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DEPARTMENT OF DEFENSE

STANDARD PRACTICE

GALVANIC COMPATIBILITY OF ELECTRICALLY CONDUCTIVE MATERIALS



AMSC N/A

AREA MFFP

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 Commanding Officer, Naval Air Warfare Center Aircraft Division Lakehurst, System Standardization and PHS&T Branch, Code BL32600, Mail Stop 120-3, Route 547, Joint Base MDL, NJ 08733-5100 or emailed to LKE-NAVAIRDocComments@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. Previously, MIL-STD-889 used the galvanic potential difference between conductive material couples to determine compatibility between dissimilar metals. In revision D, the corrosion rate of the anodic member of the galvanic couple is used to determine galvanic compatibility. This new methodology is based on the mixed potential theory of electrochemistry, which states that the common potential reached by two dissimilar materials in electrical contact, and the galvanic current between them, is determined by the crossing points of their polarization curves. We determined that summing the two curves together to form a joint polarization curve, and then crossing the anodic and cathodic side to determine the galvanic current and galvanic potential satisfied the wide range of polarization curves we collected. The measured galvanic current is then used to calculate the galvanic corrosion rate of the anodic member of a dissimilar couple. This standard establishes the new requirements for galvanic compatibility of dissimilar electrically conductive materials and outlines the procedures required to generate electrochemical data to analyze new materials, coatings, and surface treatments.
4. For guidance on the technical content of this document, contact Commander, Naval Air Warfare Center, Aircraft Division, (Materials Engineering Division – AB23000), 48066 Shaw Road, 2188 Patuxent River, MD 20670.

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1. SCOPE

1.1 Scope. This standard defines and classifies galvanic compatibility of electrically conductive materials and establishes requirements for protecting electrically conductive materials in a dissimilar couple against galvanic corrosion. Recommendations for protective coatings are provided. This standard also outlines the procedures required to generate electrochemical data for the analysis of new electrically conductive materials, coatings, and surface treatments. Data collected in this standard was completed in static, immersion conditions in artificial seawater in accordance with ASTM D1141 (without heavy metals).

1.2 Applicability. This standard is applicable to all military equipment parts, components and assemblies. Other standards may take precedence for specific applications.

1.3 Methodology. The galvanic current, which was determined from the joint polarization curve, was used to calculate the corrosion rate of the anodic member of the couple. If the corrosion rate for the anodic member is above 0.009 mil/year, the pairing is considered incompatible. The methodology for determining the galvanic corrosion rate of the anodic member of a galvanic couple is outlined in Appendix B.

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 and standards. The following standard 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 STANDARD

MIL-STD-7179 - Finishes, Coatings, and Sealants, for the Protection of
Aerospace Weapons Systems and Support Equipment

(Copies of this document are available online at <https://assist.dla.mil>.)

2.2.2 Other Government documents, drawings, and publications. The following other Government document forms 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.

UNITED STATES CODE

Title 10 ARMED FORCES, Section 2228 OFFICE OF CORROSION POLICY
AND OVERSIGHT

(Copies of this document are available online at www.govinfo.gov.)

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.

ASTM INTERNATIONAL

ASTM D1141 - Standard Practice for the Preparation of Substitute Ocean Water
ASTM G193 - Standard Terminology and Acronyms Relating to Corrosion

(Copies of these documents are available online at <http://www.astm.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

The definitions of many of the corrosion-related terms used in this standard may be found in ASTM G193, which should be referenced for the most up-to-date definitions. Additional terms and selected definitions and abbreviations are highlighted below.

3.1 Acronyms used in this standard. The acronyms used in this standard are as follows:

- | | | | |
|----|------------|---|--|
| a. | A/C | - | Anode-to-cathode ratio |
| b. | AM | - | Additive manufacturing |
| c. | CC | - | Conversion coating |
| d. | CEA | - | Cognizant Engineering Authority |
| e. | CR | - | Corrosion rate |
| f. | E_{corr} | - | Corrosion potential |
| g. | E_{gal} | - | Galvanic corrosion potential |
| h. | EHC | - | Engineered hard chrome |
| i. | ESHE | - | Potential of standard hydrogen electrode |
| j. | HE | - | Hydrogen embrittlement |
| k. | HER | - | Hydrogen evolution reaction |

l.	HRC	-	Hardness Rockwell C
m.	I_{corr}	-	Corrosion current
n.	I_{gal}	-	Galvanic corrosion current
o.	MIE	-	Metal-induced embrittlement
p.	mil	-	1 mil is one thousandth of an inch (ie. 0.001 inch)
q.	NAWCAD	-	Naval Air Warfare Center – Aircraft Division
r.	OCP	-	Open circuit potential
s.	ORR	-	Oxygen reduction reaction
t.	pH	-	Power of hydrogen ($\text{pH} = -\log[\text{H}^+]$)
u.	PH	-	Precipitation hardening
v.	QA	-	Quality assurance
w.	QC	-	Quality control
x.	SCE	-	Standard calomel electrode
y.	T*	-	Tagnite
z.	UNS	-	Unified Numbering System
aa.	UTS	-	Ultimate tensile strength
bb.	ZRA	-	Zero resistance ammeter

3.2 Cognizant Engineering Authority (CEA). For the purpose of this standard, the Cognizant Engineering Authority is that entity from the procuring activity that provides, reviews, and approves any deviations from the technical requirements contained within this standard.

3.3 Corrosion. The Congressional definition of corrosion states that corrosion is "the deterioration of a material or its properties due to a reaction of that material with its chemical environment" and can be found in Title 10 U.S.C. §2228. It is inclusive of the deterioration of all materials, which can be caused through sun exposure, mold and mildew, wind, and other environmental elements. Some non-traditional examples include rotting of wood, degradation of concrete (carbonation, alkali-silica reaction phenomena), and degradation of composite materials due to reaction with the environment.

3.4 Corrosion rate. Material loss as a function of time due to corrosion. The corrosion rate in this standard is listed in units of mil/year and is used to determine the compatibility of a dissimilar, electrically conductive material pairing.

3.5 Dissimilar conductive materials. This standard defines conductive materials as dissimilar when two conductive materials are in contact or otherwise electrically connected to each other, in a conductive environment with the anodic member corroding at a rate greater than 0.009 mil/year.

3.6 Electrically conductive materials (conductive materials). For the purposes of this standard, an electrically conductive material is defined as any solid compound capable of carrying an electric current. This definition includes conductive carbon compounds and any other solid compound capable of undergoing galvanic corrosion.

3.7 Faying surface. Two or more surfaces joined, fitted closely, or tightly together.

3.8 Galvanic compatibility. Galvanic compatibility is defined as the maximum corrosion rate

(in mil/yr.), of the anodic member in a given galvanic couple, for which no protection against galvanic corrosion is required.

3.9 Galvanic corrosion. Galvanic corrosion manifests itself in the accelerated corrosion of the more active (anodic) conductive material of a dissimilar couple and decelerated corrosive effects on the less active (cathodic) conductive material. The rate at which the anodic member of the galvanic couple corrodes depends on the galvanic current of the coupled conductive materials, under the same environmental conditions.

3.10 Galvanic series. A galvanic series is a ranking of conductive materials and alloys based on their corrosion potential in a particular electrolyte solution or other environment. Conductive materials closely positioned in the series have electrical potentials nearer one another. As materials diverge in the series, the difference in potential grows. Table IV shows the galvanic series for conductive materials in an artificial seawater solution according to ASTM D1141, without heavy metals. The table provided is a reference and is not to be used for the determination of galvanic compatibility.

4. GENERAL REQUIREMENTS (Not Applicable.)

5. DETAILED REQUIREMENTS

5.1 Galvanic compatibility. Above the maximum compatibility corrosion rate (0.009 mil/year), a galvanic couple is deemed incompatible and corrosion protection is required – the CEA or appropriate design authority shall determine the level of required protection. Galvanic compatibility does not imply complete freedom from galvanic corrosion or other types of corrosion, (e.g., crevice or pitting corrosion). This means an assembly or component containing compatible galvanic couples may still require protection against other types of corrosion. The CEA or appropriate design authority shall determine any additional required protection. (Note: Corrosion rate is calculated using the galvanic current obtained from the summation of two polarization curves [i.e., anode and cathode] using a mixed potential theory approach. Galvanic attack is influenced by corrosion current, corrosion potential, kinetic factors such as polarization effects, electrolytic environment, and physical arrangement of the conductive materials. Refer to Appendix C for additional information.)

5.2 Minimizing galvanic corrosion. When dissimilar conductive materials are used in intimate contact, protection against galvanic corrosion shall be applied. In some environments, galvanic corrosion may be appreciable, for example, with conductive materials such as magnesium, steel, zinc, and aluminum (anodes), in contact with copper, stainless steel, and nickel (cathodes), respectfully. For non-continuously immersed couples, the design shall incorporate electrical insulation of the joint and shall include methods to exclude electrolyte intrusion so that both the anodic and cathodic member of the couple are protected. Fatigue may have an impact on the galvanic corrosion rate, and relevant testing should be completed on structural joints where identified by the CEA. Conductive material compatibility shall be demonstrated through the methods outlined in Appendix B. The level of protection required on the conductive materials depends on the level of risk associated with the conductive material couple, both of which are determined by the CEA or appropriate design authority. Sacrificial coatings require different protections to be determined by the CEA.

5.3 Galvanic series in artificial seawater. Tables I, II, and III shall be used to determine galvanic compatibility between conductive materials. The conductive materials are ordered from active (anode) to noble (cathode) based on their measured open circuit potential (OCP). Any combination of conductive materials in the tables has a ranking assigned to it based on the corrosion rate (in mil/yr.) between them, with zero (0) indicating galvanic compatibility. Rankings of one (1) through six (6) indicate galvanic incompatibility and require protection. The range of incompatible rankings does not represent an assessment of risk nor implies a level or hierarchy of protection schemes – the CEA or appropriate design authority shall determine the level of required corrosion protection for their environment relative to sea water. For galvanic couples not included in Tables I, II, and III, data shall be generated according to the procedure outlined on Appendix B, and provided to the CEA or the appropriate design authority for assessment.

5.4 Protection of galvanically incompatible materials. Galvanic couples indicated as compatible do not require protection, unless indicated by the CEA or appropriate design authority to protect against other types of corrosion (see 5.1). Conductive materials that have a galvanic ranking greater than zero (i.e., corrosion rate greater than 0.009 mil/yr.) when coupled, shall not be paired without protection. Protection schemes shall be tailored to the specific application and approved by the CEA. Some recommended protection schemes are outlined in Appendix A and may be accomplished by one or more of the following:

- a. Apply a sacrificial metal coating to the cathodic member with a potential similar to or near that of the anodic member.
- b. Seal to ensure that the faying surfaces are watertight.
- c. Paint or coat all surfaces (anode and cathode) to increase the resistance of the electrical circuit.
- d. Insert a barrier material, which will isolate or insulate the faying surfaces, where the faying surfaces are not required to be electrically conductive. 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 material that will provide a barrier to both physical and galvanic corrosion. Materials used as shields will be application specific.

5.5 Anode to cathode area ratio. Geometries where the area of the cathodic material is larger than the area of the anodic material shall be avoided. Data collected in this standard was collected in a 1:1 anode-to-cathode ratio. The specific anode-to-cathode ratio (A/C) required for compatibility depends on the corrosion rate (CR) between any given galvanic couple, and is given by the following relationship:

$$A/C = \left(\frac{1}{0.009 \text{ mil/yr}} \right) CR$$

Protection of the anodic and cathodic materials is required if the anode-to-cathode ratio from the preceding expression cannot be maintained. A description of the relationship between A/C and CR is provided in Appendix C.

