FINAL REPORT ON

Galvanic Corrosion Research

Date of this Report, 15 September 1953 • Period Covered, 15 September 1951 to 14 September 1953

Contractor, Western Electric Company, Incorporated
Contract No. DA-36-039 sc-15419 with
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On behalf of Western Electric Company Incorporated

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GALVANIC CORROSION
IN
COMMUNICATION EQUIPMENTS

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ABSTRACT

The galvanic couple corrosion which is produced when two metals of different electrochemical potential are in electrical contact with each other and bridged by a film of conducting electrolytic liquid, has been studied by three methods. The potentials of the metals, the corrosion current between specimens and the weight loss have been determined under a number of conditions. The corrosion current method, which has been developed in this study, appears to be a valuable tool in making laboratory evaluations of comparative probable corrosion behavior. Measurements of the contact resistance between several combinations of dissimilar metals, indicates that galvanic couple corrosion does not add significantly to the resistance produced by the individual corrosion characteristics of the metals. A galvanic series is proposed, based on corrosion behavior, and recommendations are made as to the conditions under which various couple combinations may be employed in Signal Corps equipment.

PURPOSE AND SCOPE

The purpose of this investigation was to obtain basic information leading to a better understanding of bimetallic galvanic behavior, in so far as it may concern the proper functioning of communications and related equipment. It was felt that such a knowledge of the galvanic corrosion processes was highly desirable for the purpose of establishing more realistic specification requirements than are currently extant.

Whenever a more noble metal is electrically connected to a less noble metal in the presence of a conductive electrolyte galvanic corrosion of the more electronegative element will ensue. The degree and amount of galvanic corrosion will be governed largely by the potential difference existing between the electrodes and by polarization effects which will ensue during the course of the electrolysis. It has long been recognized that little reliance can be placed on static, open circuit potential measurements, usually in sodium chloride solutions approximately the concentration of sea water. It was felt that a more realistic approach would be to study the galvanic effects as they occur when couples are exposed to environments approximating actual service conditions.

Communication and associated equipment may be stored, transported and exposed in extremes of world-wide environmental conditions. It was therefore deemed advisable and necessary to classify the environments with respect to the expected ultimate usage of the equipment.

For the purpose of this investigation, the following major types of exposure were considered:

a. Unprotected direct exposure to the elements.

b. Exposure under cover, but not well housed, such as in louvered and roofed structures or in containers which are directly exposed to the elements.

c. Exposure under cover, well protected from the elements and generally under well-housed conditions.

While it is recognized that there are cases intermediate to these conditions, it was felt that they would cover the largest part of possible contingencies.

In addition, galvanic reactions have been studied in the laboratory under conditions of temperature and humidity designated to simulate certain service exposures. A laboratory method for evaluating galvanic currents has also been studied, making use of the "zero resistance" principle.

The galvanic effects obtained under these various environmental conditions were evaluated primarily by means of weight changes. The effect of galvanic corrosion on contact resistance and on appearance of equipment due to build-up of corrosion products were also evaluated. A couple arrangement consisting of a threaded bolt and wire assembly was employed for the determination of weight losses. This arrangement is described in detail in Report No. 1 and is shown in Figure 2 in that report.

GENERAL AND THEORETICAL

The fundamental theory of electrode potentials, the influence of polarization on the corrosion currents of galvanic couples, and the nature of the medium to which the couples are exposed has been discussed in considerable detail in earlier reports. It was shown that the magnitude of the potential difference between two metallic electrodes in a corrosive medium was a measure of the tendency for the "base" metal to be galvanically corroded, but that the actual corrosion was controlled by factors that influenced the flow of current between the two members of the couple. These factors when combined are said to comprise "polarization" and "resistance".

This study has encompassed three major phases; weight loss of specimens exposed to the atmosphere, electrode potentials in several typical media, and the measurement of galvanic corrosion currents under an arbitrary set of conditions. As a minor phase, the influence of galvanic couple corrosion on the contact resistance of two dissimilar metals, has been studied. These studies were conducted in parallel so that the results of any one did not have its proper effect upon the conduct of the others. Were some phases of this work to be repeated or extended these effects should be considered, and those cases where the range of values was large, should be studied statistically.

From the results of this work it appears that three classifications of service exposure should be used as follows:

Exposed - This is a bold exposure to the weather such as that experienced by unhoused radar antennas. It is the worst general condition, and means exposure to a damp, marine atmosphere, where accumulations of sea spray are kept moist by repeated condensation or dew, and by the impingment of fog or mist, but without the beneficial washing action of frequent rains. An exposure in an industrial atmosphere where contamination is heavy may approach this condition in severity but generally is more specific in its action due to the acid sulphate character of the contamination. Exposure to the tropical jungle atmosphere is less severe due to the lack of contamination by strong electrolytic material such as sea salt. It is expected that all Signal Corps equipment which is designed for bold exposure to the weather will at some time encounter these conditions. Only in the case of special fixed installations exposed in the interior of temperate urban areas, should the environment be considered less severe.

Sheltered - A milder exposure than above in which the exposed surfaces are protected from the direct action of the weather or wind driven sea spray. Such an exposure would be inside louvered housings, under sheds, the exteriors of equipment in vehicles, aircraft, and boats, or small portable items which are normally stored when not in use.

Housed - Apparatus, equipment and materials in buildings and the interior surfaces of equipment in sheltered locations. Such an exposure would include breathing or ventilation of unsealed equipment in a tropical climate where high humidity and condensation could be expected. However the surfaces under consideration would not be contaminated by significant amounts of sea spray, coral dust, or other corrosives.

Exposure Sites and Conditions

Point Reyes

This test site is located on the wind swept Pacific beach about thirty-five miles north of San Francisco, Cal.,[1] and is characterized by westerly winds from the ocean, frequent fogs and nightly dews, with little rain to remove the accumulation of sea spray. The test racks are located about two thousand feet from the mean water line and at an elevation of about seventy-five feet. It is at such a site that one might expect to find fire control or radar equipment. The boldly exposed specimens were mounted in an approximate horizontal position on these racks. The sheltered[2] specimens were placed in the louvered and roofed shelter shown in Figures II and III of Report No. 5, which is essentially a Stevenson screen, a box used for housing meteorological instruments, which allows free circulation of external air.

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1. This is the Point Reyes site of the American Society for Testing Materials.
2. The louvered shelters are shown as installed at Point Reyes and New York in Figure 9.

New York

This test site is on the eleventh floor roof of the Bell Telephone Laboratories building at 463 West Street in Manhattan. It is the same location as that formerly used by the American Society for Testing Materials. Contamination from industrial plants, the flue gases from buildings, boats on the North River, and power plants make this site a rather severe industrial location. There is a very slight contamination from wind driven sea salt from the Atlantic Ocean some thirteen miles away. Specimens were boldly exposed in a horizontal position and in the louvered shelter described above.

Panama

The Panama site is the jungle area in back of Fort Sherman on the Atlantic side of the Canal Zone. This is a relatively severe tropical exposure, and is characterized by nightly condensation, high humidity and frequent heavy tropical rains. The boldly exposed specimens were mounted horizontally on racks in a clearing surrounded by jungle. The sheltered specimens were placed in a louvered and roofed shelter as described above. This is the test site operated by the Navy and is the former site used by Army Ordnance for testing fire control equipment, components and materials.

Cycling Humidity Room

The cycling humidity room used in these studies, cycles between 80°F and 120°F at a nominal relative humidity of 95%. The actual relative humidity varies some what with the steps in the cycle, dropping as low as 85% during some part of the lowering temperature period, and approaching 100% during the period of rising temperature. Variations from the mean or desired relative humidity during the rising or falling part of the cycle have little meaning as the heat capacity of the specimens determines whether they are covered with condensation or become dry. Copious condensation is produced on most materials during the rising temperature portion of the cycle. In the actual operation of the room, the dry bulb temperature begins to rise from 80°F at 12:30 A.M. and reaches 120°F by 2:00 A.M. This temperature is maintained until 6:30 A.M. when a temperature reduction is initiated. The temperature drops rather uniformly until 80°F is reached at 9:30 A.M. where it is maintained until 12:30 P.M. This cycle is repeated each 12 hour period. The specimens were mounted horizontally in this room on shelves and were protected from drips.

The data indicate that Point Reyes unsheltered conditions correspond to the classification of exposure conditions defined as Exposed. The conditions in Panama and New York were considerably less severe. The corrosion on the Sheltered specimens in all locations was of a lower order of magnitude from that on specimens which were Exposed. The cycling humidity room gave a comparable but smaller rate of corrosion than the Sheltered condition and can be considered as an accelerated version of Housed.

A recent paper by Clarke and Bradshaw[3] of the British Ministry of Supply describes tests that confirm the results obtained in the present study. Specimens of zinc, aluminum, cadmium, tin and silver, in the form of electroplate and solid metal, with and without surface treatments were exposed in louvered boxes at several marine exposure sites. They report on the general corrosion, the relation between thickness of coating and protection, and the effect of bimetallic couples. It is their conclusion that in a sheltered exposure, the presence of dissimilar-metal contacts produces little or no increased corrosion of the less electropositive metal at the contacts. They also measured the change in contact resistance during the exposure and found it to be unrelated to galvanic couple corrosion.

Another recent publication of interest is the Electromotive Series for Metals and Alloys.[4] This table is somewhat misleading in that the potentials are for the most part the idealized thermodynamical values discussed in Report No. 6. For example the potential of aluminum is given as -1.3 volts whereas actual measurements in dilute chloride or sulphate solutions give values in the range of -0.55 to -0.75 volts. Chromium is misplaced, from the practical point of view, because the usual measured potential appears amidst the potentials of various

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3. Tests of the Protective Value of Metallic Coatings Under Sheltered Conditions (Marine Atmosphere), S.G.Clarke and W.N.Bradshaw, J.Applied Chemistry, 3, April 1953 (Brit.).
4. Metal Finishing, V.50, Page 89, April 1952.

stainless steels when they are in a passive condition. Again the potentials of silver and copper appear to be more noble than usual measurements indicate. Galvanic corrosion current measurements indicate the potentials of zinc and aluminum to be practically identical, with zinc sometimes anodic and at other times cathodic. This is at variance with the potential difference given in the above referenced publication which amounts to 0.57v. The above examples illustrate how unreliable this approach can be, as it does not employ realistic potentials. Furthermore, it does not take into account the flow of the galvanic corrosion current.

FACTUAL DATA

Materials

The materials used in the three principal sections of this study - weight loss, corrosion current, and contact resistance - are given below. Analyses of the materials were not made as it was felt that slight variations in composition from the nominal would not produce a significant effect on the galvanic couple corrosion.

