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Progress Report on the Corrosion and Stress Corrosion Behavior of Selected Stainless Steels in Soil Environments

Part II. Stress Corrosion and Electrochemical Behavior

W. F. Gerhold, E. Escalante, W. P. Iverson, and B. T. Sanderson

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Prepared for
Committee of Stainless Steel Producers
American Iron and Steel Institute
150 East 42nd Street
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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A. INTRODUCTION

Stainless steels have been successfully used in limited applications (such as for pipe clamps for cast-iron sewer lines) in soil environments for many years. In recent years, other applications in use or under test, include ground rods, transformer cases, submerged switches, underground residential distribution equipment, gas lines, [1,2] water lines, caskets, culverts, residential sewage disposal, etc. Corrosion data for selected annealed, unstressed austenitic and ferritic stainless steels, buried in various soils, have been reported in NBS Circular 579 [3]. Branch [1] and Steinmetz and Hoxie [2] have reported on the suitability of stainless steel alloys for some underground uses.

NBS tests conducted for 14 years in various soils in the United States showed that austenitic Type 304 (containing Ni) and the Type 316 (containing Ni and Mo) stainless steels were highly resistant to both pitting and general attack. Type 304 was susceptible to pitting corrosion in certain highly aggressive soils, while Type 316 was relatively unaffected by corrosion. The ferritic stainless steels, Type 410 (12% Cr) and Type 430 (17% Cr) were found to be fully resistant to corrosion in only one-third of those NBS soil test sites where exposed.

Stress corrosion cracking had not been reported to be a problem with Types 304 or 316 in actual underground applications. [1]

In order to evaluate more fully the corrosion and stress corrosion behavior of some of the alloys proposed for use in soil environments, NBS in cooperation with the American Iron and Steel Institute initiated in 1970 a soil burial program in representative corrosive soils utilizing 9 stainless steels, in both the annealed and cold-worked conditions, with various treatments. Test specimens incorporated welds, crevices, galvanic couples, and specimens which had been sensitized to induce carbide precipitation. In 1971 and in 1972, this program was expanded to include additional stainless steels.

The results obtained from field tests conducted to determine the general corrosion behavior of materials buried up to 2 years were given in Part I [4] of this report. This report (Part II) contains the results obtained from tests conducted to determine the stress corrosion and electrochemical behavior of the stainless steels.

B. EXPERIMENTAL PROCEDURE

1. Soils at NBS Test Sites. The soils at the 6 NBS Soil Corrosion

Test Sites have been fully described in Part I [4] of this report. Some of the properties of these soils are given in Table I.

2. Materials, Treatment, and Preparation. In order to simulate some of the conditions which may exist with components fabricated from stainless steels, materials for these soil studies included stressed and unstressed galvanically coupled specimens and stressed non-welded and welded specimens.

A description of all of the various stainless steel systems buried at each test site is given in Table II. This report contains the results obtained from the evaluation of specimens from Systems Nos. 20 through 42 and 67 through 92 after exposure for up to 2 years. The evaluation of specimens from the remaining systems was covered in Part I. [4]

Upon receipt of the materials from the stainless steel companies, the 1" x 12" sheet specimens were first stamped with identification numbers at one end using chromium plated steel dies. All of the specimens were supplied with sheared edges which had been deburred. In some instances, further deburring was necessary.

All of the sheet materials to be stressed as either single or double U-bends had oblong holes 1/4" x 1/2" punched near each end so as to be self-aligning after bending. Specimens to be connected to a dissimilar metal (galvanic couples) had an additional hole (0.093") drilled 1/4" from the end and side for wire connections.

The specimens to be stressed were initially bent in a die (shown in Figure 1) to about 20° (internal angle). The only portions of the die in contact with the specimens were fabricated from Type 304 stainless steel.

All of the stainless steel alloy specimens, both stressed and unstressed, were then degreased in trichlorethylene vapor and passivated in accordance with the treatments given in Table II. Following the passivation procedure, the specimens were scrubbed with a bristle brush, thoroughly rinsed with water, and air dried.

Single U-bend specimens were formed by bending the two ends in a wooden jig so that they were parallel (the inside diameter at the bend was approximately 1") and clamping them in this position with a Type 316 stainless steel nut and bolt. Double U-bend specimens for the crevice corrosion studies were formed in the same manner except that the two strips were bolted together prior to the bending operation. The welded double U-bend specimens were spot welded at an area centrally located from the edges and ends (Figure 2). They were then bent together to form the U and clamped at the ends with Type 316 stainless steel fasteners.

In those systems connected to steel (iron), zinc, or magnesium anodes or to copper for galvanic couple studies, 14 gauge stranded copper wire was used to make the connections to the specimens. The connections were soldered with 50-50 acid core solder. These areas, including portions of the exposed copper wire, were then covered with a bituminous coating (coal-tar epoxy).

The iron anode consisted of a 12" length of cold finished steel (AISI 1017-1018) 3/4" hexagonal shaped rod with a hole drilled in the rod mid-way between each end for the electrical connection.

The magnesium anode (48" long, bent in the form of a horseshoe) was of the commerical flexible extruded type with a cross-sectional area 3/4" x 3/8" and a continuous centrally located 1/8" diameter iron wire core. The copper stranded wire was soldered to a 1" extension of the iron wire core using a 50-50 acid core solder. A bituminous coating was applied to the exposed copper and iron surfaces at the connection and to both 3/4" faces of the anode to extend its effective life.

