W. W. Hansen Experimental Physics Laboratory
STANFORD UNIVERSITY
STANFORD, CALIFORNIA 94305-4085
GRAVITY PROBE B RELATIVITY MISSION

VERIFICATION OF DISSIMILAR METALS REQUIREMENT PLSE-12 3.3.1.1.5

S0609 Rev -

Robert Brumley 11/29/01

Prepared by: Robert Brumley **Date**
Payload Technical Manager

4/30/01

Approved by: Bruce Clarke **Date**
Payload Test Engineer

11/29/01

Approved by: A. Logan **Date**
Systems Engineering

11/29/01

Approved by: D. Ross **Date**
Quality Assurance

11/30/01

ITAR Assessment Performed ____________ **ITAR Control Req'd?** ☐ **Yes** ☒ **No**
Tom Langenstein

1. Purpose

This document serves to verify PLSE-12 3.3.1.1.5. Although the verification method for the requirement is inspection, this document serves to document and clarify some of the details pertaining to the payload's compliance to this requirement.

For purposes of this verification, the GP-B payload is defined as the assembly comprised of the science mission probe (Probe C), the flight dewar (SMD-01), and the Science Instrument Assembly (SIA). The science mission probe and the flight dewar have been previously verified to comply with this requirement, as documented in their individual Acceptance Data Packages (ADPs). Therefore this document focuses on the compliance of the Science Instrument Assembly (SIA) to the requirement.

2. Requirement

PLSE-12 #	Title	Requirement	Method
3.3.1.1.5	Dissimilar Metals	Dissimilar metal combinations shall not be used unless protected against electrolytic corrosion. Metals are considered compatible if they are in the same grouping as specified in MIL-STD-889.	I

For reference, a copy of MIL-STD-889B (the most current revision as of the writing of this document) is included as Appendix A of this document.

3. Compliance

3.1 Corrosion and the Science Instrument Assembly

The purpose of MIL-STD-889 is to ensure that galvanic corrosion does not occur between two joined metals. For a large number of metals, it lists which metals can be joined in particular media without danger of corrosion, and recommends methods for providing protective coatings for two metals which might otherwise be subject to galvanic corrosion.

The degree to which two metals will corrode in a particular media depends on the distance between the two metals in the galvanic series for that media. MIL-STD-889B describes this in the following way.

> *3.3 <u>Galvanic Series</u>. A galvanic series is a listing of metals and alloys based on their order and tendency to corrode independently, in a particular electrolyte solution or other environment. This tendency for dissolution or corrosion is related to the electrical potential of the metal in conductive medium. Galvanic corrosion is inherently affected by the relative position of the galvanic series of the metals constituting the couple. Metals closely positioned in the series will have electrical potentials nearer one another, whereas with greater divergence in position, greater differences in potential will prevail. Galvanic effects, i.e.,*

Rw —

> *corrosion of the anode will in the former condition be minimal, the latter condition will exhibit more significant corrosive effects.*

The SIA resides within the vacuum shell of Probe C. After initial integration, all air is evacuated from the space surrounding the SIA and the SIA/Probe assembly is cooled to liquid Helium temperatures (approximately 4 K). In this environment, no corrosion can occur. Paragraph 5.2(g) confirms that if the environment is properly controlled, corrosion will not occur.

> *In so called protective environments (usually referred to as humidity-controlled) caution should be applied to dissimilar metal combination treatments. If the assumption is made that no corrosion will occur because humidity control will be maintained, the stringent requirements would be unnecessary. It must be recognized that humidity and moisture controlled environments can be assured only by hermetically sealed compartments or containers in which the moisture vapor content has been adequately reduced, so as to preclude condensation of water at the lowest temperature expected to be encountered in the actual surface of the item.*

Prior to SIA/Probe integration, all SIA components were stored in a clean, humidity-controlled environment. During the integration process itself, all components were carefully cleaned and inspected for contamination, which would have indicated any corrosion present on the components.

After SIA integration into the probe, the probe was evacuated and a complete functional checkout was performed. From this moment on, no corrosion could occur because the SIA has been kept either in a high vacuum or ultra-pure Helium gas environment. In addition to this, the entire assembly has been cooled to 4 Kelvin, which further serves to prevent any chemical reaction. The assembly will remain in an ultra-high vacuum 4 Kelvin environment through launch and all on-orbit operations.

For these reasons, the functionality of the SIA is incredibly insensitive to corrosion problems. The fact that it remains in a high vacuum at 4 Kelvin completely retards any future corrosive process.

3.2 SIA Compliance to MIL-STD-889B

As stated above, all parts used in the SIA were inspected for contamination (including corrosion) prior to integration into the SIA/Probe assembly, and this assembly has been kept in a protected vacuum (and cryogenic, for the vast majority of the time) ever since. This meets the conditions of MIL-STD-889B Section 5.2g.

In addition to this, all parts in the SIA were procured in accordance with the GP-B list of authorized materials, which is contained in the Stanford University Document P0057 Magnetic Control Plan.

Inspection of the above document and the SIA drawings indicates that there is one instance in which two metals are joined that are not explicitly labeled as compatible in MIL-STD-889B.

S0609 Run –

MIL-STD-889B
7 July 1976

SUPERSEDING
MIL-STD-889A
25 September 1969

MILITARY STANDARD

DISSIMILAR METALS

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

FSC MFFP

7

S0609 · Rw -

MIL-STD-889B
7 July 1976

DEPARTMENT OF DEFENSE

Dissimilar Metals

MIL-STD-889

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

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

8

50609 Rev -

CONTENTS

TABLES

APPENDICES

9

S0609 Rev-

MIL-STD-889B
7 July 1976
SUPERSEDING
MIL-STD-889A
25 September 1969

MILITARY STANDARD

DISSIMILAR METALS

1. SCOPE.

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

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

2. REFERENCED DOCUMENTS.

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

SPECIFICATIONS

MILITARY

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

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

FSC MFFP

S0609 Rev —

3. DEFINITIONS.

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

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

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

4. GENERAL STATEMENTS. (Not Applicable)

5. DETAILED REQUIREMENTS.

5.1 Minimizing dissimilar metal corrosion.

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

11

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

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

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

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

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

S0609 Rev –

TABLE 1.

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

1ST METAL OR METAL ALLOY / JOINED TO 2ND METAL OR METAL ALLOY

ACTIVE (ANODIC) ——— NOBLE (LESS ACTIVE-CATHODIC)

	1ST METAL OR METAL ALLOY	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
A	MAGNESIUM	1 &	1, 2 C I C	1, 3 C I C	1, 4 I I I	1, 4 I I I	1, 5 I I I	1, 6 I I I	1, 6 I I I	1, 7 I I I	1, 8 I I I	1, 9 I I I	1, 9 I I I	1, 9 I I I	1, 9 I I I	1, 9 I I I	1, 9 I I I	1, 10 I I I	1, 11 I I I	1, 12 I I I	1, 13 I I I
B	ZINC, ZINC COATING		2 &	2, 3 C C C	2, 4 C I C	2, 4 C I C	2, 5 I I I	2, 6 I I I	2, 6 I I I	2, 7 I I I	2, 8 I I I	2, 9 I I I	2, 9 I I I	2, 9 I I I	2, 9 I I I	2, 9 I I I	2, 9 I I I	2, 10 I I I	2, 11 I I I	2, 12 I I I	2, 13 I I I
C	CADMIUM BERYLLIUM			3 &	3, 4 C I C	3, 4 C I C	3, 5 I I I	3, 8 I I I	3, 6 I I I	3, 7 I I I	3, 8 I I I	3, 9 I I I	3, 9 I I I	3, 9 I I I	3, 9 I I I	3, 9 I I I	3, 9 I I I	3, 10 I I I	3, 11 I I I	3, 12 I I I	3, 13 I I I
D	ALUMINUM ALUMINUM-Mg ALUMINUM-Zn				4 &	4, 4 C C C	4, 5 I I I	4, 5 I I I	4, 6 I I I	4, 7 I I I	4, 8 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 10 I I I	4, 11 I I I	4, 12 I I I	4, 13 I I I
E	ALUMINUM-Cu					4 &	4, 5 I I I	4, 6 I I I	4, 6 I I I	4, 7 I I I	4, 8 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 9 I I I	4, 10 I I I	4, 11 I I I	4, 12 I I I	4, 13 I I I
F	STEELS-CARBON LOW ALLOY						5 &	5, 6 I I C	5, 6 I I I	5, 7 I I I	5, 8 I I I	5, 9 I I I	5, 9 I I I	5, 9 I I I	5, 9 I I I	5, 9 I I I	5, 9 C I C	5, 10 I I I	5, 11 I I I	5, 12 I I I	5, 13 I I I
G	LEAD							6 &	6, 6 C C C	6, 7 C I C	6, 8 C I C	6, 9 C I C	6, 9 C I C	6, 9 I I I	6, 9 I I C	6, 9 I I C	6, 9 I I C	6, 10 I I C	6, 11 C I C	6, 12 I I C	6, 13 I I C
H	TIN TIN-Pb INDIUM								6 &	6, 7 I I I	6, 8 I I C	6, 9 I I C	6, 9 C I C	6, 9 C I C	6, 9 C I C	6, 9 C I C	6, 9 C C C	6, 10 C I C	6, 11 C C C	6, 12 C I C	6, 13 I I I
I	ST STEELS-MARTENSITIC FERRITIC									7 &	7, 8 I I C	7, 9 I I I	7, 9 I I I	7, 9 I I C	7, 9 I I I	7, 9 I I I	7, 9 I I I	7, 10 I I I	7, 11 I I I	7, 12 I I I	7, 13 I I I
J	CHROMIUM MOLYBDENUM TUNGSTEN										8 &	8, 9 C C C	8, 9 C I C	8, 9 I I C	8, 9 I I I	8, 9 C I C	8, 9 C I C	8, 10 C I C	8, 11 C I C	8, 12 C I C	8, 13 C I C
K	ST. STEELS-AUST. PH, SUPER STRENGTH, HEAT RESISTANT											9 &	9, 9 I I I	9, 9 I I I	9, 9 I I I	9, 9 C I C	9, 9 C I C	9, 10 C I C	9, 11 C I C	9, 12 C I C	9, 13 C I C
L	BRASS-Pb BRONZE												9 &	9, 9 C I C	9, 9 C I C	9, 9 I I C	9, 9 C I C	9, 10 I I C	9, 11 C I C	9, 12 C I C	9, 13 C I C
M	BRASS-LOW Cu BRONZE-LOW Cu													9 &	9, 9 C I C	9, 9 C I C	9, 9 C I C	9, 10 I I C	9, 11 C I C	9, 12 I I C	9, 13 I I C
N	BRASS-HIGH Cu BRONZE-HIGH Cu														9 &	9, 9 I I C	9, 9 C I C	9, 10 I I C	9, 11 C I C	9, 12 I I C	9, 13 I I C
O	COPPER-HIGH Ni MONEL															9 &	9, 9 C I C	9, 10 C I C	9, 11 C I C	9, 12 C I C	9, 13 C I C
P	NICKEL COBALT																9 &	9, 10 C I C	9, 11 C I C	9, 12 C I C	9, 13 C I C
Q	TITANIUM																	10 &	10, 11 C I C	10, 12 C I C	10, 13 C I C
R	SILVER																		11 &	11, 12 C C C	11, 13 C I C
S	PALLADIUM RHODIUM GOLD PLATINUM																			12 &	12, 13 C C C
T	GRAPHITE																				13 &

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

KEY: METAL 1 ——▸ ● ● ◂—— METAL 2
● ◂—— SEA WATER
MARINE ATMOSPHERE ——▸ ● ● ◂—— INDUSTRIAL ATMOSPHERE

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

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

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

13

S0609 Rev -

TABLE II. Galvanic series of selected metals in seawater.

Active (Anodic)

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

TABLE II (Continued)

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

Noble (Less Active-Cathodic)

[illegible] GENERAL REQUIREMENTS

S0609 Rev -

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

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

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

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

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

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

S0609 Rev -

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

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

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

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

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

6. APPENDICES.

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

S0609 Rev –

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

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

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

PREPARING ACTIVITY:
Air Force - 11

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

PROJECT NUMBER: MFFP-0113

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

APPENDIX A

RECOMMENDED TREATMENTS IN ORDER OF PROTECTIVE EFFECTIVENESS

10. GENERAL

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

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

20. REFERENCE DOCUMENTS

SPECIFICATIONS

FEDERAL

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

MILITARY

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

S0609 Rev –

MILITARY (CON'T)

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

30. Recommended Treatments in Order of Protective Effectiveness

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

30.1 Treatment for Magnesium

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

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

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

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

Note: Bare magnesium shall not be used.

30.2 Treatment for Zinc and Zinc Coatings

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

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

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

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

30.3 Treatment for Cadmium or Beryllium

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

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

30.4 Treatment for Aluminum and Aluminum Alloys

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

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

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

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

30.5 Treatment for Carbon and Low Alloy Steels

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

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

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

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

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

Note: Bare steel not recommended.

30.6 Treatment for Lead, Tin, Solders, and Indium

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

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

S0609 Rev -

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

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

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

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

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

30.8 Treatment for Chromium (plate), Molybdenum, Tungsten

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

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

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

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

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

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

50609 Rev –

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

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

30.10 Treatment for Titanium

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

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

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

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

30.11 Treatment for Silver

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

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

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

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

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

S0609 Rev -

30.13 Treatment for Graphite

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

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

S0609 Rev -

APPENDIX B

WHAT IS INVOLVED IN GALVANIC CORROSION

10. GENERAL

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

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

20. REFERENCED DOCUMENTS

Not Applicable.