Designation	Nominal Composition	Where Used
Al	2S Aluminum (99.5 + Al)	All studies.
Mg	FS 1 Magnesium Alloy (3% Al; 1% Zn; Bal Mg)	All studies.
430	430 Stainless Steel (16% Cr; 0.12 C; Bal Fe)	All studies.
302	302 Stainless Steel (18% Cr; 9% Ni; 1.25% Mn, .08% - .20% C; Bal Fe)	All studies.
Monel or M	Commercial Monel Metal (67% Ni; 30% Cu; 1.4% Fe; 1% Mn; .1% Si; .15% C)	All studies
Brass or B	Rod, (60-63 Cu; 2.5-3.7 Pb; Bal Zn)	Bolts and Contact Res. Studies.
	Sheet, (59-64.5 Cu; 1.3-2.3 Pb; Bal Zn)	Corrosion currents.
	Wire (68-71 Cu; .07 max Pb; Bal Zn)	Wire in wt. loss.
Cu	Commercial Electrolytic copper, (99.9% Cu)	Wt. loss and corrosion currents.
	Copper electroplate .001" thick (On steel drill rod)	Contact resistance studies.
Cd	Commercial Cadmium (99.9% Cd)	Wire in wt. loss studies.
	Cadmium electroplate .001" thick (On steel)	All other.
Zn	Commercial Zinc (99.95% Zn)	Wire in wt. loss studies.
	Zinc electroplate .001" thick, (On steel)	All other.
Ni	Commercial Nickel (99.4% Ni)	Bolts and wire in wt. loss studies.
	Nickel electroplate .001" thick, (On brass).	All other.

Designation	Nominal Composition	Where Used
Sn	Commercial Tin (99.75% Sn)	Wire in wt. loss studies.
	Tin electroplate .001" thick, (On steel)	All other.
Cr	Chromium electroplate .001" Ni + .00001 Cr, (On brass).	Contact resistance studies.
Pb	Commercial Lead (99.95% Pb)	Wire in wt. loss studies
	Lead electroplate .001" thick, (On steel).	All other.
Ag	Silver Foil (99.9 + Ag)	Corrosion Currents.
	Silver electroplate .002" and .0002" thick (On steel)	Corrosion Currents. Bolts in wt. loss studies.
	Silver electroplate .001" thick, (On brass).	Contact Resistance studies.
Au	Gold electroplate .001" and .0002" thick, (On steel).	Bolts in wt. loss. Corrosion current studies.

Contact Resistance

The contact resistance of the crossed rods, as described in earlier reports, was measured again after thirty-eight weeks exposure in the cycling humidity room. The resistance of the combinations involving aluminum showed a large general increase in resistance but the other values remained essentially the same as at the twenty week period. The earlier conclusion, that the normal atmospheric corrosion or tarnish of the individual metals is controlling with respect to contact resistance between dissimilar metals, and not the effects of galvanic corrosion, is further substantiated.

Galvanic Corrosion Currents and Potentials

The program of measurements of the galvanic corrosion currents and potentials by the method described in Quarterly Reports No. 3 and No. 7, has been completed. The values for the balance of the measurements are given in Tables 1 to 9 inclusive. It should be noted that in the case of thin electrodeposits of metals such as silver and gold, the basis metal, steel, was corroding through the pores of the coating. As a result of this situation, the weight losses of wires wound on silver or gold plated bolts may be lower than if the coatings were thicker or solid metal had been used. However, it may be realistic, as this effect may be encountered in service where use is made of silver or gold plated parts. A comparison of the corrosion currents in 0.01N NaCl is given in Table 19. The current after the first few minutes together with the sustained current after several thousand minutes is of particular significance in comparing couples. It will be noted that there is a fairly good agreement between the overall galvanic current behavior and the per cent weight loss data.

Products at Anodes and Cathodes

In connection with the corrosion behavior of galvanic couples it is of interest to consider the products at the anodes and cathodes and possible secondary reactions resulting from these products. It is a well known electrochemical fact that the anolyte tends to become more acidic due to the oxidation reaction at the anode and that the catholyte tends to become more basic due to the reduction reaction at the cathode. In the case of an electrolyte such as sodium chloride, caustic soda is produced at the cathode and a metal chloride tends to be produced at the anode. The metal chloride may hydrolize and a hydroxide, a carbonate or an oxide may be formed under suitable conditions.

Magnesium - noble metal couples in sea water illustrate an extreme example of this kind. This can best be illustrated by describing several experiments. A small strip of copper was attached to the center of a small magnesium panel (3 x 6 inches), the magnesium surface painted and then scratched through the paint radially from the copper. A film of sea water was maintained over this assembly as it was held in a horizontal position. It was found that the pH of the sea water at the edge of the copper rapidly became greater than 14 when tested with pH indicator papers. The pH of the sea water film at the periphery of the panel was initially about 8 and gradually rose as diffusion of the caustic occurred. Blistering of the paint started at the edge of the copper and slowly worked across the panel surface. The progress of the blistering to a considerable degree followed the rise in pH. Figure 8 shows the corrosion at edge of the copper and the blistering of the paint. It also shows the severe grooving at the interface between the copper and the magnesium and the pitting at more remote spots where the blistered paint has been removed.

Another experiment consisted of immersing a specimen of magnesium alloy in a small beaker of sea water. The pH slowly rose due to local couple action. In one case it reached 8 in 120 hours and in another it reached 10.1 in 288 hours. In a modification of this experiment, a three inch by six inch panel of magnesium was exposed to condensation in the cycling humidity room, while held in a horizontal position. The surface of the panel was rinsed in 75 cc. of distilled water, and the pH of the resulting solution determined. The initial pH of the distilled water was 7.5 and after rinsing was 10.0 when measured with the Beckman pH meter.

A third experiment consisted of placing a magnesium and a copper electrode in a beaker of sea water, but separating the anolyte from the catholyte by means of a porous cup. Upon shorting the two electrodes for 30 hours the pH of the catholyte was found to be 14 and that of the anolyte to be 8.6, when tested with pH indicator papers. This experiment was repeated and both the corrosion current and the variations in pH were determined at intervals until the magnesium was almost entirely consumed. Both the copper and the magnesium specimens had an initial surface area of 4 square inches. The following is a record of the observations:

Time	Current	pH of Anolyte	pH of Catholyte
Start		7.8	7.8
2 hrs.		9.8	10.1
3 hrs.		9.7	9.9
6 hrs.	10.0 ma.	9.5	9.8
24 hrs.	7.4 ma.	9.5	10.0
48 hrs.	8.4 ma.	9.5	10.8
120 hrs.	9.4 ma.	9.0	10.8
168 hrs.	5.4 ma.	9.1	11.9
192 hrs.	3.9 ma.	8.9	11.6
288 hrs.	2.0 ma.	8.9	11.3

It was noted that the stirring of the slurry of white precipitate in both the anolyte and the catholyte seemed to affect the readings of pH on the glass electrode of the Beckman pH Meter. Also, the cathode became coated with a gelatinous film of considerable thickness. Undoubtedly the pH in this film was much higher than that of the slurry. The anolyte in this case becomes slightly basic due to local action cathodic reactions on the surface of the magnesium which are occurring simultaneously with anodic reactions produced by the galvanic action of the copper. These basic cathodic reactions, plus some diffusion of the basic material through the walls of the porous cups, produce a net basic reaction in the anolyte.

It is of interest to note that the solubility of $MgCl_2$ is about 350 grams per liter of water, the pH of a 10% solution is in the neighborhood of 5.8 and the relative humidity over a saturated solution is about 35%. $Mg(OH)_2$ and $MgCO_3$ have solubilities of about 0.01 and 0.1 grams per liter, respectively and saturated solutions have a pH of about 9.9. Thus, the hygroscopicity of the magnesium corrosion product in a marine atmosphere tends to maintain a liquid film at the couple interface, and the solubility of the carbonate tends to aid in providing ions for conductivity in a condensate film such as would be encountered in the tropics.

Weight Losses on Bolt and Wire Couples

The bolt and wire couples have been described in detail in the Second Quarterly Report. They are comprised of a threaded bolt, either of solid metal or plated with the metal under study, and a weighed length of wire of the material whose corrosion behavior is under question. The wire is wound in the threads of the bolt and the ends secured to two lugs to insure positive electrical contact. Combinations of both similar and dissimilar metals were employed. The bolts on which wires of the same metal were wound constituted a blank, and the corrosion of these wires was expected to be a measure of the normal non-galvanic corrosion of the material in the several types of exposure.

The bolt and wire couples were removed from the several test locations after the following periods of exposure and stored in a dry room until weight losses were determined.

	Boldly Exposed*		
Exposure Site	**Group 1**	**Group 2**	**Sheltered****
Point Reyes	89 days	144 days	144 days
New York	101 days	***157 days	157 days
Panama	93 days		93 days
Humidity Room	92 days		

* Designated by E.
** Designated by S.
*** All specimens comprised of magnesium wire were removed at the end of 101 days due to breaks in the wire.

The general appearance of the specimens after exposure indicates the relative severity of the exposure conditions. The corrosion products on Exposed specimens are most pronounced at

Point Reyes, intermediate at New York and least at Panama. At each location Sheltered specimens appear to have suffered markedly less attack than did those which were Exposed. For example, Point Reyes Sheltered specimens appear to be in better condition than those from Panama, Exposed. Magnesium and aluminum corrosion is predominately of a pitting type and produces voluminous white corrosion products when the couple is with a more noble metal. Zinc, cadmium and tin corrosion is of a reasonably uniform nature. Mild steel exhibits typical heavy rust.

Many of the magnesium wires broke during exposure. Electrical contact with the bolt was maintained through the connecting lugs so galvanic action continued for the duration of the test. However, the degree of attack may have been affected somewhat by the relaxation of the wire in the bolt threads.

The ends of the wires which were not in contact with the bolts and which were coated with bitumen, were cut off, cleaned in boiling toluol, weighed and this weight subtracted from the original weight of the whole wire to obtain the weight of the specimen actually exposed as a galvanic couple.

Removal of Corrosion Products

The corrosion products were removed from the wire specimens of brass, copper, monel, iron, lead, nickel, tin, and corrosion resisting steels (430 and 302) by the cathodic process described in the Corrosion Handbook (Uhlig). This consisted of electrolyzing the specimen as a cathode in a bath containing 5% H_2SO_4 and 0.2% "Rodine" inhibitor. The bath was maintained at a temperature of 165°F and the current density at the cathode was held at approximately 1.3 amperes per square inch. The time of treatment usually ran from three to five minutes but longer times were sometimes required for particularly stubborn corrosion products. A soft brush was used to aid in loosening the corrosion products.

Cadmium specimens were cleaned by immersion for 2-1/2 minutes in a 10% solution of NH_4Cl, held at 70°C. Zinc wires were given the same treatment, but in addition had a 15 to 20 second immersion in a boiling solution containing 5% chromic acid and 1% silver nitrate. In both cases a light brushing aided in removal of corrosion products. Aluminum received a 5 minute treatment, with brushing, in a solution containing 30 grams of chromic acid and 25 cc. of 85% phosphoric acid per liter. The magnesium wires were cleaned for 30 seconds in a 20% solution of chromic acid containing 1% of silver nitrate. This solution was maintained at approximately 95°C.

The above cleaning procedures were applied to clean and uncorroded wires to determine the losses in weight produced by the cleaning method. The mean of the cleaning loss percentage was subtracted from the total weight loss percentage as a correction factor in each case. The following table gives the per cent weight loss on the several metals attributable to the cleaning.