The zinc anode (12" long) was also of the commercial flexible extruded type with a diamond shaped cross-section (5/8" x 7/8") and a continuous centrally located 0.1" diameter zinc coated (galvanized) wire core. The stranded copper wire was soldered to an extension of the galvanized wire core and coated as in the case of the magnesium anode.

Copper strips which were electrically coupled to the stainless steel specimens were cut from cold-rolled copper sheet, 0.065" thick and of the same dimensions as the stainless steel specimens (1" x 12").

3. Exposure. Specimens were buried at each test site about 1 foot apart in trenches approximately 2 feet wide x 2-1/2 feet deep. The U-bend specimens were connected with nylon cord looped around the bolts at one foot intervals to facilitate recovery. The specimens electrically connected to the steel and zinc anodes and to the copper strips were placed with the dissimilar metal parallel to the specimens and separated by approximately 1 foot. Specimens electrically connected to the horseshoe shaped magnesium anodes were placed at the center of the horseshoe. Upon backfilling the trenches, the insulated wires soldered to those specimens to be used in potential and corrosion current (couple corrosion) determinations were connected above ground to terminal strips mounted on 4" x 4" x 6' wooden posts. Leads from the anodes and copper strips were connected to leads from the specimens at the terminal strips (potential and current measurements).

Sufficient specimens were buried at each of the 6 test sites to permit recovery of a complete set at specified intervals (1, 2, 4, and 8 years) and a final set to be removed at a date to be determined. Each set for each removal consisted of two specimens.

4. Electrochemical Measurements. All electrochemical measurements (potential, couple current, and corrosion current) were made initially and 3 times a year when possible with the exception of Site A where measurements were usually made once a year.

Electrochemical potentials of the specimens and couples *vs.* a Cu-$CuSO_4$ half cell were measured using a high precision portable pH meter as a millivoltmeter. The half cell was placed in a remote area (usually at the edge of the test area) and shielded from the light to prevent photochemical effects.

The couple currents of the anode systems and the stainless steel-copper systems were measured using a zero impedance circuit employing an operational amplifier (Figure 3) for small currents and a commercially available zero resistance ammeter for larger currents.

Corrosion currents were measured using a modification of the linear polarization technique based on the following relationship derived by Stern and Geary [5]:

$$\frac{\Delta E}{\Delta I} = \frac{1}{2.31\ I_{corr}} \frac{B_a B_c}{B_a + B_c}$$

where ΔE is the overvoltage of the corroding specimen produced by a polarizing current, ΔI. B_a and B_c are the slopes of the anodic and cathodic polarization curves, respectively, in the Tafel region and I_{corr} is the corrosion current. Assuming B_a and B_c equal to 0.1 V in this investigation (the error will usually be about 20% or less, as established by Stern and Weisert [6]), the following equation was derived:

$$I_{corr}\ (mA) = \frac{2.7 \Delta I (mA)}{\Delta E (mV)}$$

The electrical circuit described previously, [7] but minus the bridge circuit was employed. A soil auger was utilized as the auxiliary electrode. The change in potential was measured directly, using the pH meter or an electrometer (0-10 mV scale) plus a battery and variable resistor (to null the initial potential) and a Cu-$CuSO_4$ reference electrode. Electrodes (auxiliary and reference) were placed so that the specimen was between them or at approximately right angles to them. In making these measurements, an increment of current was applied to the specimen until a stable over potential of usually 2 to 10 mV occurred. The potential and current readings were then recorded. Occasionally the open circuit potential of the stainless steel alloy was found to fluctuate and the corrosion current measurements could not be made. At other times, extremely humid or rainy conditions prevented these measurements.

C. RESULTS

1. Visual Examination. Upon removal from the test site, each of the stressed specimens was examined for indications of failure by cracking or fracture. All specimens were then returned to the laboratory for cleaning and a more thorough examination.

In the laboratory, the specimens were rinsed in tap water to remove adhering soil particles. They were then examined visually prior to further cleaning. The stressed U-bend specimens were then disassembled by removing the Type 316 stainless steel fasteners. The copper wires were unsoldered from those specimens that had been coupled to the magnesium, zinc, steel, and copper materials. All of the specimens were then cleaned ultrasonically using a 10% nitric acid solution, heated to 120 to 130°F for 20 to 30 minutes and then rinsed in distilled water and air dried.

2. General Corrosion Behavior. The results obtained from visual examination of the 300 series, the 400 series, and several proprietary stainless steel specimens, buried up to 2 years in the various soil environments, are given in Table III.

AISI 300 Series. With a few exceptions, there was little or no apparent visible corrosion noted on the stressed or unstressed stainless steel alloy specimens buried for up to 2 years in the soils at Sites A, B, and D.

Of the single U-bend specimens exposed for 2 years at Site C, the only systems on which little or no corrosion was observed were the Type 301 (full-hard), Type 304 (full-hard), and the Type 316 (annealed). Similarly, except for crevice areas, there was little or no degradation from corrosion on the Type 301 (full-hard) or the annealed Type 304 and Type 316 spot-welded double U-bend stainless steel specimens. The unstressed Type 304 (annealed) specimens that were coupled to copper were also unaffected by corrosion after exposure for 2 years at this site.

Of the stressed single U-bend specimens exposed at Site E for 2 years, the only systems which appeared to be relatively unaffected by corrosion were the non-coupled annealed Type 316 and those annealed Type 304 alloy specimens coupled to zinc, magnesium, or carbon steel. There was also no apparent corrosion noted on the annealed Type 316 spot-welded double U-bend specimens exposed at this site.