30. GENERAL REQUIREMENTS

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

$$E_c - E_a = IR_e + IR_m$$

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

S0609 Rw -

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

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

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

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

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

30.3 Conductivity of the galvanic circuit. Corrosion of a single metal in an electrolyte involves the flow of current from local anodic to local cathodic areas on the metal surface. This is termed "local cell corrosion" and is the situation of normal corrosion. Relatively small differences in potentials of local cells are the result of compositional dissimilarities on the metal surface because of different metal phases or crystal orientation, crystal imperfections segregations, grain boundaries, and other conditions. The more inhomogeneous the surface, the more susceptible it is to general attack. Dissolution of the anode relates to the galvanic current according to Faraday's law, 50609 Rev —

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

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

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

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

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

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

S0609 Rev –

should be specified and maintained as closely as possible.

TABLE IA

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

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

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

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

S0609 Rev -

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

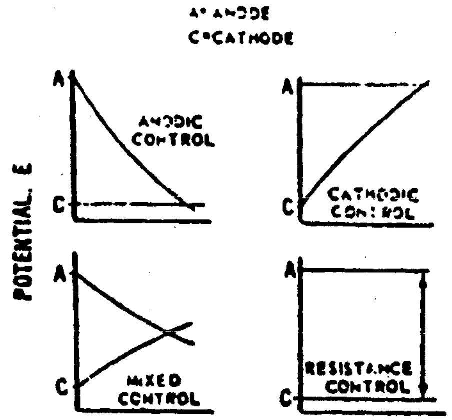


FIGURE 1A. Types of polarization and control in galvanic corrosion.

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

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

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

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

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

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

S0609 Rev -

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

50609 Rw —

INSTRUCTIONS: In a continuing effort to make our standardization documents better, the DoD provides this form for use in submitting comments and suggestions for improvements. All users of military standardization documents are invited to provide suggestions. This form may be detached, folded along the lines indicated, taped along the loose edge *(DO NOT STAPLE)*, and mailed. In block 5, be as specific as possible about particular problem areas such as wording which required interpretation, was too rigid, restrictive, loose, ambiguous, or was incompatible, and give proposed wording changes which would alleviate the problems. Enter in block 6 any remarks not related to a specific paragraph of the document. If block 7 is filled out, an acknowledgement will be mailed to you within 30 days to let you know that your comments were received and are being considered.

NOTE: This form may not be used to request copies of documents, nor to request waivers, deviations, or clarification of specification requirements on current contracts. Comments submitted on this form do not constitute or imply authorization to waive any portion of the referenced document*(s)* or to amend contractual requirements.

(Fold along this line)

(Fold along this line)

DEPARTMENT OF THE AIR FORCE

NO POSTAGE
NECESSARY
IF MAILED
IN THE
UNITED STATES

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300

BUSINESS REPLY MAIL
FIRST CLASS PERMIT NO. 73236 WASHINGTON D. C.

POSTAGE WILL BE PAID BY THE DEPARTMENT OF THE AIR FORCE

ASD/ENESS
Wright-Patterson AFB, OH 45433

S0609 Rev-

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

(See Instructions – Reverse Side)

1. DOCUMENT NUMBER	**2. DOCUMENT TITLE**
3a. NAME OF SUBMITTING ORGANIZATION	**4. TYPE OF ORGANIZATION** *(Mark one)* ☐ VENDOR ☐ USER ☐ MANUFACTURER ☐ OTHER *(Specify)*: ______
b. ADDRESS *(Street, City, State, ZIP Code)*	

5. PROBLEM AREAS

a. Paragraph Number and Wording:

b. Recommended Wording:

c. Reason/Rationale for Recommendation:

6. REMARKS

7a. NAME OF SUBMITTER *(Last, First, MI)* – Optional	**b. WORK TELEPHONE NUMBER** *(Include Area Code)* – Optional
c. MAILING ADDRESS *(Street, City, State, ZIP Code)* – Optional	**8. DATE OF SUBMISSION** *(YYMMDD)*

DD FORM 1426 82 MAR

PREVIOUS EDITION IS OBSOLETE.

(TO DETACH THIS FOR UT ALONG THIS LINE.)

Appendix B

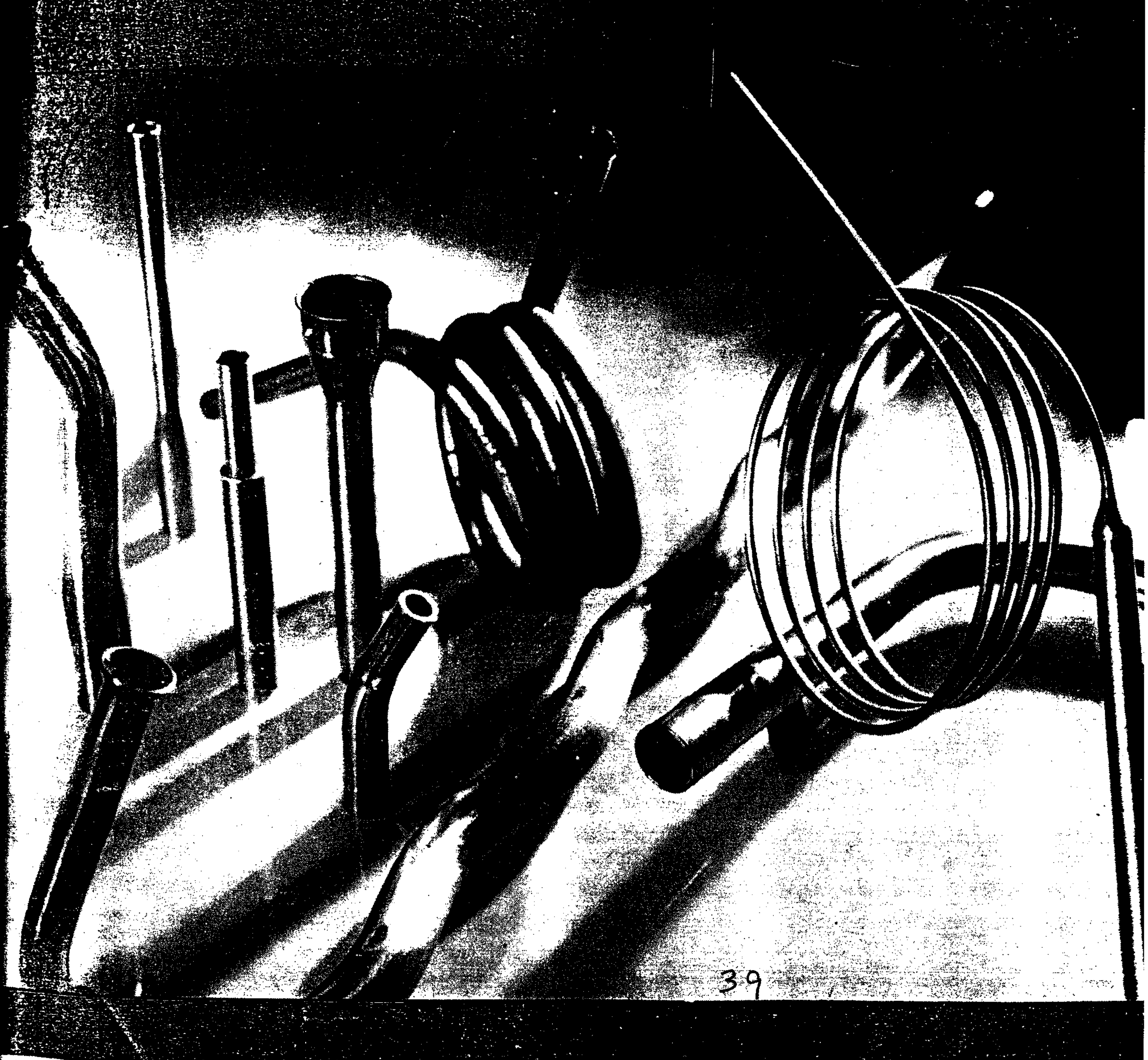
Corrosion Properties of Beryllium-Copper

35

50609 Rev-

Corrosion

NATIONAL [illegible] CORROSION ENGINEERS



39

[illegible]

S0609 Rev —

A SURVEY

Corrosion Resistance of Beryllium Copper*

By JOHN T. RICHARDS

JOHN T. RICHARDS—Chief Engineer for Penn Precision Products, Inc., Reading, Pa., formerly was development engineer for The Beryllium Corp., Reading. A veteran of World War II with naval service, he graduated from Cornell in 1943 with a BS in mechanical engineering. He is a member of ASTM, AIME, ASME, ASM, SAE and the British Institute of Metals.

Abstract

Available data are presented on the resistance offered by beryllium copper to corrosion by various media including fresh and salt water, acids, alkalies and liquid metals. Attack by various atmospheres is considered and the resulting corrosion products are described. The possible role of internal oxidation or subscale formation is also discussed. Other forms covered include galvanic corrosion, cavitation erosion, stress-corrosion and corrosion fatigue. The effect of corrosion on the processing of beryllium copper products is noted, while typical applications where corrosion may present a problem are briefly reviewed.

THE ABILITY of beryllium copper to combine good corrosion resistance with other desirable properties is frequently the reason for its selection by designers. Like other copper-base alloys, it is non-magnetic and offers good electrical and thermal conductivity. Unlike other copper materials, however, it can be heat treated to a high level of strength and hardness.

Although the term "beryllium copper" refers to a family of alloys, this survey is mainly concerned with the standard material containing nominally 1.9 percent beryllium. Unless otherwise stated, all data refer to this alloy. Typical properties and compositions for wrought and cast forms will be found in Tables I and II. More complete property and processing information appears elsewhere.[1]

The useful properties of beryllium copper result from a two-step thermal treatment. The first or solution-annealing step (1475-1500 F followed by a water quench) softens the material. This operation is generally handled by the mill prior to shipment. The second step or aging treatment (550-750 F followed by cooling at any convenient rate) hardens the material to the desired level. By altering the aging time and temperature, it is possible to select various combinations of strength, hardness, conductivity, ductility and impact resistance. In view of the hardness attained through heat treatment, it is customary to form or machine parts prior to age hardening.

In a manner similar to other high-copper products, beryllium copper provides good resistance to fresh or salt water, marine and industrial atmospheres, many alkaline solutions and some acids. The statement that the corrosion resistance of beryllium copper is equivalent to that of copper[2,3] may be too general for many specific cases. Accordingly, it is the purpose of this survey to present available data to permit a better evaluation of the corrosion resistance of beryllium copper.

Aqueous Media

Fresh and Salt Water

Beryllium copper offers good resistance to natural fresh and sea water, providing somewhat better resistance than copper. Table III indicates the effects of temper, age hardening, test temperature and beryllium content upon corrosion by normal and artificial sea water. Corrosion rates are expressed in milligrams per square decimeter per day (mdd) and inches penetration per year (ipy).

As indicated in the table, corrosion decreases with increasing beryllium content but increases slightly with moderate temperatures. Although temper or condition do not appear to affect corrosion rates, the addition of copper chloride to artificial sea water has a marked effect. There is no appreciable difference between the effect of sea water and artificial sodium chloride solutions.

Although it has not been possible to obtain his

TABLE I—Typical Properties of Wrought Beryllium Copper

Nominal Composition	**Beryllium .. 1.9%** **Cobalt .. 0.2%** **Copper .. balance**			
Condition and Heat treatment	**Heat treatable**		**Heat treated 2-3 hours at 600 F**	
Temper	**Solution Annealed (A)**	**Half Hard (½ H)**	**Solution Annealed (AT)**	**Half Hard (½ HT)**
Physical Properties:				
Density, lb per cu in.	0.299	0.299	0.301	0.301
Melting range, F.	1600-1800	1600-1800	1600-1800	1600-1800
Electrical conductivity, Percent IACS, 68 F.	17-19	15-17	22-30	22-30
Thermal conductivity, btu/sq ft/in/hr °F, 68 F.	470-600	470-600	750-890	750-890
Average coefficient of linear expansion:				
Per deg. F, —100 to +70 F	0.0000090	0.0000090	0.0000090	0.0000090
+70 to +572 F	0.0000094	0.0000094	0.0000094	0.0000094
Hardness:				
Rockwell, B or C scale	B45-78	B88-96	C36-41	C39-44
Superficial	30T46-67	30T74-79	30N56-61	30N59-65
Tensile properties:				
Ultimate tensile strength, psi	60-78,000	85,100,000	165-190,000	185-230,000
Elongation in 2 in., percent	35-60	5-20	4-10	2-6
Proportional limit (0.002% offset), psi	15-20,000	50-70,000	100-135,000	120-160,000
Yield strength (0.2% offset), psi	28-36,000	75,110,000	140-175,000	160-220,000
Elastic modulus, psi	17,000,000	16,500,000	19,000,000	18,500,000
Izod impact strength, in-lb.	100-110	32-40	12-15	10-14
Fatigue strength at 100,000,000 cycles:				
Strip, reversed bending, psi	30-35,000	32-38,000	35-40,000	38-48,000
Rod, rotating beam, psi	....	....	45-60,000	45-60,000

---

* A paper presented at the Ninth Annual Conference, National Association of Corrosion Engineers, Chicago, Ill., March 16-20, 1953.

