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In the past, there have been a number of material failures in the Army's equipment. Many of these failures have been caused by some form of corrosion. One type of corrosion involved is galvanic corrosion. This happens when dissimilar metals come in contact in an electrolyte. The electrolyte could be a marine or even a humid environment. When this occurs, the less noble metal (anode) corrodes in order to protect the more noble metal (cathode). By exposing multi-metallic galvanic couples of high strength materials in aggressive environments, the number of failures in bridges and other military equipment could be reduced. [illegible]

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22b. TELEPHONE (Include Area Code)	703-664-1127
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PREFACE

In the past, there have been a number of material failures in the Army's equipment. Many of these failures have been caused by some form of corrosion. One type of corrosion involved is *galvanic* corrosion, which occurs when dissimilar metals come in contact in an electrolyte. The electrolyte could be a marine or a humid environment. When this occurs, the less noble metal (*anode*) corrodes in order to protect the more noble metal (*cathode*). By exposing multi-metallic galvanic couples of high strength materials in aggressive environments, the number of failures in bridges and other military equipment can be reduced. This technical report presents research performed for the following dual purpose:

- To determine the effect of multi-metallic galvanic reactions on the mechanical properties of high strength materials in aggressive environments, and

- To determine the effect of placing a finite space between the three dissimilar metals as opposed to placing them in intimate contact.

The galvanic couples are made from various materials being considered for Army equipment. They are first exposed to an aggressive environment, and then corrosion rates and mechanical properties of each material are determined. From this data, it can be decided if the corrosion that develops is cosmetic, or if it has an effect on the mechanical properties of the material.

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FIGURES

SECTION I. TEST DESCRIPTION

This section presents American Society for Testing and Materials (ASTM) standards, equipment used, test procedure, and test environment for this galvanic corrosion research.

ASTM STANDARDS

ASTM proposed standard Gxx, *Test Method for Galvanic Corrosion in the Atmosphere*

ASTM E8, *Tension Testing of Metallic Materials*

ASTM G1, *Preparing, Cleaning, and Evaluating Corrosion Testing Specimens*

ASTM G31, *Laboratory Immersion Corrosion Testing of Metals*

ASTM G44, *Alternate Immersion Stress Corrosion Testing in 3.5% Sodium Chloride Solution*

ASTM G82, *Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance*

EQUIPMENT USED

Tensilkut, floor model, Sieburg International Incorporated
Cut off Wheel, Isocut Model, Buehler Limited
Immersion Bath, fabricated by Blair Incorporated
Scales, Model #B3000D, Ohaus
Baldwin Tensile Tester, Model #472470, Southwark Division, Tate-Emery Company
Calipers, Model #120, Starrett Company
Extensometer, Model #P3M, Satec Incorporated
Saw, Abrasimet Model, Buehler Limited

PROCEDURE

The galvanic testing was performed on materials that were considered for use in equipment being currently developed (Figure 1). The material known as 6061-T6 was combined with other pairs of metals, resulting in eleven different combinations (Figure 2). The procedure used was adapted from an ASTM proposed standard Gxx, *Test Method for Galvanic Corrosion in the Atmosphere*, and is as follows:

1. A 4" x 6" panel of one material (6061-T6) was degreased and weighed.

2. The panel was then sandwiched between two 1" x 3" panels of two different materials, which were also degreased and weighed (Figure 3). The samples were wet assembled using MIL-S-81733 polysulfide sealant to avoid any galvanic reaction between the stainless steel bolts and the panels.