5.6 Additive manufacturing (AM). Conductive materials produced through AM (including cold spray) shall be considered as developmental materials. Until AM processes are standardized, verified, validated, and have established QA/QC procedures, the CEA or appropriate design authority shall evaluate each batch of AM materials and alloys individually to determine galvanic compatibility and required protective treatments. Information on the process used to create the AM materials along with the data listed in B.3.7 is required by the CEA or appropriate design authority for use or consideration for inclusion in future versions of this standard.

5.7 Materials containing conductive components. Materials containing conductive components, such as specialty materials and metal-rich primers, etc., which contain embedded metallic structures and/or powders, can become galvanically active when in contact with a metallic substrate or structure. Thus, the individual metallic components within these matrices shall be tested for galvanic compatibility following the methodology outlined in Appendix B. The CEA shall determine the level of protection required based on the results of the galvanic compatibility test and the intended application of the coating matrix.

5.8 Seawater environments. When joining non-compatible conductive materials, i.e., those with a corrosion rate greater than 0.009 mil/year when coupled (see Tables I, II, III), a barrier approach (e.g., sealant, interposing material compatible with each, shim, etc.) shall be used. Conductive materials exposed to seawater environments shall be resistant to corrosion, including stress-corrosion cracking or shall be processed to resist corrosion and stress-corrosion cracking. All exposed conductive material shall be adequately protected using protection schemes (i.e. sealants, primers, coatings, etc.) sufficient for the level of exposure they will experience.

5.9 Non-metallic materials. Non-conductive materials other than true metals, which must be joined to conductive materials, shall incorporate protection schemes similar to metallic conductive materials, unless approved by the CEA or appropriate design authority. If a material fits the following characteristics, the material may be considered a non-metallic material suitable for joining to metals:

- a. Free of corrosive agents (salts)
- b. Free of acid or alkaline materials (leachant must be neutral pH)
- c. Free of carbon or metallic particles
- d. Are not electrically conductive ($>10^4$ ohm-cm resistivity)
- e. Are not subject to significant bio-deterioration
- f. Will not support fungal growth
- g. Do not absorb or wick water in amounts that make them electrically conductive

Some materials classified as non-metallic will initiate corrosion of the adjoining metals, e.g., cellulosic reinforced plastics, carbon or metal loaded resin materials, asbestos-cement composites, etc.

5.10 Magnesium. When magnesium or a magnesium alloy is one of the conductive materials involved in a couple, the maximum feasible protective system as approved by the CEA shall always be employed. Where magnesium or a magnesium alloy is one of the conductive materials involved in the dissimilar conductive material combination, it is required that the edges of the joint

shall be adequately sealed to prevent excess galvanic corrosion. Magnesium shall not be used underwater except as a sacrificial anode. Where electrical contact of the conductive materials is not required, a non-metallic insulating gasket material may be used. This is true whether the combination is to serve in an electrical conducting system or not. Magnesium and magnesium alloys shall not be used in Naval Aviation applications unless approved by the CEA or appropriate design authority.

5.11 Joining methods to prevent galvanic corrosion. Where it is necessary to join conductive materials that are not galvanically compatible as defined by this standard, the following methods shall be used to minimize or prevent galvanic corrosion, as applicable to the design.

- a. Compatible conductive materials shall be selected such that the corrosion rate when coupled does not exceed 0.009 mil/year in immersed conditions and coupled conductive materials shall be designed to ensure that the area of the cathode is smaller than the area of the anode. For example, bolts or screws of stainless steel may be used for fastening aluminum sheet, but not the reverse since stainless steel is cathodic to the aluminum.
- b. For couples that serve as an electrical connection, a compatible conductive gasket or washer shall be interposed between the dissimilar faying surface materials prior to fastening, or the cathodic member shall be plated with a material compatible with the anode.
- c. For couples that are not serving as an electrical conductor, a non-absorbing, inert gasket material or washer shall be interposed between the dissimilar conductive materials prior to connecting them. For immersion applications, full electrical isolation with insulating sleeves and washers on the bolts is required along with an insulating spacer. In addition, an applicable organic coating shall be applied to the faying surfaces prior to assembly. In situations where large faying surfaces are involved, insert a barrier layer such as sprayable or pre-cured urethane sealants which retain flexibility and are resistant to shrinking, aging and cracking.
- d. All faying edges shall be sealed to preclude the entrance of liquids.
- e. For joints that are not required to be electrically conductive, applicable corrosion-inhibiting compounds shall be applied under the heads of bare, previously plated, and treated fasteners that are inserted into dissimilar conductive material surfaces.
- f. Where practicable, or where it will not interfere with the proposed use of the assembly, the external joint shall be adequately protected using protection schemes (e.g., sealants, primers, coatings, etc.) sufficient for the level of exposure they will experience or sufficient for the environment in which they are required to operate and approved by the CEA or appropriate design authority.
- g. Welded or brazed dissimilar conductive material assemblies shall be coated with a paint system or other suitable protective coating that covers the weld and all heat-affected zones.

5.11.1 Humidity controlled environments. Materials in protective, humidity-controlled environments require careful protection. The assumption that corrosion will not occur because humidity control will be maintained must also take into account the end-use environment of the

material. Approval from the CEA or appropriate design authority is required to lessen the stringency of the protective requirements of the couple. Humidity and moisture controlled environments can only be ensured by the use of hermetically-sealed compartments or containers. The moisture vapor content must be reduced to the level at which water will not condense inside the container at the lowest temperature expected in service. If humidity and condensation cannot be consistently controlled, then the dissimilar conductive material contacts shall be protected in accordance with the worst potential 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 galvanically dissimilar conductive materials and establishes requirements for protecting coupled dissimilar conductive materials against corrosion, with attention directed to the anodic member of the couple,. Previously, galvanic tables were based solely on the corrosion potentials of the two conductive materials in a galvanic couple. Since the potential difference does not incorporate kinetics, it is recognized that the galvanic potential difference between material couples is not a true indicator of galvanic corrosion. The new methodology incorporated into the "D" revision of MIL-STD-889 is based on the mixed potential theory of electrochemistry that was developed over 70 years ago and validated by electrochemists. Mixed potential theory states that the intersection points of two dissimilar conductive materials polarization curves can be used to determine the galvanic corrosion current and galvanic potential. Instead of crossing the anodic materials curve with the cathodic materials curve, the polarization curves of the anodic and cathodic materials were summed to produce a polarization curve of the joint sample in a 1:1 ratio. The galvanic current and potential obtained from the intersection point of the summed, joint curve can be used to determine the corrosion rate. The data collected in this standard was completed in static, immersed conditions.

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.

Anode	Galvanic current
Cathode	Heat-affected zone
Chromate conversion coating	Metallic coating
Corrosion inhibitor	Organic barrier
Electrolyte	Paint
Faying surface	Resin coating
Galvanic corrosion	

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.

6.5 Calculation of corrosion rate. The corrosion rate for the anodic member in a galvanic couple and the self-corrosion rate of each conductive material (uncoupled) were determined using Faraday's Law. The density and valence of the primary conductive material in the alloy were used in the calculation. Galvanic current and I_{corr} were collected using an artificial seawater solution. The listed corrosion rate and subsequent accelerating factors should not be the only determining factor in design decisions.

6.6 Summary of material properties. Table V lists the conductive materials tested within MIL-STD-889, along with their respective UNS codes. The table also lists treatments applied to the conductive materials and specific properties for applicable conductive materials.

6.7 Surface treatment notes in all tables. The following notes explain the surface treatment nomenclature found in the following tables of MIL-STD-889: Tables I, II, III, IV, C-1, C-II and C-III.

- a. The "T*" or "Tagnite" designation after a magnesium alloy indicates the Tagnite anodic coating which is a registered trademark of the Technology Applications Group, Inc.
- b. The "Cr³⁺" designation after an aluminum alloy indicates a trivalent conversion coating, while "Cr⁶⁺" designation indicates a hexavalent conversion coating.
- c. The "Zn-Ni w CC" designation indicates an IZ-C17 zinc-nickel plating with an IZ-264 trivalent conversion coating. IZ-C17 and IZ-264 are registered trademarks of Dipsol of America.
- d. The "Cadmium w CC" designation indicates cadmium plating with a traditional generic room temperature hexavalent conversion coating dip in a solution consisting of sodium dichromate and sulfuric acid.

TABLE II. Galvanic compatibility of treated conductive materials in a 1:1 A/C in immersed artificial seawater.

		Cathodic Material													
		a	b	c	d	e	f	g	h	i	j	k	l	m	n
Anodic Material	a. Mg WE43 T*		5	5	5	5	6	5	5	5	5	6	5	5	6
	b. Mg EV31 T*			4	5	5	6	5	5	5	5	6	5	5	6
	c. Mg AZ31B T*				5	4	5	5	5	5	4	6	5	5	6
	d. Al5083 Cr+6					2	2	2	2	2	2	2	2	2	3
	e. Al6061 Cr+6						2	2	2	2	2	2	2	2	3
	f. Al5083 Cr3+							2	2	2	2	2	2	2	2
	g. Al7075 Cr6+								2	2	2	2	2	2	4
	h. Al6061 Cr+3									2	2	2	2	3	3
	i. Cadmium w CC										1	2	3	3	4
	j. Al7075 Cr+3											2	2	2	4
	k. Zn-Ni w CC												3	3	4
	l. Al2024 Cr6+													2	3
	m. Al2024 Cr3+														3
	n. Electroless Ni														

Legend:

Galvanic compatibility between two conductive materials of interest is found at the intersection point of the row and column. The anodic member of the couple is listed in the rows and the cathodic member of the couple is listed in the columns. An empty cell at the intersection point indicates that the conductive materials identified as anodic and cathodic should be switched.

This table should not be used to indicate the level of risk associated with the galvanic couple nor should it be used to determine the level of protection required to protect the conductive materials. The CEA or appropriate design authority will determine the necessary protection.

The corrosion rate was determined for conductive materials in a 1:1 surface area ratio.