Metal	Per Cent Wt. Loss	Correction Factor
Brass	0.000, 0.006, 0.009	0.00
Copper	0.120, 0.069	0.10
Monel	0.000, 0.000, 0.000	0.00
Iron	0.146, 0.170	0.16
Nickel	0.033, 0.000, 0.015	0.02
Tin	0.107, 0.100, 0.100	0.10
302	0.004, 0.015, 0.015	0.01
430	0.000, 0.007, 0.018	0.01
Cadmium	0.013, 0.017, 0.013	0.01
Aluminum	0.020, 0.030, 0.000	0.02
Magnesium	0.22, 0.16, 0.23	0.20
Zinc	0.14, 0.18, 0.17	0.16
Lead	0.000, 0.000, 0.000	0.00

The average values for total per cent weight loss were determined for each couple combination. Since the per cent weight loss of wires on bolts of the same material was presumed to be due to normal atmospheric corrosion at the particular site, this value of corrosion has been subtracted from that produced on the same wire when coupled to a dissimilar metal to give the value due to the galvanic couple effect. These data are given in Tables 10 - 15 (incl.). The range of values and the comparative magnitudes are shown in Figures 5 and 6. The relationships between the per cent weight losses at Point Reyes and the potentials in dilute sodium chloride are shown in Figures 2 - 4 (incl.). The effect of shelter is shown in Figure 7.

DISCUSSION OF DATA

In the determination of total corrosion on the wire specimens it is evident that many of the correction factors introduce an uncertainty of approximately 0.05%. An inspection of the range of values given in Tables 10-15 (incl.). indicates that weight losses below 0.1% have no significance and that direct comparisons where the losses are of comparable magnitude need to be considered in the light of reproducibility. The reproducibility is shown in part by Figures 5 and 6 but it must be remembered that only three specimens of each couple were exposed. In some instances the weight loss of specimens exposed for about 150 days was less than that produced in about 100 days, as for example, the cadmium wire in New York. Errors resulting from the removal of the corrosion products may account for these discrepancies.

The subtraction of the per cent weight losses of wires on bolts of the same material from the total per cent weight losses of dissimilar metal couples to give the corrosion resulting from galvanic action alone, probably introduces a distortion of the results. The magnitude of this distortion will be influenced by the reproducibility of values for the "blank" and the effect of the corrosion products on the rate of corrosion.

Galvanic Corrosion Currents and Potentials

As indicated earlier in this report a study of the corrosion currents produced by the various couples as given in

Table 19 shows good agreement with the weight loss data, from a comparative point of view but both the magnitude and persistence of the current must be considered when using this method of comparing couples. For instance, the zinc couples exhibit a much greater decrease in current in the first few minutes than do comparable aluminum specimens. Further comparisons of the relative weight losses shown in Figures 2, 3 and 4 with the relative corrosion currents shown in Figures 7, 8 and 9 of Quarterly Report No. 7 show a much closer general agreement than when either is compared with couple potentials. A few anomolies are encountered such as the large weight loss of aluminum in contact with iron as compared to a modest corrosion current and a relatively small couple potential. It should be remembered that the potentials given in these reports are the actual potentials measured between the specimens under test and may not agree with some of the published data.

The behavior of nickel coupled to silver is rather interesting. In Figure 4 it will be noted that the weight loss is extremely small and that the polarization is under anodic control. In Table 7 it will be observed that the potentials of both nickel and silver are more negative in distilled water than in chloride solutions and that the potential difference at the start is greater. The low value of corrosion current in both Table 7 of this report and Table 18 of Quarterly Report No. 7 is confirmed by the low weight loss.

The arbitrary method of making comparisons of galvanic corrosion currents which was described in Quarterly Report No. 3

has been proven to be a valuable tool in studying the corrosion behavior of galvanic couples. It appears to be a more reliable method of predicting probable corrosion behavior than the measurement of potential differences. While the corrosion products are confined and diffusion of the constituents of the environment is restricted,this is not unlike the situation encountered in an actual atmospheric exposure. The washing effect of rain is missing so that the accumulation of alkali at the cathode is much more pronounced than in an atmospheric exposure. Neither the influence of this effect nor the effect of restricting the access of oxygen and carbon dioxide to the anodes and cathodes have been evaluated.

The method clearly demonstrates the solubility of magnesium hydroxide and carbonate in distilled water. When the filter paper first becomes saturated with distilled water, the corrosion current tends to be low. As the magnesium reacts with the water, forming a dilute solution of magnesium hydroxide with a pH of 9 to 10 the current tends to rise for a few minutes and then slowly diminish. This behavior is different from that of most other metals where the current tends to drop by a large factor during the first several minutes. Furthermore the magnitude of the current is many times greater. If aluminum-silver is taken as 1.0, magnesium couples with silver, nickel, 430 and cadmium have factors of 30, 20, 20 and 5 respectively. Lead-copper and tin-silver on the other hand gave a factor of 0.4. It is the conductivity of the medium rather than the potential that accounts for these differences.

Galvanic Series

From the composite picture given by the corrosion currents, weight losses, and galvanic potentials, the following galvanic series can be constructed. It is assumed that alloys that are rich in the base metal belong in the same group unless otherwise specified.

- Group I - Magnesium
- Group II - Aluminum
  - Zinc
  - Cadmium
- Group III - Iron and carbon steels
  - Lead
  - Tin
- Group IV - Nickel
  - Chromium
  - Corrosion resisting steels, 430, 302, 316, etc.
- Group V - Copper-nickel and Copper-zinc alloys
  - Copper
  - Silver
  - Gold

In general this means that any metal or alloy in the above series will suffer from galvanic corrosion when coupled to a metal below it in the series and exposed to a corrosive environment. Metals at the upper end of the series are said to be anodic to those below them. Conversely, metals at the lower end are said to be cathodic to those above them. This arrangement is based on corrosion behavior and not on single electrode potentials as usually published. In general it reflects the direction in which the current flows when the metals are coupled together, although as the data indicate, reversals may be encountered under certain conditions.

The magnitude of the corrosion produced will depend upon how far the metals are apart in the series, the polarization characteristics of the couple and other factors of environment and exposure. Normally the metals within each group can be considered as compatible with each other, but under certain circumstances galvanic couple corrosion can occur within the group. For example, copper rich aluminum alloys in contact with pure aluminum will cause relatively high corrosion rates on the latter if wet with sea water. Lead and tin coatings on steel are a familiar example of the galvanic corrosion of steel at pores. Here the large ratio of cathode surface to anode surface prevents the normal cathodic control of polarization and the galvanic current, even though the potential differences are small. Another example may be found in the corrosion resisting steel alloy family where, under some conditions, 430 type steel will be badly corroded by contact with type 316.

This series can not be used rigorously for quantitative comparisons but only as a general guide. The magnitudes of the corrosion produced between groups at the anodic end is much greater than at the cathodic end of the series. The relative behavior is illustrated in the case of magnesium, aluminum and zinc by Tables 16, 17 and 18. Here the couples are grouped by per cent weight loss after an exposure of approximately three months. A general and fairly conclusive pattern appears but relative individual behavior shifts slightly from one environment to another.

From the information in Tables 11 and 16, in Figures 3 and 5 and elsewhere in these reports it is apparent that magnesium alloys can not be Exposed to the weather when coupled with most other metals. Only aluminum, zinc and tin appear to have a small enough effect that it seems reasonable to expect organic coatings to protect couples of magnesium and these metals. With the large potential differences and galvanic corrosion currents between magnesium and other metals it is unrealistic to expect organic coatings to protect a couple when Exposed to a marine atmosphere. The sea salt solution can be expected to bridge the couple in some manner either through holidays, cracks or pores or by simple permeability and permit a galvanic current to be initiated. This current will produce products that will tend to cause blistering and peeling of the organic coating with subsequent loss of protection. On the other hand, the great decrease in galvanic corrosion which accompanies a Sheltered exposure of magnesium couples, permits their use when suitably finished with an organic protective coating.

Aluminum and its alloys are in somewhat the same category as magnesium with regard to exposure as couples. However, since the potentials and galvanic corrosion currents are lower, and aluminum may be given a protective oxide coating by anodizing, adequate protection can be provided. Bare aluminum coupled to a more noble metal will give severe corrosion trouble in an _Exposed_ situation. When anodized and painted it will be satisfactory unless the coatings are damaged at or near the couple junction. In addition to the more favorable potential and galvanic current situation, the products produced by the current are less destructive to the protective coating. In a _Sheltered_ exposure bare aluminum will not suffer severe corrosion unless coupled to one of the metals in Group V. _Housed_, it will be essentially free from all dangers of galvanic couple corrosion.

Zinc, and cadmium which for the most part will appear as protective coatings on steel will suffer in much the same manner as aluminum, unless phosphatized and painted, when _Exposed_. When _Sheltered_ or _Housed_ their performance will be much the same as aluminum. (Note: Bare zinc and cadmium will develop white corrosion products under conditions of high humidity and condensation unless provided with a protective coating).

The metals in Groups III, and IV will be subject to galvanic corrosion when coupled to a member of a more noble group and _Exposed_ to the weather. When _Sheltered_ or _Housed_, no significant galvanic couple corrosion is to be expected.

The following is a table which summarizes the foregoing:

Dissimilar Metal Couples

Cathodic Groups	Condition of Exposure	Anodic Groups			
		I	II	III	IV
II	Exposed	A			
	Sheltered	A			
	Housed	A			
III	Exposed	X	A		
	Sheltered	A	A		
	Housed	A	B		
IV	Exposed	X	A	B	
	Sheltered	A	A	B	
	Housed	A	B	B	
V	Exposed	X	X	X	A
	Sheltered	A	A	A	B
	Housed	A	A	B	B

In this table, metals in the anodic groups may be coupled to those in the cathodic groups for exposure as indicated, under the following conditions, which are given by the proper symbols in the table.

A. The couple is so protected by an envelop of paint, as provided in USA Spec. 72-53, that no liquid film can connect the two elements of the couple.

B. Each of the elements of the couple may have a protective coating if required, but bare metal is exposed at the junction of the surfaces of the two metals in such a way that a liquid film could connect both elements. In some cases one or both metals may be bare, in others both or the combined assembly may be finished in accordance with Spec. 72-53.

X. This condition is not approved as it is expected that severe corrosion will be experienced. Under special circumstances where the equipment is expendable or is not exposed to the indicated environment for very long periods of time it may be permissible to employ category A.

Under special circumstances in the Sheltered and Housed conditions of exposure, a coating of oil, grease or similar material may cover the couple junction. If this protection is maintained, all couples may fall into the B category.

CONCLUSIONS

1. Galvanic couple corrosion does not have a significant effect upon the contact resistance between two dissimilar metals.
2. The use of arbitrary, or thermodynamically idealized tables of metal potentials for predicting galvanic corrosion behavior, is unrealistic.
3. In sheltered or housed equipment and apparatus, except for couples involving magnesium, galvanic couple corrosion is of little significance.
4. Three categories should be employed in classifying corrosion exposure conditions for Signal Corps Equipment. These are classified as Exposed, Sheltered and Housed.
5. The arbitrary method of measuring galvanic couple corrosion currents which was developed in this study has proven to be a much more realistic method of predicting galvanic corrosion behavior than methods based on potential measurements.
6. A table of couple combinations and the circumstances under which they may be permitted has been developed and is shown on pages 24 and 28.

