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REPORT NO. RS-TR-67-11

PRACTICAL GALVANIC SERIES

by

Charles M. Forman
E. A. Verchot

October 1967

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U.S. ARMY MISSILE COMMAND
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10 October 1967

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PRACTICAL GALVANIC SERIES

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Charles M. Forman
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DA Project No. 1C024401A328
AMC Management Structure Code No. 5025.11.294

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Materials Engineering and Development Branch
Structures and Materials Laboratory
Research and Development Directorate
U. S. Army Missile Command
Redstone Arsenal, Alabama 35809

ABSTRACT

The prime objective of this work was the development of a practical galvanic series of metals and alloys to aid in the selection of compatible materials for missile systems. This was accomplished by studying the various metals and alloys coupled with a 110 copper alloy standard as the reference electrode, and monitoring potentials with a self-balancing potentiometric-type recorder. Each couple was partially immersed in a 5-percent salt (sodium chloride) solution.

The effects of coatings and platings on the galvanic relationships existing between metals and alloys were also studied. Coatings and platings were studied with aluminum, magnesium, and steel as the substrates.

Other studies included the effects on galvanic activity when strength levels within the same alloy were varied, current versus weight-loss measurements, and the comparison of other conducting solutions with the 5-percent sodium chloride solution used in the generation of this series.

The study of the effect of strength level on galvanic activity showed that galvanic potentials can exist between specimens of the same alloy at different strength levels. Also, the galvanic potential varies with different conducting solutions.

ACKNOWLEDGEMENT

The authors wish to express their gratitude for the helpful suggestions and encouragement offered by Dr. H. H. Uhlig, Professor of Metallurgy, Massachusetts Institute of Technology, and Dr. J. A. McLaren of the Army Missile Command at Redstone Arsenal, Alabama.

FOREWORD

The work described in this report was performed as a part of the subtask "Corrosion Protection Coatings" under DA Project No. 1C024401A328, AMC Management Structure Code No. 5025.11.294, Metals Research for Army Material. The purpose of the program was the generation of a practical galvanic series of metals and alloys to aid in the seelection of compatible materials for missile systems.

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ILLUSTRATIONS

ILLUSTRATIONS (Concluded)

Section I INTRODUCTION

Designers of missile components are faced with a dilemma in selecting metals and alloys that are compatible. The term "compatible materials" refers to metals that will exhibit the least amount of galvanic activity when they are connected in a corrosive environment. A guide or reference is needed when choosing materials.

Existing "galvanic" series are generally too theoretical for practical use. They are usually obtained by measuring the potential generated between a standard hydrogen electrode and the pure metal immersed in a solution of the metal's ions, rather than by measurement of the myriad of alloys actually encountered. Also, many of these series list and treat groups of alloys as if they were completely compatible. For example, all aluminum alloys may be considered compatible by such a series. However, it becomes evident from a study of the galvanic relationships existing between metals and alloys that all alloys within a group, e. g., aluminum or stainless steel, are not compatible. Also, potential differences exist between samples of the same alloy at different strength levels.

To combat these difficulties, a galvanic series has been generated by direct measurement of the metals and alloys used in missile systems, to enable the selection of compatible materials for missile uses.

Section II. DISCUSSION

When two metals are connected in a corrosive environment, the anode (negative electrode in a discharging battery in this case) will begin to corrode. The amount of corrosion depends upon the resulting current density (current per unit area). However, since current and voltage are related in Ohm's law ($I = E/R$), the voltage or potential difference developed between the two electrodes shows the tendency of the anode to corrode.

Ohm's law, which states that current is equal to the voltage divided by the resistance, is the basis for the premise that the galvanic series may be used for the selection of compatible materials. The series is used by picking candidate materials with the least potential differences.

In this study, practical conditions were used for measurements, rather than ideal or standard. The basic setup consisted of a potentiometric-type recorder connected in series to the electrodes in the galvanic cell. This potentiometer permitted potential measurements with essentially no power withdrawn from the system being measured.

The galvanic cell was composed of two $1\ ^1/_8 \times 4 \times 0.065$-in. electrodes partially immersed in a 5-percent salt (sodium chloride) solution. One of the electrodes was the standard reference electrode, copper 110 alloy, and the other was the metal or alloy being tested. The exposed surface area of each electrode was 2 $in.^2$. A calomel half-cell was used intermittently to verify the results, thereby insuring that the galvanic response of the copper 110 reference electrode remained constant. The calomel was partially immersed in a separate container containing 1.0 N potassium chloride solution, and was connected to the 5-percent salt solution by a salt bridge also containing 1.0 N potassium chloride.

The series was compiled using open-circuit potential values, i. e., with essentially no current flowing through the cell. Copper 110, the reference material, was assigned the value of 0.00 V, and all other alloys were placed in the series according to their relationship to this standard. The series was arranged from the most anodic to the most cathodic (from the least noble to the most noble).

Passivation of stainless steel alloys was effected by immersion for 30 min in a 20-percent nitric acid solution held at 50°C.

The galvanic cell, and calomel electrode when used, were placed in a constant temperature water bath, and the temperature was held constant at 25°C. The apparatus used is shown in Figures 1 through 4.

The metals and alloys used in the series, untreated and treated, are listed in Table I. The galvanic series is presented in Table II. Figures 5 through 7 show collections of test specimens of the many metals and alloys, treated and untreated, that make up the galvanic series. Figure 5 indicates the coated magnesium and aluminum samples, and the electroplated steel samples. Figure 6 shows both the treated and untreated samples. An electrode of the type used in making the galvanic measurements is shown in Figure 7.