The number in the cells represent a range at which the anodic material will corrode when coupled with the cathodic material in artificial seawater. Any number above zero indicates galvanic incompatibility. The range of the corrosion rate in mil/year is as follows:

Galvanically Compatible:

0: <0.009 mil/year

Galvanically Incompatible:

1: 0.01-0.09 mil/year

2: 0.1-0.9 mil/year

3: 1-4.99 mil/year

4: 5-9.99 mil/year

5: 10-99.99 mil/year

6: > 100 mil/year

TABLE III. Galvanic compatibility of bare versus treated conductive materials in a 1:1 A/C in immersed artificial seawater.

	a. Mg WE43 T*	b. Mg EV31 T*	c. Mg AZ31B T*	d. Al5083 Cr+6	e. Al6061 Cr+6	f. Al5083 Cr3+	g. Al7075 Cr6+	h. Al6061 Cr+3	i. Cadmium w CC	j. Al7075 Cr+3	k. Zn-Ni w CC	l. Al2024 Cr6+	m. Al2024 Cr3+	n. Electroless Ni
1. Mg EV31	5	5	5	6	6	6	6	6	6	6	6	6	6	6
2. Mg WE43	5	5	5	6	6	6	6	6	6	6	6	6	6	6
3. Mg AZ31B	5	5	5	5	5	6	5	5	5	5	6	5	5	6
4. Zinc	5	5	5	2	2	2	3	3	4	2	4	3	3	5
5. Zn-Ni Plated	6	6	6	3	3	3	3	3	3	3	4	4	4	5
6. Al5083	6	6	5	2	2	2	2	2	2	1	2	2	3	4
7. Cadmium	6	6	6	3	3	3	3	3	4	4	5	5	5	5
8. Al6061	5	5	4	2	2	2	2	2	2	1	2	2	2	3
9. CP Aluminum	5	5	5	2	2	2	2	2	3	2	3	3	3	4
10. A356	5	5	4	2	2	2	2	2	2	2	2	2	2	3
11. 1020 Steel	6	6	6	3	3	3	3	3	4	3	3	3	3	3
12. Al7075	6	6	6	4	4	4	4	4	5	4	4	4	4	5
13. A36 Steel	6	6	6	5	5	5	5	5	5	5	5	5	5	5
14. 1018 Steel	6	6	6	5	5	5	5	5	5	5	5	5	5	5
15. 1008 Steel	6	6	6	5	5	5	5	5	5	5	5	5	5	5
16. Al7050	6	6	5	2	2	2	2	2	2	2	2	2	3	4
17. B7 Steel	6	6	6	4	4	4	4	4	5	4	4	3	3	4
18. MIL-11356 Steel	6	6	6	3	3	3	3	3	4	3	3	3	3	3
19. 4340 Steel	6	6	6	4	4	4	4	4	5	4	4	3	3	4
20. HY80 Steel	6	6	6	3	3	3	3	3	4	3	4	3	3	4
21. Tin	6	6	5	2	2	2	2	2	2	1	2	1	1	2
22. Al2024	6	6	6	3	3	3	3	3	4	3	3	3	3	4
23. Ti-6Al-4V	5	5	5	2	2	2	2	2	2	1	2	1	1	1
24. Brass, Yellow	6	6	6	4	4	3	4	4	5	4	4	4	4	3
25. Bronze	6	6	6	4	4	3	4	4	5	4	4	4	4	3
26. NiAl, C630	6	6	6	4	4	3	4	4	5	4	4	4	4	3
27. CuBe	6	6	6	4	4	3	4	4	5	4	4	4	4	3
28. CP Copper	6	6	6	4	4	3	4	4	5	4	5	4	4	3
29. PH 13-8	6	6	6	4	4	2	3	4	5	4	5	2	2	2
30. 304SS	6	6	6	3	3	2	3	3	4	3	3	3	3	2
31. PH 15-5	6	6	6	5	4	2	5	5	5	5	5	4	4	2
32. 304SS Passivated	6	6	6	4	4	2	4	4	5	4	5	4	4	2
33. 410SS	6	6	6	4	4	2	4	4	5	4	5	4	4	2
34. Inconel® 600	6	6	6	3	3	2	3	3	3	3	3	3	2	2
35. A286 Passivated	6	6	6	3	3	2	3	3	4	3	4	3	3	2
36. PH 17-4	6	6	6	4	4	2	4	4	5	4	5	4	3	2
37. 316SS	6	6	6	5	5	2	5	5	5	5	5	5	4	2
38. 316SS Passivated	6	6	6	4	4	2	4	4	5	4	4	4	3	2
39. Monel® 400	6	6	6	3	3	2	3	3	4	3	3	2	2	2
40. 410SS Passivated	6	6	6	4	4	2	4	4	5	4	4	3	3	2
41. A286	6	6	6	4	4	2	4	4	5	4	4	4	3	2
42. PH 17-4 Passivated	6	6	6	3	3	2	3	3	4	3	4	3	3	2
43. PH 13-8 Passivated	6	6	6	4	4	2	4	4	5	4	4	3	3	2
44. PH 15-5 Passivated	6	6	6	3	3	2	3	3	4	3	4	3	3	2
45. Silver	6	6	5	3	3	2	3	3	3	3	3	3	3	2
46. Graphite	6	6	6	5	5	2	5	5	5	5	5	5	5	2
47. Platinum	6	6	6	4	4	2	4	4	5	5	5	4	4	3

Legend:

Galvanic compatibility between two conductive materials of interest is found at the intersection point of the row and column. Bare materials are listed in the rows and treated materials are listed in the columns. To determine the anodic member of the couple, Table IV should be used.

This table should not be used to indicate the level of risk associated with the galvanic couple nor should it be used to determine the level of protection required to protect the conductive materials. The CEA or appropriate design authority will determine the necessary protection.

The corrosion rate was determined for conductive materials in a 1:1 surface area ratio.

The number in the cells represent a range at which the anodic material will corrode when coupled with the cathodic material in artificial seawater. Any number above zero indicates galvanic incompatibility. The range of the corrosion rate in mil/year is as follows:

Galvanically Compatible:

0: <0.009 mil/year

Galvanically Incompatible:

1: 0.01-0.09 mil/year

2: 0.1-0.9 mil/year

3: 1-4.99 mil/year

4: 5-9.99 mil/year

5: 10-99.99 mil/year

6: > 100 mil/year

TABLE IV. Galvanic series of selected conductive materials in immersed artificial seawater according to ASTM D1141 (without heavy metals). 1/

Active (More Active - Anodic)	
Magnesium WE-43 Tagnite	Tin
Magnesium EV-31	Al2024
Magnesium EV-31 Tagnite	Al2024 Cr ⁺⁶
Magnesium WE-43	Al2024 Cr ⁺³
Magnesium AZ31-B Tagnite	Ti-6Al-4V
Magnesium AZ31-B	Electroless Nickel
Al5083 Cr ⁺⁶	Brass, Yellow
Zinc	Bronze
Al6061 Cr ⁺⁶	NiAl Alloy C630
Al5083 Cr ⁺³	CuBe
Al7075 Cr ⁺⁶	Copper
Zn-Ni Plated	PH 13-8
Al6061 Cr ⁺³	304SS
Al5083	PH 15-5
Cadmium	Passivated 304SS
Al6061	410SS
Cadmium w/ Conversion Coating	Inconel [®] 600
Aluminum	Passivated A286
Al7075 Cr ⁺³	PH 17-4
A356	316SS
1020 Steel	316SS Passivated
Al7075	Monel [®] 400
Zn-Ni with Conversion Coating	410SS Passivated
A36 Steel	A286
1018 Steel	PH 17-4 Passivated
1008 Steel	PH 13-8 Passivated
Al7050	PH 15-5 Passivated
B7 Steel	Silver
MIL-11356 Steel	Graphite
4340 Steel	Platinum
HY80 Steel	
Continued in column 2...	Noble (Less Active - Cathodic)

1/ This table should not be used for the determination of compatibility. This table should only be used for determining the anodic member of a galvanic couple. To determine which material is the anodic member of a galvanic couple, locate both materials on the galvanic series table. The material “higher” in the series (closer to the more active side) will be the anodic member. The material “lower” in the series (closer to the less active side) will be the cathodic member.

TABLE V. Description of materials used to obtain data.

MIL-STD-889D Nomenclature	UNS Code	Properties	Characteristic Tested in MIL-STD-889D
A356	A13560		Bare
CP Aluminum	A91100		Bare
Al2024	A92024	Heat Treat: T-3; SAE AMS4037	Bare, Cr ⁶⁺ , Cr ³⁺
Al5083	A95083	Alloy H-32	Bare, Cr ⁶⁺ , Cr ³⁺
Al6061	A96061	Heat Treat: T-6	Bare, Cr ⁶⁺ , Cr ³⁺
Al7050	A97050		Bare
Al7075	A97075	Heat Treat: T-6	Bare, Cr ⁶⁺ , Cr ³⁺
CP Copper	C10100		Bare
CuBe	C17000		Bare
Bronze	C22000	Commercial Bronze C-220	Bare
Brass, Yellow	C26800	Alloy CA-260; ASTM B36/B36M	Bare
NiAl C630	C63000		Bare
1008 Steel	G10080		Bare
1018 Steel	G10180		Bare
1020 Steel	G10200	SAE 1020, Cold-rolled	Bare
B7 Steel	G41400		Bare
4340 Steel	G43400	AISI 4340	Bare
MIL11356 Steel	J13025		Bare
HY80 Steel	J42015		Bare
A36 Steel	K02600		Bare
Cadmium	L01951	SAE AMS-QQ-P-416	Bare, Conversion Coated
Mg AZ31	M11311		Bare, Tagnite
Mg EV31	M12310		Bare, Tagnite
Mg WE43	M18430		Bare, Tagnite
Monel[®] 400	N04400	Alloy 400	Bare
Inconel[®] 600	N06600	Alloy 600	Bare
Platinum	P04995		Bare
Silver	P07010		Bare
Ti-6Al-4V	R56400	SAE AMS-T-9046, Composition C, Type III	Bare
PH 13-8	S13800	SAE AMS5629D; Heat treat: solution treated	Bare, Passivated
PH 15-5	S15500		Bare, Passivated
PH 17-4	S15700	ASTM A693-06 Type 630	Bare, Passivated
304SS	S30400		Bare, Passivated
316SS	S31600	AISI 316	Bare, Passivated
410SS	S41000		Bare, Passivated
A286	S66286	SAE AMS5525K Cold Rolled, Annealed	Bare, Passivated
Zinc	Z15006		Bare
Graphite	NA		Bare
Tin	NA	ASTM B339A(b)	Bare
Zn-Ni Plated	NA	ASTM B841	Bare, Conversion Coated

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SURFACE PROTECTIVE TREATMENTS

A.1 SCOPE

A.1.1 Scope. This appendix lists recommended corrosion protection systems (coatings and surface finishes) for conductive materials and alloys. Selection of protection schemes require approval from the Cognizant Engineering Authority (CEA) or appropriate design authority. The CEA should account for any applicable environmental regulations or restrictions in the selection of the protection schemes. Alterations in either the protection scheme or the material to which the protection scheme is applied, requires approval from the CEA or appropriate design authority. 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 outlines the recommended protective treatments for common conductive materials and alloys used in dissimilar conductive material couples. These protective treatments should be used when galvanically incompatible materials are joined together. Environmental conditions to which the couple is expected to be subjected in-service must be taken into account. Considerations must be given to the following factors: operational conditions, electrical requirements, design requirements, and minimization of maintenance and cost. Initial increase in costs can be more than offset by reduced maintenance and repair and increased service life of the part. Specific review of proposed protective systems for dissimilar conductive material couples should be performed and authorized by the CEA or appropriate design authority 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-DTL-5002 - Surface Treatments and Inorganic Coatings for Metal
Surfaces of Weapons Systems
MIL-C-8514 - Coating Compound, Metal Pretreatment, Resin-Acid
(ASG)
MIL-PRF-8625 - Anodic Coatings For Aluminum and Aluminum Alloys
MIL-DTL-16232 - Phosphate Coating, Heavy, Manganese or Zinc Base
MIL-C-17711 - Coatings, Chromate, For Zinc Alloy Castings and Hot-dip
Galvanized Surfaces
MIL-DTL-18264 - Finishes, Organic, Weapons Systems, Application and

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- Control of
- MIL-DTL-32119 - Coatings, Electroless Nickel, Special Applications
 - MIL-DTL-81706 - Chemical Conversion Materials for Coating Aluminum and Aluminum Alloys

DEPARTMENT OF DEFENSE STANDARDS

- MIL-STD-171 - Finishing of Metal and Wood Surfaces
- MIL-STD-7179 - Finishes, Coatings, and Sealants, for the Protection of Aerospace Weapons Systems and Support Equipment

(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 A967/A967M - Standard Specification for Chemical Passivation Treatments for Stainless Steel Parts
- ASTM D1732 - Standard Practices for Preparation of Magnesium Alloy Surfaces for Painting

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

SAE INTERNATIONAL

- SAE AMS2700 - Passivation of Corrosion Resistant Steels
- SAE AMS2487 - Anodic Treatment of Titanium and Titanium Alloys Solution pH 12.4 Maximum
- SAE AMS2488 - Anodic Treatment - Titanium and Titanium Alloys Solution pH 13 or Higher
- SAE AMS-C-8837 - Coating, Cadmium (Vacuum Deposited)
- SAE AMS-C-26074 - Coatings, Electroless Nickel Requirements for
- 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)
- SAE AS12500 - Corrosion Prevention and Deterioration Control in Electronic Components and Assemblies

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

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A.3 Surface preparation for protective scheme treatment. Cleaning, prior to application of surface treatments and coatings should follow MIL-DTL-5002, MIL-STD-171, TT-C-490 or other appropriate specification as approved by the CEA or appropriate design authority.