7. The corrosion products produced by galvanic corrosion action alone in sheltered or housed exposures are not sufficiently voluminous as to cause mechanical interference. Dust particles, in most cases, would be a much greater source of trouble.

RECOMMENDATIONS

It is strongly recommended that the following paragraph be incorporated in all Signal Corps specifications dealing with finishes and corrosion.

Contact Between Dissimilar Metals

Where dissimilar metals are in direct contact (electrically) severe galvanic couple corrosion may be encountered under certain conditions of exposure. Metals are grouped in the following galvanic series in which those at the upper or anodic end will tend to be galvanically corroded by those below or towards the cathodic end of the series.

Group I -	Magnesium
Group II -	Aluminum Zinc Cadmium
Group III -	Iron and Carbon Steels Lead Tin
Group IV -	Nickel Chromium Corrosion Resisting Steels (430, 302, 316, etc.)
Group V -	Copper-nickel and Copper-zinc alloys Copper Silver Gold

The conditions under which couples formed by contacts between members of the various groups are acceptable are given in the following table:

Cathodic Member of Group	Condition of Exposure	Anodic Member of Couple From Groups I	II	III	IV
II	Exposed	A			
	Sheltered	A			
	Housed	A			
III	Exposed	X	A		
	Sheltered	A	A		
	Housed	A	B		
IV	Exposed	X	A	B	
	Sheltered	A	A	B	
	Housed	A	B	B	
V	Exposed	X	X	X	A
	Sheltered	A	A	A	B
	Housed	A	A	B	B

Notes - 1. A - The couple is so protected by an envelop of paint as provided in USA Spec. 72-53, that no liquid film can connect or bridge the two elements of the couple.

2. B - The two elements are joined with bare metal exposed at the junction of the surfaces of the two metals in such a way that a liquid film could connect both elements. Each of the metals is given the protective finish required for the particular exposure. In some cases the metals will be bare and in others will have a protective coating as provided in Spec. 72-53.

3. X - This combination is not approved. Only under special conditions can this condition be tolerated, and specific approval will be given only after an engineering study has been made.

4. In cases where the exposure is to be <u>Sheltered</u> or <u>Housed</u> and where it is feasible to maintain a film of oil, grease or similar compound over the couple junction, the above ratings may be upgraded.

5. Departures from the above tables for reasons of an abnormal ratio of anode area to cathode area must be considered a special case for individual consideration.

6. Interposing insulators or more compatible materials between the metals in question is acceptable if the resulting product meets the requirements of the above table.

Electrolyte; .01N. NaCl.

430-302

Δt Min.	E_{430} Volts	E_{302} Volts
Start	- .35	- .32
15	- .32	- .27
60	- .30	- .26
180	- .25	- .23

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	- .24	.5
1		.2
2		.2
3		.2
5		.2
15	- .24	.2
60	- .24	.2
120	- .24	.2
4195	- .20	.1
5695	- .19	0
7015	- .20	0

430 is Anodic

Couples Opened

Min.	E'_{430} Volts	E'_{302} Volts
Start	- .19	- .19
30	- .21	- .18
120	- .21	- .17

430-Ag*

Δt Min.	E_{430} Volts	E_{Ag} Volts
Start	- .32	- .15
15	- .26	- .13
60	- .23	- .13
180	- .21	- .12

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	- .15	3.2
1		1.3
2		.8
3		.8
4		.7
5		.6
15	- .16	.5
60		.4
120	- .16	.4
4080	- .19	.2
5580	- .18	.1
6900	- .17	.1

*Pure Ag Foil

430 is Anodic

Couples Opened

Min.	E'_{430} Volts	E'_{Ag} Volts
Start	- .19	- .19
30	- .23	- .17
120	- .23	- .17

Corrosion Current and Potential Measurements

Area of Electrodes 1 Sq. Inch Pot. vs. AgCl

µ amps = microamperes

TABLE 1

Electrolyte; .01N. NaCl.

Pb-302

Δt Min.	E_{Pb} Volts	E_{302} Volts
Start	- .67	- .40
15	- .67	- .39
60	- .68	- .39
120	- .67	- .37

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	- .63	35
1		12
2		10
3		10
5		10
15	- .64	9
30		9
90	.62	9
240	- .61	8
4250	- .56	6
5790		6
7230	- .56	6
8670		6
10110	- .56	6

Pb is Anodic

Couples Opened

Min.	E'_{Pb} Volts	E'_{302} Volts
Start	- .56	- .47
60	- .57	- .30
120	- .58	- .26

Sn-302

Δt Min.	E_{Sn} Volts	E_{302} Volts
Start	- .46	- .32
15	- .45	- .30
60	- .43	- .22
120	- .43	- .20

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	- .32	51
1	- .32	35
2		36
3		36
5		37
15	- .38	48
30		48
60		48
120		36
300	- .48	24
4280		16
5720	- .51	20
7160	- .52	25
10040	- .52	32

Sn is Anodic

Couples Opened

Min.	E'_{Sn} Volts	E'_{302} Volts
Start	- .54	- .48
60	- .54	- .34
120	- .55	- .27

Corrosion Current and Potential Measurements

Area of Electrodes 1 Sq. Inch — Pot. vs. AgCl

µ amps = microamperes

TABLE 2

Electrolyte; .01N. NaCl

Gold plated on steel
Note effect of pores

Au-Brass

Δt Min.	E_{Au} Volts	E_{Brass} Volts
Start	-.33	-.38
0	-.48	-.29
15	-.54	-.27
60	-.55	-.27

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.53	34
1		20
2		19
3		18
5		16
15	-.54	11
150	-.56	11
300	-.57	9.7
1680	-.60	11
5640	-.58	13
7140	-.54	19

Gold plated steel
is anodic to Brass

Couples Opened

Min.	E'_{Au} Volts	E'_{Brass} Volts
Start	-.52	-.50
60	-.52	-.42
120	-.52	-.42

Rust stains on
both electrodes

Au-430

Δt Min.	E_{Au} Volts	E_{430} Volts
Start	-.37	-.20
15	-.43	-.20
60	-.49	-.28
120	-.51	-.30

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.40	52
1		12
2		11
3		9.4
5		8.2
15	-.49	6.7
135	-.50	6.2
300	-.50	6.0
1665	-.43	6.2
5625	-.35	6.0
7125	-.33	9.0

Gold plated steel
is anodic to 430

Couples Opened

Min.	E'_{Au} Volts	E'_{430} Volts
Start	-.31	-.30
60	-.31	-.25
120	-.31	-.24

Rust stains on
both electrodes

Gold Thickness - 0.0002" on flat surfaces

Corrosion Current and Potential Measurements

Area of Electrodes 1 Sq. Inch

Pot. vs. AgCl

µ amps = microamperes

TABLE 3

Electrolyte: .01N. NaCl

Gold plated on steel
Note effect of pores

Au-Ni

Δt Min.	E_{Au} Volts	E_{Ni} Volts
Start	-.34	-.33
15	-.41	-.31
60	-.45	-.29
120	-.47	-.26

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.47	20
1		7.5
2		7.2
3		7.2
5		7.2
15	-.47	7.3
120		7.4
1495	-.43	6.2
5635		7.8
7015	-.38	8.4
9955	-.36	9.4

Gold plated steel
is anodic to Ni

Couples Opened

Min.	E'_{Au} Volts	E'_{Ni} Volts
Start	-.37	-.35
60	-.37	-.26
120	-.37	-.26

Rust stains on
both electrodes

Au-Cu

Δt Min.	E_{Au} Volts	E_{Cu} Volts
Start	-.36	-.20
15	-.41	-.20
60	-.45	-.22
120	-.47	-.22

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.45	52
1		20
2		16
3		15
5		14
15	-.48	12
120	-.49	12
1475	-.47	12
5615	-.43	12
6995	-.46	13
9935	-.40	17

Gold plated steel
is anodic to Cu

Couples Opened

Min.	E'_{Au} Volts	E'_{Cu} Volts
Start	-.41	-.38
60	-.43	-.28
120	-.43	-.27

Rust stains on
both electrodes

Gold Thickness - 0.0002" on flat surfaces

Corrosion Current and Potential Measurements
Area of Electrodes 1 Sq. Inch
Pot. vs. AgCl

µ amps = microamperes

TABLE 4

Electrolyte; Distilled Water

Brass-Ag*

Δt Min.	E_{Brass} Volts	E_{Ag} Volts
Start	-.2	-.2
60	-.3	-.1
120	-.3	-.1

Couples Shorted

Min.	E_c Volts	I_c μ amps
Start	-.2	19
1		5.3
2		5.0
3		5.0
4		5.0
5		4.9
20	-.3	5.0
60	-.3	3.8
200	-.3	2.9
5765	-.4	1.1
7205	-.4	1.0

Couples Opened

Min.	E'_{Brass} Volts	E'_{Ag} Volts
Start	-.4	-.3
60	-.4	-.3
120	-.4	-.3

*Pure Ag Foil

Mg-Ag*

Δt Min.	E_{Mg} Volts	E_{Ag} Volts
Start	-1.6	0
120	-1.6	-.2

Couples Shorted

Min.	E_c Volts	I_c μ amps
Start	-1.3	1880
1		1690
2		1600
3		1560
4		1540
5		1560
15	-1.3	1380
120	-1.3	430
240	-1.3	350
335	-1.3	290
1290	-1.3	136
3075		86
7075	-1.2	65

Couples Opened

Min.	E'_{Mg} Volts	E'_{Ag} Volts
Start	-1.6	-.8
60	-1.6	-.4
120	-1.7	-.3

*Pure Ag Foil

Corrosion Current and Potential Measurements
Area of Electrodes 1 Sq. Inch
Pot. vs. AgCl

μ amps = microamperes

TABLE 5

Electrolyte; Distilled Water

Al-Ag*			Sn-Ag*		
Δt Min.	E_{Al} Volts	E_{Ag} Volts	Min.	E_{Sn} Volts	E_{Ag} Volts
Start	-.7	0	Start	-.6	0
120	-.8	-.1	60	-.5	-.2
			120	-.5	-.2

Couples Shorted

Min.	E_c Volts	I_c µ amps	Min.	E_c Volts	I_c µ amps
Start	-.6	108	Start		97
2		83	1		25
3		71	2		23
4		66	3		22
5		59	4		21
15	-.6	43	5		21
95	-.6	36	60		11.3
215	-.6	31	140	-.3	8.1
310	-.5	27	260	-.3	8.8
1265	-.5	13	1785	-.3	5.1
3070	-.5	11	5630	-.3	2.6
7060	-.4	8	7140	-.3	2.2
			8580	-.4	1.9

Couples Opened

Min.	E'_{Al} Volts	E'_{Ag} Volts	Min.	E'_{Sn} Volts	E'_{Ag} Volts
Start	-.6	-.4	Start	-.6	-.4
60	-.9	-.2	60	-.6	-.2
120	-.9	-.2	120	-.6	-.2