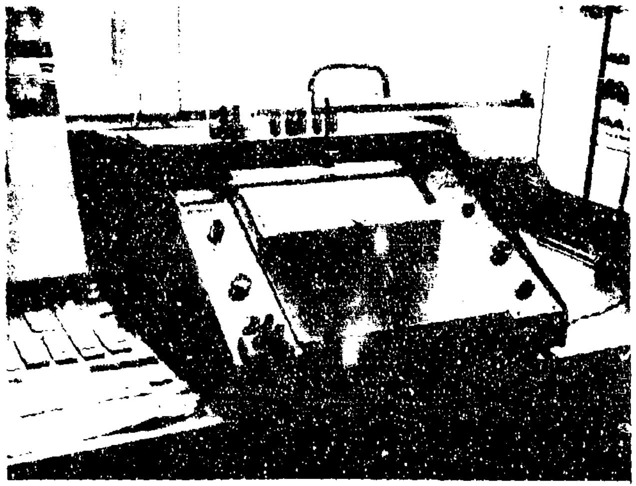

FIGURE 1. RECORDER

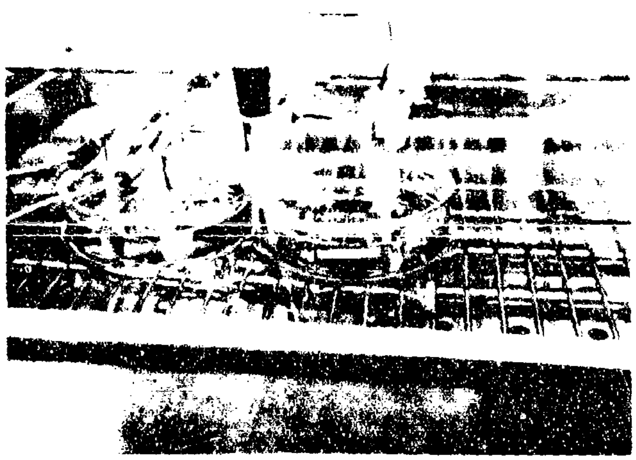

FIGURE 2. GALVANIC CELL (INCLUDING CALOMEL "CHECK" ELECTRODE)