With the exception of the non-coupled annealed Type 316 and the full-hard Type 301 single U-bend specimens, all of the specimens exposed at Site G were affected in varying degrees by corrosion.

400 Series. Materials in this series included in this investigation were the Type 434 and the Type 409 stainless steels. Of these, the Type 434 was exposed in the stressed condition (single U-bend and spot-welded double U-bend specimens), while the Type 409 was galvanically coupled to copper and exposed in the unstressed condition.

The Type 434 was relatively unaffected by corrosion at Sites A, B, and D. However, pitting and tunneling corrosion was noted at crevice areas on one of the spot-welded double U-bend specimens that had been buried for 2 years at Site A. Pitting corrosion was noted on stressed specimens exposed at Sites C and G for 2 years, while pitting and tunneling corrosion was noted on the specimens exposed at Site E.

Corrosion in the form of pitting, etching, or general attack was observed on unstressed Type 409 specimens coupled to copper and exposed at Sites A, C, D, E, and G. Similar specimens at Site B were relatively unaffected by corrosion after exposure for 2 years.

Proprietary Alloys. Materials included in this portion of the investigation may be grouped as follows according to major alloying constituents:

1. Cr-Ni Stainless Steels

   18 Cr-8Ni(N)
   26Cr-6.5Ni
   20Cr-24Ni-6.5Mo

2. Cr Stainless Steels

26Cr-1Mo
18Cr-2Mo

In general, these alloys were relatively unaffected by corrosion in any of the soil environments. Corrosion, where noted, (See Table III) was generally very localized and superficial.

3. Stress Corrosion Behavior. The results of visual and micro examinations, made to determine failure of the various systems due to stress corrosion cracking, are given in Table IV for non-galvanically coupled specimens and in Table V for stressed galvanically coupled specimens. It may be noted that many of the specimens contained microcracks. While cracking of these specimens could not be ascertained without optical means, these specimens were considered to have failed.

Non-Galvanically Coupled Stressed Specimens

300 Series. Examination of Type 301 in the half-hard condition, after exposure for 2 years in the various soils, indicated that the alloy was susceptible to stress corrosion cracking in the acid clay at Site C. Microcracking was observed on 1 specimen exposed for 2 years at this site. Sensitization of the half-hard alloy increased the susceptibility to stress corrosion cracking in all of the soil environments, particularly at Sites C, D, and E, where all of the specimens had failed. The same alloy exposed in the full-hard condition had not failed after 2 years in 5 of the 6 soil environments. Microcracks were noted at the edge on 1 of the spot welded double U-bend specimens exposed in tidal marsh (Site G). No failures were noted for the Type 304 specimens exposed in the half-hard condition. Sensitized Type 304 specimens buried in the acid clay at Site C were found to be susceptible to stress corrosion cracking. Similar specimens exposed in the other soil environments did not fail. Type 316 stainless steel did not fail in any of the soils in which it was exposed and sensitization of this alloy did not appear to affect its stress corrosion behavior.

AISI 400 Series. Type 434 stainless steel was the only alloy in this series exposed in the soils. There were no apparent failures of this alloy in any of the soil environments.

Proprietary Stainless Steels. Alloys in this category included 26Cr-1Mo, 18Cr-2Mo, 20Cr-24Ni-6.5Mo, 18Cr-8Ni(N), and 26Cr-6.5Ni. There were no apparent failures of stressed specimens of these alloys after exposure for 2 years in any of the soil environments.

Galvanically Coupled Stressed Specimens

There were no apparent failures of the Type 304 (full-hard), 26Cr-1Mo (annealed), or 26Cr-6.5Ni (annealed) stainless steels that were coupled to zinc, magnesium, or carbon steel after exposure up to 2 years in the 6 soil environments.

Type 301 (half-hard) specimens that were coupled to carbon steel and exposed for two years at Site C had failed. Type 301 (full-hard) specimens coupled to carbon steel failed in one year at Site C and 2 years at Site G. No failures were observed for Type 301 (half-hard or full-hard) specimens exposed at the other sites.

Failures were noted on all of the Type 301 (half-hard and full-hard) specimens coupled to magnesium and exposed for one and two years at Sites B, C, D, E, and G. At Site A one specimen exposed for one year and one specimen exposed for two years had not failed while other specimens exposed at this site for one and two years did fail.

No failures were noted on Type 301 (half-hard) specimens coupled to zinc and exposed at Site A for one and two years or at Site B for one year. One of the two specimens exposed at Site B for two years had failed. Of the specimens at Site D, failures were noted on one each after exposure for one and two years. All of the specimens galvanically coupled to zinc and exposed for one and two years at Sites C, E, and G had failed.

There were no failures of Type 301 (full-hard) specimens coupled to zinc and exposed at Site A for one year, but after exposure for two years one specimen had failed. Failures were noted on all of the Type 301 (full-hard) specimens galvanically coupled to zinc and exposed for one and two years at Sites B, C, D, E, and G.

4. Electrochemical Behavior. All of the results given in this section pertaining to the electrochemical behavior of the stainless steels galvanically coupled to dissimilar metals refer to materials still buried in the soils at the 6 test sites. Further, the results are based solely on data gathered *in situ* through electrochemical means (i.e., couple currents, and potentials). This should be considered when comparing these results with visual observations previously given for materials removed from the soils after exposure for 2 years.