* Pure Ag Foil

* Pure Ag Foil

Corrosion Current and Potential Measurements

Area of Electrodes 1 Sq. Inch — Pot. vs. AgCl

µ amps = microamperes

TABLE 6

Electrolyte; Distilled Water

Ni-Ag*

Δt Min.	E_{Ni} Volts	E_{Ag} Volts
Start	-.4	-.1
60	-.5	-.2
120	-.4	-.1

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.2	5.1
1		2.4
2		1.9
3		1.6
4		1.5
5		1.5
20	-.2	0.9
60	-.2	0.2
145	-.2	0.2
265	-.2	0
1795		0
5610	-.2	0
7020	-.2	0
8460	-.3	0

Couples Opened

Min.	E'_{Ni} Volts	E'_{Ag} Volts
Start	-.3	-.3
60	-.3	-.3
120	-.2	-.2

*Pure Ag Foil

Cu-Ag*

Δt Min.	E_{Cu} Volts	E_{Ag} Volts
Start	-.4	-.2
60	-.3	-.1
120	-.3	-.1

Couples Shorted

Min.	E_c Volts	I_c µ amps
Start	-.2	6.9
1		3.7
2		2.9
3		2.7
4		2.8
5		1.8
15	-.2	1.6
55	-.2	1.0
195	-.2	0.8
5760	-.3	0.2
7200	-.3	0.2

Couples Opened

Min.	E'_{Cu} Volts	E'_{Ag} Volts
Start	-.3	-.2
60	-.3	-.2
120	-.3	-.2

*Pure Ag Foil

Corrosion Current and Potential Measurements
Area of Electrodes 1 Sq. Inch
Pot. vs. AgCl

µ amps = microamperes

TABLE 7

Electrolyte; Distilled Water

430-Ag*

Δt Min.	E_{430} Volts	E_{Ag} Volts
Start	-.1	-.1
60	-.3	-.3
120	-.3	-.2

Couples Shorted

Min.	E_c Volts	I_c μ amps
Start	-.3	8.3
1		1.1
2		1.0
3		0.8
4		0.8
5		0.8
20	-.3	0.3
60	-.3	0.2
370	-.3	0
1305	-.3	0
7065	-.3	0
8505	-.3	0

Couples Opened

Min.	E'_{430} Volts	E'_{Ag} Volts
Start	-.3	-.3
60	-.3	-.3
120	-.3	-.3

*Pure Ag Foil

Cu-430

Δt Min.	E_{Cu} Volts	E_{430} Volts
Start	-.1	-.1
60	-.3	-.3
120	-.3	-.2

Couples Shorted

Min.	E_c Volts	I_c μ amps
Start	-.3	2.3
1		.9
2		.7
3		.7
4		.7
5		.7
20	-.3	.6
60	-.3	.5
375	-.3	.3
1310	-.3	.1
7070	-.3	0
8510	-.3	.1

Couples Opened

Min.	E'_{Cu} Volts	E'_{430} Volts
Start	-.3	-.3
60	-.2	-.2
120	-.2	-.2

Corrosion Current and Potential Measurements
Area of Electrodes 1 Sq. Inch
Pot. vs. AgCl

μ amps = microamperes

TABLE 8

Electrolyte; .01N. Na_2SO_4

Brass-Ag*			Al-Ag*			Zn-Fe		
Δt Min.	E_{Br} Volts	E_{Ag} Volts	Δt Min.	E_{Al} Volts	E_{Ag} Volts	Δt Min.	E_{Zn} Volts	E_{Fe} Volts
Start	-.33	- .12	Start	- .88	- .18	Start	-1.22	- .80
60	-.33	- .09	60	- .86	- .16	60	-1.14	- .73
120	-.32	- .09	120	- .93	- .20	120	-1.07	- .73
			285	- .96	- .17			

Couples Shorted			Couples Shorted			Couples Shorted		
Min.	E_c Volts	I_c µ amps	Min.	E_c Volts	I_c µ amps	Min.	E_c Volts	I_c µ amps
Start	- .26	253	Start	- .52	155	Start	- .97	510
1		61	1		87	1		194
2		42	2		62	2		166
3		24	3		59	3		150
4		14	4		57	4		149
5		13	5		56	5		140
15		12	15		55	15		127
60	- .28	8	30	- .67	64	60	-1.04	119
210	- .31	4	60	- .68	77	120		101
1315	- .33	2	215	- .66	71	200	-1.06	108
7075		2	1150	- .58	36	5515		62
8515	- .34	2	6910		18	6925	- .95	54
			8350	- .60	20	8365		53
						9805	- .98	52

Couples Opened			Couples Opened			Couples Opened		
Min.	E'_{Br} Volts	E'_{Ag} Volts	Min.	E'_{Al} Volts	E'_{Ag} Volts	Min.	E'_{Zn} Volts	E'_{Fe} Volts
Start	- .35	- .33	Start	- .86	- .44	Start	-1.06	- .88
60	- .35	- .26	60	- .99	- .18	60	-1.10	- .77
120	- .35	- .26	120	- .98	- .17	120	-1.10	- .77

*Pure Ag Foil *Pure Ag Foil

Corrosion Current and Potential Measurements

Area of Electrodes 1 Sq. Inch Pot. vs. AgCl

µ amps = microamperes

TABLE 9

PER CENT WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

Exposure Site		New York		Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		X	S	X	X	S	X	S	X
Duration, Days		101	101	89	144	144	93	93	92
Wire	Bolt								
Magnesium	Mg	.86	.12	6.2	7.4	1.4	.8	.34	.24
	Al	3.3	.69	11	13	1.8	2.8	.61	
	Zn	3.3		11	17		3.8		1.6
	Cd	8.5		24	36		4.4		2.6
	Sn	4.7		11	16		3.9		2.2
	Pb	6.8		22	36		6.2		3.4
	Fe	10.3	.58	30	42	2.6	15	.65	
	Ni	11.0		25	49		13		2.3
	Cu	8.6	.92	29	44	3.1	12	.82	
	Monel	10.6		34	36		12		2.6
	Brass	6.0	.99	20	33	3.8	8.3	.52	
	430	7.8		26	58		7.2		
	302	5.9		20	40		8.6		3.7
	Ag	6.5	.95	24	50	3.3	5.6	.92	4.9
	Au	9.3		41	50		8.8		4.9

DIFFERENCES IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank	(Mg-Mg)	.86	.42	6.2	7.4	1.4	.80	.34	24
Magnesium	Al	2.4	.27	4.9	6.0	.4	2.0	.47	
	Zn	2.4		4.8	9.5		3.0		1.4
	Cd	7.6		18	29		3.6		2.4
	Sn	3.8		4.8	8.5		3.2		2.0
	Pb	5.9		15	19		5.3		3.2
	Fe	9.4	.16	26	35	1.2	14	.31	
	Ni	10.1		19	41		12		2.1
	Cu	7.7	.49	23	37	2.7	12	.48	
	Monel	9.7		28	29		11		2.4
	Brass	5.1	.17	14	25	2.4	7.5	.18	
	430	6.9		20	30		6.4		
	302	5.0		14	32		7.8		3.5
	Ag	5.6	.53	18	42	3.9	5	.58	4.7
	Au	8.6		35	42		8		4.7

TABLE 10

PER CENT WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

Exposure Site		New York			Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		X	X	S	X	X	S	X	S	X
Duration, Days		101	157	157	89	144	144	93	93	92
Wire	Bolt									
Aluminum	Al	.18	0	.08	1.5	3.8	.46	.12	0	.06
	Mg	.05	0	0	6.8	12	.1	0	.39	-
	Zn	.06	.15		.90	1.3		.14		.27
	Cd	.07	.02		1.7	1.3		.24		.09
	Sn	.26	.33		4.1	7.1		1.3		.05
	Pb	.23	.38		13	19		.40		.08
	Fe	.51	.74	.24	19	27	1.4	5.0	.24	.25
	Ni	.66	.84		8.9	10		1.1		.20
	Cu	2.3	4.4	.29	22	32	2.0	7.0	1.4	.09
	Monel	1.0	2.8		6.4	8.7		1.3		.04
	Brass	1.2	2.5	.46	14	21	2.4	2.4	.14	.05
	430	.53	.87		11	18		2.6		.16
	302	.64	.99		8.0	14		2.6		.12
	Ag	1.2	2.3	.58	18	27	4.1	5.0	.45	.33
	Au	1.0	2.3		14	18		5.5		.26

DIFFERENCE IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank	(Al-Al)	.18	0	.08	1.5	3.8	.46	.12	0	.06
Aluminum	Mg	0	0	0	5.3	9.2	0	0	.39	-
	Zn	0	.15		0	0		.02		.21
	Cd	0	.02		.2	0		.12		.03
	Sn	.08	.33		2.6	3.3		1.2		0
	Pb	.05	.38		12	15		.28		.08
	Fe	.33	.74	.16	18	23	.96	4.9	.24	.14
	Ni	.48	.84		7.4	6.2		1.0		.14
	Cu	2.1	4.4	.21	21	28	1.6	6.9	1.4	.03
	Monel	.82	2.8		4.9	4.9		1.2		0
	Brass	1.0	2.5	.38	13	17	1.9	2.3	.14	0
	430	.35	.87		10	14		2.5		.10
	302	.46	.99		7	10		2.5		.06
	Ag	1.0	2.3	.50	17	23	3.6	4.9	.45	.27
	Au	.8	2.3		13	14		5.4		.20

TABLE 11

PER CENT WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

Exposure Site		New York			Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		E	E	S	E	E	E	E	S	E
Duration, Days		101	157	157	89	144	144	93	93	92
Wire	Bolt									
Zinc	Zn	.94	1.0	.27	2.7	3.0	.23	1.3	.70	.29
	Mg	0	0	.03	.65	.77	.01	.05	.32	
	Al	1.4	1.9	.50	3.2	3.9	.18	1.1	.43	.27
	Cd	7.2	10		6.8	10		2.0		.49
	Sn	2.0	2.4		6.1	7.0		3.0		.27
	Pb	2.6	3.5		9.0	12		3.5		.29
	Fe	3.8	3.7	1.0	8.0	10	.21	5.2	.79	.34
	Ni	1.7	2.2		7.2	8.6		3.4		.79
	Cu	2.4	3.2	.61	8.7	9.1	.52	4.0	.74	.57
	Monel	1.8	2.4		8.2	8.8		3.4		.41
	Brass	2.2	2.7	1.0	8.1	10	.60	4.4	1.1	.41
	430	1.7	2.3		5.8	6.6		3.0		
	302	1.7	2.5		5.6	6.5		2.9		.24
	Ag	2.3	2.8	1.5	8.4	8.8	.86	4.5	1.1	.42
	Au	2.2	2.6		7.4	9.6		4.3		