40

50609 Rev—

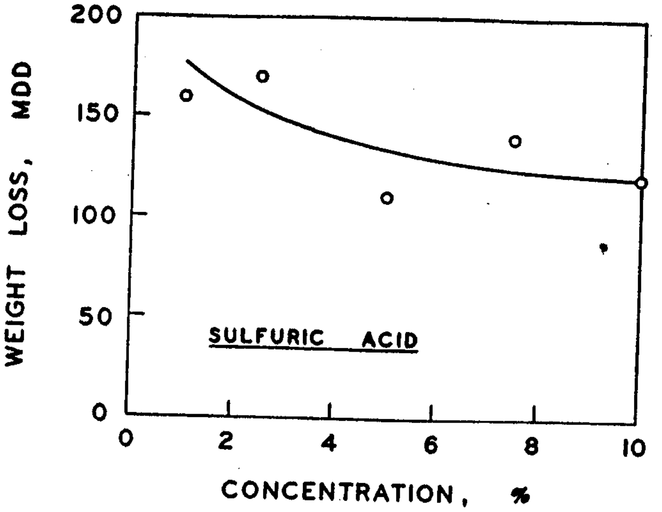


Figure 1—Weight loss of a 2.05 percent beryllium copper alloy (as cast) continuously immersed for 24 hours at 68 F in various concentrations of sulfuric acid. Terem.(5)

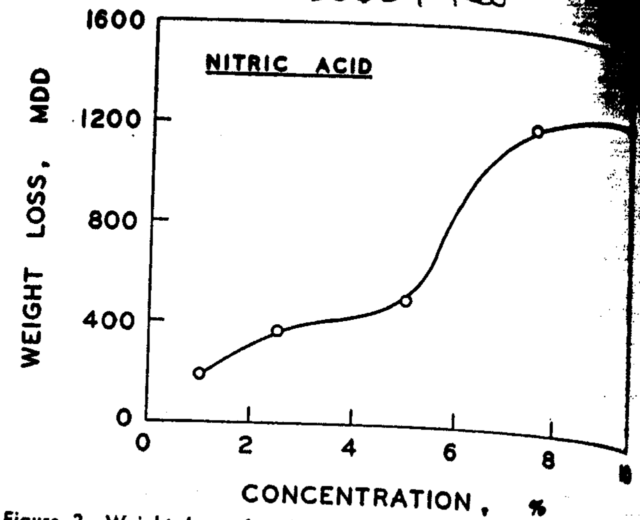


Figure 2—Weight loss of a 2.05 percent beryllium copper alloy (as cast) continuously immersed for 24 hours at 68 F in various concentrations of nitric acid. Terem.(5)

TABLE II—Typical Properties of Cast Beryllium Copper

Nominal Composition	Beryllium .. 2.0% Cobalt .. 0.4% Copper .. balance			
Heat Treatment	Heat Treatable		Heat Treated 2-3 hours at 650 F	
Condition	Cast	Cast and Solution Annealed	Cast	Cast and Solution Annealed
Physical Properties:				
Density, lb per cu in.	0.290	0.290	0.292	0.292
Melting range, F	1585-1780	1585-1780	1585-1780	1585-1780
Electrical conductivity, Percent IACS, 68 F	17-22	14-18	19-24	20-25
Thermal conductivity, Btu/sq ft/in/hr/°F, 68 F	....	....	....	650-800
Average coefficient of linear expansion:				
Per deg F, 68 to 392 F	0.000009	0.000009	0.000009	0.000009
Hardness:				
Rockwell, B or C scale	B75-85	B65-75	B90-100	C-38-45
Tensile properties:				
Ultimate tensile strength, psi	70-85,000	60-70,000	85-110,000	150-175,000
Elongation in 2 in., percent	15-30	30-45	10-25	1-4
Proportional limit (0.002% offset), psi	20-30,000	8-15,000	25-40,000	105-125,000
Yield strength (0.2% offset), psi	40-50,000	25-40,000	45-60,000	115-155,000
Elastic modulus, psi	17,500,000	17,000,000	18,500,000	18,500,000
Izod impact strength, in-lb.	65-80	90-110	50-60	5-12
Fatigue strength at 100,000,000 cycles:				
Rotating beam, psi	....	....	....	20-30,000

report, Bojkov[4] has determined certain corrosion rates for various beryllium copper alloys. Some specimens were subjected to continuous and intermittent immersion in artificial sea water for 1380 hours. Others were suspended over boiling sea water. Best resistance was offered by an alloy containing 1.95% beryllium, 4.35% aluminum, balance copper.

Acids

In acids, beryllium copper compares favorably with pure copper. While good resistance is offered to non-oxidizing acids, oxidizing acids (including nitric and chromic) as well as those containing certain metallic salts may prove extremely corrosive. In general, beryllium copper is not rapidly corroded by dilute sulfuric, cold concentrated sulfuric, cold dilute hydrochloric and many organic acids. However, corrosion rates may increase, often to a high degree with temperature, velocity, aeration and concentration.

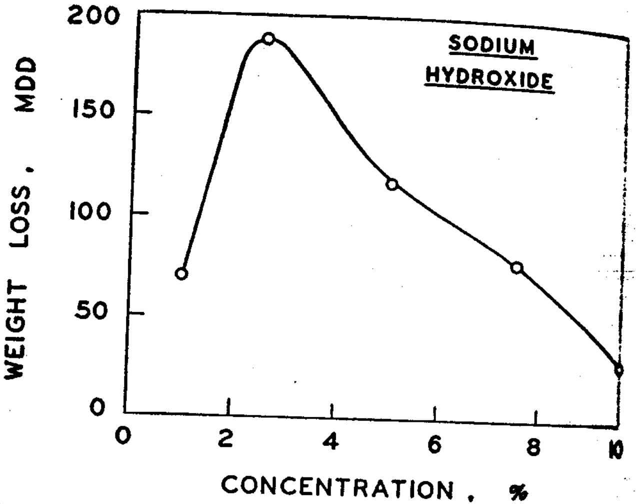


Figure 3—Weight loss of a 2.05 percent beryllium copper alloy (as cast) continuously immersed for 24 hours at 68 F in various concentrations of sodium hydroxide. Terem.(5)

As indicated in Tables IV and V, corrosion rates in sulfuric acid vary widely and are apparently dependent upon beryllium content, concentration (see Figure 1) and temperature. Although heat treatment has no marked effect, the addition of an oxidizing agent such as potassium dichromate increases corrosion rates to a high degree. Variation among the results of individual investigators is rather wide and is probably due to differences in method. Terem[5] alone has described test procedures in detail.

Generally, hydrochloric acid attacks beryllium copper at the same rate as sulfuric acid (see Tables VI and VII). From the results presented, beryllium copper is equal to aluminum bronze but superior to either copper or tin bronze in resisting hydrochloric acid.

The influence of various concentrations of nitric acid on alloys of different beryllium contents are given in Table VIII and Figure 2. Similar data for acetic acid are presented in Table IX. Although corrosion rates in nitric acid are excessive for safe handling, beryllium copper provides sufficient resistance to acetic acid to make it practical for many applications.

As part of an extensive corrosion testing program [illegible] by the Tennessee Valley Authority, Yates[6] [illegible] considerable data on the corrosion of [illegible] materials exposed to phosphoric acid under [illegible] and plant conditions. Part of these results [illegible] in Table X. Disk specimens were [illegible] on spools and exposed from 15 to 30 days [illegible] and pilot plant sumps, tanks, pipelines, etc. [illegible] listed in the last column of the table were [illegible] in plant vapor ducts that contained phos[illegible] acid as mist and some fluorine, probably [illegible] hydrogen fluoride. Although oxygen and [illegible] vapor were also present, the principal constit[illegible] the gas carrying the mist was nitrogen. On [illegible] of the nature of these tests, close control [illegible] exercisable over concentration, temperature [illegible]ation.

[illegible]

[illegible] results have been obtained with beryllium [illegible] in many cold concentrated and hot or cold [illegible] alkalies. Sodium and potassium hydroxide solutions can be handled at room temperature, but ammonium hydroxide rapidly attacks beryllium copper. Data for sodium and ammonium hydroxide will be found in Tables XI and XII. The effect of sodium hydroxide concentration is illustrated in Figure 3.

Organic Media

Beryllium copper provides excellent resistance to such organic chemicals as hydrocarbons, alcohols, ketones, aldehydes and esters. Water-free organic compounds are generally noncorrosive at ordinary temperatures but increases in temperature and moisture may accelerate corrosion rates. Good resistance is also offered to fluorinated hydrocarbons.

Atmospheric Attack

Like other copper-base alloys, beryllium copper will stain and darken when exposed to humid or sulfur-bearing atmospheres. A black surface is produced in sulfide atmospheres, while a green film results from salt deposited in marine or salt-spray exposures. The tarnish formed has no apparent influence upon mechanical properties.

Salt spray tests indicate that beryllium copper becomes covered with a green film, but that even after six weeks the green tarnish is still superficial.[7,8,9] The influence of beryllium content upon resistance to salt-spray corrosion is indicated in Figure 4.[10]

Tests also have been conducted under conditions of cyclic humidity. The daily cycle includes 8 hours in a warm dry atmosphere averaging 130 F and 65 percent humidity. This is followed by 16 hours in dampness (100 percent humidity with condensate) obtained by cooling to atmospheric temperature. Under these conditions, beryllium copper exhibited only slight discoloration or tarnishing after 50 days.[7,8] In cases where specimens were severely handled after chemical cleaning, finger prints quickly resulted in superficial staining. Under somewhat similar conditions, Cook and Merritt[9] observed a slight tarnish after 15 days of cyclic humidity.

Gases

Halogens

Beryllium copper is not corroded by fluorine, chlorine, bromine or iodine when perfectly dry at room temperatures, but traces of moisture increase the corrosiveness of these gases. At slightly elevated

TABLE III—Corrosion Resistance of Beryllium Copper in Sea Water

TEST MEDIA*	Temperature, F	Specimen	Duration	Beryllium Content, Percent	Condition and Heat Treatment	CORROSION RATE	
						mdd	ipy
[illegible]	32-70	Strip, 0.050 x 0.625 x 8 in.	10 mos.	0	Phosphorus deoxidized copper	5.6	0.0009
				2.0	AT (quenched from 1470 and aged 3 hr at 570 F)	2.3	0.0004
					HT (quenched from 1470 F, cold rolled and aged 2 hr. at 525 F)	2.3	0.0004
[illegible] alternate immersion [illegible] water[3]	140	Wire	96 hours	0		46.5	0.0075
				0.91	Not aged	46.5	0.0081
		Strip	96 hours	0		23.3	0.0037
				1.89	Not aged	19.4	0.0034
				2.74	Not aged	3.9	0.0007
				2.99	Not aged	7.8	0.0014
[illegible] NaCl [illegible]	59	Strip, 0.039 x 1.18 x 2.36 in.	7 weeks	0	Annealed ½ hr. at 1020 F	2.3	0.0004
				2.0	A (quenched from 1510 F)	4.3	0.0008
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	3.4	0.0006
				2.5	A (quenched from 1510 F)	2.0	0.0003
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	2.2	0.0004
				3.5	A (quenched from 1510 F)	2.2	0.0004
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	2.3	0.0004
	113	Strip, 0.039 x 1.18 x 2.36 in.	3 weeks	0	Annealed ½ hr. at 1020 F	3.3	0.0005
				1.5	A (quenched from 1510 F)	4.3	0.0008
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	3.2	0.0006
				2.0	A (quenched from 1510 F)	3.6	0.0006
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	3.0	0.0005
				2.5	A (quenched from 1510 F)	2.6	0.0005
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	2.8	0.0005
				3.5	AT (quenched from 1510 F and aged 3 hr. at 660 F)	2.8	0.0005
[illegible] NaCl [illegible] saturated with CuCl	Room	Strip, 0.039 x 1.18 x 2.36 in.	3 weeks	0	Annealed ½ hr. at 1020 F	112.1	0.0180
				1.5	A (quenched from 1510 F)	118.8	0.0207
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	107.3	0.0187
				2.0	A (quenched from 1510 F)	100.2	0.0175
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	78.4	0.0137
				2.5	A (quenched from 1510 F)	150.7	0.0263
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	154.9	0.0270
				3.5	A (quenched from 1510 F)	42.9	0.0075
					AT (quenched from 1510 F and aged 3 hr. at 660 F)	51.5	0.0090
Artificial sea water[5]	68	Cast, 0.394 x 0.394 x 0.394 in.	15 days	0.49	As cast	30	0.0052
				1.00	As cast	6	0.0010
				2.05	As cast	3	0.0005
				5.05	As cast	4	0.0007
				9.96	As cast	4	0.0007
Artificial sea water[50]	Room	Strip	163 hours	0	Electrolytic copper	16.9	0.0029
				2.12	H (cold rolled)	15.7	0.0027
					A (quenched from 1480 F)	14.6	0.0025
					AT (quenched from 1480 F and aged 3 hr. at 570 F)	16.2	0.0028

* Superior figures in this column refer to references at end of article.