A.4 Corrosion protection. Protection schemes for various conductive materials and metal alloy groups are recommended. Within each category, the protection schemes are listed in decreasing order of protectiveness. Application specific protective schemes are also recommended below. Protective schemes should be selected with consideration to the factors listed in A.1.2, opting for the most stringent protective scheme possible. Specific enhancing effects can be accomplished by selecting a higher-level treatment for each conductive material in the couple. Protective schemes should be designed for both the anodic and cathodic member of the galvanic couple. Redundant protection (i.e., combinations of recommended protection schemes) is recommended when design permits. Surface pretreatments, passivation treatments, metallic coatings, insulating shims or gaskets, primers, topcoats and sealants should all be considered by the CEA or appropriate design authority for inclusion in the design of the part or component to preclude or minimize the risk of dissimilar conductive material corrosion.

The protection schemes described in this appendix are recommended to protect against galvanic corrosion. Additional corrosion protections may be required to protect the materials from other types of corrosion such as pitting or crevice corrosion.

NOTE: Many coatings and platings may have a detrimental effect on the fatigue life of base metals and alloys. The CEA or appropriate design authority is responsible for accounting for any loss in fatigue properties and the implementation of methods to prevent fatigue property loss (i.e., shot peening to impart surface compressive stresses, etc.), if necessary.

A.4.1 Treatment for magnesium and magnesium alloys.

- a. Anodic coating (ASTM D1732) post-treated with an alkali-resistant paint or resin coating system. Fayed surfaces should be protected according to MIL-STD-7179.
- b. For general use in non-persistent wet or marine atmosphere an anodic coating without organic coating system; chromate conversion coating (SAE AMS-M-3171) post-treated with an alkali-resistant paint or resin coating system.
- c. For electrical, thermal conducting purposes, in absence of wet, saline or acidic atmospheric conditions: Metallic coating, electroless nickel (SAE AMS-C-26074, or MIL-DTL-32119 where applicable) with cadmium over plating (SAE AMS-QQ-P-416).
- d. Chromate treatment. Suitable for assured condensation-free and acid-free conditions.

Note: Bare magnesium should not be used. Magnesium and magnesium alloys should not be used in Naval applications unless approved by the CEA or appropriate design authority.

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A.4.2 Treatment for zinc and zinc coatings.

- a. Anodic coating post-treated with a paint or resin coating system, primarily for castings.
- b. For electrical and thermal conducting purposes in mild atmospheres in the absence of wet, saline or acidic conditions: Chromate conversion coating (MIL-C-17711) post treated with a paint or resin coating system or anodic coating without organic coating system.
- c. Chromate conversion coating without paint or resin coating system.
Note: Bare zinc plated should not be used in a marine environment.

A.4.3 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 (i.e., wetted) 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.

NOTE: For more information on electronics and avionics corrosion, prevention and control (CPC) requirements, refer to SAE AS12500.

A.4.4 Treatment for cadmium (SAE AMS-QQ-P-416, SAE AMS-C-8837 or SAE AMS-C-81562) or beryllium.

- a. Chromate conversion coating post-treated with a paint or resin coating system.
- b. For electrical and thermal conducting purposes in mild atmospheres in absence of wet, saline or acidic conditions: Chromate conversion coating without an organic coating system. Recommended for beryllium in high temperature applications to forestall catastrophic oxidation in an oxygen-containing atmosphere.

A.4.5 Treatment for aluminum and aluminum alloys.

- a. Anodize to produce a coating according to MIL-PRF-8625 and post-treat with a corrosion resistant finish approved by the CEA or appropriate design authority. Hot water seal should not be used unless authorized by the CEA or appropriate design authority. Parts subject to wear, abrasion, erosion, and severe corrosion should not be anodized unless authorized by the CEA or appropriate design authority and the detrimental effects on fatigue life are accounted for in the design of the part.
- b. Chromate conversion coating (MIL-DTL-81706) post treated with a paint or

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resin coating system; or anodic coating, sealed, with resin seal (when porous castings are used, impregnated with resin prior to surface treating and finishing). This is required for locations classified as exterior aircraft surfaces by MIL-STD-7179, unless identified by the CEA or appropriate design authority.

- c. For electrical and thermal conducting purposes in mild atmospheres in absence of saline, alkaline or acidic conditions: Chromate conversion coating without paint or resin coating system.

NOTE: Bare aluminum - may be used when surface treating would interfere with application, under conditions free of salinity or extended wetness, or when the alloy has sufficient corrosion resistance for the application. Faying edges should be sealed to prevent crevice corrosion.

A.4.6 Treatment for carbon and low alloy steels.

- a. Apply an appropriate corrosion protective coating to the surface of the steel as specified by the CEA or appropriate design authority for the specific dissimilar material coupling, environment and unique design requirements. Protective coatings include, but are limited to, nickel, copper, zinc, cadmium, chromium, aluminum, nickel boron, nickel cadmium, electroless nickel, zinc-nickel, thermal spray coatings, ceramic coatings, etc. Not all combinations of corrosion protective coatings and steel alloys are compatible (e.g. the selection of an appropriate coating can be dependent on the heat treatment (mechanical properties) of the steel). Some of the metallic coatings are used specifically for corrosion protection (e.g. cadmium, aluminum, zinc-nickel, etc.) while others are used for other engineering purposes yet still provide effective corrosion protection (e.g., engineering hard chrome (EHC) plating and nickel plating for wear applications). The CEA or appropriate design authority must balance all design requirements to select and specify the coating system that provides maximum corrosion protection while also meeting all other design requirements. When the design permits, the CEA or appropriate design authority should also specify corrosion protective surface treatments, primers, paints, resin coatings and sealants that can be applied over the dissimilar metal couple or faying edges of the dissimilar metal couple. Barrier gaskets, protective films and other electrically insulating technologies should also be included if design requirements permit. Detailed requirements for corrosion protection coatings, finishes and sealants are provided in other standards and specifications such as MIL-STD-7179, TT-C-490, MIL-STD-171.
- b. Application of metallic coatings without supplemental sealant, primer, paint or resin coating may be necessary in some designs. For applications requiring high electrical or thermal conductivity or in designs where use of supplemental protection such as sealants, primers, paints or resin coatings is not feasible, use metallic coatings as specified by the CEA.
- c. Special purpose chemical conversion coatings and pretreatments for metallic

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substrates (base coatings for organic coatings) such as zinc phosphates and iron phosphates (TT-C-490), resin acid pretreatments (MIL-C-8514) and manganese or zinc base heavy phosphate conversion coating (MIL-DTL-16232) can improve both corrosion protection and primer and topcoat adhesion. Use of these conversion coatings on steels that are susceptible to hydrogen embrittlement require that the CEA or appropriate design authority define the pre- and post-processing precautions discussed in A.4.6.e.

- d. Surface finishing requirements for steel surfaces of military hardware and vehicles are also included in MIL-STD-171. This standard covers surface cleaning methods, electroplating, conversion coatings, wash primers, paint primers and topcoats. It is the responsibility of the CEA or appropriate design authority to specify the surface finish requirements necessary to meet the design requirements.
- e. Prevention of Hydrogen Embrittlement (HE) of high strength steels during manufacture or rework: Steels heat-treated to an ultimate tensile strength (UTS) of 180 KSI (Rockwell C scale hardness of 40) or higher are susceptible to hydrogen embrittlement. Many coatings and coating processes have the potential to cause HE of steels. Designs calling for the use of coatings or coating deposition processes that can cause HE must specify specific processing requirements to both prevent and eliminate HE. Preventive measures may include reducing high residual surface tensile stresses through thermal stress relieving, or imparting beneficial compressive stresses to the surface by shot peening and careful control of the coating deposition process to minimize the evolution of hydrogen during the deposition process. Some specifications for coatings or coating deposition processes specify periodic testing of coupons to assess and control the process. Elimination of HE (de-embrittlement) of high strength steels following coating deposition is by low temperature heating (baking) of the part or component in air for specific time periods (normally 375 ± 25 °F (190.5 ± 13.9 °C) for non-surface hardened parts and 275 ± 25 °F (135 ± 13.9 °C) for carburized or nitrided parts for 23 hours). The requirements for prevention and elimination of HE in high strength steels vary widely within both government and industry specifications and standards. It is the responsibility of the CEA or appropriate design authority to define the specific engineering requirements for the prevention and elimination of HE of steels based on the requirements of the governing specification, unique design requirements, and engineering best practices.

A.4.7 Treatment for titanium and titanium alloys.

- a. Anodize for anti-galling and wear resistance. Application of primer coating or sealant should be applied according to MIL-STD-7179 to faying surfaces. Metals should be anodized according to SAE AMS2487 and SAE AMS2488.
- b. Apply metallic coating post-treated with a paint or resin coating system.

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Caution: Titanium and titanium alloys can be susceptible to metal-induced embrittlement (MIE) in contact with some low melting metals including cadmium, zinc, and silver. MIE can occur as either solid metal or liquid metal embrittlement. Use of cadmium and zinc in contact with titanium or titanium alloys is prohibited. Silver plating over an underplating of nickel is permitted.

- c. For electrical or thermal conducting purposes, apply metallic coating (Cd, Zn prohibited, Ag over Ni acceptable), seal faying edges.
- d. For electrical or thermal conducting purposes, titanium may be used bare with faying edges sealed as stated in MIL-STD-7179. Use of bare titanium is prohibited when titanium is in contact with magnesium, zinc, silver, or cadmium.

A.4.8 Treatment for electrically conductive composites.

- a. Apply a non-conductive layer (such as fiberglass ply) as a barrier ply to the composite surface. Prime and fay surface seal the metallic surface to preclude moisture. Fastener materials for use in carbon fiber reinforced composite structures should be titanium, A286, or Inconel 718 or other approved fasteners (i.e., pre-coated, etc.). Additional protection can be afforded using sealant to wet install the fasteners.

A.4.9 Treatment for graphite.

- a. Plate graphite with a conductive material that is galvanically compatible to both the graphite and the conductive material it is joined to minimize galvanic current. If service is electrical, seal faying edges to preclude corrosion at contacting surface of the conductive material member or apply a conformal coating according to MIL-STD-7179.
- b. Graphite may be used bare in electrical or thermal conducting service, conditions permitting. Faying edges should be sealed.

A.4.10 Treatment for austenitic, precipitation hardening (PH), ferritic (200 series) and martensitic (400 series) stainless steels.