Aluminum Alloys
- 5052-H32
- 6061-T6
- 7075-T73

Carbon Steels
- 1045
- C1117 Cadmium Plated

Stainless Steels
- 304
- 430

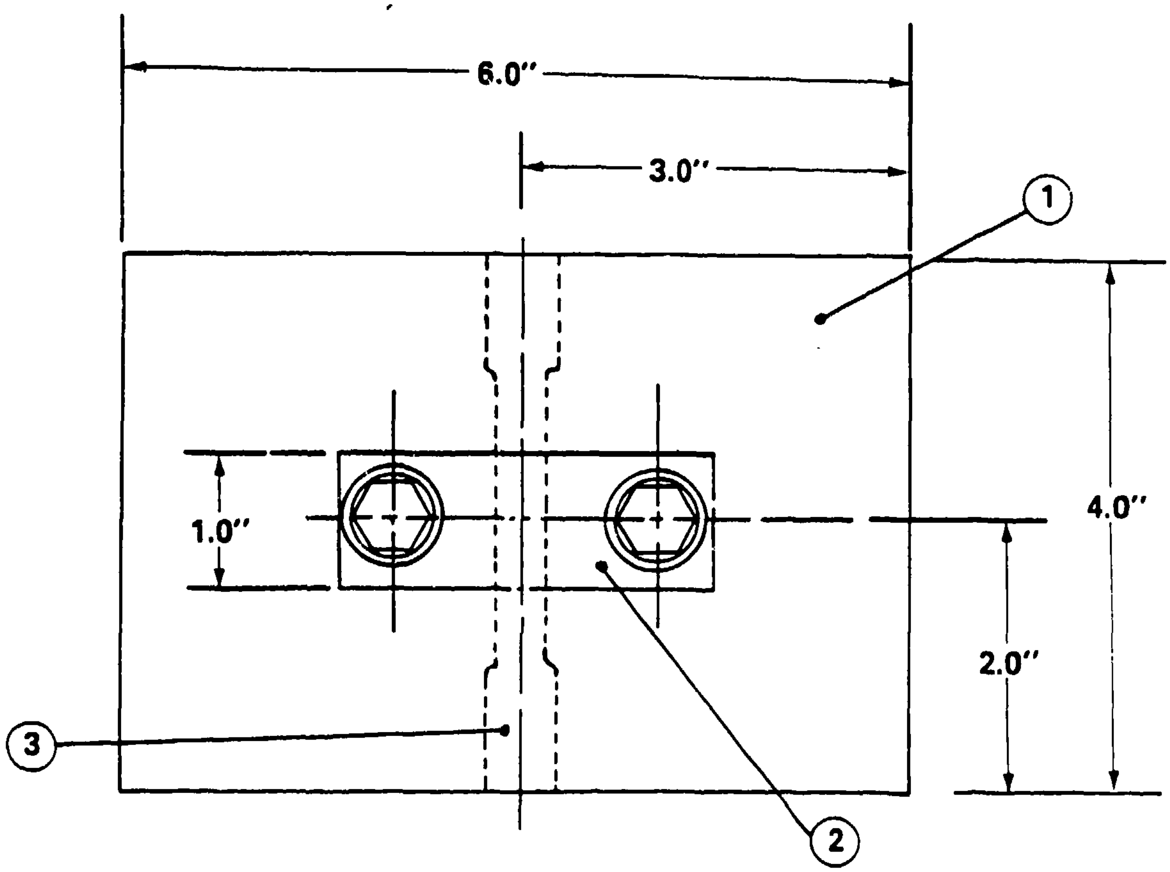
Brass
- 360 1/2 hard

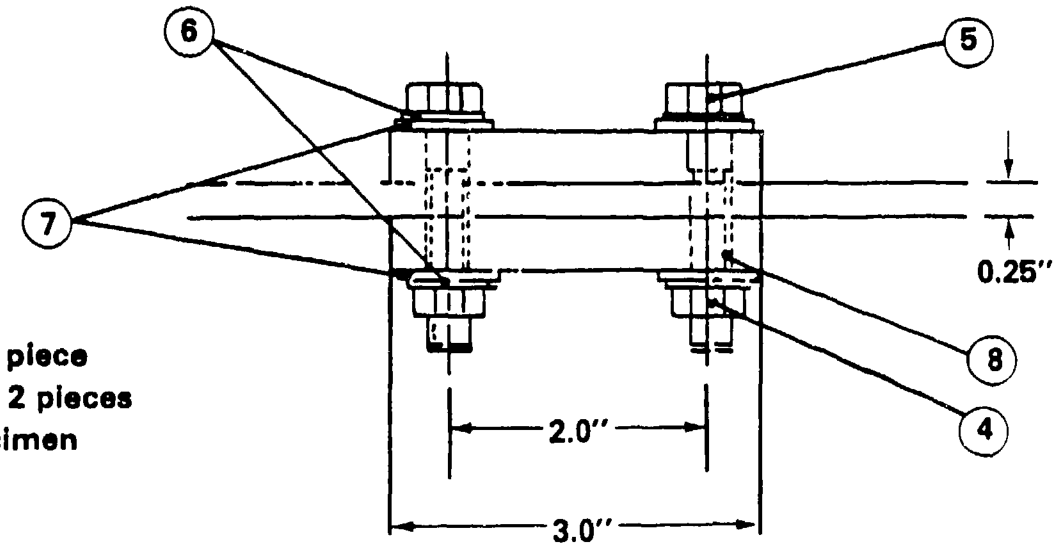
Composites
- Graphite Epoxy
- Graphite Epoxy coated with Fiberglass

Figure 1. Materials for Testing

	ANODE 4" x 6" PANEL	CATHODE A 1" x 3" PANEL	CATHODE B 1" x 3" PANEL
1	6061-T6	6061-T6	6061-T6
2	6061-T6	430 SS	5052-H32
3	6061-T6	1045	360 Br
4	6061-T6	360 Br	C1117
5	6061-T6	430 SS	C1117
6	6061-T6	304 SS	C1117
7	6061-T6	7075-T73	430 SS
8	6061-T6	1045	1045
9	6061-T6	1045	304 SS
10	6061-T6	1045	Composite
11	6061-T6	Comp-Fiberglass	Composite

Figure 2. Galvanic Couples Tested





KEY:
1. anodic panel - 1 piece
2. cathodic panel - 2 pieces
3. tensile test specimen
4. nut - 2 pieces
5. bolt - 2 pieces
6. washers - 4 pieces
7. insulating washers - 4 pieces
8. insulating sleeve - 2 pieces

Figure 3. Specimen for Galvanic Corrosion Testing

3. Three samples of each combination were then placed in the test environment for a given length of time.

4. Another set of the same combinations were assembled, this time placing a 0.065" thick teflon spacer between each of the metals.

5. After environmental testing of the panels was completed, the panels were photographed, disassembled, and rephotographed in the area under the small panels.