S0609 Rev —

temperatures the beryllium content is attacked selectively and lost from the surface of this alloy, apparently because of the high volatility of beryllium halides.[11] Consequently, beryllium copper should be used with caution where exhaust gas from bromine-treated tetraethyl lead gasoline is present.

Good resistance to various organic refrigerants (freon, etc.) has been observed in the absence of moisture. As a result, beryllium copper is frequently employed in refrigeration temperature control equipment.

Other Gases

Although moist ammonia may prove corrosive,[12] good results have been observed for beryllium copper feather valves handling moist carbon dioxide.

Effect of Elevated Temperature

Oxidation and Scaling

As in the case of other copper alloys, the resistance offered by beryllium copper to attack, when heated in an oxidizing atmosphere is largely dependent upon the type of resulting scale. In general, the scale which forms at elevated temperatures is compose outer layer of black cupric oxide (CuO), a mediate layer of red cuprous oxide (Cu_2O) inner layer of gray-to-colorless beryllium (BeO). Although it is anticipated that bery oxide would confer added resistance to oxidatio virtue of its stability, the improvement over copper is not impressive due to the presence of refractory copper oxides.[13,14]

As a result of a new derivation of Wagner's pression, Thomas and Price[15] predicted that oxi with low electrical conductivities should prod films with high oxidation resistance. Since it is erally agreed that the growth of copper oxide fil occurs by the diffusion of copper ions outward, it to be expected that scales preventing or retard this diffusion (films of low conductivity) will hance the resistance to oxidation. The electrical co ductivities of several oxides are listed in Tab XIII.[16,17]

On the basis of this work by Price and Thoma the oxidation resistance of a number of copper allo can be approximated. If sufficient beryllium is pre ent in copper to cause the formation of a berylliu oxide film, the rate of oxidation w be reduced approximately 8,000,00 to 1. Froehlich,[18] however, foun that the addition of 2.4 percen beryllium to copper reduced th oxidation rate by a factor of abou 40 only.

According to the theory advanced by Price and Thomas, the film produced by Froehlich probably was not pure beryllium oxide but contained copper oxide in solution, thereby increasing the electrical conductivity and reducing the oxidation resistance.

Qualitatively, Thomas and Price[19] demonstrated that considerable resistance to tarnishing can be developed by selective oxidation. The treatment suggested for forming a thin beryllium oxide film on the surface calls for 20 minutes heating at 932 F in an atmosphere of hydrogen containing 0.1 mm water vapor. Since this operation would cause rapid overaging of beryllium copper, treatments should be carried out below 600 F if possible. There is no available evidence indicating that this method has been successfully applied in practice. However, it appears to have sufficient merit warrant consideration.

Under normal conditions, the type of oxide produced depend upon the exposure temperatur Hickman[20] found that both cupro and cupric oxide are formed temperatures up to 400 C where

TABLE IV—Effect of Immersion in Sulfuric Acid on 2% Beryllium Copper

TYPE OF TEST*	Temperature, F.	Specimen	Duration	Beryllium Content, Percent	Condition and Heat Treatment	CORROSION RATE mdd	CORROSION RATE ipy
Alternate immersion in 10% solution, 1½ min. in solution and 1½ min. in air[12]	140	Strip, 0.050 x 0.625 x 8 in.	......	0 2.0	Phosphorus deoxidized copper AT (quenched from 1470 F and aged 3 hr. at 570 F) HT (quenched from 1470 F, cold rolled and aged 2 hr. at 525 F)	3780 5115 4880	0.609 0.892 0.852
Interrupted alternate immersion in 10% solution[10]	140	Strip	96 hours	0 1.89	Not aged	1240 1148	0.199 0.198
Continuous immersion in 10% solution[5]	68	Cast, 0.394 x 0.394 x 3.94 in.	24 hours	2.05	As cast	100	0.0174
Continuous immersion in 5% sulfuric acid[50]	Room	Strip	24 hours	0 2.12	Electrolytic copper H (cold rolled) A (quenched from 1480 F) AT (quenched from 1480 F and aged 3 hr. at 570 F)	30 25 24 27	0.0052 0.0044 0.0042 0.0047
Continuous immersion in 10% solution[7]	Room	Strip	6 hours 24 hours	2.1 2.1	Apparently rolled, annealed and aged Same	negligible 31	...... 0.0054
5% sulfuric acid + 3% potassium dichromate	Room	Strip	6 hours 24 hours	2.1 2.1	Same Same	19,840 18,600	3.46 3.24

*Superior figures in this column refer to references at end of article.

TABLE V—Influence of Beryllium Content in Varying Concentrations of Sulfuric Acid

(Loss in mdd)

TEST CONDITIONS**	Beryllium Content, Percent	CONCENTRATION 1%	2.5%	5%	7.5%	10%
Interrupted alternate immersion for 96 hours at 140 F on strip specimens (not age hardened)[10]	0 1.89 2.74 2.99	....	....	....	....	1240 1148 1244 1170
Continuous immersion for 24 hours at 68 F on cast specimens (not age hardened)[5]	0.49 1.00 2.05 5.50 9.96	180 110 160 90 20	170 150 170 50 5	150 250 110 100 5*	120 130 140 80 31*	130 120 120 100 14*

* Increase in weight, mdd.

** Superior figures in this column refer to references at end of article.

S0609 RW –

500 C both cuprous oxide and beryllium oxide are present and heating to higher temperatures produces beryllium oxide. Cooling to room temperature 400 C or higher does not result in any change, beryllium oxide remains. Similar observations been reported by other investigators,[21,22] al- pressure may exert some influence.[23,24,25]

sing and Dahl[26] were the first to investigate the rate of beryllium copper. They determined effect of beryllium content on the weight increase from heating for 36 hours at 752 F in a current of air. As indicated in Figure 5, an increase in beryllium content causes a marked improvement in oxidation resistance.

Subsequently, Froehlich[18] conducted an extensive study of the scaling of pure and alloyed copper in an attempt to determine the direction of the process. In this investigation, Froehlich reaffirmed the increased resistance to scaling with higher beryllium content (see Figure 6). From Froehlich's data, it is also possible to estimate the influence of various additives on the oxidation rate of copper. Figure 7 shows that beryllium is the most effective in this respect, as predicted by Price and Thomas.[15] Froehlich observed a thin external black scale (cupric oxide) which covered a very thin white film (beryllium oxide). Resistance to scaling is attained when this inner film of the solute oxide prevents further diffusion of copper toward the cupric oxide.*

Terem[27] has carried the investigation of scaling further in include different exposure temperatures and higher beryllium concentrations. The effect of time and temperature upon the oxidation of an alloy in both wire and plate forms containing 2.05 percent beryllium content, indicates that optimum resistance to scaling is obtained with 2 percent beryllium. Terem also observed a whitish layer of beryllium oxide and found that this film afforded substantial protection against corrosion by nitric acid.

Most of the preceding investigation of scaling rate apply to elevated temperatures — temperatures well above the usual operating range for beryllium copper. More recently, Campbell and Thomas[28] determined oxidation curves at more moderate temperatures. The data for beryllium copper strip are reproduced in Figure 10, while Figure 11 presents a comparison of the effect of temperature on the oxidation rate of several materials. The low slope for beryllium copper is in accord with theory, because beryllium will diffuse more readily at higher temperatures, providing a larger proportion of the highly protective beryllium oxide. The role of the diffusion rate on the protection offered by beryllium oxide films also has been considered by Smirnov.[29]

In addition to external scaling, internal oxidation or subscale for-

TABLE VI—Effect of Immersion in Hydrochloric on 2% Beryllium Copper

TYPE OF TEST*	Temperature, F	Specimen	Duration	Beryllium Content, Percent	Condition and Heat Treatment	CORROSION RATE mdd	CORROSION RATE ipy
	70-75	Strip, 0.050 x 0.625 x 8 in.	......	0 2.0	Phosphorus deoxidized copper AT (quenched from 1470 F and aged 3 hr. at 570 F) HT (quenched from 1470 F, cold rolled, and aged 2 hr. at 525 F)	453 332 332	0.073 0.058 0.058
	140	Strip	96 hours	0 1.89	Not aged..............	147 182	0.024 0.031
	Room	Strip, 0.039 x 1.18 x 2.36 in.	7 days	0 2.0	Annealed.............. Annealed..............	1079 568	0.174 0.099
			2 days	2.0	A (quenched from 1470 F) AT (quenched from 1470 F and aged at 660 F)	629 707	0.110 0.123
				2.5	A (quenched from 1470 F) AT (quenched from 1470 F and aged at 660 F)	400 449	0.070 0.078
	Room	Strip, 0.039 x 1.18 x 2.36 in.	7 days	2.0	A (quenched from 1470 F) AT (quenched from 1470 F and aged at 660 F)	402 656	0.070 0.115
				2.5	A (quenched from 1470 F) AT (quenched from 1470 F and aged at 660 F)	368 585	0.064 0.102
	68	Cast, 0.394 x 0.394 x 3.94 in.	24 hours	2.05	As cast................	50	0.009
	68	Cast, 0.394 x 0.394 x 3.94 in.	24 hours	2.05	As cast................	90	0.016
	Room	Strip	24 hours	0 2.12	Electrolytic copper...... H (cold rolled).......... A (quenched from 1480 F) AT (quenched from 1480 F and aged 3 hr. at 570 F)	56 42 43 45	0.010 0.007 0.007 0.008

* Superior figures in this column refer to references at end of article.

TABLE VII—Influence of Beryllium Content in Varying Concentrations of Hydrochloric Acid
(Loss in mdd)

TEST CONDITIONS**	Composition*	CONCENTRATION 1%	2.5%	3%	5%	7.5%	10%
uous immersion for 7 days at room temperature on strip specimens. 0.039 x x 2.36 in., in annealed condition[26]	100% Cu 1.5% Be 2.0% Be 2.5% Be 3.0% Be 3.5% Be	... ...	... ...	1079 568 568 325 400 404	... ...	... ...	... ...
	10% Sn 12% Sn 14% Sn	... ...	... ...	1168 915 974	... ...	... ...	... ...
	6% Al 8% Al	... ...	... ...	425 586	... ...	... ...	... ...
ous immersion for 24 hours at 68 F specimens (not age hardened)[5]	0.49% Be 1.00% Be 2.05% Be 5.05% Be 9.96% Be	100 80 50 70 30	50 60 40 160 50	... ...	60 60 50 170 60	90 90 110 130 80	40 100 90 190 100
ous immersion for 24 hours at 68 F drawn specimens, 0.32 in. diam. x 0.60 long (not age hardened)	100% Cu 2.3% Be 10% Al	100 70 40	70 50 10	... ...	90 50 60	100 90 70	140 120 90

* Balance copper.

** Superior figures in this column refer to references at end of article.

---

* The effectiveness of beryllium additions in reducing oxidation rates recently has been confirmed further—see J. P. Dennison and A. Preece, "High-Temperature Oxidation Characteristics of a Group of Oxidation-Resistant Copper-Base Alloys," Journal of the Institute of Metals, Vol. 81, pp. 229-234 (1953).

S0609 Rev -

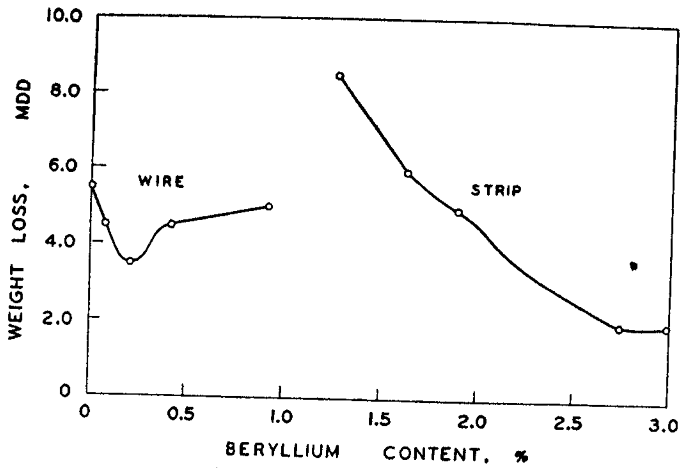


Figure 4—Weight loss resulting from salt spray as affected by beryllium content. Bassett.(4)

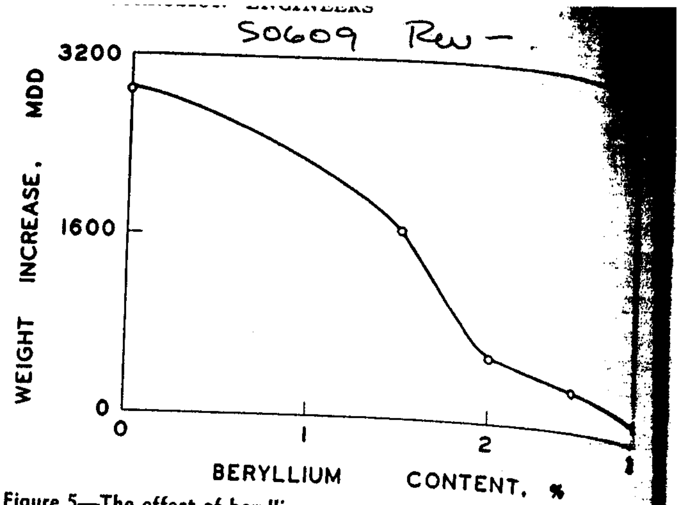


Figure 5—The effect of beryllium content on oxidation rate of beryllium copper strip, 0.040 in. thick, heated 36 hours at 752 F. Masing and Dahl.(26)