Galvanic Couples

Unstressed Stainless Steel Alloys vs. Copper. The direction of current flow between two dissimilar metals, such as stainless steel coupled to copper, indicates which of the materials is corroding (or which of the two is anodic), while the magnitude of the current gives an indication of the degree of corrosion.

Measurements obtained for a particular stainless steel coupled to copper indicates that the couple current may fluctuate through zero from time to time or remain consistently positive or negative. An illustration of these conditions is given in Figure 4, which shows the magnitude of the couple current and its direction as a function of time for one of the systems buried at the six test sites.

Table VI gives the couple current data obtained for the unstressed stainless steel specimens coupled to copper at each of the six test sites. For purposes of brevity, only the maximum current at either condition of polarity is given. Where only one value is given, there was no observed current reversal. Thus, Type 304 stainless steel specimen 91-10 was cathodic to copper at Site A throughout the 2-year period with a maximum current of 193 μA. The current for a similar specimen exposed at Site E fluctuated from anodic to cathodic with maximum current of 46 and 56 μA respectively. These fluctuations can be seen in Figure 4.

From the data given in Table VI it can be seen that Type 304 is predominantly cathodic to copper at Sites A, B, and C with Site C being somewhat on the border line. At Sites D and E, the direction of the current varies from specimen to specimen. For specimens exposed at Site G, Type 304 was found to be anodic to copper.

Type 409 stainless steel appeared to be predominantly anodic at Site A and at Site B (to a lesser degree than at Site A). At Sites C, E, and G, Type 409 tended to be anodic with relatively high currents. Type 409 coupled to copper was variable in the soil at Site D and could be either anodic or cathodic.

Alloy 26Cr-6.5Ni connected to copper produced very low couple currents. At Site B, initial couple current measurements indicated that this alloy was anodic to copper. Within 4 months, the situation was reversed with the result that the alloy was protected by the copper. This effect is not evident from the data given in Table VI. At Site C Alloy 26Cr-6.5Ni was cathodic initially but then became anodic to the copper and generally remained that way. At Site D, the couple currents were low and uncharacterized. The behavior of Alloy 26Cr-6.5Ni was similar at Sites E and G in that the alloy was in general cathodic to copper. One exception was noted for one specimen exposed at Site G which switched from a cathode to an anode without further change.

Stressed Stainless Steel Alloys vs. Magnesium, Zinc, or Carbon Steel. While the connection of some stainless steels to copper may possibly result in general corrosion or pitting corrosion of the stainless steel, other stainless steel galvanic couples may fail by different mechanisms. Hydrogen embrittlement as a result of cathodic protection of the stainless steel is one example. To evaluate the susceptibility of various stainless steels to this form of failure, stressed specimens were connected to 3 types of anodes (magnesium, zinc, and steel) which produced 3 ranges of potentials (1.5 V, 1.1 V, and 0.7 V vs. Cu-$CuSO_4$ respectively). In addition, similar specimens, not coupled, were also included in this study as controls which may or may not give an indication of other modes of failure such as stress corrosion cracking. Table VII gives the average couple currents for specimens still buried and the number of failures of similar specimens observed after exposure for 2 years in the 6 soil environments.

Type 301 in the half-hard or full-hard condition was found to be susceptible to cracking at the higher current densities. All of the Type 301 specimens coupled to magnesium had failed after exposure for 2 years regardless of the soil environment in which they were buried. With a few exceptions, most of the Type 301 specimens coupled to zinc had also failed while most of the specimens coupled to the carbon steel had not failed. Similar uncoupled specimens were nearly completely resistant to cracking in all of the soil environments (Table VI). There appears to be a clear correlation between current density and susceptibility to cracking of this alloy.

Alloys 18Cr-8Ni(N), 26Cr-1Mo and 26Cr-6.5Ni appeared to be completely resistant to cracking whether coupled to a dissimilar metal or not.

Stressed Stainless Steel Alloys (Non-Coupled). The corrosion current for each of 10 different stainless steels was measured at approximately 4-month intervals over a period of 2 years. Four stressed specimens of each material were evaluated at each site. The resulting average current obtained for these stainless steels is shown in Table VIII. Throughout the two years, fluctuations in corrosion occurred and are reflected in the table as a maximum and minimum corrosion current for each type of material. The measured corrosion current gives an indication of the degree of electrochemical dissolution occurring at the specimen. This corrosion current will be correlated with the actual observed corrosion when these specimens are recovered and evaluated.

D. SUMMARY

In order to evaluate more fully the corrosion and stress corrosion behavior of stainless steels in soil environments, stressed and unstressed stainless steels were buried in 6 different soils. Test specimens incorporated welds, crevices, galvanic couples, and specimens which had been sensitized by heat treatment. The general corrosion behavior of unstressed and non-galvanically coupled specimens has been reported in Part I [4] of this paper. This report (Part II) gives the results obtained for non-galvanic coupled stressed specimens and galvanically coupled stressed and unstressed specimens buried up to 2 years in the soils.

1. Non-Galvanic Coupled Stressed Materials. In general, the corrosion behavior in the various soil environments was similar to that observed in Part I of this paper.