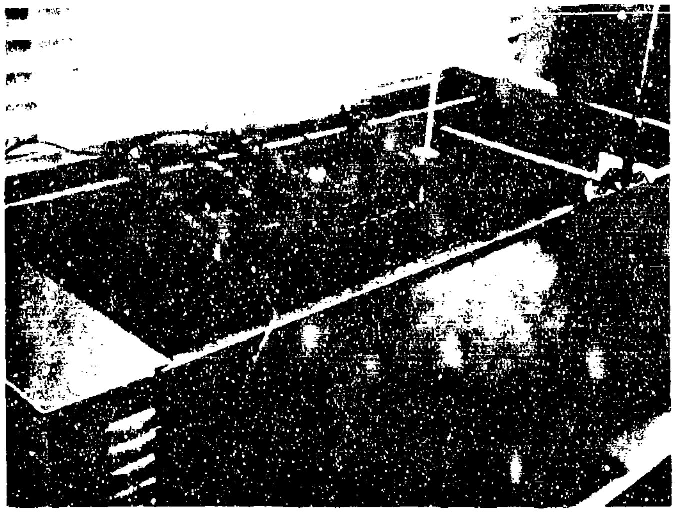

FIGURE 3. WATER BATH, GALVANIC CELL, CALOMEL REFERENCE, AND THERMOMETER

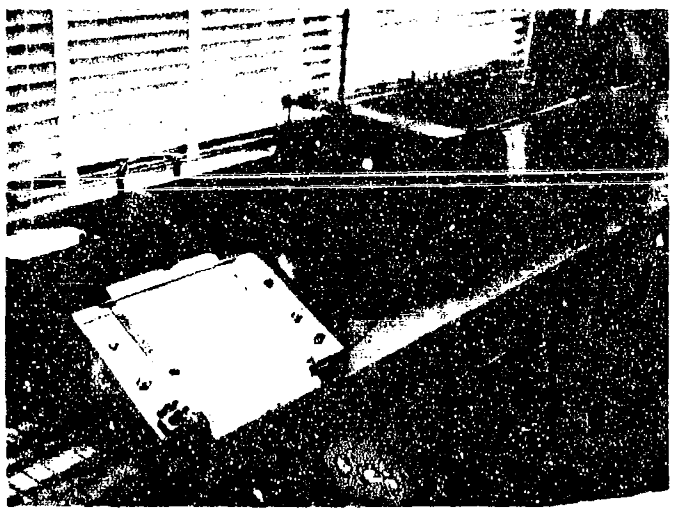

FIGURE 4. OVERALL SETUP

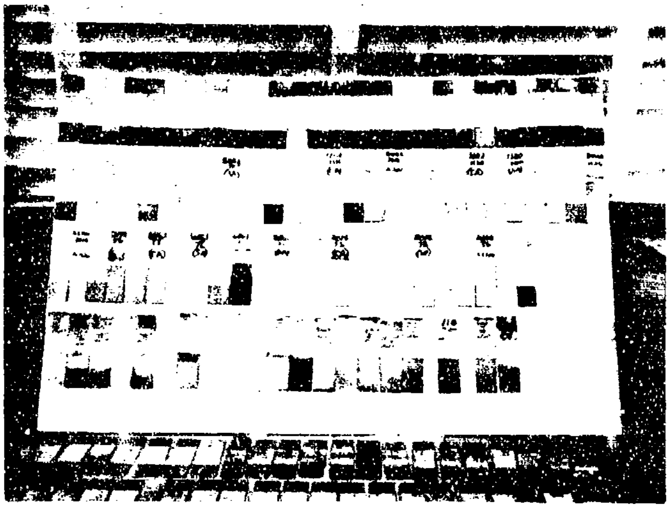

FIGURE 5. TREATED MAGNESIUM, ALUMINUM, AND STEEL SAMPLES

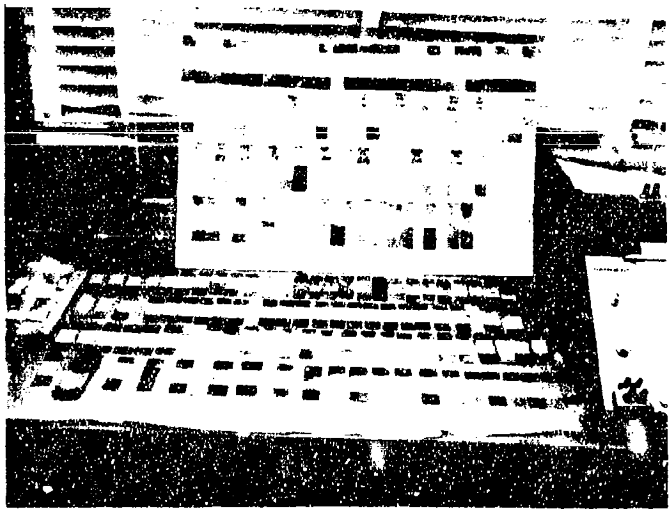

FIGURE 6. METALS AND ALLOYS, TREATED AND UNTREATED, INCLUDED IN SERIES

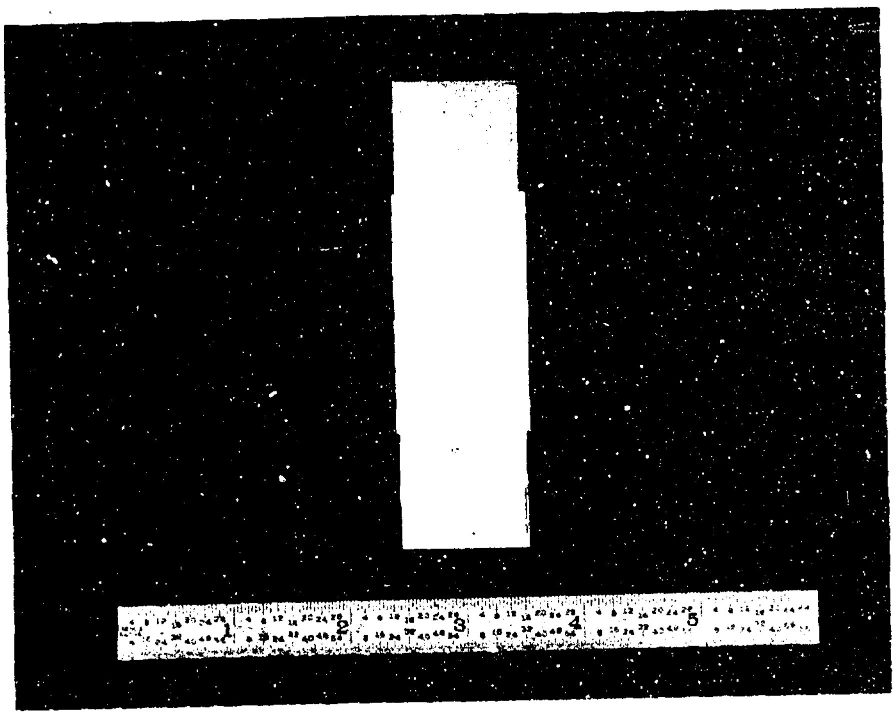

FIGURE 7. TYPICAL ELECTRODE

TABLE I. LIST OF METALS AND ALLOYS ON WHICH GALVANIC MEASUREMENTS WERE MADE

	Magnesium Alloys	
	AZ 31 B	
	AZ 91 B	
	Zinc Alloys	
	AG40A zinc-base alloy die casting	
	M & H Zinc Company zinc:	
	Pb: 0.05-0.07	
	Cd: 0.005 max	
	Fe: 0.010 max	
	Cu: 0.95-1.05%	
	Mg: 0.010-0.012%	
	Titanium Alloys	
75 A		
6 Al-4 V	1	Heat treatment not known, probably annealed. Rockwell C hardness, 36.
	2	Heat treated: 1700°F for 15 min, water quenched, 950°F for 4 hr. Rockwell C hardness, 41.5
5 Al-2.5 Sn		
8 Mn		
13 V-11 Cr-3 Al	1	Annealed: 1450°F for 30 min, air cooled. Rockwell C hardness, 33.5
	2	Heat treated: 1450°F for 30 min, water quenched, 900°F for 24 hr. Rockwell C hardness, 45.5

TABLE I. LIST OF METALS AND ALLOYS ON WHICH GALVANIC MEASUREMENTS WERE MADE (Continued)

Aluminum-Base Alloy Die Castings

Alloy 13 or 512A
Alloy A360 or SG100A
Alloy A380 or SC84A
Alloy 218 or G8A

Copper Alloys

Copper 110
Bronze 220
Low bronze 240
Muntz metal 280
Naval brass 464
Phosphor bronze (B-1) 534
Ambraloy 612
Everdur 655
Cupro nickel (30%) 7151
Nickel silver (18%) 770
Yellow brass 268

Aluminum Alloys Wrought

2014 (T6 + 0)
2024 (T4 + 0)
7075 (T6 bare and alclad + 0)
1100 (H14 + 0)
5083 H34
5456 (H343 + 0)
3003 H25
5052 (H12 + 0)
4043 H14
6061 (T6 + 0)
1160 H14
5056 H14
6151 T6
7079 T6
5052 H32
7071 T6
2014 T3

Steels

Stainless: Type 430 (A & P)*
Type 304 (A & P)
Type 347 (A & P) — In active state: annealed, 1/4, 1/2, and full hard. Only annealed in passive state
17-7 PH (A & P)
Carp 20cb (A & P)
Type 316 (A) — Annealed, 1/4, 1/2, and full hard
Type 410 (A)

* (A) - active state
(P) - passive state

TABLE I. LIST OF METALS AND ALLOYS ON WHICH GALVANIC MEASUREMENTS WERE MADE (Continued)

	Steels (Continued)	
Stainless:	Type 321 (A & P)	In active state: annealed, $\frac{1}{4}$, $\frac{1}{2}$, and full hard.
		Only annealed in passive state
	Type 202	Bright (A & P)
		Dull (A & P)
	Type 350 (A & P)	
	AM 355 (A & P)	
	Type 301 (A & P)	
	Type 305L (A & P)	
	Type 309 (A)	
	Type 316L (A & P)	
	Type 201 (A & P)	
	Type 286 (A & P)	
	Type 310 (A & P)	
Other:	AISI 1010	
	Al-Si coated steel (T1)	
	Al (pure) coated steel (T2)	
	Other Metals and Alloys	
	Molybdenum	
	Tungsten	
	Columbium (niobium)	
	Tantalum	
	Columbium - 1% zirconium	
	90-10 Tantalum-tungsten	
	Cadmium	
	Lead	
	Nickel	
	Monel	
	Uranium, depleted (unalloyed)	
	Uranium, depleted (8% Mo)	
	Graphite	
	Tin	
	Beryllium	
	Indium	

TABLE I. LIST OF METALS AND ALLOYS ON WHICH GALVANIC MEASUREMENTS WERE MADE (Concluded)

Coated Aluminum Alloys	Coated Magnesium Alloys
Alloys used:	Alloys used:
1. 1100 H14	1. AZ 31 B
2. 2014 T6	2. AZ 91 B
3. 3003 H25	
4. 5052 H12	Coatings applied:
5. 6061 T6	1. Chrome pickle (Dow 1)
6. 7075 T6	2. Sealed chrome pickle (Dow 10)
	3. Dichromate (Dow 7)
Coatings applied:	4. Galvanic anodize (Dow 9)
1. Sulfuric acid anodize	5. Dilute chromic acid (Dow 19)
2. Chromic acid anodize	6. Dow 17 a. 60-65 V
3. Conversion coating 1 (Alrok)	b. 90 V
4. Conversion coating 2	7. HAE a. 60-65 V
5. Conversion coating 3	b. 85 V