TABLE VIII—Influence of Beryllium Content in Varying Concentrations of Nitric Acid

(Loss in mdd)

TEST CONDITIONS**	Composition*	CONCENTRATION						
		1%	2.5%	3%	5%	6.3%	7.5%	10%
Continuous immersion for 18 days at room temperature on strip specimens, 0.039 x 1.18 x 2.36 in., in annealed condition[26]	100% Cu	...	...	312	...	...	...	...
	1.5% Be	...	...	269	...	...	...	...
	2.0% Be	...	...	285	...	...	...	...
	2.5% Be	...	...	253	...	...	...	...
	3.0% Be	...	...	177	...	...	...	...
	3.5% Be	...	...	251	...	...	...	...
	10% Sn	...	...	215	...	...	...	...
	12% Sn	...	...	253	...	...	...	...
	14% Sn	...	...	189	...	...	...	...
	6% Al	...	...	184	...	...	...	...
	8% Al	...	...	226	...	...	...	...
Continuous immersion for 24 hours at 68 F on cast specimens (not age hardened)[5]	0.49% Be	170	120	...	150	...	170	210
	1.00% Be	90	90	...	90	...	150	110
	2.05% Be	200	150	...	80	...	150	120
	5.05% Be	6500	12,500	...	24,000	...	28,500	31,500
	9.96% Be	13,500	40,000	...	71,500	...	94,500	94,500
Continuous immersion for 24 hours at 68 F on drawn specimens, 0.32 in. diam. x 0.60 in. long (not age hardened)	100% Cu	170	270	...	1070	...	750	500
	2.3% Be	190	370	...	500	...	1210	1320
	10% Al	3410	8530	...	8170	...	11,580	11,050
Continuous immersion for 24 hours at room temperature on strip specimens as follows:[50]								
Electrolytic copper............	10% Cu	...	...	...	...	1695	...	...
Beryllium copper:								
H (cold rolled)............	2.12% Be	...	...	...	...	1681	...	...
A (quenched from 1480 F)...	2.12% Be	...	...	...	...	1748	...	...
AT (quenched from 1480 F and aged 3 hr. at 570 F).	2.12% Be	...	...	...	...	1928	...	...

* Balance copper.

** Superior figures in this column refer to references at end of article.

TABLE IX—Influence of Beryllium Content in Varying Concentrations of Acetic Acid[5]

(Loss in mdd)

TEST CONDITIONS	Beryllium Content, Percent	CONCENTRATION				
		1%	2.5%	5.0%	7.5%	10%
Continuous immersion for 24 hours at 68 F on cast specimens (not age hardened)	0.49	18	20	20	30	40
	1.00	5	20	80	20	30
	2.05	8	20	30	30	40
	5.05	5	30	20	30	20
	9.96	16	20	10	70	10

mation also may result when beryllium copper is heated at relatively high temperatures in the presence of oxygen. The subscale zone generally has a well-defined boundary which moves inward from the metal surface with increasing time of oxidation. The zone consists essentially of isolated particles of beryllium oxide deposited in a matrix of almost pure copper.[30]

Diffusion appears to be the motivating force. Oxygen diffuses inward from the external surface of the metal to the subscale boundary (reaction front) where it combines with beryllium diffusing outward. On account of its stability, beryllium oxide forms in preference to cuprous oxide. Because beryllium oxide probably has rather limited solubility in copper, it will precipitate within the zone of internal oxidation.

As a result of comprehensive investigations covering dilute binary alloys of beryllium and copper, Rhines[31,32] has established rates for simple internal oxidation and for combined internal and external oxidation. The beryllium contents ran from 0.02 to 0.101 percent, while the temperatures ranged from 1112 to 1832 F. Ternary alloys with zinc, tin or aluminum also were considered.

Figure 12 shows a typical zone of internal oxidation (gray area) resulting from prolonged heating at 1450 F in a salt bath. Note the relatively heavy formations of beryllium oxide appearing as black deposits along the grain boundaries. Figure 13 is similar except that it has been etched to show the base metal more clearly. In both instances, there is a relatively sharp line of demarcation between subscale and unaffected metal.

Although Rhines[33] has called attention to the possible role of internal oxidation in age hardening beryllium copper, it is difficult to obtain this condition. In practice, heating times are too short and temperatures too low to produce this effect.

Meijering and Druyvesteyn[34,35,36] have demonstrated that precipitated beryllium oxide may cause dispersion hardening, depending upon the size of the particles. As a result, the subscale may be slightly harder than pure copper but substantially softer than hardened beryllium copper with a tendency toward brittleness. Consequently, material having internal oxidation could not be expected to withstand sev

50609 Rev—

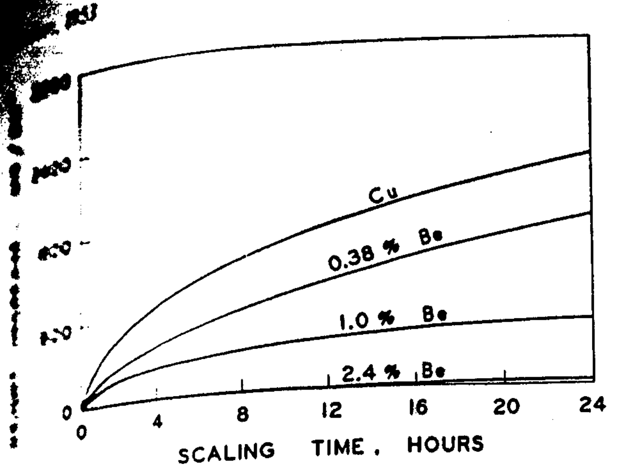


Figure 6—The influence of time and beryllium content on the scaling of beryllium copper strip in a slow air stream at 1472 F. Froehlich.[18]

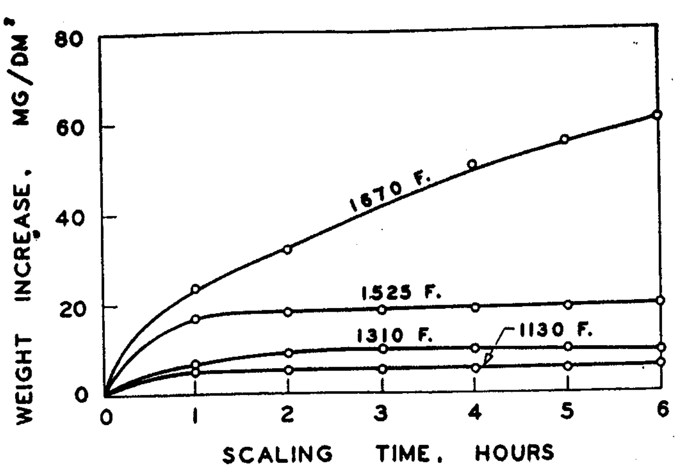


Figure 8—The influence of time and temperature on the scaling of beryllium copper wire and strip (2.05% Be). Terem.[27]

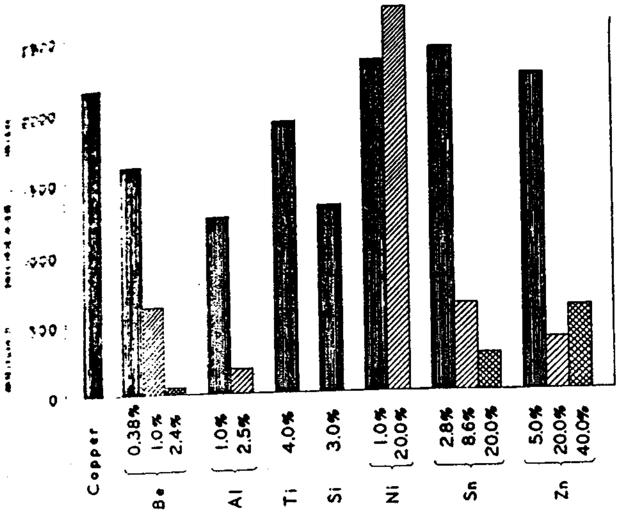


Figure 7—The effect of concentration on the scaling of copper alloys in strip form at 1472 F for 24 hours. Froehlich.[18]

erating conditions and would be exceedingly prone premature failure under dynamic loading.

Although specific data is lacking, it is probable at beryllium copper offers slightly better resistance attack by sulfur and its gaseous compounds than re copper. Sulfide or mixed sulfide and oxide scales result from exposure to atmospheres containing hydrogen sulfide or sulfur dioxide.[37] Price and Thomas[16] have expressed the opinion that selective oxidation of beryllium copper will prevent attack in oxidizing atmospheres containing sulfur.

Hydrogen Embrittlement

In further work with dilute solutions of beryllium in copper, Rhines[38] has observed hydrogen embrittlement when specimens were alternately annealed under oxidizing and reducing conditions. Since there is no apparent weakening of the material as evidenced by the bend test data reported, it is probable that structural changes have been observed during metallographic studies.

The mechanism for hydrogen embrittlement proposed by Rhines follows:

1. During the oxidizing cycle, oxygen diffuses into the alloy producing a subscale composed of precipitated beryllium oxide in a matrix of almost pure copper.
2. Subsequent annealing in hydrogen will reduce the beryllium oxide of the subscale, producing water vapor.
3. Since hydrogen diffuses faster through copper than water vapor, sufficient pressure is built up to produce holes along the grain boundary within the oxidized zone.

TABLE X—Corrosion Rates in Phosphoric Acid and Vapor Containing Phosphoric Acid[11]

MATERIAL TESTED	Corrosion Rate Units	3-14% H_3PO_4 Containing Small Quantity of Fluorine Compounds At 150 F	70-80% H_3PO_4 Containing Small Quantity of Fluorine Compounds At 185-212 F	70-80% H_3PO_4 (Dripping) Containing Small Quantities of Fluorine Compounds in a Mist of H_3PO_4 At 203-230 F	75-80% H_3PO_4 At 167 F	85-95% H_3PO_4 (Dripping) Containing Small Quantities of Fluorine Compounds in a Mist of H_3PO_4 At 212-239 F	85-95% H_3PO_4 Containing a Small Amount of Fluorine Compounds At 165-185 F	Elemental Phosphorus in Storage At 149-158 F	Vapor Containing a Small Quantity of H_3PO_4 as a Mist and Traces of Fluorine Compounds At 185-212 F
um Copper.....	mdd	12.6	50.2	3368	37.7	354	36.5	6.8	263
2% Be, 0.21 Ni)...	ipy	0.0022	0.0088	0.5900	0.0066	0.0620	0.0064	0.0012	0.0460
Bronze-C....	mdd	11.1	68.1	4950	40.8	693	52.0	6.8	538
% Sn)........	ipy	0.0018	0.0110	0.8000	0.0066	0.1120	0.0084	0.0011	0.0870
[illegible]	mdd	5.6	83.9	4039	62.1	515	136.8	7.5	398
% Cu)........	ipy	0.0009	0.0135	0.6500	0.0100	0.0830	0.0220	0.0012	0.0640
nim Bronze.....	mdd	....	....	....	1451	....	....	....	1709
% Al)........	ipy	....	....	....	0.2550	....	....	....	0.3000
Brass........	mdd	25.9	142	578	106	802	118	4.1	318
% Zn)........	ipy	0.0044	0.0240	0.980	0.0180	0.1360	0.0200	0.0007	0.0540
Nickel........	mdd	17.3	48.4	4378	148	272	43.2	5.6	272
% Ni, 5% Zn)...	ipy	0.0028	0.0080	0.7100	0.0240	0.0440	0.0070	0.0009	0.0440
Bronze........	mdd	29.7	41.6	416	32.1	262	32.7	7.1	190
% Si, 1.1% Mn)	ipy	0.0050	0.0070	0.0700	0.0054	0.0440	0.0055	0.0012	0.0320
% Cu)........	mdd	17.2	369	....	148	461	86.1	4.9	274
Steel........	ipy	0.0028	0.0600	....	0.0240	0.0750	0.0140	0.0008	0.0445
24% C)........	mdd	170	Excessive	....	18,720	....	45,500	21.9	197
	ipy	0.0310	Excessive	....	3.4200	....	8.3100	0.0040	0.0360

50609 Rw —

In practice, hydrogen embrittlement has not been observed in commercial beryllium copper alloys of higher beryllium content (over 1 percent). The absence of this phenomenon is perhaps due to the difficulty in producing subscale during normal operating procedures. In addition, it is doubtful whether it is possible to reduce beryllium oxide with hydrogen even at temperatures as high as the melting temperature of beryllium copper. Consequently, if hydrogen embrittlement does occur, some other reaction must be responsible.

Liquid or Molten Metals

In contact with liquid metals, the usefulness of beryllium copper is determined by its resistance to alloying (solid solution or intermetallic compound formation), intergranular penetration, selective attack of surface beryllium, and chemical compound (oxide) formation. Kelman and co-workers[39] have reported good resistance to attack by mercury up to 200 F, with limited usefulness in the range 200-700 F. Good resistance is also offered to sodium, potassium and sodium-potassium alloys, at least to 1112 F.

On the basis of poor resistance provided by copper,[39] it is anticipated that beryllium copper would not be suitable in connection with gallium, lead, bismuth, eutectic bismuth-lead, tin, thallium, indium, cadmium, lithium or aluminum in their molten states.