The austenitic (300 series) alloys, with a few exceptions, exhibited good resistance to stress corrosion cracking in all of the soil environments. One of the single U-bend Type 301 (half-hard) specimens buried in the acid clay (Site C) had failed after exposure for 2 years. Similarly one of the spot-welded double U-bend specimens buried in the tidal marsh (Site G) for 2 years had also failed. Sensitization of Type 301 (half-hard) induced failures in all of the soils, while sensitization of Type 304 resulted in failures of specimens exposed at Sites C and E (Coastal sand) only. No failures were observed on the Type 316 specimens buried in any of the soils for 2 years. Failure of the materials noted above is attributed to stress corrosion cracking.

Of the 2 stressed Type 434 ferritic systems included in this investigation, none had failed after exposure in the 6 soils for 2 years.

Similarly, there were no failures noted for any of the proprietary (Alloys 18Cr-8Ni(N), 26Cr-6.5Ni, 26Cr-1Mo, 18Cr-2Mo, and 20Cr-24Ni-6.5Mo) stainless steels.

2. Galvanically Coupled Stressed and Unstressed Materials. There was little or no apparent corrosion observed on the Type 304 alloy specimens coupled to copper after exposure for 2 years in 4 of the 6 soils. Unstressed Type 409 coupled to copper was completely unaffected by corrosion at Site B only. There was no apparent corrosion on any of the unstressed Alloy 26Cr-6.5Ni specimens galvanically coupled to copper and buried for 2 years in the various soil environments.

Of the stressed systems galvanically coupled to zinc, magnesium or steel, there were no apparent failures of Type 304 or of Alloys 26Cr-1Mo and 26Cr-6.5Ni in any of the soils. Type 301 in the half-hard condition when coupled to zinc was immune to cracking at Site A. No failures were observed on the Type 301 half-hard or full-hard specimens coupled to steel and buried at Sites A, B, D, and E. Specimens of this alloy in the half-hard condition had not failed after exposure for 2 years at Site G, but specimens in the full-hard condition exposed at this site for 2 years had failed.

In general, although some failures apparently due to hydrogen embrittlement were noted on stressed specimens, there appeared to be little or no appreciable degradation of the systems buried for 2 years in the soils at Sites A, B, and D. Pitting and/or general corrosion was noted on many of the systems exposed at Sites C, E, and G.

3. Electrochemical Measurements. Based on electrochemical measurements obtained from specimens still buried in the various soils, the Type 304 alloy appeared to be cathodic to copper at Sites A, B, and C and anodic to copper at Site G. At Sites D and E, it varied from specimen to specimen (being anodic on one and cathodic on another). Type 409 stainless steel appeared to be predominantly anodic to copper at Sites A and B and anodic with relatively high corrosion currents at Sites C, E, and G. At Site D it was variable and could be either anodic or cathodic to the copper. Alloy 26Cr-6.5Ni was initially anodic to copper at Site B, but had reversed in less than 4 months to being cathodic to copper. At Site C the alloy was cathodic initially but became anodic to the copper and remained that way. In general, at Sites E and G, the alloy was cathodic to copper.

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Table I. Properties of Soils at Test Sites.

Site Iden	Soil	Location	Internal Drainage of Test Site	Resistivity[a] (ohm - cm)	pH	TDS[b]	Ca	Mg	Na + K as Na	CO_3	HCO_3	So_4	Cl	NO_3
						Composition of Water Extract (Parts per Million)								
A	Sagemoor sandy loam	Toppenish, Wash.	Good	400	8.8	7,080	108	23	1,960	0.0	5,002	216	330	6
B	Hagerstown loam	Loch Raven, Md.	Good	34,760	5.3	(c)	-	-	-	-	-	-	-	-
C	Clay	Cape May, N.J.	Poor	770	4.3	14,640	540	754	2,242	0.0	0.0	6,768	3,529	118
D	Lakewood sand	Wildwood, N.J.	Good	45,700	5.7	(c)	-	-	-	-	-	-	-	-
E	Coastal sand	Wildwood, N.J.	Poor	27,200	7.1	11,020	302	329	3,230	0.0	55	1,133	5,765	31
G	Tidal marsh	Patuxent, Md.	Poor	5,300	6.0	11,580	140	165	2,392	0.0	0.0	1,709	3,259	37
						(Milligram equivalents per 100 grams of soil)								
A	-	-	-	-	-	-	0.54	0.19	8.50	0.0	8.20	0.45	0.93	0.01
B	-	-	-	-	-	(c)	-	-	-	-	-	-	-	-
C	-	-	-	-	-	-	2.70	6.18	9.51	0.0	0.0	14.0	9.94	0.19
D	-	-	-	-	-	(c)	-	-	-	-	-	-	-	-
E	-	-	-	-	-	-	1.51	2.70	13.9	0.0	0.09	2.36	16.2	0.05
G	-	-	-	-	-	-	0.70	1.35	10.2	0.0	0.0	3.56	9.18	0.06

(a) Resistivity determinations made at the test site by Wenner's 4-pin method except for Site A where Shepard's cane was used.

(b) TDS, total dissolved solids - residue dried at 105°C.

(c) Analysis not made for soils at Sites B and D because of the very low concentration of soluble salts in these soils.