Electroplated Coatings on Steel

Brass on AISI 1010 steel
Cadmium (brush plated) on AISI 1010 steel
Cadmium (brush plated) on 202 stainless steel
Cadmium on AISI 1010 steel
Cadmium (brush plated) on 321 stainless steel
Chromium on nickel on copper on AISI 1010 steel
Chromium on nickel on AISI 1010 steel
Chromium on 202 stainless steel
Chromium on AISI 1010 steel
Chromium on 410 stainless steel
Chromium on electroless nickel on AISI 1010 steel
Chromium on 430 stainless steel
Electroless nickel on AISI 1010 steel
Nickel on copper on AISI 1010 steel
Nickel on AISI 1010 steel
Tin on AISI 1010 steel
Zinc on AISI 1010 steel

TABLE II. PRACTICAL GALVANIC SERIES

(Open Circuit Potential Values - Compared to Copper 110 Alloy Reference)

Alloy	Treatment	Voltage
AZ 91B Magnesium	HAE coating applied at 60-65 V	-1.480
AZ 31B Magnesium	Chrome pickle treatment	-1.357
AZ 91B Magnesium	Chrome pickle treatment	-1.350
AZ 31B Magnesium	Dow 19 treatment	-1.345
AZ 31B Magnesium	Untreated	-1.344
AZ 31B Magnesium	HAE coating applied at 60-65 V	-1.332
AZ 31B Magnesium	Galvanic anodize treatment	-1.330
AZ 31B Magnesium	Dichromate treatment	-1.330
AZ 91B Magnesium	Dichromate treatment	-1.323
AZ 91B Magnesium	Untreated	-1.314
AZ 91B Magnesium	Dow 19 treatment	-1.313
AZ 91B Magnesium	Sealed chrome pickle treatment	-1.310
AZ 31B Magnesium	Sealed chrome pickle treatment	-1.305
AZ 91B Magnesium	Galvanic anodize treatment	-1.300
AZ 31B Magnesium	Dow 17 coating applied at 60-65 V	-1.294
AZ 31B Magnesium	HAE coating applied at 85 V	-1.284
AZ 91B Magnesium	Dow 17 coating applied at 60-65 V	-1.261
AZ 31B Magnesium	Dow 17 coating applied at 90 V	-1.257
AZ 91B Magnesium	Dow 17 coating applied at 90 V	-1.234
AZ 91B Magnesium	HAE coating applied at 85 V	-1.226
Zinc on AISI 1010 steel		-0.793
Zinc (AG40A)		-0.786
Zinc (M & H Zinc Company)		-0.784
Beryllium		-0.780
6061 T6 Aluminum	Alrok treatment	-0.752
7075 T6 Aluminum	Alclad	-0.645
2014 T3 Aluminum		-0.639
1160 H14 Aluminum		-0.609
7075 0 Aluminum		-0.604
3003 H25 Aluminum	Conversion coating 2	-0.596
7079 Aluminum		-0.584
6061 T6 Aluminum	Conversion coating 2	-0.580
5052 H12 Aluminum	Conversion coating 2	-0.571

TABLE II. PRACTICAL GALVANIC SERIES (Continued)

Alloy	Treatment	Voltage
Cadmium (brush plated) on AISI 1010 steel		-0.557
Uranium (depleted) unalloyed		-0.556
Cadmium (brush plated) on 202 stainless steel		-0.554
Die-cast 218 Aluminum		-0.549
1100 H14 Aluminum	Alrok treatment	-0.546
5052 H12 Aluminum		-0.545
Type II (Aluminum coated stainless steel)		-0.541
5052 0 Aluminum		-0.534
Cadmium on AISI 1010 steel		-0.534
Cadmium (brush plated) on 321 stainless steel		-0.532
7075 T6 Aluminum	Conversion coating 2	-0.524
5052 H12 Aluminum	Sulfuric anodize treatment	-0.524
5083 Aluminum		-0.524
1100 H14 Aluminum	Conversion coating 2	-0.520
6151 T6 Aluminum		-0.520
5052 H12 Aluminum	Alrok treatment	-0.519
Cadmium		-0.519
5052 H12 Aluminum	Chromic anodize treatment	-0.514
5456 0 Aluminum		-0.514
1100 H14 Aluminum	Chromic anodize treatment	-0.514
5456 H343 Aluminum		-0.507
4043 H14 Aluminum		-0.507
Type I (Aluminum-silicon coated stainless steel)		-0.504
7075 T6 Aluminum	Alrok treatment	-0.504
5052 H12 Aluminum	Conversion coating 3	-0.504
3003 H25 Aluminum	Sulfuric anodize treatment	-0.504
5052 H32 Aluminum		-0.502

TABLE II. PRACTICAL GALVANIC SERIES (Continued)

Alloy	Treatment	Voltage
1100 0 Aluminum		-0.499
3003 H25 Aluminum		-0.496
3003 H25 Aluminum	Chromic anodize treatment	-0.494
1100 H14 Aluminum	Sulfuric anodize treatment	-0.494
6061 T6 Aluminum		-0.493
3003 H25 Aluminum	Alrok treatment	-0.492
3003 H25 Aluminum	Conversion coating 3	-0.486
1100 H14 Aluminum	Conversion coating 3	-0.484
7075 T6 Aluminum	Chromic anodize treatment	-0.484
6061 T6 Aluminum	Chromic anodize treatment	-0.484
7071 T6 Aluminum		-0.484
6061 T6 Aluminum	Sulfuric anodize treatment	-0.480
Die-cast A360 Aluminum		-0.479
Die-cast 13 Aluminum		-0.477
6061 T6 Aluminum	Conversion coating 3	-0.476
7075 T6 Aluminum	Sulfuric anodize treatment	-0.472
2024 0 Aluminum		-0.472
7075 T6 Aluminum (Bare)		-0.470
2014 T6 Aluminum	Chromic anodize treatment	-0.464
1100 H14 Aluminum		-0.464
2014 T6 Aluminum	Conversion coating 2	-0.462
2014 T6 Aluminum	Sulfuric anodize treatment	-0.460
2014 T6 Aluminum	Alrok treatment	-0.459
2014 T6 Aluminum	Conversion coating 3	-0.456
6061 0 Aluminum		-0.454
2014 T6 Aluminum		-0.452
7075 T6 Aluminum	Conversion coating 3	-0.448
Indium		-0.448
Die-cast A380 Aluminum		-0.444
2014 0 Aluminum		-0.444
2024 T4 Aluminum		-0.370
5056 H16 Aluminum		-0.369
Tin on AISI 1010 steel		-0.333
430 Active stainless steel		-0.324

TABLE II. PRACTICAL GALVANIC SERIES (Continued)