From an application standpoint, beryllium copper plunger tips are extensively used in aluminum die casting, while pressure-cast beryllium copper dies are sometimes employed in casting zinc. In the former application, attack is steady but is rapid enough to prevent successf use. In the latter case, the dies wil eventually wash but have prove economical for short or moderate runs.

TABLE XI—Influence of Beryllium Content in Varying Concentrations of Sodium Hydroxide
(Loss in mdd)

TEST CONDITIONS*	Beryllium Content, Percent	CONCENTRATION					
		1%	2.5%	4%	5%	7.5%	10%
Continuous immersion for 24 hours at 68 F on cast specimens (not age hardened)[5]	0.49	120	210	...	139	40	30
	1.00	60	200	...	130	61	21
	2.05	70	188	...	121	78	30
	5.05	90	210	...	139	100	21
	9.96	80	118	...	50	20	30
Continuous immersion for 24 hours at room temperature on strip specimens as follows:[50]							
Electrolytic copper	0	...	...	9.4	...	...	...
Beryllium copper:							
H (cold rolled)	2.12	...	...	10.6	...	...	...
A (quenched from 1480 F)	2.12	...	...	7.7	...	...	...
AT (quenched from 1480 F) and aged 3 hr. at 570 F)	2.12	...	...	11.6	...	...	...

* Superior figures in this column refer to references at end of article.

TABLE XII—Influence of Beryllium Content in Varying Concentrations of Ammonium Hydroxide
(Loss in mdd)

TEST CONDITIONS*	Beryllium Content, Percent	CONCENTRATION					
		1%	2.5%	3.5%	5%	7.5%	10%
Continuous immersion for 24 hours at 68 F on cast specimens (not age hardened)[5]	0.49	910	830	...	660	720	710
	1.00	680	850	...	530	550	530
	2.05	730	540	...	560	550	540
	5.05	540	390	...	820	380	370
	9.96	420	510	...	510	330	290
Continuous immersion for 24 hours at room temperature on strip specimens as follows:[50]							
Electrolytic copper	0	...	...	88	...	...	...
Beryllium copper:							
H (cold rolled)	2.12	...	...	60	...	...	...
A (quenched from 1480 F)	2.12	...	...	60	...	...	...
AT (quenched from 1480 F and aged 3 hr. at 570 F).	2.12	...	...	62	...	...	...

* Superior figures in this column refer to references at end of article.

TABLE XIII—Electrical Conductivity of Several O
Price and Thomas[16]

OXIDE	Conductivity, $\frac{\text{mhos}}{\text{cm}^3}$		
	At 1000 C	At 500 C	At
BeO	10^{-9}	very small	very
Al_2O_3	10^{-7}	very small	very
SiO_2	10^{-6}	10^{-9}	......
MgO	10^{-5}	10^{-8}	very
TiO_2	10^{-4}	......	......
SnO_2	10^{-2}	......	......
NiO	10^{-2}	10^{-4}	......
Cr_2O_3	10^{-1}	10^{-2}	10^{-4}
Fe_2O_3	10^{-1}	10^{-4}	......
ZnO	1	......	10^{-4}
Cu_2O	10^{+1}	10^{-1}	......
CuO	10^{+1}	10^{-2}	10^{-4}
FeO	10^{+2}	......	......

TABLE XIV—Galvanic Series Based Upon Potential Measure in Artificial Sea Water at 77 F Against Calomel Half Cell[7]

METAL OR ALLOY	Potential in V
Magnesium and alloys	—1.60
Zinc and alloys Zinc plating on steel	—1.05 to 1.1
Cadmium	—0.75 to 0.
Aluminum and alloys	—0.62 to 0.
Tin	—0.62
Lead	—0.61
Iron Carbon steel	—0.46 to 0.
Tin/lead solders	—0.50
Brass Copper Bronze Nickel silver Cupro-nickel	—0.22 to 0.
Beryllium copper	—0.20
Silver	+0.02
Gold	+0.06
Platinum	+0.10
Rhodium	

Galvanic Corrosion

In the absence of specific data o the galvanic corrosion of berylliu copper, it must be assumed that i will behave like pure copper in thi respect. As a result, it may b safely coupled to other copper a loys. Tests conducted with bery lium copper in contact with copp in a salt spray for one month, in cate that the weight loss is greater than normally encounte with beryllium copper alone un similar test conditions.[10]

Table XIV lists the contact tentials of various metals.[7] Th values, which are the potential the individual metals immerse artificial sea water at 77 F m ured against a normal calomel cell, should be used only as a

S0609 Rw –

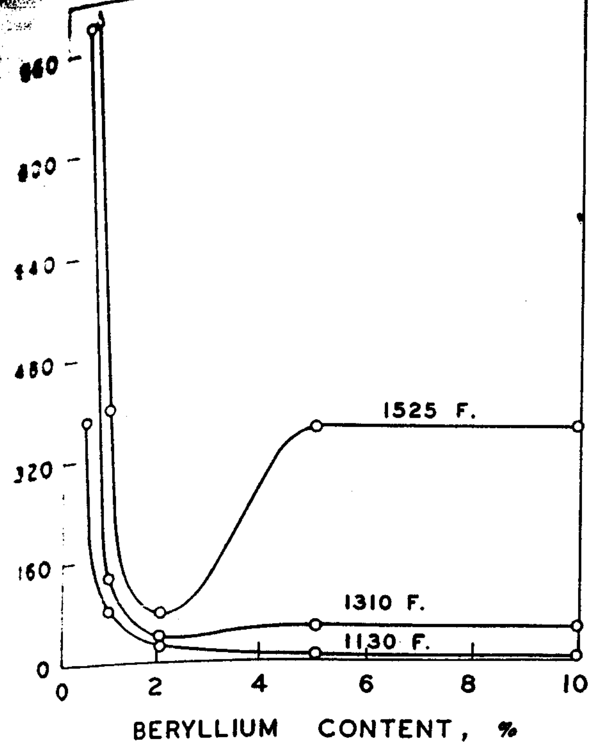


Figure 9—The effect of beryllium content and temperature upon the oxidation rate of beryllium copper exposed for 6 hours. Terem.(27)

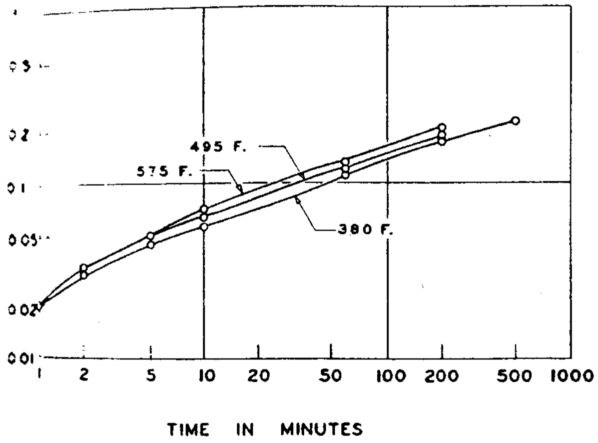


Figure 10—Oxidation curves for beryllium copper half-hard strip, 0.005 in. thick and nominally 2% Be. Campbell & Thomas.(28)

view of the many variables usually present. For example, Tracy[12] observed in a potential test in sea water that beryllium copper was anodic to phosphorus deoxidized copper by 50 millivolts when both metals were immersed, but within 24 hours the potential was reversed and beryllium copper was cathodic by 50 millivolts.

When it is necessary to connect beryllium copper galvanically with zinc, aluminum or magnesium under corrosive conditions, some means of insulation should be considered to prevent accelerated corrosion of these latter materials. Under certain conditions it may be desirable to plate beryllium copper with tin for contact with aluminum alloys or with zinc or cadmium for use against zinc alloys. In the case of iron or steel, where the potential difference would be less, galvanic action would probably only be encountered in the case of relatively large areas of beryllium copper.

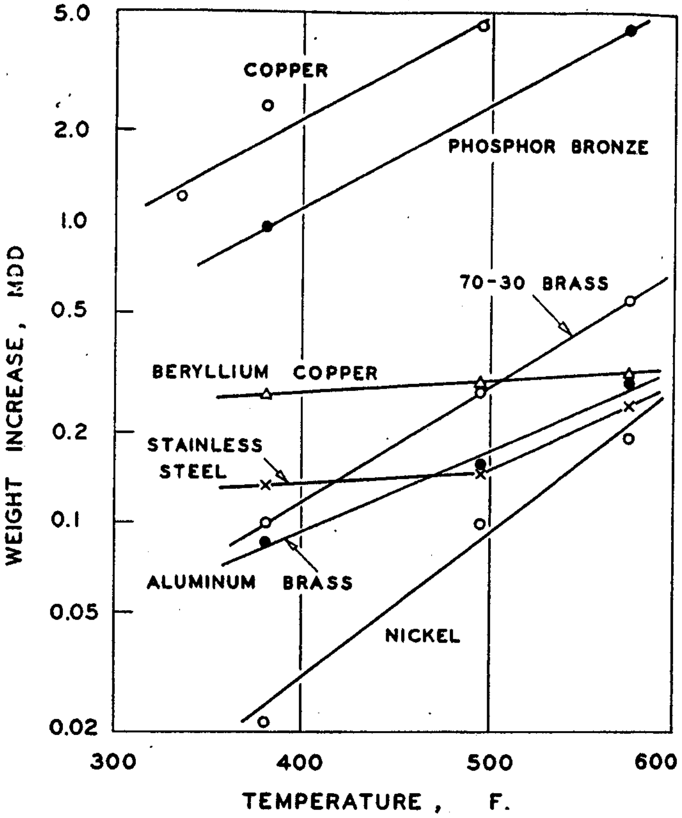


Figure 11—Effect of temperature on the oxidation rates of several strip materials, 0.005-inch thick, exposed for one hour. Campbell & Thomas.(28)

Mechanical Factors

In the field, corrosion phenomena are frequently complicated by mechanical factors. Since mechanical action generally increases corrosion rates, often to a high degree, its effect must be carefully considered. Types discussed include stress-corrosion and cavitation-erosion. Stress-corrosion can be further divided, depending upon the nature of the stress, to give stress-corrosion-cracking (static stress) and corrosion-fatigue (dynamic stress).

Stress Corrosion Cracking

In stress-corrosion-cracking, stresses may be either induced (service loading) or internal (fabricating). The term "season cracking" can be considered as a

TABLE XV—Characteristics of Beryllium Copper Alloys Subjected to Stress Corrosion on Tests[40]
(See Figure 14)

	ALLOY DESIGNATION	
	A	B
Chemical composition:		
Beryllium	1.37	0.71
Cobalt	....	1.45
Manganese	1.56	....
Iron	0.15	....
Copper	96.92	97.84
Mechanical properties:		
Tensile strength, psi	87,800	53,800
Yield strength, psi	72,200	26,000
Elastic limit, psi	58,500	17,000
Elongation in 2 in., percent	14	25
Rockwell hardness	B42-55	B68-83

S0609 Rw -

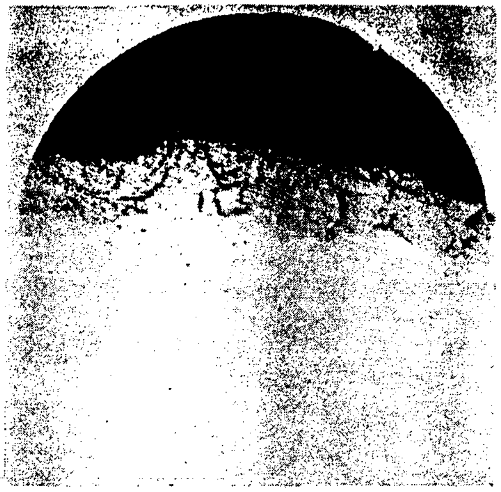


Figure 12—Internal oxidation (gray area) resulting from prolonged heating in salt bath at 1450 F. Note distinct boundary between subscale and normal material (light area). No etch (magnified 500 X).

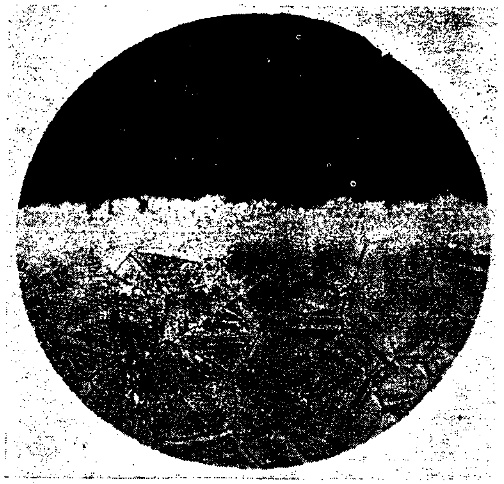


Figure 13—Internal oxidation similar to Figure 12 but etched to show base metal. Ammonium persulfate etch (magnified 500 X).