- a. Passivation: Stainless steels (200, 300, 400 series) and precipitation-hardened stainless steels should be passivated in accordance with ASTM A967/A967M or SAE AMS2700, or by other methods approved by the CEA or appropriate design authority. Passivation should be followed by a thorough rinsing and drying. Passivation is not required for corrosion resistant steels that are to be inorganically coated.
- b. Martensitic and PH stainless steels heat treated to HRC 40 or above require HE prevention and relief processing as defined in A.4.6.e.

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- c. Austenitic and PH stainless steels can be used effectively in dissimilar conductive material couples by using insulating gaskets and/or applying primers, paints or other organic coatings without application of metallic coatings. Primers, paint and sealants should be considered for faying surface edges.
- d. Apply appropriate metallic coatings to the surface of the steel as specified by the CEA or appropriate design authority for the specific dissimilar conductive material coupling, environment, and design requirements. When the design permits, the CEA or appropriate design authority should also specify corrosion protective surface treatments, primers, paints, resin coatings and sealants that can be applied over the metallic coatings or faying edges of the couple. A wide variety of surface treatments, primers, paints, resin coatings are available for corrosion protection of stainless steels in various corrosive environments. Barrier gaskets, protective films and other electrically insulating technologies should also be included if design requirements permit. Detailed requirements for corrosion protection coatings, finishes and sealants are provided in other standards and specifications such as MIL-STD-7179, TT-C-490, and MIL-STD-171, etc.
- e. Ferritic and martensitic stainless steels used in dissimilar conductive material couples should be coated or plated with metallic coatings followed by treatment with primers, paints or other corrosion protective coatings.

A.4.11 Treatment for copper and copper alloys. Copper and copper alloys include pure copper, bronze, brass, aluminum bronzes, phosphor bronzes, nickel aluminum bronze and copper beryllium alloys.

- a. Copper and copper alloy part surfaces should be passivated if applicable for the specific alloy. The CEA or appropriate design authority should select the optimum metallic coating, such as cadmium, nickel-cadmium, tin-cadmium, tin-lead, tin, zinc, nickel, or metallic-ceramic to minimize galvanic incompatibility.
- b. When the design permits, the CEA or appropriate design authority should also specify corrosion protective surface treatments, primers, paints, resin coatings and sealants that can be applied over the metallic coatings or faying edges of the couple. A wide variety of surface treatments, primers, paints, resin coatings are available for corrosion protection of copper and copper alloys in various corrosive environments. Barrier gaskets, protective films and other electrically insulating technologies should also be included if design requirements permit. Detailed requirements for corrosion protection coatings, finishes and sealants are provided in other standards and specifications such as MIL-STD-7179, TT-C-490, MIL-STD-171, etc.

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A.4.12 Treatment for chromium (chrome) plating.

- a. Engineering hard chrome plating extending beyond the faying surfaces of a dissimilar coupling and exposed to a corrosive environment that does not provide sufficient corrosion protection of the substrate should have an undercoat of 0.0010 to 0.0016 inch of nickel on steel or zinc parts or an undercoat of 0.0008 to 0.0010 inch of nickel on copper alloy parts.
- b. Craze cracks in “runout” areas of engineering hard chrome plate may be sealed with organic coatings or dry film lubricants to prevent moisture intrusion on parts that do not have nickel underplating. Sealing of craze cracking in chrome plating should not be done in areas of the plating subjected to sliding wear or contact with seals and wiper rings.

A.4.13 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.4.14 Treatment for rhodium, palladium, gold, platinum and their alloys. Use bare, with compound sealant at edges of dissimilar conductive material joint, or by enveloping dissimilar conductive material joint in conformal coatings, where feasible.

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MATERIAL PREPARATION AND ACQUISITION OF POLARIZATION DATA

B.1 SCOPE

B.1.1 Scope. This appendix is intended for the collection of polarization data for MIL-STD-889. The purpose of this appendix is to provide the procedure that ensures, to the best extent possible, the uniform collection of electrochemical data, which reduces variability and allows for comparison between laboratories and samples. This appendix lists the requirements for laboratories generating data under MIL-STD-889. This appendix also includes information regarding the stringency in the procedures and lessons learned to help laboratories troubleshoot potential issues with data collection. This appendix is required for accurate generation and replication of polarization data for purposes of MIL-STD-889. This Appendix is a mandatory part of the specification. The information contained herein is intended for compliance.

B.1.2 Application. The sample preparation processes used to prepare the samples for testing is described. The data collection, transformation, and other best practices used in the creation of this standard are outlined.

B.2 APPLICABLE DOCUMENTS

B.2.1 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 D1141 - Standard Practice for the Preparation of Substitute Ocean Water
ASTM E178 - Standard Practice for Dealing with Outlying Observations

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

B.3 GENERAL REQUIREMENTS

B.3.1 Data validation and verification. Information pertaining to generation or submission of data in accordance with MIL-STD-889 can be obtained from Commander, Naval Air Warfare Center, Aircraft Division (NAWCAD), Air Systems Group (ASG): Corrosion and Wear Branch, Code AB23600, 48066 Shaw Rd, Bldg 2188, Unit 5, Patuxent River, MD 20670-1161. New polarization data for galvanic couples not currently contained in this Standard or new polarization data that differs from that currently in this standard shall be sent to the NAWCAD ASG: Corrosion and Wear Branch prior to data being accepted under MIL-STD-889. NAWCAD ASG: Corrosion and Wear Branch reserves the right to reject any data based on discrepancies seen with the listed samples. To provide validation and verification, the submitting entity must provide data for a galvanic couple of bare aluminum 7075 T-6 and bare 1020 carbon steel, cold-rolled in addition to the data for the new material. All information to be presented is listed in B.3.7.

B.3.2 Surface preparation. The following procedures shall be used when preparing samples of bulk materials for data generation under MIL-STD-889.

- a. Machining: The surface shall be milled or ground to remove surface features and obtain the bulk microstructure.
- b. Surface finish: The surface of the conductive materials shall be ground with P800 (or ANSI 400) grinding paper for surfaces representative of non-functional or bare surfaces. The surface undergoing test shall be ground to a uniform finish. Grinding paper shall be aluminum oxide-based for softer conductive materials (e.g., aluminum and magnesium alloys) and silicon carbide-based for harder conductive materials (see B.4 for exceptions and discussion).

NOTE: Grinding media and grit size can affect the results of electrochemical testing. Grinding aluminum alloys with silicon carbide can embed silicon in the sample surface, which will affect the polarization curve. The grit size used for grinding the sample directly relates to the surface roughness and thus the surface area of the sample.

- c. Samples with grease or oil on the surface require a degreasing step prior to final surface preparation. To degrease the samples, a 4-step sonication process shall be completed in the following order: (1) ACS grade hexanes, (2) ACS grade diethyl ether, (3) ACS grade acetone, and (4) 200-proof ethanol. The samples shall be fully immersed and sonicated in each chemical for 10-minutes. Observe the safety regulations of your facility when using an ultrasonic cleaner with flammable solvents.
- d. Surface preparation: Following grinding with P800 or ANSI 400 abrasive paper, test samples shall be ultrasonically cleaned immediately using ACS grade acetone for 10 minutes followed by 200 proof ethanol for 10 minutes, and air-dried at room temperature. Observe the safety regulations of your facility when using an ultrasonic cleaner with flammable solvents.
- e. Samples requiring any further treatment (e.g., passivation, anodization, plating, etc.) must be prepared in accordance with B.3.2 prior to treatment and cleaned following treatment using acetone and ethanol.
- f. Immediately following cleaning, specimens shall be placed in a chamber maintaining 77 ± 0.63 °F (25 ± 0.35 °C) and 80 percent relative humidity for twenty-four (24) hours before testing (see B.4 for more discussion). Testing shall commence immediately after the twenty four (24)-hour humidity period. Materials showing signs of staining or corrosion shall be rejected for testing and reprepared according to B.3.2.
- g. Samples prone to crevice corrosion during testing (e.g., some stainless steels) shall be masked to avoid the crevice formed by the interface with the O-ring on the electrochemical cell. Masking material shall be chemically resistant to the electrolyte used in the electrochemical test, potential compounds that are produced as a result of the test, and acidic or basic pH levels. The masking material shall also be free from conducting elements.

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- h. Each test requires a freshly prepared sample in accordance with steps a–f.

B.3.3 Electrochemical cell. Polarization curves shall be collected using an electrochemical flat cell. Regardless of manufacturer of the flat cell, ensure the following:

- a. The O-rings used to seal the working electrode are chemically resistant to the electrolyte used in the electrochemical test, side products produced as a result of the test, and acidic or basic pH levels. The O-rings shall also be free from conducting elements (see B.4 for more discussion).
- b. The counter electrode shall be inert. The counter electrode shall be at least twice the area of the working electrode so that the current the counter electrode provides to or accepts from the working electrode is not limited. A platinum mesh counter electrode is recommended.
- c. The counter electrode shall be arranged in a parallel orientation to the working electrode.
- d. The reference electrode shall be placed in a bridge cell or Luggin tube between the working and counter electrodes. The tip of the bridge cell or Luggin tube shall be placed as close to the surface of the working electrode as possible, ensuring no electric current shielding takes place during the polarization scan. The distance from the bridge cell or Luggin tube to the working electrode will vary based on the diameter of the tip of the bridge cell or Luggin tube.
- e. The electrochemical cell shall be placed in a Faraday cage to minimize noise in the data.

B.3.4 Reference electrode. The most common reference electrodes along with their conversion factors are provided in Table B-I:

TABLE B-I. Summary of common reference electrodes.

Reference Electrode	Potential (V vs. ESHE)	Potential (V vs. SCE)
Standard Hydrogen Electrode	0.00	-0.241
Ag/AgCl, saturated KCl	+0.199	-0.042
Saturate Calomel Electrode	+0.241	0.00
Copper Sulfate, saturated	+0.318	+0.077

Any other reference electrode that is properly maintained and compatible with the electrolyte is acceptable. (See B.3.5 for maintenance recommendations.)

B.3.5 Reference electrode maintenance. A health check of the reference electrode shall be completed against an unused reference electrode of the same type (i.e., SCE to SCE) to ensure that no additional systematic errors are introduced to the measured data. An unused reference electrode shall be properly stored and maintained in its filling solution. The unused reference

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electrode shall only be used to compare with other reference electrodes and shall not be used for polarization measurements. This reference electrode shall be replaced every 6-12 months with a new one to ensure the health of the unused electrode. To check if the reference electrode being used for an electrochemical test is within a correct range:

1. Place the unused reference electrode and the reference electrode to be checked in a small container with electrolyte (KCl or NaCl).
2. Measure the potential difference between the two electrodes using a digital multimeter or potentiostat, with the reference to be checked connected as working electrode and the unused reference connected as reference electrode using the Open Circuit Potential (OCP) measurement mode. The measured potential shall be equal to or less than 5.0 mV for a period of 15 minutes when checking, e.g., SCE vs SCE of standard. If this is not the case, the test reference electrode may need new filling solution or the frit may need replacement. If the frit is replaced, adequate time must be given for the frit to become wet. Refer to the manufacturer's instructions for the amount of time to wetness.