Alloy	Treatment	Voltage
Lead		-0.316
Chromium on nickel on copper on AISI 1010 steel		-0.301
AISI 1010 steel		-0.297
Tin		-0.281
Chromium on nickel on AISI 1010 steel		-0.250
410 Active stainless steel		-0.230
Chromium on 202 stainless steel		-0.209
Copper on AISI 1010 steel		-0.203
Chromium on 410 stainless steel		-0.194
Nickel on copper on AISI 1010 steel		-0.192
Chromium on electroless nickel on AISI 1010 steel		-0.178
Chromium on 430 stainless steel		-0.169
Tantalum		-0.166
350 Active stainless steel		-0.149
Electroless nickel on AISI 1010 steel		-0.138
90-10 Tantalum-tungsten		-0.124
310 Active stainless steel		-0.124
301 Active stainless steel		-0.120
305L Active stainless steel		-0.113
304 Active stainless steel		-0.106
430 Passive stainless steel		-0.094

TABLE II. PRACTICAL GALVANIC SERIES (Continued)

Alloy	Treatment	Voltage
17-7 PH Active stainless steel		-0.076
Tungsten		-0.047
Niobium - 1% zirconium		-0.044
Yellow brass 268		-0.043
Uranium (depleted) 8% molybdenum		-0.041
Naval brass 464		-0.041
Muntz metal 280		-0.034
Brass on AISI 1010 steel		-0.032
Nickel silver 18% 770		-0.022
Ambraloy 612		-0.019
Low brass 240		-0.016
316L Active stainless steel		-0.013
Bronze 220		-0.012
Everdur 655		-0.007
Copper 110	(Reference electrode) ↑ (-) ↓ (+)	0.000
347 Active stainless steel		+0.006
Molybdenum		+0.006
Cupro nickel (30%) 7151		+0.012
202 Active (dull) stainless steel		+0.014
Niobium		+0.018
Phosphor bronze (B-1) 534		+0.034
202 Active (bright) stainless steel		+0.051
Monel		+0.051
347 Passive stainless steel		+0.058
Nickel		+0.064
201 Active stainless steel		+0.070

TABLE II. PRACTICAL GALVANIC SERIES (Continued)

Alloy	Treatment	Voltage
Carp 20 CB Active stainless steel		+0.074
321 Active stainless steel		+0.077
316 Active stainless steel		+0.082
Nickel on AISI 1010 steel		+0.086
304 Passive stainless steel		+0.098
17-7 PH Passive stainless steel		+0.098
305L Passive stainless steel		+0.100
309 Active stainless steel		+0.108
310 Passive stainless steel		+0.109
301 Passive stainless steel		+0.112
321 Passive stainless steel		+0.116
201 Passive stainless steel		+0.129
286 Active stainless steel		+0.156
316L Passive stainless steel		+0.156
202 Passive (dull) stainless steel		+0.159
AM 355 Active stainless steel		+0.167
202 Passive (bright) stainless steel		+0.183
Carp 20 CB Passive stainless steel		+0.186
AM 355 Passive stainless steel		+0.204
286 Passive stainless steel		+0.311

TABLE II. PRACTICAL GALVANIC SERIES (Concluded)

Alloy	Treatment	Voltage
5 Al-2.5 Sn Titanium		+0.423
13 V-11 Cr-3 Al Titanium	Annealed, Rockwell C hardness, 33.5	+0.436
6 Al-4 V Titanium	Heat treatment: 1700°F for 15 min, water quenched, 950°F for 4 hr. Rockwell C hardness, 41.5	+0.455
Graphite		+0.473
6 Al-4 V Titanium	Annealed, Rockwell C hardness, 36	+0.481
8 Mn Titanium		+0.493
13 V-11 Cr-3 Al Titanium	Heat treatment: 1450°F for 30 min, water quenched, 900°F for 24 hr. Rockwell C hardness 45.5	+0.498
75 A Titanium		+0.506
350 Passive stainless steel		+0.666

Section III. METHODS AND PROCEDURES

The following methods and procedures were used in applying the various coatings, both chemical and electrochemical, to magnesium, aluminum, and steel.

1. Coatings Used on Magnesium

The magnesium samples were cleaned by immersing in dilute nitric acid and rinsing with water. The solutions used for these metal treatments were compounded as described in various references, e. g., the Metal Finishing Guidebook Directory. Dow 17 (anodize) and HAE coatings were applied by another laboratory because of the high voltages required.

a. Dow 1 (Chrome Pickle Treatment)

Each sample of AZ 31B alloy magnesium was dipped for 1 min in the chrome pickle solution prescribed for wrought magnesium, then rinsed in cold, running water followed by a dip in hot water to facilitate drying. Operating temperature of this solution was 70° to 90°F.

The die-cast AZ 91B magnesium samples were first cleaned and then immersed for 15 to 30 sec in hot water, then for 10 sec in the appropriate pickle solution at 120° to 140°F, and finally rinsed and dried.

b. Dow 7 (Dichromate Treatment)

The magnesium samples were immersed in a fluoride bath at a temperature of 70° to 90°F for 15 min to activate the surfaces, then rinsed. The activated samples were then immersed in the dichromate bath at a temperature of 210° to 212°F for 30 min, rinsed, and dipped in hot water to hasten drying.

c. Dow 10 (Sealed Chrome Pickle Treatment)

Parts were given a chrome pickle treatment as described in 1.a. and rinsed in cold water. Immediately following this, the samples were boiled in the dichromate bath as described in 1.b., followed by cold water rinsing and a hot water dip to facilitate drying.

d. Dow 9 (Galvanic Anodize Treatment)

The magnesium samples were treated in the acid fluoride bath as in 1.b., then anodized for 10 min at 54°C using a current of 2 amp. The stainless steel beaker served as the cathode. Samples were then rinsed and dipped in hot water to hasten drying.

e. Dow 19 (Dilute Chromic Acid Treatment)

This coating was applied to magnesium by simple immersion of the samples in the solution, followed by cold water rinsing and oven drying, if necessary. Hot water rinsing was not allowed with this treatment.