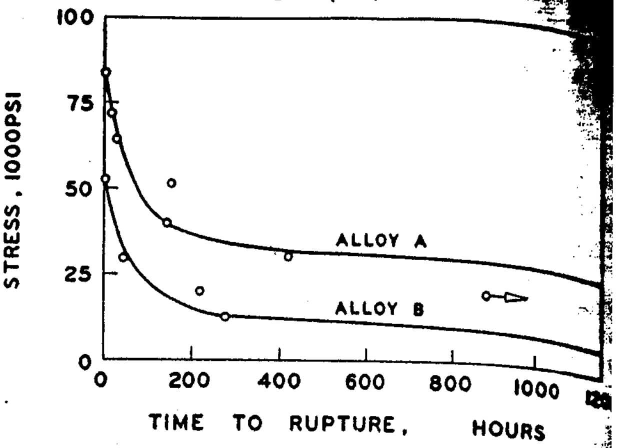


Figure 14—Stress-rupture characteristics of beryllium copper in atmosphere (non-standard alloys, see Table XV). Clenny.

special type of stress-corrosion resulting from ternal or residual stresses and is usually applied brasses containing less than 85 percent copper.

It is probable that stress-corrosion-cracking can produced in almost all metals and alloys under ce tain combinations of stress, time and corrosives. D tailed data for beryllium copper are unavailabl however, field reports indicate excellent resistanc The only known published figures result fro Clenny[40] and cover non-standard casting alloys (Figure 14 and Table XV). In view of the lo tensile and hardness properties shown (appro mately 50-65% of anticipated), specimens may ha been tested in the "as cast" conditions, without th usual solution and aging treatments.

Corrosion-Fatigue

Corrosion-fatigue combines dynamic or cyc stresses with corrosion. Damage from this form attack can be especially severe, since the roughene or pitted surface resulting from corrosion increas the rate of crack propagation d to dynamic loading. In many ca the protective oxide films whi form on corrosion-resistant ma rials are rendered useless by virt of cyclic stressing.

Among available alloys, ber lium copper provides unusual sistance to corrosion-fatigue. T conducted in salt spray solutio indicate that the normal endura of this material is not apprecia lowered under corrosive conditio The results of several corros fatigue studies on beryllium co in various forms are listed in T XVI, while Figure 15 comp several materials on the bas their relative resistance to co sion-fatigue. The comparative presented is based on av values obtained from a numb references.[41,47]

TABLE XVI—Summary of Corrosion Fatigue Data for Beryllium Copper

	Gough and Sopwith[41]	Sopwith[42]		Stewart and Williams[43]				
Corrosive media	3% salt in distilled water			Brackish water (1/6-1/3 salinity of sea water)				
Type test	Rotating beam, 2200 RPM			Rotating beam, 1450 RPM				
Composition								
Beryllium	2.25			2.36	2.91		0.31	0.53
Nickel	0.30			2.42	....		1.64	....
Cobalt	....			....	....		....	2.85
Iron	0.10			0.02	0.10		0.13	0.32
Magnesium	....			....	0.33		....	0.16
Copper	97.26			95.09	97.04		97.91	96.46
Form	Rod			Cut from cast test blocks, 2 in. x 12 in. x 12 in.				
Condition	Cold drawn	Solution treated	Solution treated and aged 1 hr. at 680 F	Solution treated and aged 4 hr. at 660 F	Solution treated and aged 4 hr. at 525 F	Solution treated and aged 4 hr. at 575 F	Solution treated and aged 2 hr. at 750 F	Solution treated and aged 2 hr. at 930 F
Mechanical properties:								
Tensile strength, psi	93.600	72,100	182.000	107,800	150,000	119,600	32,100	49.000
Proportional limit, psi	30,700	12,100	53,800	40,000	51,500	83,500	......	24.000
Rockwell hardness	B87	B68	C42	C34	C40	C42	B97	B93
Fatigue strength at 50,000,000 cycles:								
In air, psi	36,500	35,800	43,500	13,000	17,500	15,500	8,000	7,000
In salt water or spray, psi	39,000	30,500	35,600	12,500	13,500	15,500	7,700	7,000

50609 Rev —

Cavitation-Erosion

Cavitation-erosion may be defined as the damage of material associated with the formation and collapse of cavities in the liquid at a solid-liquid interface.[48] irregularities produce low-pressure areas, allowing pockets of vapor to form. The collapse of these vapor pockets, due to abrupt flow or pressure causes high shock pressures in localized leaving a roughened surface.

Several test methods have been devised to simulate cavitation-erosion conditions. In addition to the corrosion-fatigue tests conducted by Stewart and Williams and listed in Table XVI, several of the same beryllium copper alloys in cast form were exposed to laboratory hydraulic cavitation tests in sea water under laboratory conditions. Relative resistances for alloys are shown in Table XVII. As in the original paper,[13] relative resistance is the ratio of weight loss for a standard manganese bronze sample to the weight loss for the test material.* The beryllium contents afford a comparison with other given in Table XVI.

Conclusions

From the corrosion data presented, it is possible to consider corrosion problems encountered in processing and service. Perhaps the most important factor from a processing standpoint is the effect of heat treatment upon surface condition. Obviously the solution treatment (up to 3 hours at 1475 F) would be more severe than age hardening (up to 3 hours at 550-750 F). Unless prevented by controlled atmospheres, scaling will occur during both operations. In addition to heavier scaling during solution treating, beryllium oxide will also form at the temperatures involved. This oxide will present special problems in subsequent machining, pressworking, plating or joining—unless removed. Similarly, beryllium oxide can be expected to present service problems. For example, its low electrical conductivity means high contact resistance. In addition, it may cause premature wear in mating parts. On the other hand, beryllium oxide films may impart special resistance to certain corrosive environments or be the answer to critical wear problems. Consequently, all processing and service requirements should be carefully weighed in determining whether the beryllium oxide film is an asset.

Safety tools perhaps represent the most familiar application of beryllium copper where corrosion presents a problem. In addition to the nonsparking feature, these tools provide the resistance to corrosion needed in many marine, petroleum and chemical operations. Beryllium copper scraper blades, springs, shaft seals and a host of other components find use in chemical processing equipment. Instrument springs as well as bellows, diaphragms and bourdon tubes are exposed to atmospheres ranging from polar to tropic and rural to industrial. Beryllium copper reed and flapper valves employed in outboard motors are subjected simultaneously to fatigue load-

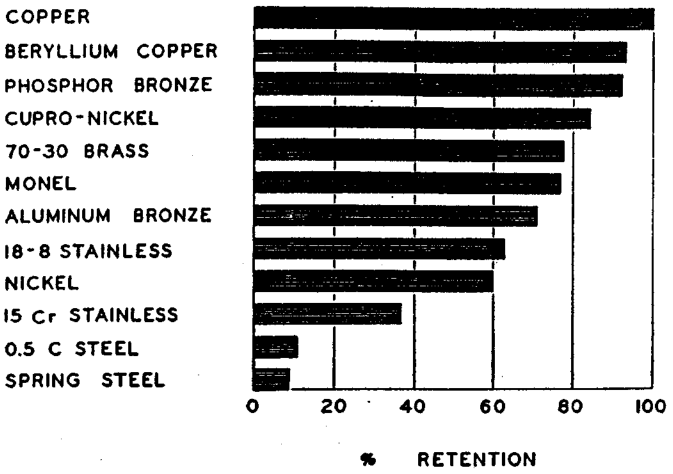


Figure 15—Relative corrosion fatigue of several materials based upon retention in salt spray of normal endurance properties.[41-47]

TABLE XVII—Relative Resistance of Beryllium Copper Casting Alloys to Hydraulic Cavitation Tests[43]
(Vibration Time—120 Minutes)

ALLOY	Composition	Condition	Tensile Strength, psi	Relative Resistance to Cavitation Erosion
Manganese Bronze	41 Zn, 0.29 Mn, 1.1 Fe	As cast	73,200	1.00
Cu-Co-Be........	0.53 Be, 2.85 Co	Heat Treated	49,000	0.78
Cu-Be...........	2.91 Be	As cast	......	1.83
Cu-Ni-Be........	2.36 Be, 2.48 Ni	Heat Treated	107,800	2.48
Cu-Be...........	2.91 Be	Heat Treated	150,000	6.00

TABLE XVIII—Corrosion Resistance of Beryllium Copper Summarized

Approximate Service Ratings (see note)		
Good	**Limited**	**Poor**
Acetic acid, 0.1% (RT) Alcohols Alum Ammonia, dry Atmosphere, rural marine industrial Boric acid Brines Bromine, dry Calcium chloride Carbon dioxide, dry or moist Carbon tetrachloride Chloride, dry Citric acid Fluorine, dry Freon Fresh water Gasoline Hydrocarbons Hydrogen sulfide, dry Ketones Mercury (RT-200 F) Oxalic acid Phosphorus (150 F) Potassium, molten (up to 1112 F) Sea water (RT) Sodium chloride Sodium, molten (up to 1112 F) Sodium-potassium alloys, molten (up to 1112 F) Steam Sulfur dioxide, dry Tannic acid Trichlorethylene	Acetic acid, 2.5-10% (RT) Bromine, moist (RT) Chlorine, moist (RT) Fluorine, moist (RT) Hydrochloric acid, 0-5% (RT) Mercury (200-700 F) Mine water Phosphoric acid, 3-95% (RT-212 F) Sea water (140 F) Sodium chloride, 3% + copper chloride Sodium hydroxide, 1-10% (RT) Sulfur dioxide, moist Sulfuric acid, 0-10% (RT) Zinc, molten	Aluminum, molten Ammonia, moist Ammonium hydroxide Bismuth, molten Bismuth-lead eutectic, molten Bromine, moist (ET) Cadmium, molten Chlorine, moist (ET) Chromic acid Ferric chloride Fluorine, moist (ET) Gallium, molten Hydrochloric acid, 10% (140 F) Hydrochloric acid, over 5% (RT) Hydrogen sulfide, moist Indium, molten Lead, molten Lithium, molten Nitric acid Sulfuric acid, 10% (140 F) Sulfuric acid, 5% + potassium dichromate, 3% Thallium, molten Tin, molten

RT—room temperature ET—elevated temperature

Note: These ratings, based upon laboratory and field tests, are offered only as a guide, since corrosion rates are affected by agitation, temperature, aeration, concentrations, etc. Ratings based upon laboratory tests have the following significance:

Rating	Rate of attack, ipy
Good	less than 0.001
Limited	0.001 to 0.010
Poor	more than 0.010

---

* A high value indicates improved resistance or decreased weight loss.

S0609 Rw –

ing and salt water impingement. Many other equally severe applications can be cited.

To combat certain types of corrosion, it may be desirable to lacquer or plate beryllium copper components. Many types of plating, including gold, silver, tin, zinc, cadmium, copper, nickel and chromium can be applied readily where needed.[49]

The accompanying Table XVIII summarizes the corrosion resistance of beryllium copper to various media under normal conditions. Data are based upon laboratory tests and service experience. This table is offered only as a guide or starting point—to be supplemented by tests under actual operating conditions whenever possible.