B.3.6 Electrolyte. The electrolyte used for the data collection for MIL-STD-889 is artificial seawater in accordance with ASTM D1141, without heavy metals. The solution can be commercially acquired or prepared in-house per the standard. If prepared in-house, use de-ionized water (18 M Ω -cm) to prepare the electrolyte. In addition, if prepared in-house, the solution shall be prepared at least twenty-four (24) hours prior to the beginning experiment. The electrolyte shall be aerated vigorously for 10 minutes immediately before use in an electrochemical test but left quiescent (naturally aerated) for the duration of the test, at 25 ± 1.67 °C (77 ± 3 °F), and with pH 8.2. A pH check shall be performed prior to the beginning of the test. See Section B.4.5 for instructions on adjusting the pH.

B.3.7 Polarization curve data acquisition. Pre-Test Data Measurements: The following data shall be provided to NAWCAD Air Systems Group, Corrosion and Wear Branch for both anodic and cathodic test specimens. Failure to provide all required data may delay or prevent acceptance of polarization curves:

1. OCP vs. time:
 - a. Sampling Period – a sampling period of 1 data point per second for 24 hours (for more noble, OCP > -200 mV vs. SCE) and 4 hours (for less noble, OCP < -200 mV vs. SCE) conductive materials during surface stabilization in the test cell.
2. Polarization parameters:
 - a. A full polarization curve shall consist of a cathodic curve and anodic curve generated with separate specimens, respectively. According to Table B-II, anodic curves shall be generated from OCP to +0.7 V vs. OCP, or when the anodic current density reaches a maximum current of 10 mA/cm². Cathodic curves shall be generated from OCP to -1.4 V vs. SCE, or when the cathodic current density reaches a maximum current of 10 mA/cm².
3. Material Characteristics:
 - a. Substrate material
 - b. Heat treatment condition, specification, lot number, etc. of the material
 - c. Dimensions of the sample (thickness, length, width, area of sample exposed for

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- testing)
- d. Grinding media size and type (e.g., SiC or Al₂O₃)
 - e. All data on surface preparation method (grinding and surface profiling, heat treating, cleaning, coating, time since prepared, etc.)
4. All relevant data defining the polarization test measurements:
- a. Electrolyte chemistry
 - b. Type of reference electrode (including reference check values)
 - c. Scan rate of polarization curve
 - d. Temperature
 - e. Humidity
 - f. pH of electrolyte (before and after testing)
 - g. Test cell manufacturer/part number including all dimensional specifications on size, shape and positioning of the working electrode, counter electrode, and reference electrode.

B.3.8 Data reproducibility. At a minimum, three (3) complete data sets shall be taken (anodic and cathodic curves) in order to determine the spread in the data for a given material. A summary of the conditions and parameters for polarization measurements is presented in Table B-II.

TABLE B-II. Summary of parameters for polarization data.

Item	Notes	
Equipment	Electrochemical cell.	
Reference electrode	SCE, Ag/AgCl, or other suitable electrode.	
Electrolyte	Artificial sea water per ASTM D1141 without heavy metals, 25 ± 1.67 °C (77 ± 3 °F), pH 8.2 ± 0.02, vigorously aerated (10-20 minutes) prior to testing, then quiescent condition (naturally aerated; no bubbling)	
Working electrode	Specimen to be tested. Stationary. Abraded with appropriate P800 or ANSI 400 grinding paper, cleaned with acetone then ethanol, and surface treated appropriately (if required).	
OCP stabilization	The surface should be stabilized in the electrolyte, but not for a time that causes the surface condition to change significantly (e.g. crevice or pitting):	
	MORE Noble (OCP > -200 mV vs. SCE):	LESS Noble (OCP < -200 mV vs. SCE):
	24 hours in electrolyte prior to polarization measurement	4 hours in electrolyte prior to polarization measurement
Polarization curve	<ul style="list-style-type: none"> - Anodic polarization: OCP to +0.7 V vs. OCP, or when the anodic current density reaches a maximum current of 10 mA/cm² - Cathodic polarization: OCP to -1.4 V vs. SCE, or when the cathodic current density reaches a maximum current of 10 mA/cm² <p>Note: Cathodic and anodic curves shall be obtained on separate specimens prepared according to B.3.2.</p>	
Sweep rate	100 μV/s for entire potential range	
IR correction	The reference electrode should be placed >2x diameter of Luggin tip from the working electrode.	

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B.4 Notes. The following notes provide additional information for troubleshooting purposes and exceptions to the procedure outlined.

B.4.1 Exceptions to material preparation. Preparation of soft materials (i.e., lead, silver, and magnesium) may require hand polishing. To hand polish, the following procedure shall be used. Materials shall be polished using the grinding paper listed in B.3.2.

1. Polish the conductive material in straight lines.
2. Rotate the conductive material 90 degrees and polish in straight lines.
3. Repeat until the surface is free from defects and is uniform.
4. Rinse the surface with a reagent grade acetone followed by a rinse in 200-proof ethanol. Then place in the humidity chamber for 24 hours.

Note: To achieve a consistent measurement for lead, gentle wiping with a lint-free, 1-ply Kimwipe was required prior to mounting the sample for testing.

B.4.2 O-rings. Selected O-rings in contact with the sample, shall be resistant to chemicals that are present in the electrolyte, side products produced during the electrochemical test, and acidic or basic pH levels. The O-rings shall also be free from conducting elements. O-rings that easily break down in the chemical or pH environment can affect the results of the electrochemical test by changing the exposed surface area or adding additional components to the chemistry of the electrolyte. Although the pH of the artificial seawater specified in this document is slightly basic, acidic conditions may develop local to the surface in the crevice formed by the O-ring, which will cause rapid degradation of the O-ring.

It is preferred that O-rings be replaced between runs. If this is not practical, O-rings shall be thoroughly cleaned between runs. Contaminants on the O-Ring could cause changes in the pH close to the surface of the test sample and affect the results of the electrochemical test.

B.4.3 Sample storage prior to testing. To ensure uniform results, samples shall be stored in a temperature and humidity controlled chamber at 77 ± 0.63 °F (25 ± 0.35 °C) and 80 percent relative humidity for 24 hours prior to testing. If corrosion, such as flash corrosion, or staining develops during the 24 hour period prior to testing, the sample shall be re-prepared according to the steps outlined in B.3.2. While more surface characterization is required to test this hypothesis, it is suspected that these conditions create a uniform type, quality, and/or thickness of the oxide layer on the sample.

B.4.4 Polarization curve test parameters. Polarization curves shall be run at a scan rate of 100 μ V/s, starting at the Open Circuit Potential of the sample. Both the scan rate and the starting point of polarization curves will affect the results of the test. High scan rates can skip over polarization curve features because the surface cannot stabilize at the speed of the test. Low scan rates can allow the surface to over-stabilize and produce results such as unstable passivation on aluminum. Starting even 5-10 mV away from OCP (either anodic or cathodic) will affect the sample's surface and change the electrochemical data that is collected.

B.4.5 pH variabilities. To ensure there is no drift in the pH, prior to testing, the pH of the solution shall be measured and adjusted to 8.2 ± 0.02 using sodium hydroxide or hydrochloric acid, as appropriate. Dilution of the sodium hydroxide and hydrochloric acid using 18 M Ω -cm

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deionized water will prevent large shifts in the pH when adjusting.

B.4.6 OCP variabilities. If the user has followed the procedures outlined in this document and large variations in OCP are witnessed, this may be a result of the interaction of the conductive material surface and the electrolyte that is close to a transition in the respective Pourbaix diagram. For instance, a pH of 8.2 is close to the active/passive line in the Pourbaix diagram for Aluminum 7075-T6. Minor fluctuations in the pH local to the surface caused by any factor including the cleanliness of the O-ring and flat cell could shift the surface to either side of the passive/active line. This results in large disparities in the open circuit potential of the samples. For Al 7075-T6, the OCP in the passive region is about -750 mV vs. SCE and the OCP in the active region is about -1000 mV vs. SCE.

B.4.7 Connection issues with potentiostat. The following is a list of issues that may indicate that there is a connection problem with the leads from the potentiostat:

- a) An OCP that is drastically different from anticipated
- b) An OCP that varies very linearly over time
- c) An OCP that is sensitive to movement and presence of people nearby
- d) Deposits on the counter electrode

Potential causes with their solutions of these connection issues are shown in Table B-III.

TABLE B-III. Potential causes of potentiostat connection issues.

Potential Causes	Solution
Air bubbles in the Luggin tube or bridge cell	Gentle tapping or a piece of thin tubing inserted into Luggin Tube/bridge cell
Corrosion on metallic connectors (on alligator clips, banana clips, connection plates, etc.)	Replace connectors or remove corrosion from the metallic connectors
Poor metallic-metallic interface between connection plate and sample (e.g., material from a mask causing a gap and poor interface with the connection plate)	Etch material where the connector is attached or remove mask from that area of the connector.
Deposit on the counter electrode	Clean counter electrode appropriately (for platinum mesh counter electrode, soak in 50 percent nitric acid overnight)

B.4.8 Post-processing transformation. To ensure consistency in polarization curve analysis, all polarization curves shall be normalized to units of mA/cm² prior to post-processing. This allows for reasonable comparisons across electrochemical cell configurations.

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B.4.8.1 Pairing polarization data. Anodic and cathodic curves shall be paired into complete polarization curves before comparison on replicate trials. The most important criteria in combining anodic and cathodic polarization curves for a given conductive material is the alignment of OCP values. OCP is the strongest indicator of consistent surface preparation between polarization curves of the same conductive material. Aligned OCP values indicate the conductive material began each test with similar surface conditions.

B.4.8.2 Deconvolution overview. Deconvolution of the polarization curves is required to obtain electrochemical parameters used in the calculation of corrosion rates. Deconvolution shall be completed following the method outlined in *An Iterative Method For Fitting Complex Electrode Polarization Curves* by K.S. Yeum and O.F. Devereux, Corrosion, Vol. 45, pp. 478-487 (1989). The deconvolution process determines the contributions of individual electrochemical reactions to the complete polarization curve. The total current of a given polarization curve is the result of a summation of the contributions of individual electrochemical reactions. These individual reactions take on a roughly exponential form with respect to potential. An individual electrochemical reaction can be approximated with the following six reaction types, where different rate limiting features are dominant.

1. Charge Transfer Control
2. Passivation
3. Diffusion Limited
4. Ohmic drop
5. Diffusion Limited w/Ohmic Drop
6. Passivation w/Ohmic Drop

The process uses regression algorithms to determine constants for each reaction equation that best fits the contributions of these individual reactions to the provided polarization curve.

To eliminate operator bias, three independent operators perform the deconvolution process on three separate polarization curves for each given sample type. The goal is to obtain consensus on the reactions present in each polarization curve. After a consensus of reaction types is achieved, each operator performs deconvolution according to the agreed upon reaction types. Each operator must then take an average of each reaction's constants across the three fit polarization curves. Then, the global average of the three operators' averaged results is completed.

B.4.8.3 Outlier analysis. To ensure data integrity, outlier analysis shall be performed according to ASTM E178. Utilize the Student's t-test method with a 0.01 significance level for each averaged reaction constant as described in 7.1.1 of ASTM E178. Remove user's deconvolution datasets with reaction constants that exceed the 0.01 significance level for equality of mean.

B.4.8.4 Generating an individual material polarization curve. After the deconvolution and averaging processes for the individual reactions are completed, the averaged reactions shall be used to generate an averaged polarization curve. This shall be completed with a simple sum in current across the potential. This method takes into account the three polarization curves collected and deconvoluted by each operator.

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B.4.8.5 Generating a joint sample polarization curve. The averaged polarization curves can then be utilized to determine properties of the galvanic coupling. First, sum the anodic reactions of both conductive materials. Then, sum the cathodic reactions of both conductive materials. The intersection point of the summed anodic reactions with the summed cathodic reactions provides the galvanic potential and current. Galvanic potential is the potential value at the intersection point. Galvanic current is the current value at the intersection point.

