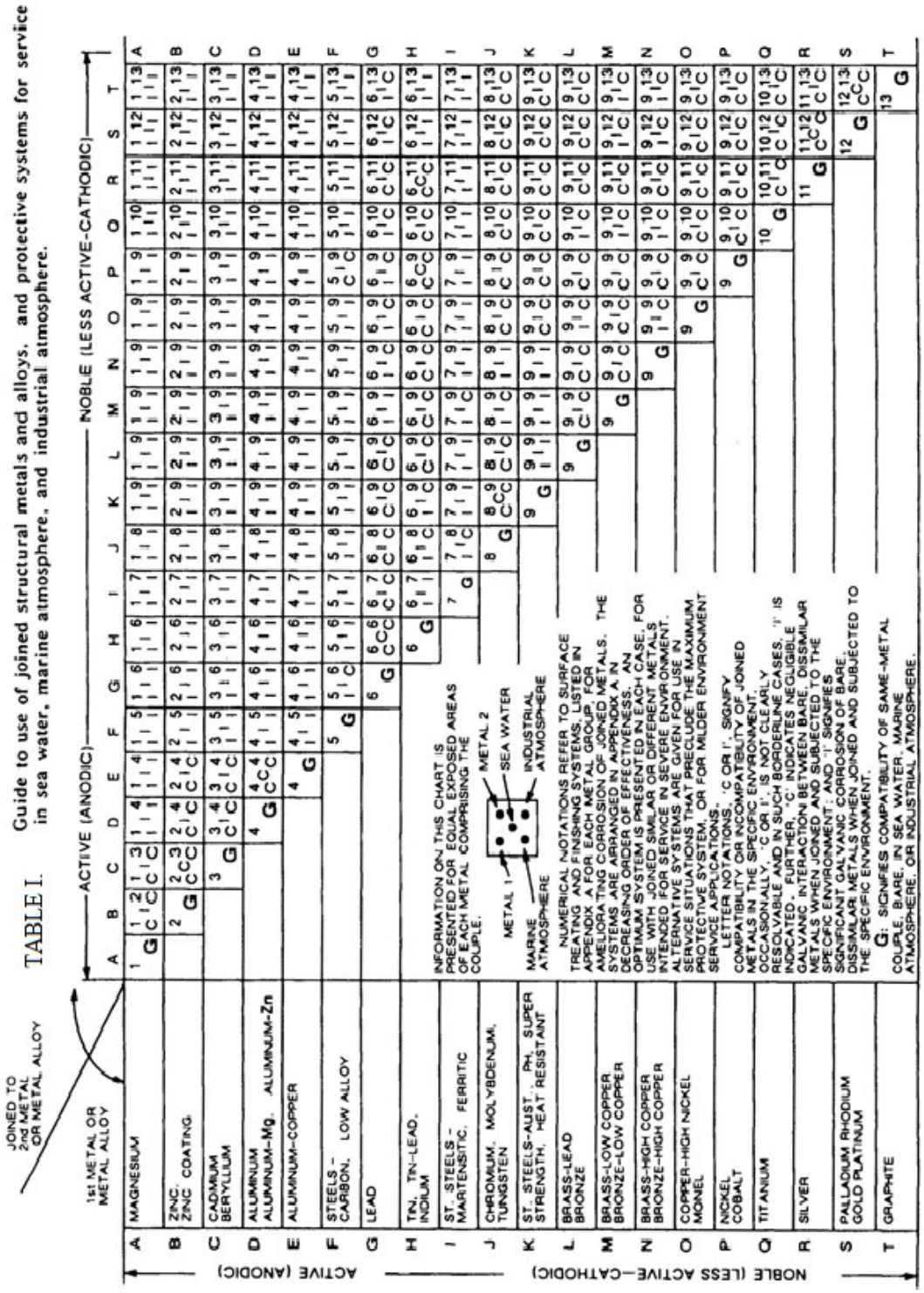
6.3 Subject term (key word) listing.