6. The panels were chemically cleaned according to ASTM G1, *Preparing, Cleaning, and Evaluating Corrosion Test Specimens*, and then reweighed. The corrosion rate of each panel was found by using the equation:

$$\text{Corrosion Rate} = (K*W)/(A*T*D)$$

where:

K = constant ($3.45*10^6$ for mpy)
T = time of exposure (hours)
A = area (cm^2)
W = mass loss (grams)
D = density (g/cm^3)

7. Any change in the mechanical properties was then determined. A subsize 1/4" wide tensile sample with a 1" gage length was cut out of the center of the large panel and tested according to ASTM E8, *Tension Testing of Metallic Materials*. The properties measured were ultimate strength, yield strength, and percent elongation.

8. These properties were compared to the baseline to determine any deviation caused by the galvanic reaction between the materials in the given environment.

ENVIRONMENT

The environment chosen for this experiment was selected with the intent of recreating actual conditions that these materials may be exposed to when used in military equipment. The test environment was an immersion bath.

In this test, the panels were exposed to a 3.5% Sodium Chloride (NaCl) solution, acidified to a pH of 4.1. This pH was chosen to simulate an acid rain environment and the 3.5% NaCl was the most corrosive marine solution. Panels were cycled in and out of this bath—10 minutes soaking and 50 minutes air drying—for 75 days. The immersion test was run at 35°F.