Table II. Stainless Steel Systems in Underground Corrosion Tests[a]

System	Burial Year	Stainless Steel	Spec. Config. & Size*	Treatment+	Passivation° Procedure	Stressed●	Spec. Coupled To
1	1971	26 Cr-1 Mo	Sheet (8"x12")	--	I	--	--
2	"	18 Cr (Ti)	" "	--	I	--	--
3	"	"	" "	XBW	I	--	--
4	"	20 Cr-24 Ni-6.5 Mo	" "	--	I	--	--
5	"	"	" "	S	I	--	--
6	"	18 Cr-2 Mo	" "	--	I	--	--
7	1972	18 Cr-2 Mo (Nb)	" "	--	I	--	--
8	1971	18 Cr-8 Ni(N)	" "	--	I	--	--
9	"	"	" "	XBW	I	--	--
10	"	26 Cr-6.5 Ni	" "	--	I	--	--
11	1972	18 Cr-2 Mo (Nb)	" "	XBW	I	--	--
12	"	"	Tube (2" ODx12")	HW	I	--	--
14	1971	Composite A	Sheet (8"x12")	--	--	--	--
15	"	Composite B	" "	--	--	--	--
16	"	Composite C	" "	--	--	--	--
17	"	26 Cr-1 Mo	Tube (2" ODx12")	HW	I	--	--
18	"	18 Cr (Ti)	(1 1/8" ODx12")	HW	I	--	--
19	"	20 Cr-24 Ni-6.5 Mo	(7/8" ODx12")	HW	I	--	--
20	"	26 Cr-1 Mo	Sheet (1"x12")	--	I	(UU)	--
21	"	"	" "	--	I	U	--
22	"	20 Cr-24 Ni-6.5 Mo	" "	--	I	(UU)	--
23	"	"	" "	--	I	U	--
24	"	"	" "	S	I	UU	--
25	"	18Cr-2Mo	" "	--	I	(UU)	--
26	"	"	" "	--	I	U	--
27	"	18 Cr-8 Ni(N)	" "	--	I	(UU)	--
28	"	"	" "	--	I	U	--
30	"	26 Cr-6.5 Ni	" "	--	I	U	--
33	"	26 Cr-1 Mo	" "	--	I	U	Zn
34	"	"	" "	--	I	U	Mg
35	"	"	" "	--	I	U	Fe
36	"	26 Cr-6.5 Ni	" "	--	I	U	Zn
37	"	"	" "	--	I	U	Mg
38	"	"	" "	--	I	U	Fe
42	"	"	" "	--	I	--	Cu
50	1970	201	Sheet (8"x12")	--	I	--	--
51	"	202	" "	--	I	--	--
52	"	301	" "	--	I	--	--
53	"	"	" "	S	I(g)	--	--
54	"	"	" "	XBW	I	--	--
55	"	304	" "	--	I	--	--
56	"	"	" "	S	I(g)	--	--
57	"	"	Tube (2" ODx12")	HW(b)	I	--	--
58	"	316	Sheet (8"x12")	--	I	--	--
59	"	"	" "	S	I	--	--
60	"	409	" "	--	III	--	--
61	"	"	" "	C	--	--	--
62	"	"	Tube (1-1/8" ODx12")	HW	III	--	--
63	"	"	Tube (7/8" ODx12")	HFW	III	--	--
64	"	410	Sheet (8"x12")	--	III	--	--
65	"	430	" "	--	II	--	--
66	"	434	" "	--	I	--	--
67	"	301	Sheet (1"x12")	HH	I	U	--
68	"	"	" "	HH	I	(UU)	--
69	"	"	" "	HH+S	I(g)	UU	--
70	"	"	" "	FH	I	U	--
71	"	"	" "	FH	I	(UU)	--
72	"	304	" "	--	I	U	--
73	"	"	" "	--	I	(UU)	--
74	"	"	" "	HH	I	U	--
75	"	"	" "	HH	I	(UU)	--
76	"	"	" "	S	I(g)	UU	--
77	"	316	" "	--	I	U	--
78	"	"	" "	--	I	(UU)	--
79	"	"	" "	S	I(g)	UU	--
80	"	434	" "	--	I	U	--
81	"	"	" "	--	I	(UU)	--
82	"	301	" "	HH	I	U	Zn
83	"	"	" "	HH	I	U	Mg
84	"	"	" "	HH	I	U	Fe
85	"	"	" "	FH	I	U	Zn
86	"	"	" "	FH	I	U	Mg
87	"	"	" "	FH	I	U	Fe
88	"	304	" "	--	I	U	Zn
89	"	"	" "	--	I	U	Mg
90	"	"	" "	--	I	U	Fe
91	"	"	" "	--	I	--	Cu
92	"	409	" "	--	III	--	Cu

* All sheet and tube specimens 0.064" thick.
+ All specimens in the annealed condition unless noted otherwise.
(a) Systems 1-19, 50-66, covered in this report.
(b) Welded with a full finish per ASTM Specification A249.

Table II. (Cont'd)

Key:
S - Sensitized (by heating at 1200°F for 2 hours, followed by air cooling and descaling in sodium hydroxide);
XBW - Cross bead weld (specified to be done in accordance with Welding Research Council recommendations. On half of these specimens, the welds were cleaned prior to exposure. The other half of the specimens were to be exposed "as welded."
HW - Heliarc weld,
HFW - HFW High frequency weld;
C - Coated;
HH - Half hard;
FH - Full hard.

°Key:
-- = Unstressed;
U = Single U-bend specimen;
UU = Double U-bend specimen, no spot weld;
(UU) = Double U-bend specimen joined by spot weld.

°Passivation procedure:

I. 20 to 40% by volume of 67% nitric acid at 120-160°F for 20-30 minutes.
II. 20% by volume of 67% nitric acid plus 2-6% sodium dichromate at 110-140°F for 20-30 minutes.
III. 20 to 40% by volume of 67% nitric acid at 110-140°F for 20-30 minutes.
(g) Minimum specified concentration of acid, temperature and time for sensitized materials.