Galvanic corrosion	Chromate conversion coating
Anode	Metallic coating
Cathode	Paint
Resin coating	Electrolyte
Corrosion inhibitor	

6.4 Changes from previous issue. Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extent of the changes.

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TABLE I. Guide to use of joined structural metals and alloys, and protective systems for service in sea water, marine atmosphere, and industrial atmosphere.



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TABLE II. Galvanic series of selected metals in sea water.

Per: Army Missile Command Report ARS-TR-67-11, Practical Galvanic Series

Active (Anodic)

Magnesium
Mg Alloy AZ-31B
MG Alloy HK-31A
Zinc (hot-dip, die cast or plated)
Beryllium (hot pressed)
Aluminum (Al) 7072 cl. on 7075
Al alloy 2014-T3
Al alloy 1160-1114
Al alloy 7079-T6
Cadmium (plated)
Uranium
Al alloy 218 (die cast)
Al alloy 5052-0
Al alloy 5052-H12
Al alloy 5456-0, H353
Al alloy 5052-H32
Al alloy 1100-0
Al alloy 3003-H25
Al alloy 6061-T6
Al alloy A360 (die cast)
Al alloy 7075-T6
Al alloy 1160-1114
Al alloy 6061-0
Indium
Al alloy 2014-0
Al alloy 2024-T4
Al alloy 5052-H16
Tin (plated)
Stainless steel 430 (active)
Lead
Steel 1010
Iron, cast
Stainless steel 410 (active)
Copper (plated, cast or wrought)
Nickel (plated)
Chromium (plated)
Tantalum
AM350 (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 8% Mo
Brass, Naval, 464
Yellow brass
Muntz metal 280
Brass plated
Nickel-silver (18% Ni)
Stainless steel 316L (active)
Bronze 220
Copper 110
Red brass
Stainless steel 347 (active)
Molybdenum, Comm pure
Copper-Nickel 715
Admiralty brass
Stainless steel 202 (active)
Bronze, Phosphor 534 (B-1)
Monel 400
Stainless steel 201 (active)
Carpenter 20 (active)
Stainless steel 321 (active)
Stainless steel 316 (active)
Stainless steel 309 (passive)
Stainless steel 17-7 PH (passive)
Silicone Bronze 655

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TABLE II. Galvanic series of selected metals in seawater - (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)
AM355 (active)
Stainless steel 202 (passive)
Carpenter 20 (passive)
AM355 (passive)
A286 (passive)
Titanium 5A1, 2.5 Sn
Titanium 13V, 11Cr, 3A1 (annealed)
Titanium 6A1, 4V (solution treated and aged)
Titanium 6A1, 4V (annealed)
Titanium 8 Mn
Titanium 13V, 11Cr, 3A1 (solution treated and aged)
Titanium 75A
AM350 (passive)
Silver
Gold
Graphite

Noble (Less Active-Cathodic)

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APPENDIX A

RECOMMENDED PROTECTIVE TREATMENTS

A.1 SCOPE

A.1.1 Scope. This appendix lists protective systems for each metal or alloy with optimum treatments listed first, and others in descending order of preference. Each listing is presented as a guide only. Each application must be reviewed considering service conditions, design requirements and maintenance costs. This Appendix is not a mandatory part of this standard. The information contained herein is presented for guidance only.

A.1.2 Application. This Appendix provides 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 sub-listings 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, and minimization of maintenance and cost. Costs should not compromise the level of protection desired. Specific review of proposed protective systems for dissimilar metal couples should be performed by the procuring agency, and authorization of the agency of the use of the selected systems is required prior to their introduction or adoption.

A.2 APPLICABLE DOCUMENTS

A.2.1 Specifications. The following specifications form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

FEDERAL SPECIFICATION

TT-C-490	-	Chemical Conversion Coatings and Pretreatments for Metallic substrates (Base for Organic Coatings)

DEPARTMENT OF DEFENSE SPECIFICATIONS

MIL-A-8625	-	Anodic Coatings For Aluminum and Aluminum Alloys
MIL-C-8514	-	Coating Compound, Metal Pretreatment, Resin-Acid
MIL-C-17711	-	Coatings, Chromate, For Zinc Alloy Castings and Hot dip Galvanized Surfaces
MIL-DTL-5541	-	Chemical Conversion Coatings on Aluminum and Aluminum Alloys
MIL-DTL-16232	-	Phosphate Coating, Heavy, Manganese or Zinc Base

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APPENDIX A

MIL-DTL-32119 - Coatings, Electroless Nickel, Special Applications

(Copies of these documents are available online at https://assist.dla.mil.)