DIFFERENCE IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank Zinc	(Zn-Zn)	.94	1.0	.27	2.7	3.0	.23	1.3	.7	.29
	Mg	0	0	0	0	0	0	0	0	-
	Al	.1	.9	.23	.5	.9	0	0	0	0
	Cd	6.3	9.0		4.1	7.0		.7		.2
	Sn	1.2	1.4		3.4	4.0		1.7		0
	Pb	1.7	2.5		6.3	8.6		2.2		0
	Fe	2.9	2.7	.73	5.3	7.0	0	3.9	.09	.05
	Ni	.8	1.2		4.5	5.6		2.1		.5
	Cu	1.5	2.2	.34	6.0	6.0	.3	2.7	.04	.28
	Monel	.9	1.4		5.5	5.8		2.1		.12
	Brass	1.3	1.7	.73	5.3	7.2	.4	3.1	.4	.12
	430	.8	1.3		3.1	3.6		1.7		
	302	.5	1.5		3.0	3.5		1.6		0
	Ag	1.4	1.8	.78	5.6	5.8	.6	3.2	.4	.13
	Au	1.3	1.6		4.7	6.6		3.0		

TABLE 12

PER CENT WEIGHT LOSS OF WIRE IN BOLT AND WIRE COUPLES

Exposure Site		New York			Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		E	E	S	E	E	S	E	S	E
Duration, Days		101	157	157	89	144	144	93	93	92
Wire	Bolt									
Cd	Cd	2.7	2.0	.67	.24	.45	.14	1.9		.03
	Mg	1.5	.04		.1	.13		2.2		
	Al	3.3	3.0		.44	.54		2.7		.03
	Zn	1.4	.04	.3	0	.27	.05	2.6		.01
	Fe	6.6	6.8		6.4	7.9	.18	6.4		.08
	Ni	2.2	4.8		2.4	5.8		2.6		.01
	Cu	5.0	3.6		6.1	9.5	.12	6.0		.05
	Brass	4.9	3.5		6.7	8.3		3.8		.01
Ni	Ni	.39	.50	.90	0	0	.04	.06	.01	0
	Fe	.30	.40		.15	.36		.09		0
	Cu	0	0		0	0		.04		0
	Ag	.45	.65	1.6	0	.05	0	.06	.05	0
Cu	Cu	.18	.20	0	.19	.25	.13	.10	.06	0
	Ni	.99	.76		.49	.55		.08		0
	Ag	.53	1.2	.20	.61	1.5	.04	.16	.11	0

DIFFERENCE IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank Cd	(Cd-Cd)	2.7	2.0	.67	.24	.45	.14	1.9		.03
	Mg	0	0		0	0		.3		
	Al	1.1	1.0		.20	.10		.8		0
	Zn	0	0	0	0	0		.7		0
	Fe	3.9	4.8		6.2	7.5	.04	4.3		.05
	Ni	0	2.8		2.2	3.4		.7		0
	Cu	2.3	1.6		5.9	9.2		4.2		.03
	Brass	2.2	1.5		6.5	7.9		1.9		0
Blank Ni	(Ni-Ni)	.39	.50	.90	0	0	.04	.06	.01	0
	Fe	0	0		.15	.35		.03		0
	Cu	0	0		0	0		0		0
	Ag	.06	.15	.7	0	.05	0	0	.04	0
Blank Cu	(Cu-Cu)	.18	.20	0	.19	.25	.23	.10	.06	0
	Ni	.44	.56		.30	.29		0		0
	Ag	.63	1.0	.20	.62	1.2	0	.06	.05	0

TABLE 13

PER CENT WEIGHT LOSS OF WIRE IN BOLT AND WIRE COUPLES

Exposure Site		New York			Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		E	E	S	E	E	S	E	S	E
Duration, Days		101	157	157	89	144	144	93	93	92
Wire	Bolt									
430	430	.08	.08	.05	.10	.12	.02	.15	.06	.05
	Fe	.08	.06	0	.06	.20	.02	.19	.20	
	302	.09	.07		.13	.20		.22		.07
	Brass	.09	.07		.42	.62		.13		.04
302	302	0	0	0	0	.19	.04	.08	.10	
	Fe	0	0	0	0	.67	.01	.35	0	
Brass	Brass	.13	.22	.13	.04	.08	.09	.05	.07	
	Fe	.16	.26	.25	.67	.45	.07	.33	.03	.11
	Ni	.75	1.1		.10	.30		.19		.07
	Cu	.12	.72	.35	.16	.32	.14	.15	.12	.09
	Ag									
Monel	Monel	.07	.12	.42	.02	.05	.07	.05	.05	.04
	Fe	.38	.17	.20	.02	.10	.06	0	.04	
	Ni	.11	.14		.01	.02	.20	.03		.01
	Cu	.01	.03		0	.02		0		.02

DIFFERENCE IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank	(430-430)	.08	.08	.05	.1	.12	.02	.13	.06	.05
430	Fe	0	0	0	0	.08	0	.06	.14	
	302	.01	0		.03	.08		.09		.08
	Brass	.01	0		.32	.50		0		0
Blank	(302-302)	0	0	0	0	.19	.04	.08	.1	
302	Fe	0	0	0	0	.48	0	0	0	
Blank	(Brass-Brass)	.13	.22	.13	.04	.08	.09	.05	.07	
Brass	Fe	.03	.04	.30	.63	.37	0	.28	0	.11
	Ni	.62	.88		.06	.12		.14		.07
	Cu	0	.50	.22	.12	.24	.05	.11	.05	.09
	Ag									
Blank	(Monel-Monel)	.07	.12	.42	.02	.05	.07	.05	.05	.04
	Fe	.01	.05	0	0	.05	0	0	0	
	Ni	.04	.02		0	0	.13	0		0
	Cu	0	0		0	.03		0		0

TABLE 14

PER CENT WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

Exposure Site		New York			Point Reyes			Panama		Murray Hill Cycling Humidity Room
Type of Exposure		E	E	S	E	E	S	E	S	E
Duration, Days		101	157	157	89	144	144	93	93	92
Wire	Bolt									
Sn	Sn	.04	.03	0	1.0	1.4	.63	.11	.13	.02
	Brass	1.1	.93		3.8	5.1		.28		.01
	Fe	.05	.04	.06	2.3	3.3	.15	.27	.32	.04
	Ni	.4	.3		2.8	3.0		.29		.01
	Cu	1.3	1.1	0	5.0	6.6	.26	.26	.31	.01
Pb	Pb		.15	.05	.13	.17	.21	.18	0	.11
	Fe		.34	.06	2.1	2.0	.05	2.2	.22	.47
	Ni		.15		.68	.52		1.2		.20
	Cu		8.1	.06	1.7	2.6	.03	2.9	.07	1.2
	Zn		.09		.09	.15		.12		.09
Fe	Fe	14	22	3.6	14	16	1.6	6.1	.24	.45
	Sn	15	22		15	17		4.7		.66
	302	17	23		23	26		8.0		
	Ni	14	20		21	25		8.2		.65
	Cu	18	25	4.5	23	29	2.5	9.4	.57	1.3

DIFFERENCE IN PER CENT WEIGHT LOSS BETWEEN COUPLES AND BLANKS (WIRE AND BOLTS OF SAME MATERIAL)

Blank	(Sn-Sn)	.04	.03	0	1.0	1.4	.63	.11	.13	.02
Sn	Brass	1.1	.90		2.8	3.7		.17		0
	Fe	.01	.01	.06	1.3	1.9	0	.16	.19	.02
	Ni	.4	.3		1.8	1.8		.18		0
	Cu	1.3	1.1	0	4.0	5.2	0	.15	.18	0
Blank	(Pb-Pb)		.15	.05	.13	.17	.21	.18	0	.11
Pb	Fe		.19	.01	2.0	1.8		1.0	.22	.36
	Ni		0		.55	.35		1.0		.09
	Cu		7.9	.01	1.6	2.4		1.9	.07	1.1
	Zn		0		0	0		0		0
Blank	(Fe-Fe)	14	22	3.6	14	16	1.6	6.1	.24	
Fe	Sn	1	0		1	1		0		
	302	3	1		9	10		1.9		
	Ni	0	0		7	9		2.1		
	Cu	4	3	.9	9	13	.5	3.3	.33	

TABLE 15

Galvanic Corrosion of Magnesium Wires in Bolt and Wire Couples Exposed to the Weather

	Point Reyes	New York	Panama	Murray Hill Cycling Humidity Room
% Wt. Loss		Bolt Material		
30-35	Au			
25-30	M			
20-25	Fe,430,Cu			
15-20	Ni,Cd,Ag,Pb			
12.5-15	B,302			
10-12.5		Ni	Fe,Ni, Cu,M	
7.5-10		M,Fe,Au, Cu,Cd	Au,302, B	
5-7.5		430,Pb,Ag, B,302	430,Pb, Ag	
3-5	Al,Zn,Sn	Sn	Cd,Sn, Zn	Au,Ag,302,Pb
2-3		Zn,Al	Al	M,Cd,Ni,Sn
1-2				Zn
.5-1				
.1-.5				
< .1				
Blank (Magnesium Wire & Bolt)	6.2	.86	.80	.24

TABLE 16

Galvanic Corrosion of Aluminum Wires in Bolt and Wire Couples Exposed to the Weather

	Point Reyes	New York	Panama	Murray Hill Cycling Humidity Room
% Wt. Loss		Bolt Material		
20-25	Cu			
15-20	Fe,Ag			
12.5-15	Au,B,Pb			
10-12.5	430			
7.5-10	Ni,302			
5-7.5	Mg,M		Cu,Au, Ag,Fe	
3-5	Sn			
2-3		Cu	430,302, B	
1-2	Cd	Ag,B, Au,M	M,Sn,Ni	
.5-1	Zn	Ni,302, 430,Fe		
.1-.5		Sn,Pb	Pb,Cd,Zn	Ag,Au,Zn,Ni, Fe,430,302
< .1		Cd,Zn,Mg	Mg	Cu,Cd,Pb,B, Sn,M
Blank (Aluminum Wire & Bolt)	1.5	.18	.12	.06

TABLE 17

Galvanic Corrosion of Zinc Wires in Bolt and Wire Couples Exposed to the Weather

	Point Reyes	New York	Panama	Murray Hill Cycling Humidity Room
% Wt. Loss		Bolt Material		
7.5-10	Pb,Cu,Ag M,B,Fe			
5-7.5	Au,Ni,Cd Sn,430,302	Cd	Fe	
3-5	Al	Fe	Ag,B,Au, Cu,Pb,Ni, M,430,Sn	
2-3		Cu,Ag,Au, B,Sn	302,Cd	
1-2		M,430,302 Ni,Al,Pb	Al	
.5-1				Ni,Cu
.1-.5				Cd,Ag,B,M,Fe, Pb,Sn,Al,302
< .1		Mg	Mg	
Blank (Zinc Wire & Bolt)	2.7	.94	1.3	.29

TABLE 18

Galvanic Corrosion Currents

Electrolyte: 0.01N. NaCl

Area of Electrodes 1 Sq. In.