Table III. Summary of results obtained from visual examination of 1" x 12" stressed and unstressed specimens exposed for up to two years in various soil environments.

System	Stainless Steel	Treatment	Type of Specimen	Coupled to	Test Site	Exposed 1 yr (a) Exposed surfaces	Exposed 1 yr (a) Crevice areas	Exposed 2 yrs (a) Exposed surfaces	Exposed 2 yrs (a) Crevice areas
Exposed in 1970									
67	Type 301	Half-hard	U	--	A	N	--	N	--
					B	N	--	IP	--
					C	N	--	A (E,mod), P	--
					D	N	--	N	--
					E	N	--	IF	--
					G	Et (sli)	--	IP	--
68	Type 301	Half-hard	(UU)	--	A	N	N	N	N
					B	N	N	N	N
					C	N	N	P,IP	T (E), P
					D	N	N	N	N
					E	RS	N	Et (sli), IP	T
					G	N	Et	P (E)	Et (sev)
69	Type 301	Half-hard	UU	--	A	N	N	RS, IP	RS
					B	Et (sli)	N	Et (sli)	IF
					C	Et (sev), P	N	A (sev), P	P (E), Et (sli)
					D	Et, P	N	RS, P	RS, Bl, IP
					E	N	N	P, A, IP, RS	RS, P, IP
					G	Et (sev)	N	P, IP, RS	A (sev), P, IP
70	Type 301	Full-hard	U	--	A	N	--	N	--
					B	N	--	N	--
					C	N	--	N	--
					D	N	--	N	--
					E	N	--	T	--
					G	N	--	N	--
71	Type 301	Full-hard	(UU)	--	A	N	N	N	N
					B	N	N	N	IR
					C	A (E)	N	N	P (AW)
					D	N	N	N	N
					E	N	P (W)	T, P (W, AW)	P, Et, RS, T
					G	Et (sli), P (E, W)	A (sev), P (AW)	A (E), P, IP	P, IP, A (mod)
72	Type 304	--	U	--	A	N	--	N	--
					B	N	--	IP	--
					C	P (E)	--	A (sev), P, IP	--
					D	N	--	N	--
					E	AT	--	P, T, IP	--
					G	P	--	P, IP	--
73	Type 304	--	(UU)	--	A	N	N	N	N
					B	N	N	N	N
					C	Et	N	N	P, T
					D	N	N	N	N
					E	N	A	T	RS
					G	P	A	P (F, E), A (E), IP	P, IP, A
74	Type 304	Half-hard	U	--	A	N	--	N	--
					B	IF	--	N	--
					C	IP, A (E)	--	N	--
					D	N	--	N	--
					E	N	--	P, T, IP	--
					G	IP	--	P, A (sev), IP	--
75	Type 304	Half-hard	(UU)	--	A	N	Et (sli)	N	N
					B	N	Et (sli)	N	IP
					C	Et (sli)	Et (sli)	Et (sli)	P, Et, T
					D	N	Et (sli)	N	N
					E	Et (sli)	Et (sli)	T	P
					G	Et (sli)	A, P	P, IP	P, IP, A
76	Type 304	S	UU	--	A	Et	N	Et (sli)	Et (sli)
					B	Et (sli)	N	Et (sli)	Et (sli), IP
					C	Et (sli), P (E)	N	Et (sev), P, IP	A (sev), P, IP
					D	Et (sli)	N	N	N
					E	Et (sli)	N	H, A (E), P	Et (mod)
					G	N	IP	Et (sli), P, IP	Et (sli), P, IP
77	Type 316	--	U	--	A	N	--	N	--
					B	N	--	N	--
					C	N	--	IF	--
					D	N	--	N	--
					E	N	--	N	--
					G	N	--	N	--
78	Type 316	--	(UU)	--	A	N	N	N	N
					B	N	N	N	N
					C	N	N	N	IF
					D	N	N	N	N
					E	N	N	N	N
					G	N	N	P, IP	N

Table III. (cont'd.)