SECTION II. TEST OBSERVATIONS

EFFECTS OF SPACERS

When the set of galvanic couples containing the spacer in between the panels was compared to the set without spacers, the greatest effect was seen in the corrosion rates. Over half of the couples with spacers had a higher corrosion rate than those without the spacer in this acidic marine environment. This was especially true when one of the metals coupled to the 6061-T6 was a plain carbon steel (for example, 1045). The couples containing stainless steel or graphite carbon epoxy with the 6061-T6 were the least affected and showed no increase in corrosion rates. The corrosion rates for 6061-T6 (anode) are shown in Figure 4 and the Appendix. The corrosion rates for the cathodes are shown in Figure 5 and also in the Appendix. Further studies are needed to determine the reason for these differences.

These results were also reflected in the change in elongation of the 6061-T6 when the samples were mechanically tested. Those combinations having high corrosion rates with the spacers showed a loss of elongation (see Figure 6 and the Appendix). This loss of elongation indicated that the material was becoming brittle and could result in catastrophic failure. This included the couples with 1045 as well as the 6061-T6 control. The samples containing the stainless steels, 304 and 430, had higher or equal percent elongation of the 6061-T6 with the spacer than without.

The spacers between the panels had no significant effect on the yield strength (43.1 ksi) or ultimate strength (47.1 ksi) of the 6061-T6 (see Appendix). These properties remained stable for the 6061-T6 whether or not the couples contained spacers.

GALVANIC CORROSION

The multi-metallic galvanic couples presented different corrosion trends than the bi-metallic couples. When 1045 was one of the cathodes in combination with any of the other materials, it caused the highest corrosion rates of the aluminum. This was contrary to the typical Galvanic Series in Seawater.* According to the series, the graphite-epoxy composites should have had the greatest effect on the corrosion rate of 6061-T6. Instead, the corrosion rate of the aluminum with the composite was only half of or less than the corrosion rate when 6061-T6 was in any of the combinations containing 1045. In the case of the 6061-T6 coupled with 1045 and the composite, the corrosion rate of the 1045 panel more than doubled compared to the other couples containing 6061-T6, 1045, and another metal. Although the 1045 was separated from the composite by the 6061-T6, it acted as an anode, more so than the aluminum. The 430 stainless steel coupled with the C1117 or 7075-T73 showed the smallest deviation from the control (6061-T6/6061-T6).

The elongation of the 6061-T6 during mechanical testing correlated with the corrosion rates. Those couples with high corrosion rates (those containing 1045) showed a decrease from the baseline of the percent elongation. The 360 Brass/C1117 coupled to 6061-T6 also had a noticeable decrease in percent elongation. The remainder of the couples did not exhibit any significant loss of elongation.

Neither the yield strength nor the ultimate strength was affected by the galvanic couple in this environment. There were no significant losses of strength for any of the couples. Of those that suffered the high corrosion rates, the loss of strength was only a few percent.

* *Failure Analysis & Prevention*, Metals Handbook Vol. 10, ASTM 1975, p. 182.