Currents in Microamperes

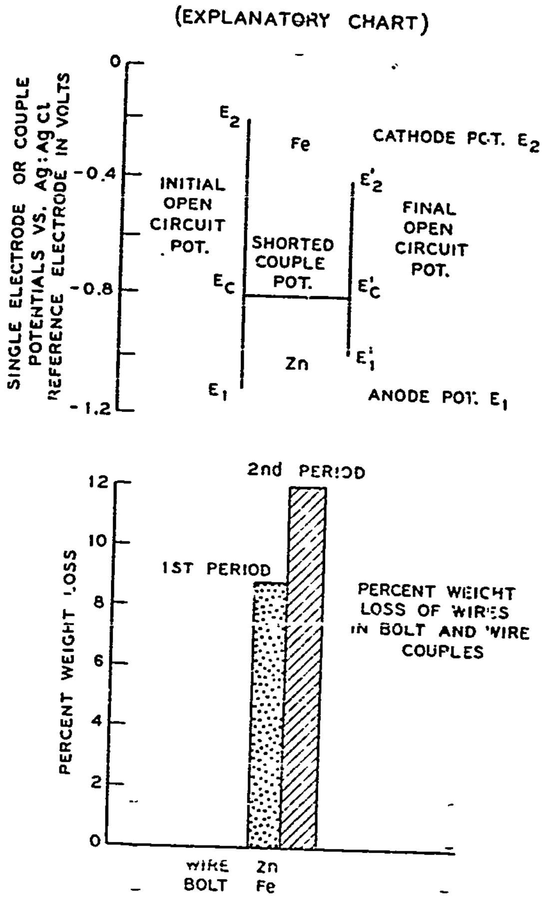
Anode	Magnesium						
Cathode	Cu	Fe	430	Ag	Cd	Al	Zn
Time, Min.							
Start	5100	7200	3700	1640	1500	180	134
1	3300	6500	5600	1600	1300	220	360
2	3800	5100	5100	1500		260	385
5	3300	4300	4000	1200	1200	340	366
10	3200	3800	4000	1000	1000	420	358
30	2020	3000	2900	900		390	320
100	1200	1500	1600	700	530	260	280
500	690			480	280		211
1000	460	500	280		230	29	180
3000			200				
5000	420	200	187	580		28	210
8000	480	150	190	580	210		150

Anode	Aluminum								
Cathode	Ag	Cu	302	430	Ni	B	Fe	Sn	Cd
Time, Min.									
Start	215	173	99	68	180	51	67	56	13
1	200	87	34	50	96	49	33	40	10
2	220	80	32	44	74	49	30		
5	240	79	30	37	61	52	31		9.2
10	240	81	31		75	59		29	9.1
30	188	92	31		90	73	45	29	
100	120	95	50	63		77	80	27	8.2
500	95				63	57			
1000				72		52	44	16	7.9
3000	86		36	59	36	56	32		
5000	88	91				59	10		
8000		110	39		31	65	8.5		9.4

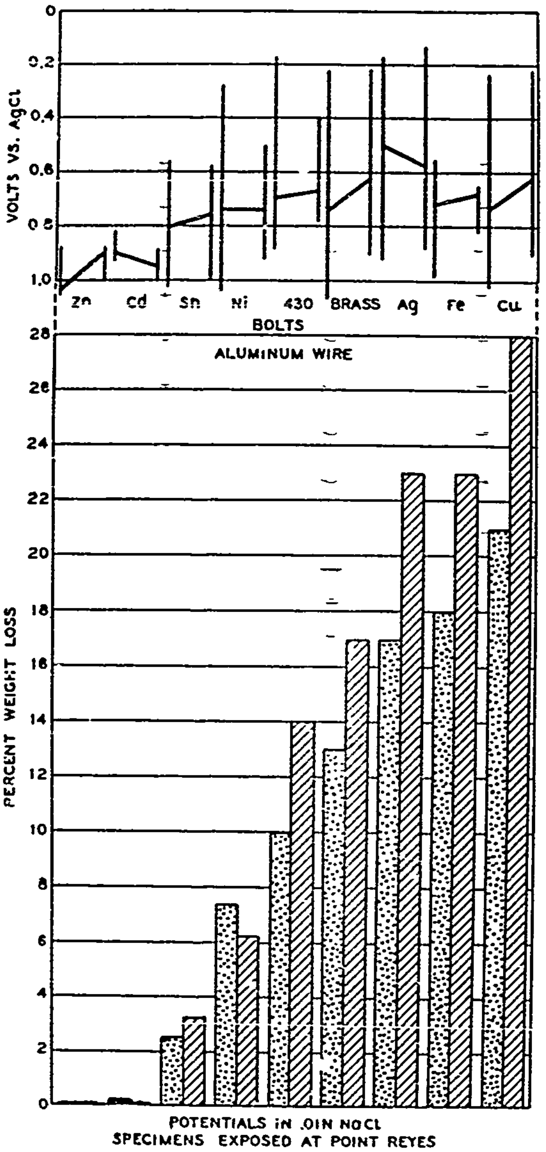
Anode	Zinc						
Cathode	Cu	Ag	Fe	302	430	Cd	Al
Time, Min.							
Start	650	815	305	210	188	96	13
1	190	215	170	124	111	45	11
2	145	218	150	110		40	10
5	139	196	130	108	114	38	8
10	140	150	110	108	137	35	8
30		130	84	107	142	31	8
100	70	76	65	98	6.9	22	7
500	28	45	57	70	6.0	7.6	7
1000	27	40	52	40	5.5	6.4	1
3000	26	36	52	35	4.6	5.8	+.5
5000		39	40	35		5.0	-.4
8000		40		26		4.0	-.1

Anode	Iron		Tin				Brass	Nickel	Lead		430		
Cathode	Cu	430	Ag	Cu	Ni	302	Ag	Ag	Cu	302	Cu	302	Ag
Time, Min.													
Start	388	312	34	22	1.1	51	33	2.9	29	35	-.1	.5	3.2
1	122	57	25	21	1.0	35	11	1.1	24	12	-.2	.2	1.3
2	79	41	28	19	1.0	36	10	.9	23	10	-.1	.2	.8
5	61	28	33	21	1.0	37	9	.7	24	10	0	.2	.6
10	55	25	30	16	1.1	48	8.5	.6	20	9	0	.2	.5
30	57	22	21	16	1.4	48	6.5	.5	20	9	0	.2	.4
100	60	22	18	13	3.6	36	5.2	.3	23	9	+.5	.2	.4
500	51	20		12	4.6	25	4.6	0	24	8	+.6	.2	.3
1000	38	20	19	13	4.8	18	3.7	0	24	7	+.9	.1	.3
3000	30	23	18	14	5.0	16	3.4	0	18	6	+.5	.1	.3
5000		33	16	11	7.3	20	3.4	0	16	6	+.6	0	.2
8000		33	13	10	6.9	25	3.2	0	15	6	+.7	0	.1

TABLE 19


(EXPLANATORY CHART)
SINGLE ELECTRODE OR COUPLE POTENTIALS VS. Ag:Ag Cl REFERENCE ELECTRODE IN VOLTS
0
-0.4
-0.8
-1.2
E2
Fe
CATHODE POT. E2
E'2
INITIAL OPEN CIRCUIT POT.
SHORTED COUPLE POT.
FINAL OPEN CIRCUIT POT.
EC
E'C
Zn
E'1
E1
ANODE POT. E1
2nd PERIOD
1ST PERIOD
PERCENT WEIGHT LOSS
12
10
8
6
4
2
0
PERCENT WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES
WIRE
BOLT
Zn
Fe