2. Coatings Used on Aluminum

The aluminum samples were cleaned by degreasing with acetone (or methyl ethyl ketone), etching in an alkaline cleaner, dipping in 50-percent nitric acid to remove smut, then rinsing, and drying.

a. Sulfuric Acid Anodize Treatment

The aluminum samples to be anodized were made the anodes and immersed in a 15 percent by weight sulfuric acid solution contained in a lead tank which served as the cathode. Operating conditions were 10 to 25 amp/ft^2 (or 15 V) at a temperature of 60° to 80°F for 30 min. Samples were then sealed by boiling in water for 15 min.

b. Chromic Acid Anodize Treatment

The aluminum samples were made the anodes and immersed in a 5 to 10 percent by weight chromic acid solution contained in a steel tank which served as the cathode. Operating conditions were 40 V at a temperature of 95°F for 30 to 40 min. Finally, samples were rinsed in hot water at 150° to 180°F to facilitate drying.

c. Conversion Coating 1 (Alrok)

This coating was applied by simple immersion of the clean aluminum parts into the solution (alkali dichromate) for 10 to 20 min at 150° F. Sealing was then effected by dipping the sample in a boiling dilute dichromate solution.

d. Conversion Coating 2

Conversion coating 2 was applied by immersion of the samples into a proprietary solution for 3 min at 75° to 95° F. This was followed by rinsing and drying.

e. Conversion Coating 3

Conversion coating 3 was applied by immersion of samples into a proprietary solution for 2 to 3 min at room temperature, followed by rinsing with water and drying with cloth or in air.

3. Electroplated Coatings on Steel

Table III gives the operating conditions under which the various electroplated coatings were applied to AISI 1010 steel. Thickness of plating, anode material, and type of solution are also given.

TABLE III. OPERATING CONDITIONS FOR ELECTROPLATED COATINGS ON STEEL

Type Plating	Temperature (°C)	Current (amp/in^2)	Time (min)	Thickness of Plating (mils/side)	Anode Material	Type Solution
Cadmium	R. T.	0.05	30	0.5	Cadmium	Cyanide
Copper	65-72	0.1 -0.4	15-20	0.5	Copper	Cyanide
Zinc	25-30	0.1 -0.2	15-30	0.5	Zinc	Sulfate
Tin	35	0.2	15	0.5	Tin	Sulfate
Brass	43	0.03-0.15	15-30	0.5	Brass	Cyanide
Nickel	50-80	0.11-0.25	15-30	0.5	Nickel	Sulfate and Proprietary
Electroless Nickel	90	---	360	0.3	-----	Chloride
Chromium	70-80	4.0	15	0.5	Lead	Proprietary

Section IV. RESULTS

1. Coated Magnesium

Coatings studied for their effect on the galvanic activity of magnesium included Dow 19 (dilute chromic acid), Dow 9 (galvanic anodize), Dow 7 (dichromate treatment), Dow 1 (chrome pickle), Dow 10 (sealed chrome pickle), Dow 17 (anodize), and HAE.

The majority of the coatings gave an apparent lowering of generated potential. This lowering ranged from 12 to 87 mV and 4 to 88 mV for the AZ 31B magnesium and AZ 91B magnesium respectively. However, this lowering of potential due to the treatment was not observed in all cases. For example, chrome pickle treatment exhibited higher voltages with both AZ 31B and AZ 91B magnesium; 13 mV higher with the AZ 31B and 36 mV higher with AZ 91B. Dow 19 treatment resulted, in both cases, in the same voltage as that of the untreated magnesium. A voltage 9 mV higher than that of uncoated magnesium was observed with AZ 91B magnesium treated with dichromate solution. Another effect noted was that the HAE and Dow 17 treatment when applied at 60 to 65 V made the AZ 91B alloy more anodic than did the same treatment when applied at 85 to 90 V.

2. Coated Aluminum

Table IV gives a comparison of the effects of the various coatings on the galvanic activity of aluminum. These values are included in the practical galvanic series, but are listed in this chart because of their wide separation in the series. This was not necessary with the coated magnesium samples since they are all listed together in the series.

No set pattern of variance in potential can be established from the effects of the various coatings on the galvanic activity of aluminum. Although all values of the coated samples of 2014 T6 and 1100 H14 aluminum are higher than those of the uncoated samples, a set pattern is still not evident. The other four alloys tested gave both higher and lower values for the coated samples. The highest potential differences recorded resulted from conversion coating 1 and conversion coating 2, but this was not true for alloys tested. Conversion coating 3 gave lower potentials with all alloys than did any of the other treatments.

TABLE IV. EFFECTS OF VARIOUS COATINGS ON THE GALVANIC ACTIVITY OF ALUMINUM

(Values in Volts Compared to Copper 110)

Alloy	Untreated	Conversion Coating 1 (Alrok)	Conversion Coating 2	Chromic Anodize Treatment	Sulfuric Anodize Treatment	Conversion Coating 3
2014 T6	-0.452	-0.459	-0.462	-0.464	-0.460	-0.456
1100 H14	-0.464	-0.546	-0.520	-0.514	-0.494	-0.484
7075 T6	-0.470	-0.504	-0.524	-0.484	-0.472	-0.448
6061 T6	-0.493	-0.752	-0.580	-0.484	-0.480	-0.476
3003 H25	-0.496	-0.492	-0.596	-0.494	-0.504	-0.486
5052 H12	-0.545	-0.519	-0.571	-0.514	-0.524	-0.504

3. Electroplated Steel

The study of the effects of electroplated coatings on the galvanic activity of steel included cadmium, chromium, nickel, electroless nickel, copper, zinc, brass, and tin platings. Silver, gold, rhodium, platinum and palladium coatings were evaluated but were not included in the galvanic series because of their porosity. Rusting of the steel substrate was evident in several cases, indicating defective plating. The prime substrate was AISI 1010 steel, although several stainless steel alloys were used for cadmium and chromium platings.

Table V shows the galvanic relationships of these platings to copper 110. Also included in this table are the measured potential values of zinc, several brasses, cadmium, tin, and nickel metals. This allows a comparison of the galvanic response of the basic metal to the response when electroplated onto a different metal, e. g., comparing the galvanic response of zinc metal to that of zinc electroplated onto a steel substrate. Results showed that a metal gives essentially the same galvanic response as the same metal electroplated onto a steel substrate.

4. Effects of Varying Degrees of Strength Level on the Galvanic Properties of the Same Alloy

The data contained in Table VI were collected during the study of the effects of alloy strength level on the galvanic activity of several aluminum alloys. Measurements had been made previously on four of these alloys, but these measurements were repeated in order to give a good comparison of the seven alloys. Three types of surface treatments were used: chemical etch, steel wool, and sandpaper. Only one was used for the previous measurements.

From a close inspection of the table, it is evident that a set pattern cannot be established for the effect of strength level on the galvanic activity of aluminum. However, in several instances, the voltage varied considerably between the two strength level conditions studied. Alloys 2024 (etched), 1100 (sanded), and 7075 (all three surface treatments) showed the greatest variation due to strength level. No appreciable difference is noted between the etched and steel wool polished samples, but the sanded samples varied substantially in most cases from the other treatments. Aluminum indicated greater variations in galvanic activity, due to surface treatment, than other materials.