PRINCIPLES OF GALVANIC CORROSION

C.1 SCOPE

C.1.1 Purpose. This appendix explains the principle factors that are involved in the phenomenon of galvanic corrosion. This Appendix is not a mandatory part of this standard. The information contained herein is presented for guidance only.

C.1.2 Application. The principle factors involved in the phenomenon of galvanic corrosion are explained.

C.2 GENERAL INFORMATION

C.2.1 Factors influencing galvanic corrosion. Several factors can influence the kinetics of galvanic corrosion. Among these are the polarization behavior of the conductive materials under the prevailing conditions; the areas of the anode and cathode; the electrical resistance; the type and concentration of the electrolyte; the pH of the electrolyte medium; the distance between, and the geometry of, the anode and cathode; and 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 is the potential of the anode (as polarized); I is the current in amperes; R_e is the resistance of the electrolyte solution path in the galvanic current (internal circuit) and R_m is the resistance of the electrodes (external circuit).

C.2.2 Corrosive environment. Each conductive material, in an electrolyte at a specific concentration and temperature, has a specific electrical potential, i.e., ability to undergo dissolution - to form metal ions with the release of electrons. In a corrosive solution having high conductivity and producing readily soluble corrosion products of the conductive materials, 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. In contrast, the same conductive material 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.

a. Galvanic effects may change because of different pH conditions within an electrolyte. A conductive material, which is the anode in a neutral or acidic solution, may become the cathode if the solution is 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. The

amount of available oxygen and the rate of its diffusion therefore can change the rate of 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.

C.2.3 Conductivity of the galvanic circuit. Corrosion of a single conductive material in an electrolyte involves the flow of current from local anodic to local cathodic areas on the conductive material 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 conductive material surface because of different conductive material 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 mass or quantity of conductive material 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 conductive material (atomic weight divided by valence or charge of ions produced); F is Faraday's constant (96,5000 coulombs per mol).

Galvanic corrosion is different from corrosion of a single conductive material experiencing current flow in an electrolyte solution. The latter type of corrosion is caused by differences in oxygen content of the electrolyte solution at different surfaces of the conductive material; differences in solute ion concentration or differential aeration; or differential ion or concentration.

C.2.4 Components of polarization curve. To understand the components of a polarization curve, it is first necessary to understand an Evans Diagram. Figure C-1 illustrates an Evans diagram with an arbitrary scale. It is typical to see the data plotted with a logarithmic current, leading to a linear plot. The slope of the line is called the Tafel slope and is usually expressed in mV/decade.

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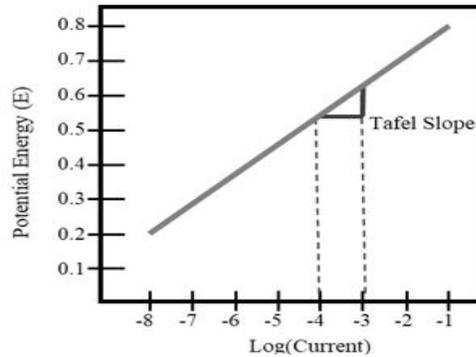


FIGURE C-1. Evans diagram with an arbitrary scale.

There are two common cathodic reactions in polarization curves: hydrogen evolution reactions (HER) and oxygen reduction reactions (ORR). HER are common due to water having two hydrogen atoms to reduce. In solutions containing dissolved oxygen, the ORR will occur at high currents and when not enough oxygen can diffuse to the electrode. This results in a diffusion limited system.

Figure C-2 shows a Tafel plot of a diffusion limited system. The plot is no longer linear as the current no longer depends on the electrode and is dependent on diffusion of oxygen or other ions.

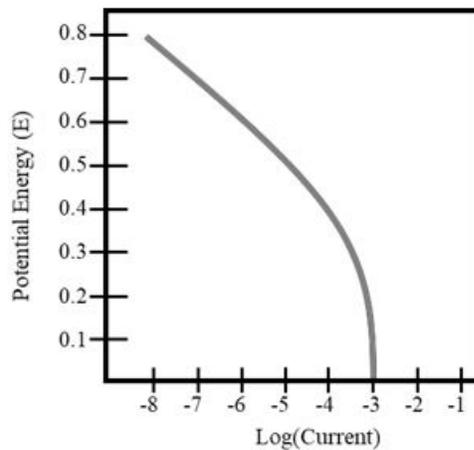


FIGURE C-2. Tafel plot of a diffusion limited system.

When corrosion occurs, oxidation and reduction reactions occur simultaneously. The point at which the lines intersect can be used to determine the corrosion current (I_{corr}) and the corrosion potential (E_{corr}). Figure C-3 illustrates this principle on an Evans diagram.

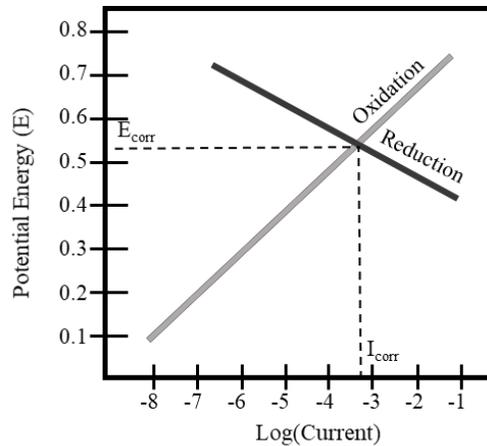


FIGURE C-3. Evans diagram with E_{corr} and I_{corr} .

Since Evans diagrams are normally used for quantitative purposes, polarization curves can be used to collect data on a system of interest to determine its E_{corr} and I_{corr} values. Figure C-4 shows the polarization curve with the Evans diagram overlaid on it. The linear slopes on the polarization curves are extrapolated to where they intersect. This intersection point determines the E_{corr} and I_{corr} .

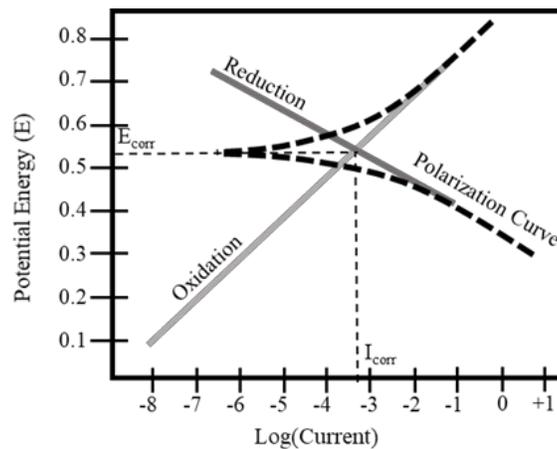


FIGURE C-4. Polarization curve with an Evans Diagram.

C.2.5 Mixed conductive material polarization curves. Traditionally, when applying the theory outlined in C.2.4 to mixed conductive materials, the polarization curves for two conductive materials are overlaid and the values at the point of intersection are determined to be the galvanic current and the galvanic potential. The established method of curve crossing worked as predicted for materials that have significantly different OCPs. However, materials that had

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very close OCPs resulted in erroneous galvanic current values due to the extremely small current values near OCP where the materials' curves crossed. Summation of the anodic scans of both materials and the cathodic scans of both materials allows for the elimination of the issue with close-OCP pairings, while not affecting the results from pairings that cross far from OCP. The intersection point of the anodic and cathodic portions of the galvanic curve is then determined to be the galvanic current and galvanic potential.

To verify this approach, two conductive materials of interest were joined together, ensuring electrical contact. A polarization curve on the joined conductive material couple was completed. The generated polarization curve of the joined materials was compared to the polarization curves produced using mixed potential theory. The results showed that both polarization curves had the same features at nearly the same E_{gal} and I_{gal} . In addition to this test, a zero resistance ammeter (ZRA) was performed on the same conductive materials. The ZRA confirmed these results by outputting a galvanic current and galvanic potential near where the mixed conductive materials curves intersect.

C.2.6 Accelerating factor determination. When coupling different conductive materials, the corrosion rate of the anodic member of a couple increases compared to the corrosion rate of the same conductive material if it was unpaired. The increase in corrosion rate can be quantified as the acceleration factor. To determine this, the corrosion rate of the anodic member in a galvanic couple is divided by the self-corrosion rate of the same anodic member. The summary of the acceleration factors is listed in Tables C-I, C-II and C-III.

C.2.7 Polarization control. The polarization of electrodes in an electrolyte solution occurs because a film of oxide, gas, or other compound changes the electrode surfaces. These changes reduce the potential difference relative to the open circuit potentials and lessen the corrosion rate. These changes on the surface increase the resistance of the external circuit and diminish current flow. They also tend to intensify or diminish with the change in galvanic current or applied current. Electrode polarization behavior is a means by which the compatibility of coupled dissimilar conductive materials 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 on Figure C-5. When polarization mainly occurs at the anode, it is under anodic control. For a polarization reaction that occurs mainly at the cathode, the corrosion reaction is under cathodic control. If polarization reactions occur equally at both the anode and cathode, it is under mixed control. When the electrodes do not polarize, resistance of the circuit, the solution path (R_e) and the metallic portion (R_m) control the reaction. Galvanic corrosion and current flow are polarization and resistance controlled.

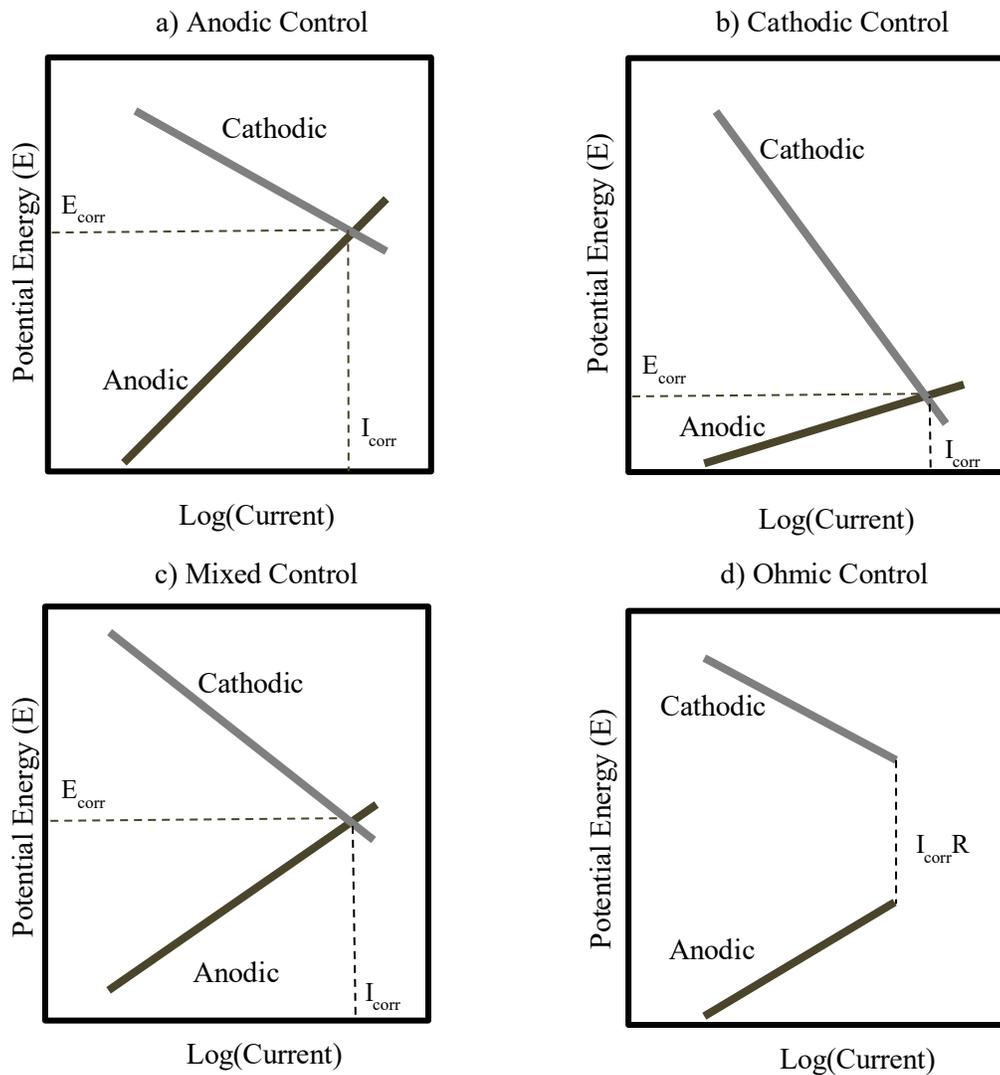


FIGURE C-5. Types of polarization and control in galvanic corrosion.