A.2.2 Non-Government publications. The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those cited in the solicitation or contract.

ASTM INTERNATIONAL

ASTM D1732 - Standard Practices for Preparation of Magnesium Alloy Surfaces for Painting

(Copies of this document are available online at http://www.astm.org.)

SAE INTERNATIONAL

SAE AMS-C-8837	-	Coating, Cadmium (Vacuum Deposited)
SAE AMS-C-26074	-	Electroless Nickel Coatings
SAE AMS-C-81562	-	Coatings, Cadmium, Tin-Cadmium and Zinc (Mechanically Deposited)
SAE AMS-M-3171	-	Magnesium Alloy, Processes for Pretreatment and Prevention of Corrosion on
SAE AMS-QQ-P-416	-	Plating, Cadmium (Electrodeposited)

(Copies of these documents are available online at http://www.sae.org.)

A.3 Recommended treatments in order of protective effectiveness. The 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.

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A.3.1 Treatment for magnesium.

a. Anodic coating (ASTM D1732) post treated with an alkali-resistant paint or resin coating system.

b. Chromate conversion coating (SAE AMS-M-3171) post treated with an alkali-resistant paint or resin coating system. Alternate for general use in non-persistent wet or marine atmosphere; or anodic coating without organic coating system.

c. Metallic coating, electroless nickel (SAE AMS-C-26074, or MIL-DTL-32119 where applicable) with cadmium overplating (SAE AMS-QQ-P-416). For electrical, thermal conducting purposes, in absence of wet, saline or acidic atmospheric conditions.

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

Note: Bare magnesium should not be used.

A.3.2 Treatment for zinc and zinc coatings.

a. Anodic coating post treated with a paint or resin coating system, primarily for castings.

b. Chromate conversion coating (MIL-C-17711) post treated with a paint or resin coating system; or anodic coating without organic coating 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 should not be used in a marine environment.

A.3.3 Treatment for cadmium or beryllium.

a. Chromate conversion coating (SAE AMS-QQ-P-416, SAE AMS-C-8837 or SAE AMS-C-81562) post-treated with a paint or resin coating system.

b. Chromate conversion coating without organic coating 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.

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A.3.4 Treatment for aluminum and aluminum alloys.

a. Anodic coating (MIL-A-8625) post treated with a paint or resin coating system.

b. Chromate conversion coating (MIL-DTL-5541) post treated with a 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 system, 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.

A.3.5 Treatment for carbon and low alloy steels.

a. Metallic coating (e.g., sacrificial Zn or Cd, with supplemental passivation or surface treatment or non-sacrificial, e.g., Cu or Ni), with a paint or resin coating system. For steels of strengths greater than 220 ksi metallic coatings should be applied by non-electrolytic methods. 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 passivation or surface treatment or non-sacrificial, e.g., Cu or Ni) ,without paint or resin 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, should be applied by non-electrolytic methods.

c. Zinc phosphate conversion coating (TT-C-490) post treated with a paint or resin coating system. Caution, if a phosphate coating is used on steels of strengths between 150 to 220 ksi, stress relief is required prior to phosphating and hydrogen embrittlement relief is required after phosphating. Zinc phosphate coatings are prohibited for steels of strength greater than 220 ksi.

d. Pretreatment primer (MIL-C-8514) post treated with a paint or resin coating system.

e. Heavy phosphate conversion coating (MIL-DTL-16232) post treated with a supplemental treatment. Not for steels of strengths greater than 220 ksi.

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A.3.6 Treatment for lead, tin, solders and indium coatings.