Stainless steel alloys 316, 321 and 347 were also used in the study of the effect of strength level variation on galvanic activity. However, no definite conclusions have been drawn from this investigation because of the difficulty

TABLE V. GALVANIC POTENTIAL MEASUREMENTS ON ELECTROPLATED SPECIMENS

-0.793	Zinc on AISI 1010 steel
-0.786	Zinc metal (AG40A)*
-0.557	Cadmium (brush plated) on AISI 1010 steel
-0.554	Cadmium (brush plated) on 202 stainless steel
-0.534	Cadmium on AISI 1010 steel
-0.532	Cadmium (brush plated) on 321 stainless steel
-0.519	Cadmium metal*
-0.333	Tin on AISI 1010 steel
-0.301	Chromium on nickel on copper on AISI 1010 steel
-0.281	Tin metal*
-0.250	Chromium on nickel on AISI 1010 steel
-0.209	Chromium on 202 stainless steel
-0.203	Chromium on AISI 1010 steel
-0.194	Chromium on 410 stainless steel
-0.192	Nickel on copper on AISI 1010 steel
-0.178	Chromium on electroless nickel on AISI 1010 steel
-0.169	Chromium on 430 stainless steel
-0.138	Electroless nickel on AISI 1010 steel
-0.064	Nickel metal*
-0.043	Yellow brass*
-0.041	Naval brass*
-0.032	Brass on AISI 1010 steel
-0.016	Low brass*
0.000	Copper 110 (Reference electrode)
+0.086	Nickel on AISI 1010 steel

* Placed in chart for comparison to plated samples.

TABLE VI. EFFECT OF STRENGTH LEVEL ON GALVANIC ACTIVITY * OF SEVERAL ALUMINUM ALLOYS
(Values in Volts Compared to Copper 110)

Surface Treatment	Alloy Designation and Hardness							
	1100		2014		2024		5052	
	H14	0	T6	0	T4	0	H12	0
Etched with Etchalume 14 akaline cleaner	-0.464* -0.501 V	-0.499	-0.452* -0.489	-0.444* -0.471	-0.370* -0.379	-0.472* -0.488	-0.545* -0.549	-0.534
Steel wool cleaned with "00" (very fine) steel wool	-0.501	-0.507	-0.474	-0.474	-0.514	-0.489	-0.539	-0.539
Sanded with 180 grit sandpaper	-0.634	-0.559	-0.496	-0.464	-0.486	-0.479	-0.566	-0.594

Surface Treatment	Alloy Designation and Hardness					
	5456		6061		7075 (Bare)	
	H343	0	T6	0	T6	0
Etched with Etchalume 14 akaline cleaner	-0.507* -0.544	-0.514	-0.493* -0.499	-0.454* -0.486	-0.470* -0.472	-0.604* -0.629
Steel wool cleaned with "00" (very fine) steel wool	-0.544	-0.544	-0.504	-0.478	-0.516	-0.621
Sanded with 180 grit sandpaper	-0.589	-0.594	-0.519	-0.499	-0.539	-0.613

*Voltage values recorded from first measurements (same as values shown in galvanic series developed thus far).

encountered in obtaining consistent results. The voltages developed by these samples were erratic and did not "level off" at a constant value. For this reason, none of these values were included in the galvanic series. The results of these studies are shown in Tables VII through X.

TABLE VII. EFFECT OF STRENGTH LEVEL ON GALVANIC ACTIVITY OF 300 SERIES STAINLESS STEELS

(Voltage Allowed to "Level Off" as Much as Was Possible, Solution not Stirred. Values in Volts Compared to Copper 110.)

Alloy	Hardness			
	Annealed	1/4 Hard	1/2 Hard	Full Hard
316 (Active)	+0.136	+0.147	+0.042	+0.103
321 (Active)	+0.037	+0.070	+0.049	+0.048
347 (Active)	+0.070	-0.036	-0.026	-0.008

TABLE VIII. EFFECT OF STRENGTH LEVEL ON GALVANIC ACTIVITY OF 300 SERIES STAINLESS STEELS

(Instantaneous Voltage Readings, not Allowed to "Level Off," Solution not Stirred. Values in Volts Compared to Copper 110.)

Alloy	Hardness			
	Annealed	1/4 Hard	1/2 Hard	Full Hard
316 (Active)	-0.003	-0.043	-0.032	-0.028
321 (Active)	-0.146	-0.140	-0.138	-0.164
347 (Active)	-0.166	-0.113	-0.118	-0.132

TABLE IX. EFFECT OF STRENGTH LEVEL ON GALVANIC ACTIVITY OF 300 SERIES STAINLESS STEELS

(Using Magnetic Stirrer at Half Speed, Voltage Allowed to "Level Off" as Much as Possible. Values in Volts Compared to Copper 110.)

Alloy	Hardness			
	Annealed	¼ Hard	½ Hard	Full Hard
316 (Active)	+0.032	+0.032	+0.032	+0.032
321 (Active)	+0.142	+0.142	+0.142	+0.122
347 (Active)	+0.069	-0.022	+0.004	-0.008

TABLE X. EFFECT OF STRENGTH LEVEL ON GALVANIC ACTIVITY OF 300 SERIES STAINLESS STEELS

(Using Magnetic Stirrer at Full Speed, Voltage Allowed to "Level Off" as Much as Possible. Values in Volts Compared to Copper 110.)

Alloy	Hardness			
	Annealed	¼ Hard	½ Hard	Full Hard
316 (Active)	-0.165	-0.198	-0.178	-0.153
321 (Active)	-0.078	-0.148	-0.078	-0.078
347 (Active)	-0.018	+0.012	+0.042	+0.042

The galvanic potential generated with titanium alloy 13 V-11 Cr-3 Al (heat treated: 1450°F for 30 min, water quenched, 900°F for 24 hr) was more noble than the potential generated with this same alloy in the annealed condition (heat treated: 1450°F for 30 min, air cooled). Alloy 6 Al-4 V (heat treated: 1700°F for 30 min, water quenched, 950°F for 4 hr) gave a less noble potential than did the same alloy in the annealed condition. These results are shown in Table XI.