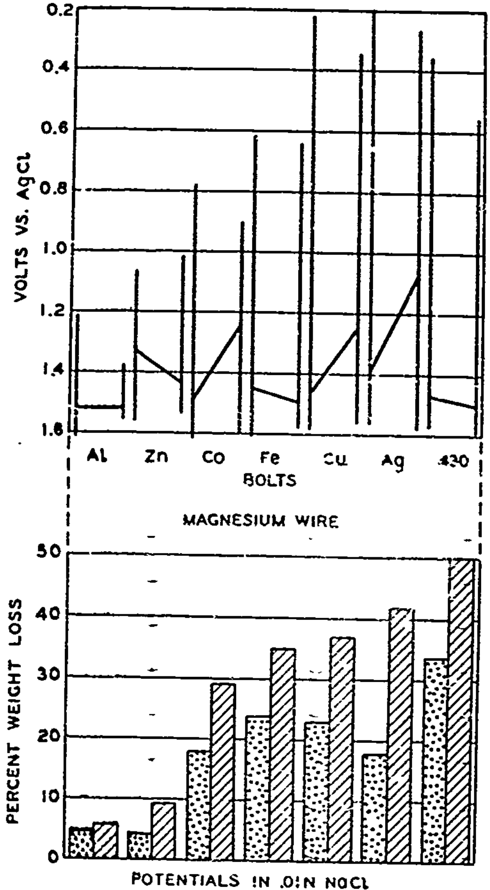
F G 1



POTENTIALS IN .01N NaCl
SPECIMENS EXPOSED AT POINT REYES

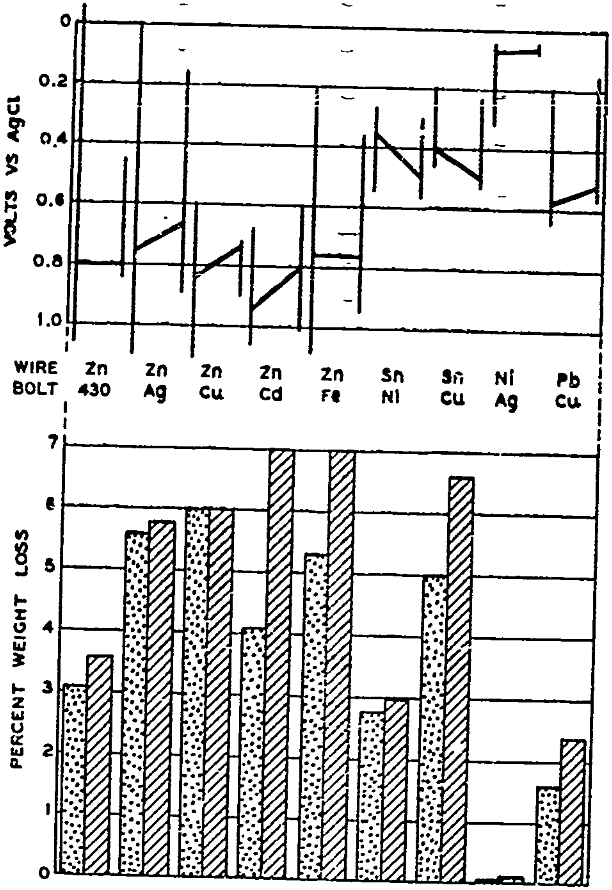
POTENTIALS AND WEIGHT LOSS OF GALVANIC COUPLES

FIG. 2



POTENTIALS AND WEIGHT LOSS OF GALVANIC COUPLES

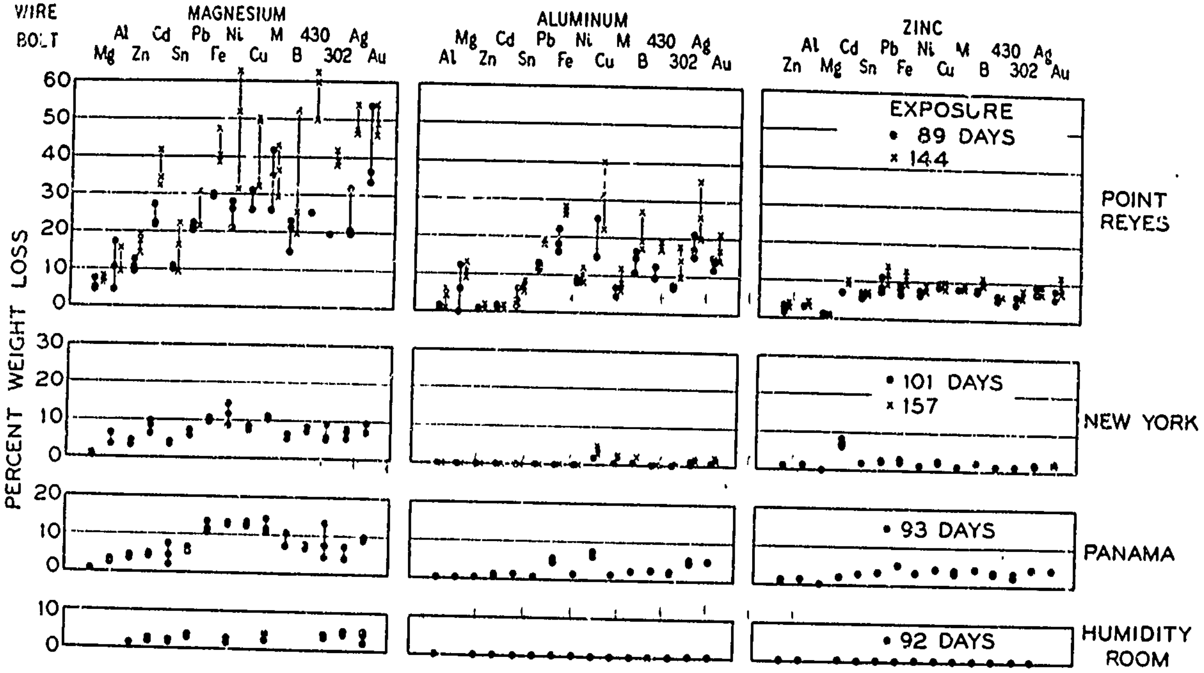
FIG. 3



POTENTIALS IN .01N NaCl
SPECIMENS EXPOSED AT POINT REYES

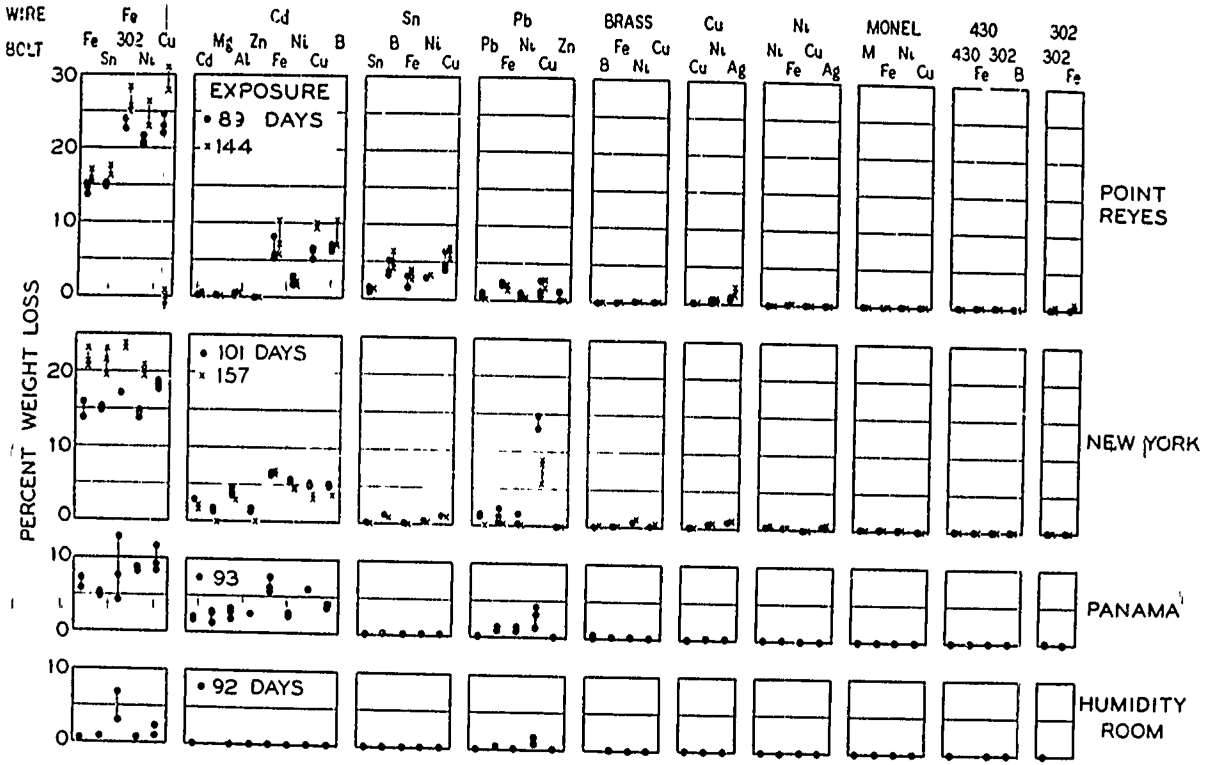
POTENTIALS AND WEIGHT LOSS OF GALVANIC COUPLES

FIG. 4



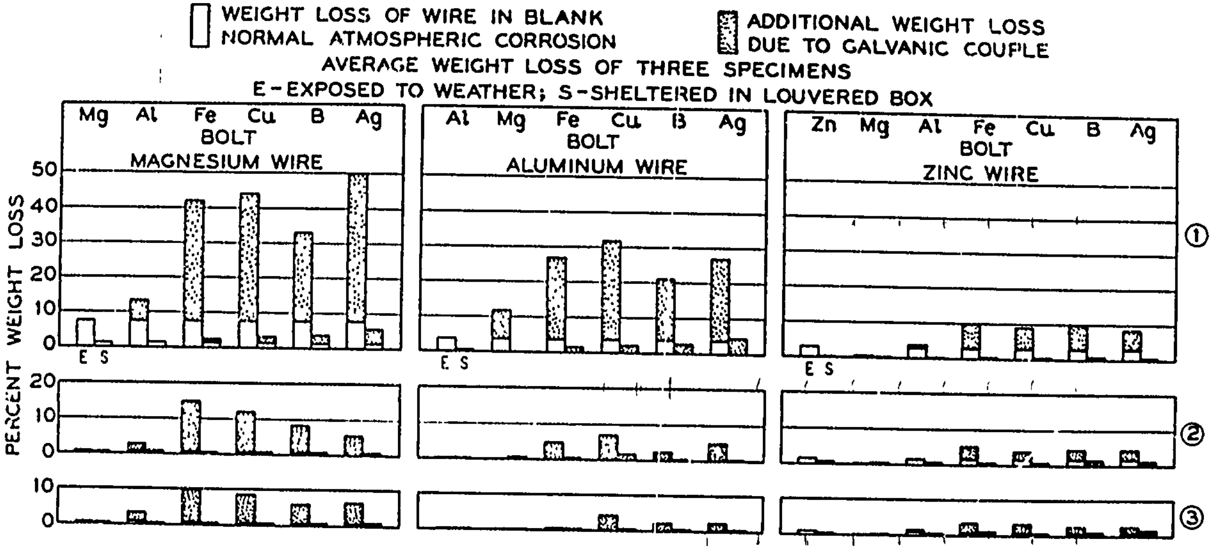
WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

FIG. 5



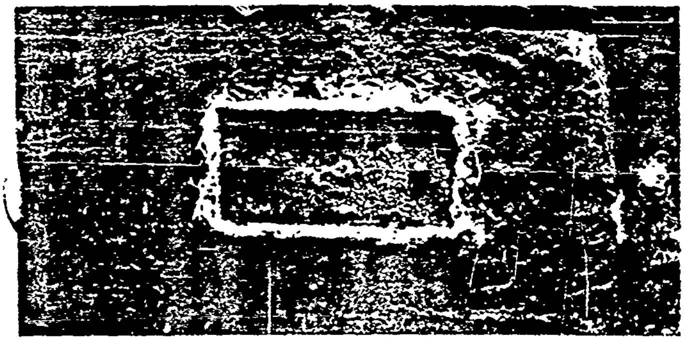
WEIGHT LOSS OF WIRES IN BOLT AND WIRE COUPLES

FIG. 6



EFFECT OF SHELTER ON WEIGHT LOSS OF GALVANIC COUPLES
① POINT REYES
② PANAMA
③ NEW YORK

FIG. 7



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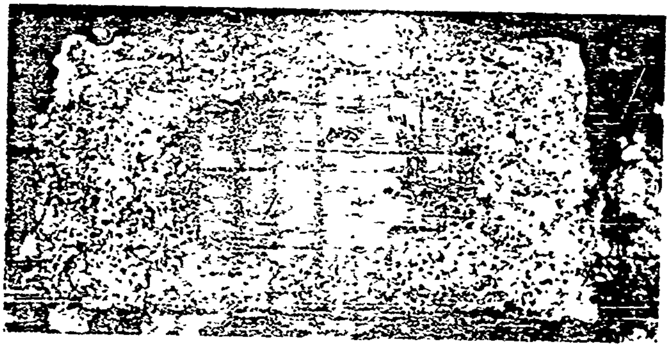
PAINTED COUPLE SHOWING CORROSION AT COUPLE JUNCTION AND BLISTERING OF PAINT.



COUPLE WITH LOOSE PAINT REMOVED, SHOWING DEEP GROOVE AT COUPLE JUNCTION AND PITTING WHERE PAINT WAS BLISTERED.

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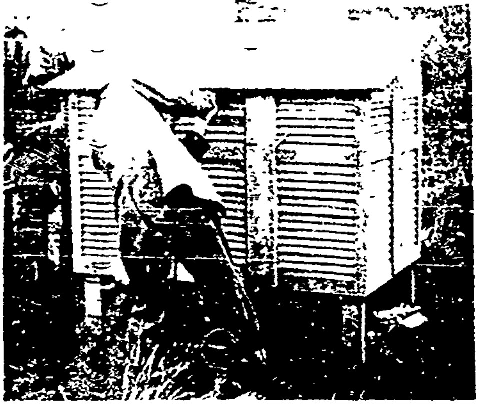
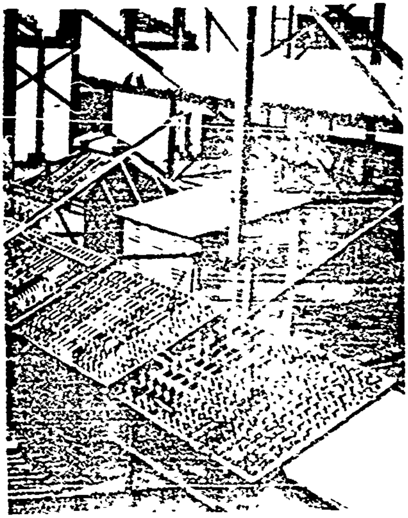
FIGURE 8

SHELTER BEFORE
SHIPMENT TO PANAMA



SHELTER INSTALLED AT POINT REYES



SHELTER INSTALLED ON NEW YORK ROOF

SHELTERS

FIGURE 9