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 is required for electrical purposes.

A.3.7 Treatment for martensitic and ferritic stainless steels.

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. Apply paint or resin coating system.

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.

A.3.8 Treatment for chromium (plate), molybdenum, tungsten.

a. Paint or apply resin coating system 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.

A.3.9 Treatment for steels stainless-austenitic, PH, super strength, heat resistant, brass-leaded, bronze, brass bronze-low 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 system, 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.

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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 not practical.

A.3.10 Treatment for titanium.

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

b. Apply metallic coating (Cd, Zn prohibited, Ag over Ni acceptable) post-treated with a paint or resin coating system.

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.

A.3.11 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 post treated with a corrosion inhibiting fluid film to parts of electrical plugs, receptacles, etc.

A.3.12 Treatment for rhodium, palladium, gold, platinum and alloys.

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

A.3.13 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.

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

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APPENDIX B

FACTORS INVOLVED IN GALVANIC CORROSION

B.1 SCOPE

B.1.1 Scope. This appendix explains the principal factors that are involved in the phenomenon of galvanic corrosion. This appendix is tutorial only and is not contractually binding. This Appendix is not a mandatory part of this standard. The information contained herein is presented for guidance only.

B.1.2 Application. The principal factors that are involved in the phenomenon of galvanic corrosion are explained.

B.2 APPLICABLE DOCUMENTS

Not applicable.

B.3 GENERAL REQUIREMENTS

B.3.1 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); I is the current in amperes; R_e the resistance of the electrolyte solution path in the galvanic current (internal circuit); and R_m the resistance of the electrodes (external circuit).

B.3.2 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 metals, corrosion will continue. In a limited volume of solution, where conditions are more likely to develop that will hamper corrosion, e.g., increase of concentration of metal ions, the corrosion will 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.

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a. 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.

b. 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.

c. 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.

B.3.3 Conductivity of the galvanic circuit. Corrosion of a single metal in an electrolyte involves the flow of current from local anodic to locate 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 is the current in amperes; t is the time of current flow in seconds; e is the equivalent of the anode metal (atomic weight divided by valence or charge of ions produced); F is the faraday (96,5000 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.

B.3.4 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 galvanic 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.

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APPENDIX B

From the standard electrode potentials shown in Table B-I, 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 (see 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 B-I. Standard electrode potentials - aqueous solution, respective metal ion, 25 ºC, 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
$Copper^{2+}$	$^{+}0.34$
$Silver^{+}$	$^{+}0.80$
$Mercury^{2+}$	$^{+}0.85$
$Platinum^{2+}$	$^{+}1.2$
$Gold^{+}$	$^{+}1.69$

B.3.5 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 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.

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APPENDIX B

Polarization of galvanic electrodes is illustrated on Figure B-1. 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 (R_m) control the reaction.

A = Anode
C = Cathode

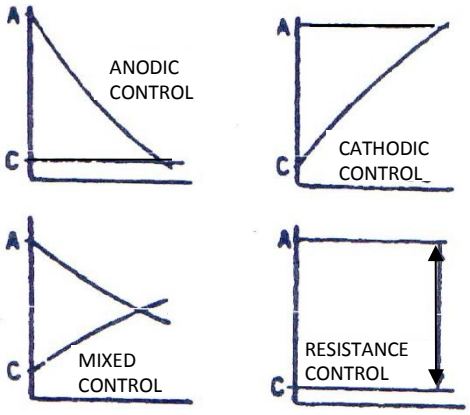


FIGURE B-1. Types of polarization and control in galvanic corrosion.

B.3.6 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.

B.3.7 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, in 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.

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B.3.8 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.

B.3.9 Aeration, diffusion, and agitation of solution.Oxygen dissolved in the electrolyte solution can act to depolarize the cathode, and increase cathodic current. 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 diffusion-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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CONCLUDING MATERIAL

Custodians:
Navy – AS
Air Force – 20

Preparing activity:
Navy - AS
Project MFFP-2016-011

Review activities:
Air Force – 19, 184, 99
Navy – MC, SH

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