TABLE XI. EFFECT OF STRENGTH LEVEL ON THE GALVANIC ACTIVITY OF 13 V-11 Cr-3 Al AND 6 Al-4 V TITANIUM ALLOYS

(Values in Volts Compared to Copper 110)

13 V-11 Cr-3 Al	Annealed (1450°F for 30 min, air cooled; Rockwell C hardness, 33.5)	0.436
13 V-11 Cr-3 Al	(Heat treated: 1450°F for 30 min, water quenched, 900°F for 24 hr; Rockwell C hardness, 45.5)	0.498
6 Al-4 V	Annealed (Rockwell C hardness, 36)	0.481
6 Al-4 V	(Heat treated: 1700°F for 15 min, water quenched, 950°F for 4 hr; Rockwell C hardness, 41.5)	0.455

5. Current Versus Weight-Loss Measurements

Theoretically, weight loss by galvanic corrosion is directly proportional to the amount of current per unit area flowing through a cell; however, some of the results given in Table XII do not follow this rule. There are several reasons for this peculiar behavior. Polarization effects probably account for most of this, especially in the case of aluminum. The buildup of corrosion products, both on the electrodes and in the solution, may result in anodic or cathodic polarization. The increase in alkalinity by these corrosion products may result in greater corrosion than would normally take place as a result of the current generated by the cell. Recorded current values may be questionable since readings were only taken intermittently and were not monitored continuously. Electrode size and length of corrosion time may also account for these results.

6. Effect of Conducting Solutions on Galvanic Relationships of Metals as Compared with Five-Percent Sodium Chloride Solution

Alloys representative of the various metal groups studied were tested in four different conducting solutions, including sodium chloride solution. Lowest voltage values were recorded with distilled water. Results from the other solutions were varied, depending on the alloy being tested. These results are shown in Table XIII.

TABLE XII. CURRENT-WEIGHT LOSS MEASUREMENTS

Weight Loss (g)		Current (mamp x 10^{-2})			
		Initial	After 19 hr	After 24 hr	After 115 hr
Magnesium	- 2.45218	1240	1810	1890	750
Zinc	- 0.55570	265	348	335	267
Cadmium	- 0.45330	300	220	188	110
Steel	- 0.34188	285	279	272	266
Lead	- 0.16170	290	102	102	46.0
Aluminum	- 0.09685	130	180	190	223
Copper	- 0.06955	16.3	24.0	24.0	31.0
Stainless steel	- 0.00870	5.0	5.9	5.3	8.2
Tungsten	- 0.00830	10.4	8.4	7.1	4.5
Nickel	- 0.00338	2.0	2.0	2.4	2.9
Molybdenum	- 0.00320	5.1	5.8	5.0	1.2
Niobium	- 0.00318	2.3	------	------	0.06
Tantalum	- 0.00070	1.1	------	------	0.04
Titanium			------	------	------

TABLE XIII. EFFECT OF SEVERAL CONDUCTING SOLUTIONS ON GALVANIC RELATIONSHIPS OF SEVERAL METALS COMPARED WITH FIVE-PERCENT SODIUM CHLORIDE SOLUTION

(Values in Volts Compared to Copper 110)

Everdur 655	Stainless Steel (Active) 347	Titanium 5-5-5	Aluminum 6061 T6	Magnesium AZ 91B
		Distilled H_2O		
+0.219	+0.020	+0.068	-0.264	-0.584
		5% Sulfuric Acid		
+0.181	-0.132	-0.082	-0.369	-1.194
		5% Sodium Hydroxide		
-0.270	-0.119	-0.394	-1.264	-1.064
		5% Sodium Chloride		
-0.007	+0.006	-0.104	-0.493	-1.064

Section V. FUTURE PLANS

Work now in progress is directed toward relating current density to corrosion, which, in conjunction with the open-circuit potentials, will allow a clearer understanding of galvanic relationships. This study will climax with the generation of a second galvanic series, which will relate changes in potential due to current flow. The current-weight loss studies have been modified to fit this plan. No actual weight losses will be involved but may be calculated from recorded data, if desired. The modifications resulted from discussion with Dr. H. H. Uhlig, Professor of Metallurgy at Massachusetts Institute of Technology.

Section VI. CONCLUSIONS

The practical galvanic (voltage) series is a valid guide or reference in the selection of compatible materials. It gives a clear indication of the tendency of metals and alloys to corrode, thus aiding in materials selection. The value of the series lies in its practical applications. Direct measurements were made between each specific metal or alloy and the copper standard; thus the potential between any two or more of the metals or alloys can be readily determined. Sodium chloride solution was used as the electrolyte, simulating a severe, practical corrosion environment.

Based upon the recorded galvanic potentials, several of the coatings and platings that were applied to magnesium, aluminum, and steel show high potential for enhancing galvanic corrosion protection. Dow 17 applied at 90 V and HAE applied at 85 V rendered the magnesium most noble; i. e., less potential was developed between these two coatings and the reference electrode than between the reference electrode and the other coatings and untreated magnesium samples. The most effective coatings on aluminum, indicated by potentials lower than those for the untreated samples, were: conversion coating 3, chromic anodize, conversion coating 1 (Alrok) and sulfuric anodize on 5052 aluminum; conversion coating 3 on 7075 aluminum; conversion coating 3, sulfuric anodize, and chromic anodize on 6061 aluminum; and conversion coating 3 on 3003 aluminum. Of the metallic coatings studied for steel, electroplated nickel showed the lowest degree of galvanic activity.

In some metals, potential differences exist between different strength levels of the same alloy, and this difference should be given consideration when selecting compatible materials. The direction of the variation in potential depends on the alloy.

Galvanic potentials vary with different conducting solutions; this should be considered when corrosion problems exist, or when selecting a couple for a particular application.

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13. ABSTRACT

The prime objective of this work was the development of a practical galvanic series of metals and alloys to aid in the selection of compatible materials for missile systems. This was accomplished by studying the various metals and alloys coupled with a 110 copper alloy standard as the reference electrode, and monitoring potentials with a self-balancing potentiometric-type recorder. Each couple was partially immersed in a 5-percent salt (sodium chloride) solution.

The effects of coatings and platings on the galvanic relationships existing between metals and alloys were also studied. Coatings and platings were studied with aluminum, magnesium, and steel as the substrates.

Other studies included the effects on galvanic activity when strength levels within the same alloy were varied, current versus weight-loss measurements, and the comparison of other conducting solutions with the 5-percent sodium chloride solution used in the generation of this series.

The study of the effect of strength level on galvanic activity showed that galvanic potentials can exist between specimens of the same alloy at different strength levels. Also, the galvanic potential varies with different conducting solutions.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Galvanic series of metals						
Galvanic series of alloys						
110 copper alloy						
Metal coating, platings effects on galvanic relationships						
Galvanic potential						