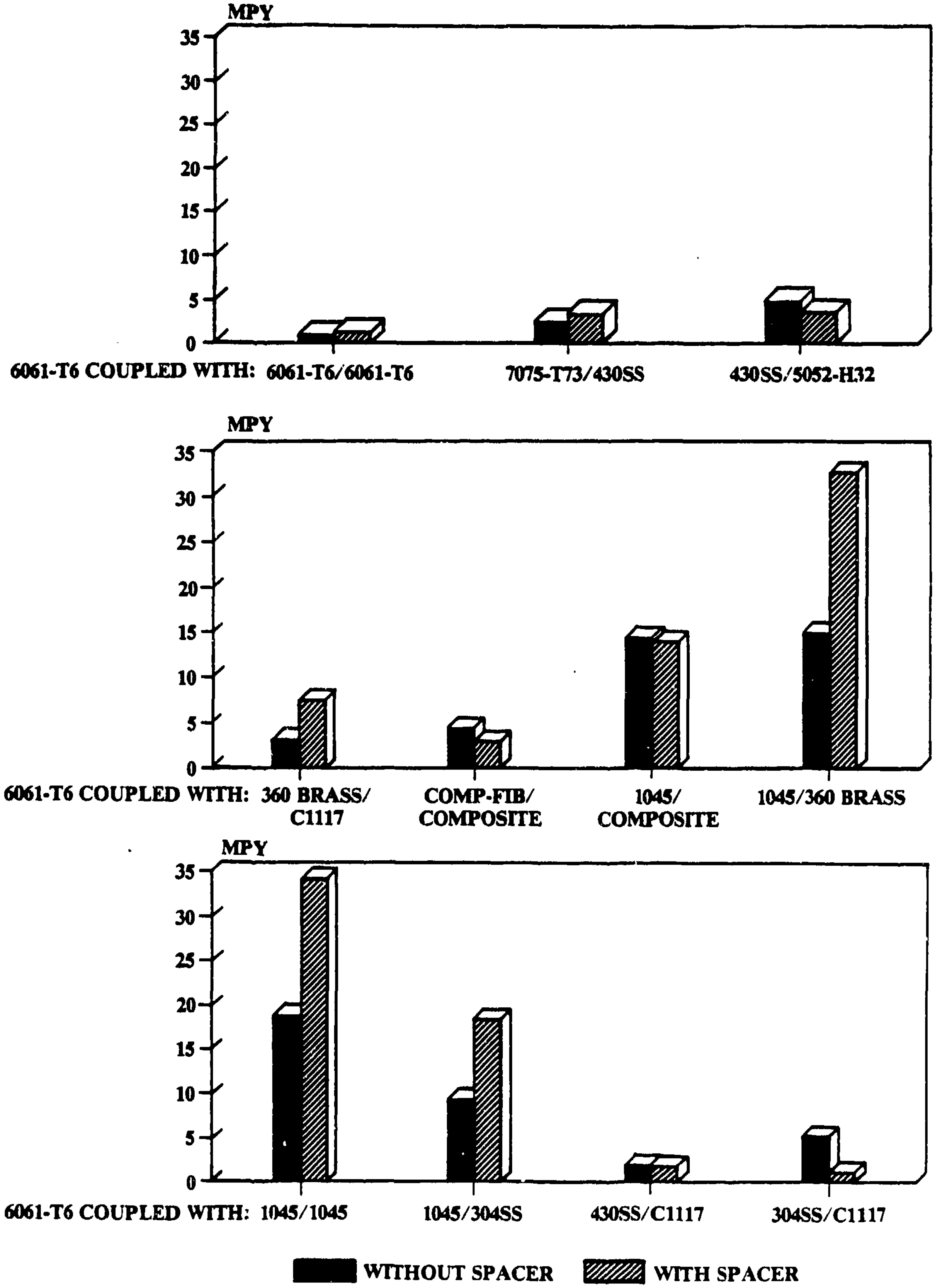


Figure 4. Corrosion Rates of 6061-T6

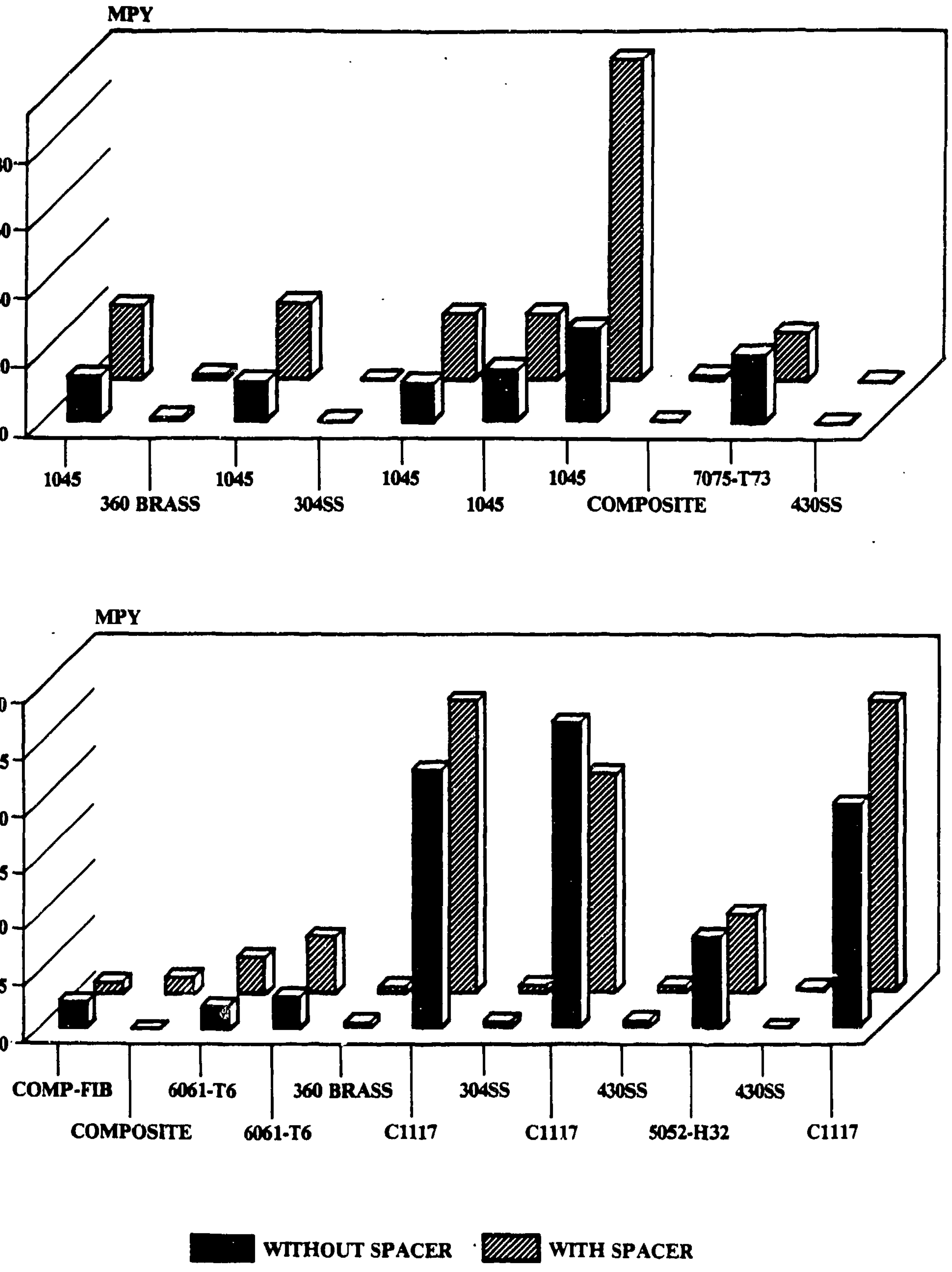


Figure 5. Corrosion Rates of Cathodes

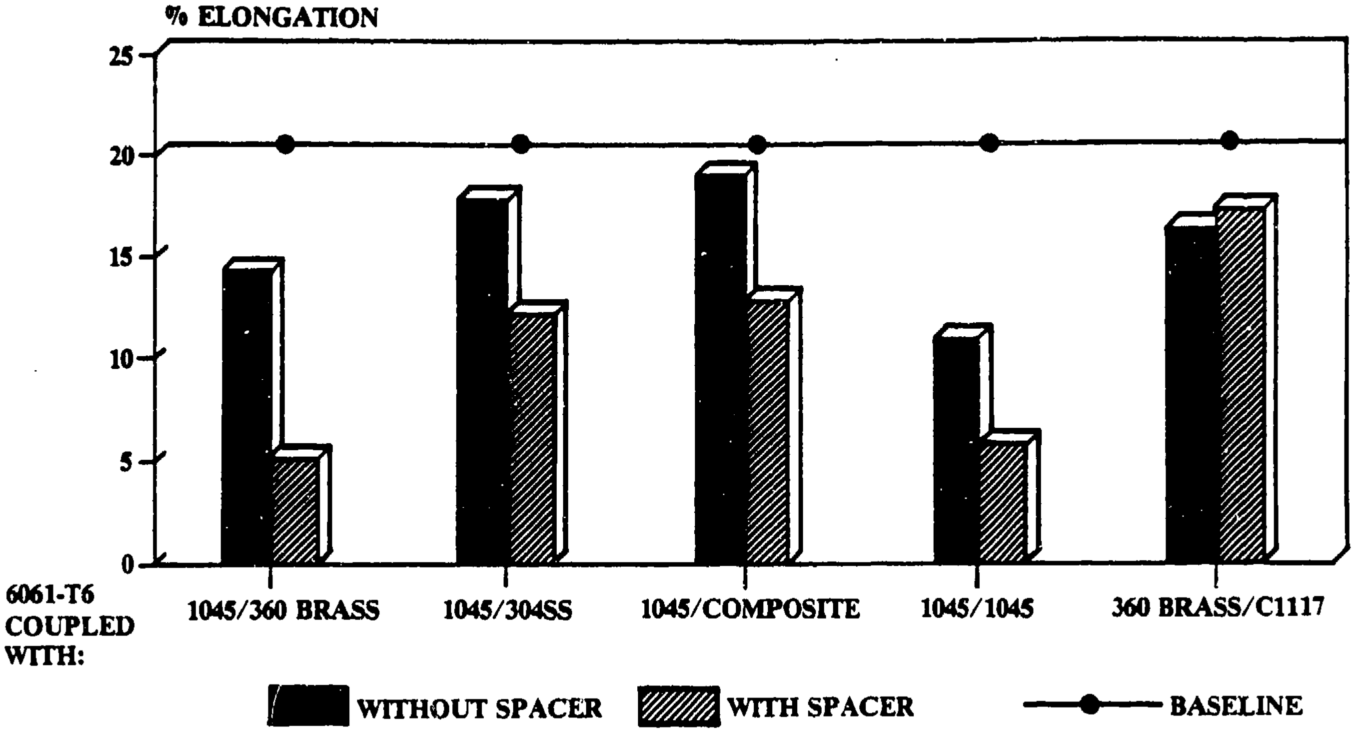


Figure 6. Elongation of 6061-T6

SECTION III. TEST CONCLUSIONS

Placing a small space between the panels, thus avoiding intimate contact, had an adverse effect on the corrosion rate which in turn affected the elongation of most material couples.

The couples containing steels and brass were the most affected by the spacers, while those containing stainless steel and composite were the least affected.

The composite had a larger effect on the corrosion rate of the small 1045 panel than on the 6061-T6 panel that was in direct contact with it. Whether this was due to the temperature or pH of the solution, the size of the panels or the nature of this composite cannot be determined at this time.

Electrochemical potential tests are needed to explain some of the galvanic reactions that occurred in this 35°F environment.