References

1. J. T. Richards. Beryllium Copper. *Mat. and Meth.*, **31**, No. 4, 75-90 (1950) April.
2. Otto Dahl. On the Resistance to Corrosion of Bronzes. *Korrosion.* Bericht uber die III. Korrosionstagung, 23-36 (1933).
3. The Corrosion of Metals. Part VI. The Corrosion of Copper and Its Alloys, *Sheet Metal Ind.*, **24**, 145-151 (1947) January.
4. P. E. Bojkov. Use of Beryllium in Copper-Base Alloys for Reliable Castings. *Liteinoe Delo.*, **8**, 23-31 (1937).
5. Haldun N. Terem. The Corrosion of Beryllium Bronzes. *Bull. de la societe chimique de France*, **4**, 1509-1524 (1937); also *Comptes rendus*, **204**, 1426-1428 (1937).
6. L. D. Yates. Corrosion Tests of Metals and Ceramics. Tennessee Valley Authority, Wilson Dam, Alabama, Chemical Engineering Report No. 9 (1951), 56 pp.
7. Pickling and Electroplating Beryllium Copper Alloy Components. *Prod. Fin.*, **16**, 22-48 (1951) Nov.
8. E. E. Halls. Plating and Pickling Beryllium-Copper Components. *Metallurgia*, **39**, 181-186 (1949) February.
9. C. D. Cook and C. Merritt, Jr. Materials and Finishes for Tropical Services. *Mat. and Meth.*, **25**, No. 5, 77-80 (1947) May.
10. W. H. Bassett. Beryllium Copper Alloys. *Trans. Amer. Inst. Mining and Met. Eng.* **75a**, 218-232 (1927).
11. Anaconda Beryllium Copper. American Brass Co., Publication B-21 (1941), p. 12.
12. A. W. Tracy. Corrosion of Copper-Beryllium Alloys. Section from Corrosion Handbook, John Wiley & Sons, Inc., New York (1948) pp. 110-112.
13. U. R. Evans. Tarnishing and Related Phenomena. *Sheet Metal Ind.*, **24**, 2189-2205 (1947) Nov.
14. R. F. Tylecote. Review of Published Information on the Oxidation and Scaling of Copper and Copper-Base Alloys. *Inst. Metals*, **78**, 259-300 (1950) Nov.
15. G. J. Thomas and L. E. Price. Selective Oxidation as a Fundamental Principle in Metallic Protection. *Nature*, **141**, 830-831 (1938).
16. L. E. Price and G. J. Thomas. Oxidation-Resistance in Copper Alloys. *J. Inst. Metals*, **63**, 21-28 (1938).
17. L. E. Price and G. J. Thomas. Oxidation-Resistance in Copper Alloys. *Metal Ind.*, **53**, 413-416 (1938) Oct.
18. Karl Wilhelm Froehlich. The Scaling of Pure and Alloyed Copper. *Zeitschrift fur Metallkunde*, **28**, 368-375 (1936) Dec.
19. G. J. Thomas and L. E. Price. Preventing Oxidation and Tarnishing. *Metal Ind.*, **54**, 189-190 (1939) Feb.
20. J. W. Hickman. Oxide Films Formed on Metals Binary Alloys. An Electron Diffraction St *Trans., Amer. Inst. Mining and Met. Eng.*, **180**, 5 564 (1948) Dec.; also Proceedings, Pittsburgh I ternational Conference on Surface Reactions, Co rosion Publishing Co., Pittsburgh (1948), pp. 142-15
21. Ichiro Iitake and Shizuo Miyake. Oxide Films Some Alloys. *Nature*, **137**, 457 (1936).
22. Shizuo Miyake. A Study of Oxide Films on Meta Surface with Cathode-Ray Diffraction. I. Copper and Its Alloys. *Bull. Inst. Phys. Chem. Res.*, **14**, 704-713 (1935); also *Scientific Papers of the Inst. Phys. Chem. Res.*, **29**, 167-178 (1936) July.
23. K. One, S. Yoshida and I. Takeda. Study of Cu-Be Alloy by Electron Diffraction Method. *Materials for the Researches of the Electrical Communication Laboratory*, No. 3, 1-12 (1949) Dec.
24. Kazumasa Ono. "Study of Cu-Be (Be 3%) Alloy by Electron Diffraction Method. *Materials for the Researches of the Electrical Communication Laboratory*, No. 13, 1-14 (1950) Dec.
25. K. Ono, S. Yoshida and I. Takada. Selective Oxidation of Alloys. *J., Inst. of Met.* (Japan), **15B**, 55-57 (1951).
26. Georg Masing and Otto Dahl. Physical Properties and Afe-Hardening of Beryllium copper Alloys. *Wissenschaftliche Veroffentlichungen aus dem Siemens-Konzern*, **8**, 101-125 (1929); also Beryllium—Its Production and Application. Translation by Richard Rimbach and A. J. Michel, Reinhold Publishing Corp., New York (1932), pp. 121-150.
27. Haldun N. Terem. Oxidation of Beryllium Bronzes. *Bull. societe chimique de France*, **5**, 589-600 (1938); also *Comptes rendus*, **205**, 47-49 (1937).
28. W. E. Campbell and U. B. Thomas. The Oxidation of Metals. *Trans., Electrochem. Soc.*, **91**, 623-39 (1947).
29. A. Smirnov. A Theory of the Oxidation of Alloys. *Acta Physicochimica* (U.S.S.R.), **22**, 162-186 (1947).
30. F. N. Rhines. Internal Oxidation. *Corrosion and Mat. Prot.*, **4**, 15-20 (1947) Mar.-Apr.
31. F. N. Rhines. A Metallographic Study of Internal Oxidation in the Alpha Solid Solutions of Copper. *Trans., Amer. Inst. Min. Met. Eng.*, **137**, 246-290 (1940).
32. F. N. Rhines, W. A. Johnson and W. A. Anderson. Rates of High-Temperature Oxidation of Dilute Copper Alloys. *Trans., Amer. Inst. Min. Met. Eng.*, **147**, 205-220 (1942).
33. F. N. Rhines. Available Beryllium Reduced by Internal Oxidation. *Metal Prog.*, **47**, 282 (1945). Feb.
34. J. L. Meijering and M. J. Druyvesteyn. Hardening of Metals by Internal Oxidation. *Philips Research Reports*, **2**, 81-102 (1947) April; 260-280 (1947) Aug.
35. J. L. Meijering. Some Aspects of Internal Oxidation in Silver, Copper, Nickel and Iron Alloys. Proc., Pittsburgh International Conference on Surface Reactions, Corrosion Publishing Co., Pittsburgh (1948), pp. 101-104.
36. J. L. Meijering. Some Aspects of Internal Oxidation in Silver, Copper, Nickel and Iron Alloys. Report of Conference on Strength of Solids, Physical Society, London (1948), pp. 140-151.
37. F. N. Rhines. Copper and Copper Alloys, Section from Corrosion Handbook, John Wiley & Sons, Inc., New York (1948), pp. 621-630.
38. F. N. Rhines and W. A. Anderson. "Hydrogen Embrittlement of Pure Copper and of Dilute Copper Alloys by Alternate Oxidation and Reduction. *Trans., Amer. Inst. Min. Met. Eng.*, **143**, 312-325 (1941).
39. LeRoy R. Kelman, Walter D. Wilkinson and Frank L. Yaggee. Resistance of Materials to Attack by Liquid Metals. Chapter from Liquid-Metals Handbook, Office of Naval Research, Washington, June 1 (1950), pp. 77-126.
40. J. T. Clenny. Stress Corrosion. *Iron Age*, **167**, 85- (1951) June 21.

H. Gough and D. G. Sopwith. Resistance of Some Special Bronzes to Fatigue and Corrosion Fatigue. *J. Inst. Metals*, **60**, 143-158 (1936).

D. G. Sopwith. The Resistance of Aluminum and Beryllium Bronzes to Fatigue and Corrosion Fatigue. Aeronautical Research Council, Report and Memoranda No. 2486 (1951).

C. Stewart and W. L. Williams. Investigation of Materials for Marine Propellers. *Proc., Amer. Soc. Test. Mat.*, **46**, 836-845 (1946).

Wilkins and E. S. Bunn. Copper and Copper Alloys. McGraw-Hill Book Co., New York

McAdam, Jr. Corrosion-Fatigue of Non-Metals. *Proc., Amer. Soc. Test. Mat.*, **27** II, [illegible] (1927).

46. D. J. McAdam, Jr. Fatigue and Corrosion-Fatigue of Spring Materials. *Trans., Amer. Soc. Mech. Eng.*, **51**, 45-58 (1929).

47. Blaine B. Westcott. Corrosion-Fatigue. Section from Corrosion Handbook, John Wiley & Sons, Inc., New York (1948), pp. 578-590.

48. Corrosion Handbook, John Wiley & Sons, Inc., New York (1948), pp. xxvi.

49. J. T. Richards. How to Work With Beryllium Copper Strip. *Amer. Mach.*, **96**, 99-114 (1952) March 31.

50. Kenzo Inamura and Hidekichi Ohashi. Some Properties of Beryllium Bronzes. *Sumitomo Kinzoku Kogyo Kenkyu Hokoku*, **2**, 656-668 (1936).

NACE Practice on Reprinting Technical Material

Requests for prices on reprinting material appearing in CORROSION should be addressed to National Association of Corrosion Engineers, 1061 M & M Building, Houston 2, Texas. Prices usually cannot be given until after articles have appeared in CORROSION although requests for prices may be submitted at any time. Type from which technical articles are printed is kept standing for 90 days after date of issue, and reprints ordered during that interval will be from standing type. For reprints ordered after expiration of this period, write for details. Single copies of reprints of material from CORROSION are listed in advertisements appearing in many issues. Usually single copies may be obtained only in the form of tear sheets, or whole copies of the issue in which the article appears.

Permission to reprint articles usually is given to responsible firms and individuals who wish to have the work done themselves. NACE requires, however, that proper credit be given CORROSION at an appropriate place on all reprint material. The association also requests that reprint style closely conform to that approved by its board to be in keeping with the aims and objectives of the association and that copies of reprints made under this authority are supplied NACE for recording purposes.

S0609 Rev -

TABLE 1.

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

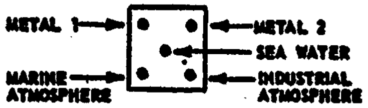
ACTIVE (ANODIC) ⟵ ⟶ NOBLE (LESS ACTIVE–CATHODIC)

	1ST METAL OR METAL ALLOY \ JOINED TO 2ND METAL OR METAL ALLOY	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	
A	MAGNESIUM	1 G	1 I 2 C C	1 I 3 C C	1 I 4 I I	1 I 4 I I	1 I 5 I I	1 I 6 I I	1 I 6 I I	1 I 7 I I	1 I 8 I I	1 I 9 I I	1 I 9 I I	1 I 9 I I	1 I 9 I I	1 I 9 I I	1 I 9 I I	1 I 10 I I	1 I 11 I I	1 I 12 I I	1 I 13 I I	A
B	ZINC, ZINC COATING		2 G	2 C 3 C C	2 I 4 C C	2 I 4 C C	2 I 5 I I	2 I 6 I I	2 I 6 I I	2 I 7 I I	2 I 8 I I	2 I 9 I I	2 I 9 I I	2 I 9 I I	2 I 9 I I	2 I 9 I I	2 I 9 I I	2 I 10 I I	2 I 11 I I	2 I 12 I I	2 I 13 I I	B
C	CADMIUM BERYLLIUM			3 G	3 I 4 C C	3 I 4 C C	3 I 5 I I	3 I 6 I I	3 I 6 I I	3 I 7 I I	3 I 8 I I	3 I 9 I I	3 I 9 I I	3 I 9 I I	3 I 9 I I	3 I 9 I I	3 I 9 I I	3 I 10 I I	3 I 11 I I	3 I 12 I I	3 I 13 I I	C
D	ALUMINUM ALUMINUM–Mg ALUMINUM–Zn				4 G	4 C 4 C C	4 I 5 I I	4 I 6 I I	4 I 6 I I	4 I 7 I I	4 I 8 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 10 I I	4 I 11 I I	4 I 12 I I	4 I 13 I I	D
E	ALUMINUM–Cu					4 G	4 I 5 I I	4 I 6 I I	4 I 6 I I	4 I 7 I I	4 I 8 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 9 I I	4 I 10 I I	4 I 11 I I	4 I 12 I I	4 I 13 I I	E
F	STEELS – CARBON LOW ALLOY						5 G	5 I 6 I C	5 I 6 I I	5 I 7 I I	5 I 8 I I	5 I 9 I I	5 I 9 I I	5 I 9 I I	5 I 9 I I	5 I 9 I I	5 I 9 C C	5 I 10 I I	5 I 11 I I	5 I 12 I I	5 I 13 I I	F
G	LEAD							6 G	6 C 6 C C	6 I 7 C C	6 I 8 C C	6 I 9 C C	6 I 9 C C	6 I 9 I I	6 I 9 I C	6 I 9 I C	6 I 9 I C	6 I 10 I C	6 I 11 C C	6 I 12 I C	6 I 13 I C	G
H	TIN TIN–Pb INDIUM								6 G	6 I 7 I I	6 I 8 I C	6 I 9 I C	6 I 9 C C	6 I 9 C C	6 I 9 C C	6 I 9 C C	6 C 9 C C	6 I 10 C C	6 C 11 C C	6 I 12 C C	6 I 13 I I	H
I	ST. STEELS – MARTENSITIC FERRITIC									7 G	7 I 8 I C	7 I 9 I I	7 I 9 I I	7 I 9 I C	7 I 9 I I	7 I 9 I I	7 I 9 I I	7 I 10 I I	7 I 11 I I	7 I 12 I I	7 I 13 I I	I
J	CHROMIUM MOLYBDENUM TUNGSTEN										8 G	8 C 9 C C	8 I 9 C C	8 I 9 I C	8 I 9 I I	8 I 9 C C	8 I 9 C C	8 I 10 C C	8 I 11 C C	8 I 12 C C	8 I 13 C C	J
K	ST. STEELS–AUST., PH, SUPER STRENGTH, HEAT RESISTANT											9 G	9 I 9 I I	9 I 9 I I	9 I 9 I I	9 I 9 C C	9 I 9 C C	9 I 10 C C	9 I 11 C C	9 I 12 C C	9 I 13 C C	K
L	BRASS–Pb BRONZE												9 G	9 I 9 C C	9 I 9 C C	9 I 9 I C	9 I 9 C C	9 I 10 I C	9 I 11 C C	9 I 12 C C	9 I 13 C C	L
M	BRASS–LOW Cu BRONZE–LOW Cu													9 G	9 I 9 C C	9 I 9 C C	9 I 9 C C	9 I 10 I C	9 I 11 C C	9 I 12 I C	9 I 13 I C	M
N	BRASS–HIGH Cu BRONZE–HIGH Cu														9 G	9 I 9 I C	9 I 9 C C	9 I 10 I C	9 I 11 C C	9 I 12 I C	9 I 13 I C	N
O	COPPER–HIGH Ni MONEL															9 G	9 I 9 C C	9 I 10 C C	9 I 11 C C	9 I 12 C C	9 I 13 C C	O
P	NICKEL COBALT																9 G	9 I 10 C C	9 I 11 C C	9 I 12 C C	9 I 13 C C	P
Q	TITANIUM																	10 G	10 I 11 C C	10 I 12 C C	10 I 13 C C	Q
R	SILVER																		11 G	11 C 12 C C	11 I 13 C C	R
S	PALLADIUM RHODIUM GOLD PLATINUM																			12 G	12 C 13 C C	S
T	GRAPHITE																				13 G	T

ACTIVE (ANODIC) ⟵ ⟶ NOBLE (LESS ACTIVE–CATHODIC)

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

KEY:



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

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

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

S0609 Rus -

TABLE II. Galvanic series of selected metals in seawater.

Active (Anodic)

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

S0609 Rev –

TABLE II (Continued)

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

Noble (Less Active-Cathodic)

55