C.2.8 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, reduces 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. General 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.

C.2.9 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). These factors 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.

C.2.10 The electrolyte medium. In each liquid medium or solution (for a given concentration of the electrolyte and temperature of the medium), a conductive material has a specific electrical potential. In a very corrosive solution, i.e., a solution 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 conductive materials may exhibit different responses in the electrolyte solution because of pH changes. A conductive material, 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 the aluminum is rendered anodic, a reversal of polarity. In a 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.

C.2.11 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. The amount of available oxygen and the rate of its diffusion can therefore change 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.

C.2.12 Importance of kinetics. Based on the previous definition of dissimilar conductive materials, it could be inferred that aluminum alloys would experience less corrosion when paired with stainless steels rather than titanium. This determination was based solely on the difference in the potentials – the difference in potential between aluminum and titanium is greater than the difference between aluminum and stainless steels. Under the previous method, smaller differences in potential indicated less propensity to corrode.

In comparison, when looking at the current of conductive materials in various sodium chloride concentrations, titanium is almost a magnitude lower in current than stainless steels. Although

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the potential indicates that titanium is a worse pairing with aluminum, it takes a longer time for the corrosion to occur.

In practice, we see that aluminum alloys corrode at a slower rate when coupled with titanium than when coupled with stainless steels. This proves that even though the potential difference between the aluminum and titanium is not favorable, the kinetics show that it will take longer for the aluminum paired to the titanium to corrode compared to the stainless steel with the aluminum.

C.2.13 Calculating anode to cathode (A/C) ratio. To determine the desired A/C ratio for a galvanically incompatible conductive material couple, the equation listed in 5.5 shall be used. To use this equation, the galvanic corrosion rate for a selected conductive material couple shall be divided by 0.009 mil per year, which is the corrosion rate at which a galvanic conductive material couple is compatible. If the exact galvanic corrosion rate is not known, use the upper value of the corrosion rate rating. An example of this calculation is provided below.

Conductive Material Pair - 1020 Steel with Inconel® 600

Corrosion Rating – 3 (1.0-4.99 mil/year)

$$\frac{A}{C} = \left(\frac{1}{0.009 \frac{\text{mil}}{\text{yr}}} \right) CR \quad \rightarrow \quad \frac{A}{C} = \left(\frac{1}{0.009 \frac{\text{mil}}{\text{yr}}} \right) 4.99 \frac{\text{mil}}{\text{yr}} \quad \rightarrow \quad A/C = 554.44$$

Anode to Cathode Ratio of 554.44: 1

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TABLE C-II. Accelerating factors of treated conductive materials in a 1:1A/C in immersed artificial seawater.

	Cathodic Material														
	a	b	c	d	e	f	g	h	i	j	k	l	m	n	
Anodic Material	a. Mg WE43 T*	1.8	1.8	11	5.9	14	9.3	8.4	8.5	10	17	9.8	11	19	
	b. Mg EV31 T*			1.5	12	5.2	31	8.8	7.7	9.1	9.8	99	10	11	432
	c. Mg AZ31B T*				150	49	279	99	107	179	64	944	203	175	4938
	d. Al5083 Cr+6					1.2	1.2	1.2	1.1	1.0	1.0	1.2	1.1	1.6	8.6
	e. Al6061 Cr+6						2.1	2.1	1.7	1.3	1.3	2.8	2.9	5.3	30
	f. Al5083 Cr3+							2.1	1.8	2.1	1.5	3.7	3.2	3.3	3.6
	g. Al7075 Cr6+								1.8	1.2	1.1	2.4	1.3	3.1	29
	h. Al6061 Cr+3									2.2	1.5	4.5	4.6	7.0	32
	i. Cadmium w CC										1.4	18	29	51	220
	j. Al7075 Cr+3											38	21	66	586
	k. Zn-Ni w CC												2.6	4.1	17
	l. Al2024 Cr6+													5.8	172
	m. Al2024 Cr3+														74
	n. Electroless Ni														

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TABLE C-III. Accelerating factors of bare versus treated conductive materials in a 1:1 A/C in immersed artificial seawater.

	a. Mg WE43 T*	b. Mg EV31 T*	c. Mg AZ31B T*	d. Al5083 Cr+6	e. Al6061 Cr+6	f. Al5083 Cr3+	g. Al7075 Cr6+	h. Al6061 Cr+3	i. Cadmium w CC	j. Al7075 Cr+3	k. Zn-Ni w CC	l. Al2024 Cr6+	m. Al2024 Cr3+	n. Electroless Ni
1. Mg EV31	3.2	1.3	1.3	25	9.9	67	18	17	7.8	28	133	20	28	248
2. Mg WE43	3.2	4.1	3.8	99	30	273	65	62	24	118	500	73	118	835
3. Mg AZ31B	7.3	6.6	79	9.7	1.7	59	5.2	3.6	5.4	8.1	144	7.0	9.5	333
4. Zinc	10	10	112	1.3	2.1	2.6	3.5	3.6	18	3.1	26	12	12	59
5. Zn-Ni Plated	18	107	1493	5.6	19	17	18	1.1	1.3	1.0	2.0	1.5	1.5	2.7
6. Al5083	15	44	460	1.0	1.3	1.5	1.2	1.5	2.4	1.7	11	13	22	96
7. Cadmium	19	262	3684	8.2	28	26	28	31	1.0	1.0	1.4	1.3	1.3	2.0
8. Al6061	10	10	70	1.0	1.5	2.6	1.3	2.9	1.3	1.1	5.2	4.7	11	63
9. CP Aluminum	8.3	9.5	221	1.7	4.4	5.1	4.2	6.0	27	1.0	1.9	2.0	2.6	8.8
10. A356	1.7	2.0	58	1.0	1.5	2.7	1.3	3.2	5.0	12	5.2	4.7	9.3	56
11. 1020 Steel	20	503	8913	5.3	18	17	17	20	127	343	1.2	1.3	1.4	2.5
12. Al7075	17	66	998	12	43	39	42	46	311	844	1.1	1.1	1.2	1.7
13. A36 Steel	20	746	8655	37	127	116	123	136	918	2492	69	1.0	1.1	1.2
14. 1018 Steel	20	991	12267	24	84	77	82	90	608	1651	46	1.0	1.1	1.3
15. 1008 Steel	21	1045	11930	27	94	86	90	101	680	1821	51	1.0	1.0	1.2
16. Al7050	13	26	190	1.0	1.9	2.9	1.7	3.5	13	26	1.7	3.1	5.8	25
17. B7 Steel	21	1021	16494	9.5	33	30	31	36	245	629	19	1.1	1.2	1.8
18. MIL-11356 Steel	20	957	11432	5.0	17	15	15	19	146	303	11	1.1	1.2	2.4
19. 4340 Steel	20	1205	15537	10	35	31	32	40	331	644	24	1.0	1.1	1.6
20. HY80 Steel	20	459	8244	7.5	26	23	24	29	210	490	16	1.1	1.2	2.0
21. Tin	12	17	334	1.0	1.8	3.0	1.2	3.7	14	11	1.6	2.0	2.8	46
22. Al2024	16	32	845	4.2	15	7.2	12	18	130	257	9.9	1.0	1.1	4.6
23. Ti-6Al-4V	2.4	3.1	113	1.0	1.5	2.9	1.2	3.4	9.6	9.8	1.4	1.6	1.1	4.3
24. Brass, Yellow	16	61	920	13	44	22	43	47	317	861	24	349	256	37
25. Bronze	19	215	3036	13	46	8.4	44	49	331	899	25	365	268	12
26. NiAl, C630	20	413	5566	9.4	33	16	32	35	239	641	18	255	185	26
27. CuBe	18	138	1974	9.7	34	6.8	33	36	246	664	19	268	197	9.8
28. CP Copper	17	111	1351	14	49	11	47	52	353	960	26	390	289	17
29. PH 13-8	21	2677	26582	10	36	3.4	24	59	694	663	50	36	8.9	1.0
30. 304SS	19	247	3430	5.6	20	3.4	19	21	142	383	11	141	77	1.2
31. PH 15-5	20	676	7417	18	61	3.4	59	66	447	1203	33	403	204	1.5
32. 304SS Passivated	19	465	4527	15	53	3.4	50	56	382	1030	29	343	178	1.6
33. 410SS	20	632	8646	14	47	3.4	46	51	343	925	26	333	186	1.5
34. Inconel® 600	20	632	8646	3.2	11	3.4	9.8	13	97	205	7.4	61	29	1.5
35. A286 Passivated	20	521	7636	7.7	27	3.4	26	29	198	523	15	154	69	1.1
36. PH 17-4	20	513	8543	16	57	3.4	54	61	417	1111	31	343	160	1.3
37. 316SS	20	555	6723	20	71	3.4	68	76	521	1396	39	482	259	1.5
38. 316SS Passivated	20	563	6911	11	40	3.4	38	43	291	776	22	246	118	1.7
39. Monel® 400	19	317	3900	3.8	13	3.4	10	17	129	228	9.8	32	12	1.4
40. 410SS Passivated	20	319	5141	9.5	33	3.4	32	35	240	648	18	224	115	1.1
41. A286	19	195	2504	12	41	3.4	39	45	315	806	24	285	165	1.4
42. PH 17-4 Passivated	20	756	9617	7.7	27	3.4	26	29	194	523	15	175	85	1.7
43. PH 13-8 Passivated	19	236	2633	10	35	3.4	34	38	258	688	19	217	106	1.3
44. PH 15-5 Passivated	19	260	3201	6.6	23	3.4	22	25	168	445	13	138	64	1.5
45. Silver	19	176	2280	2.5	8.7	3.4	8.4	9.4	63	171	5.0	69	50	1.3
46. Graphite	15	39	574	87	304	3.5	290	326	2234	5982	166	2369	1719	2.8
47. Platinum	21	231	5646	17	58	3.5	56	65	469	1149	35	448	331	6.5

CONCLUDING MATERIAL

Custodians:

Navy – AS
Air Force – 20
Army – MR

Preparing activity:

Navy - AS
Project: MFPP-2020-011

Review activities:

Navy – MC, SH
Air Force – 19, 184

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