APPENDIX
CORROSION RATES AND MECHANICAL PROPERTIES

CORROSION RATES OF IMMERSION BATH 35°F FOR 75 DAYS

			WITHOUT SPACER AVG MPY			WITH SPACER AVG MPY		
ANODE	CATHODE A	CATHODE B	ANODE	CATHODE A	CATHODE B	ANODE	CATHODE A	CATHODE B
6061-T6	1045	360 Brass	14.74	12.99	1.19	32.45	21.37	1.37
6061-T6	1045	304 SS	9.43	11.64	0.39	18.60	22.57	0.00
6061-T6	Comp-Fib	Composite	4.38	2.44	0.00	2.90	0.98	1.47
6061-T6	6061-T6	6061-T6	0.98	2.06	2.96	1.34	3.27	5.02
6061-T6	1045	1045	19.02	11.40	15.54	34.34	19.30	19.16
6061-T6	1045	Composite	14.20	27.37	0.00	13.85	94.59	1.07
6061-T6	360 Brass	C1117	3.34	0.56	23.04	7.65	0.64	25.87
6061T6	304 SS	C1117	5.30	0.58	27.11	1.20	0.58	19.47
6061-T6	430 SS	5052-H32	4.89	0.75	8.07	3.59	0.59	6.96
6061-T6	430 SS	C1117	2.01	0.00	19.83	1.86	0.30	25.79
6061-T6	7075-T73	430 SS	2.45	19.58	0.10	3.43	14.11	0.40

TENSILE DATA OF 6061-T6
IMMERSION BATH

METAL CATHODES	BASELINE AVG	BASELINE STANDARD DEVIATION	WITHOUT SPACER GALVANIC AVG	WITHOUT SPACER GALVANIC STANDARD DEVIATION	WITH SPACER GALVANIC AVG	WITH SPACER GALVANIC STANDARD DEVIATION
% ELONGATION						
430SS/C1117	20.00	0.90	19.83	0.73	19.13	0.82
1045/304SS	20.00	0.90	17.88	1.47	12.25	1.15
7075-T73/430SS	20.00	0.90	19.37	2.04	20.10	1.47
1045/Comp	20.00	0.90	19.13	2.30	12.80	0.30
6061-T6/6061-T6	20.00	0.90	21.07	1.05	20.18	0.61
Comp-Fib/Comp	20.00	0.90	20.08	0.97	19.42	0.52
1045/360Brass	20.00	0.90	14.40	2.40	5.14	2.04
1045/1045	20.00	0.90	10.85	3.63	5.80	1.67
430SS/0502-H32	20.00	0.90	19.78	1.80	21.80	1.30
360Brass/C1117	20.00	0.90	16.36	0.82	17.30	2.12
304SS/C1117	20.00	0.90	20.04	1.64	22.68	2.21
ULTIMATE STRENGTH (ksi)						
430SS/C1117	47.1	0.5	45.4	0.4	45.3	0.2
1045/304SS	47.1	0.5	43.9	0.6	44.5	0.9
7075-T73/430SS	47.1	0.5	44.9	1.6	44.9	0.7
1045/Comp	47.1	0.5	44.8	1.5	44.6	0.1
6061-T6/6061-T6	47.1	0.5	45.4	0.4	44.4	0.4
Comp-Fib/Comp	47.1	0.5	46.1	0.8	45.3	1.1
1045/360Brass	47.1	0.5	42.8	1.3	43.2	1.3
1045/1045	47.1	0.5	42.1	1.4	43.0	1.2
430SS/0502-H32	47.1	0.5	44.9	1.5	45.2	1.2
360Brass/C1117	47.1	0.5	44.3	1.0	44.8	1.5
304SS/C1117	47.1	0.5	45.4	0.3	44.9	0.7
YIELD STRENGTH (ksi)						
430SS/C1117	43.1	0.3	42.1	0.5	42.2	0.4
1045/304SS	43.1	0.3	41.1	0.8	41.2	1.0
7075-T73/430SS	43.1	0.3	43.6	1.8	42.1	0.7
1045/Comp	43.1	0.3	41.7	1.2	41.7	0.2
6061-T6/6061-T6	43.1	0.3	42.5	0.8	41.8	0.4
Comp-Fib/Comp	43.1	0.3	43.3	0.9	42.3	1.3
1045/360Brass	43.1	0.3	42.8	1.8	40.4	1.3
1045/1045	43.1	0.3	40.1	0.6	40.7	1.2
430SS/0502-H32	43.1	0.3	42.3	1.4	42.4	1.0
360Brass/C1117	43.1	0.3	41.6	1.4	41.6	1.5
340SS/C1117	43.1	0.3	42.6	0.2	42.1	0.6

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