System	Stainless Steel	Treatment	Type of Specimen	Coupled to	Test Site	Exposed 1 yr (a) Exposed surfaces	Exposed 1 yr (a) Crevice areas	Exposed 2 yrs (a) Exposed surfaces	Exposed 2 yrs (a) Crevice areas
79	Type 316	S	UU	--	A	N	N	Et (sli)	N
					B	Et (sli)	N	N	N
					C	Et (sli), A (E)	N	A (E)	N
					D	Et (sli)	N	N	RS
					E	A (E)	N	A (E, sev), P	A (E), Et (sli)
					G	IP, Et (sli)	N	N	IP
80	Type 434	--	U	--	A	N	--	N	--
					B	N	--	N	--
					C	A (E)	--	P (F, E), IP	--
					D	N	--	N	--
					E	P, A (E)	--	P, T, IP	--
					G	IP	--	P	--
81	Type 434	--	(UU)	--	A	N	N	N	P, T
					B	N	N	N	N
					C	N	N	P (E)	P (E)
					D	IF	N	N	IF
					E	IF	A	P, T	P, Et (sli)
					G	P, A (E)	A	P (F, E), A (E), IP	P, IP
82	Type 301	Half-hard	U	Zn	A	N	--	N	--
					B	N	--	N	--
					C	N	--	Et (sli), P, IP	--
					D	N	--	RS	--
					E	A (E)	--	Et (sli)	--
					G	Et (sli), IP	--	P (E), IP	--
83	Type 301	Half-hard	U	Mg	A	N	--	N	--
					B	N	--	N	--
					C	N	--	P, IP, Et (sli)	--
					D	N	--	Et (sli)	--
					E	N	--	Et (sli), IP	--
					G	IP	--	P, IP	--
84	Type 301	Half-hard	U	Steel	A	N	--	N	--
					B	N	--	N	--
					C	IP	--	IP, P, Et (mod)	--
					D	N	--	N	--
					E	N	--	IF, IP	--
					G	N	--	P	--
85	Type 301	Full-hard	U	Zn	A	N	--	Et (sli)	--
					B	N	--	IP (E)	--
					C	N	--	P (F, E), IP, Et (sli)	--
					D	N	--	Et (sli)	--
					E	N	--	Et (mod)	--
					G	P, E	--	P (F,E), IP	--
86	Type 301	Full-hard	U	Mg	A	N	--	N	--
					B	N	--	N	--
					C	N	--	Et (sli), P (F, E), IP	--
					D	N	--	N	--
					E	N	--	IF	--
					G	E	--	P (F, E), IP (F, E)	--
87	Type 301	Full-hard	U	Steel	A	N	--	Et (sli), P	--
					B	N	--	N	--
					C	N	--	Et (sli), P, IP	--
					D	N	--	N	--
					E	N	--	Et (sli)	--
					G	P	--	P, IP	--
88	Type 304	--	U	Zn	A	N	--	N	--
					B	N	--	N	--
					C	N	--	P (E), IP, RS	--
					D	N	--	N	--
					E	N	--	N	--
					G	N	--	Et (mod), P, IP	--
89	Type 304	--	U	Mg	A	N	--	N	--
					B	N	--	N	--
					C	IF	--	P, IP	--
					D	N	--	N	--
					E	N	--	N	--
					G	Et (sli), IP	--	P, IP, Et (sli)	--
90	Type 304	--	U	Steel	A	N	--	N	--
					B	N	--	N	--
					C	IP, Et (sli)	--	P (F, E), IP	--
					D	N	--	N	--
					E	N	--	N	--
					G	N	--	P	--

Table III. (cont'd.)

System	Stainless Steel	Treatment	Type of Specimen	Coupled to	Test Site	Exposed 1 yr (a)		Exposed 2 yrs (a)	
						Exposed surfaces	Crevice areas	Exposed surfaces	Crevice areas
91	Type 304	--	Unstressed	Cu	A	N	--	N	--
					B	N	--	N	--
					C	IP	--	N	--
					D	Et (sli), IP	--	N	--
					E	N	--	Et, A	--
					G	Et (sev), P	--	P (E)	--
92	Type 409	--	Unstressed	Cu	A	Et, P	--	Et (sli), A, P (sev)	--
					B	Et	--	IF	--
					C	H (E), Et	--	P, Et (sev), IP	--
					D	IP	--	P, IP	--
					E	A (E)	--	A (sev), H	--
					G	A (sev)	--	P (E), Et (sli), IP	--
Exposed in 1971									
20	26 Cr- 1 Mo	--	(UU)	--	A	N	P	N	N
					B	N	N	N	N
					C	IP	IP	N	IF, RS, IP
					D	N	P, IP	N	N
					E	P	N	N	N
					G	N	N	N	IP
21	26 Cr- 1 Mo	--	U	--	A	N	--	N	--
					B	N	--	N	--
					C	N	--	RS, IF	--
					D	N	--	N	--
					E	N	--	N	--
					G	N	--	N	--
22	20 Cr-24 Ni-6.5 Mo	--	(UU)	--	A	N	N	N	N
					B	N	IP	IF	N
					C	N	N	N	RS, IF
					D	N	N	N	N
					E	N	N	N	N
					G	N	N	RS	RS
23	20 Cr-24 Ni-6.5 Mo	--	U	--	A	N	--	N	--
					B	N	--	N	--
					C	N	--	N	--
					D	N	--	N	--
					E	N	--	N	--
					G	N	--	N	--
24	20 Cr-24 Ni-6.5 Mo	S	UU	--	A	N	N	N	RS, IF
					B	N	N	N	N
					C	Et (sli)	Et (sli)	IP, RS	Et (sli)
					D	N	N	N	N
					E	IP	IP	N	N
					G	IP, Et (sli)	P, IP, Et	Et (sli), IP	N
25	18 Cr-2 Mo	--	(UU)	--	A	N	N	IF	IF
					B	N	RS (AW)	N	N
					C	N	N	N	IF, RS
					D	P, T	T	N	IF, RS (AW)
					E	IF	IF	IF, IP	N
					G	P, IP	P, IP, A (AW)	RS	N
26	18 Cr-2 Mo	--	U	--	A	N	--	N	N
					B	RS, IP (E)	--	N	N
					C	IP	--	RS	N
					D	N	--	N	N
					E	N	--	N	N
					G	P, IP	--	N	N
27	18Cr-8Ni(N)	--	(UU)	--	A	N	N	N	N
					B	N	N	N	N
					C	P, IP	RS	RS	IP
					D	N	N	N	N
					E	IF	IF	IF	RS
					G	N	N	N	RS (AW)
28	18Cr-8Ni(N)	--	U	--	A	N	--	N	--
					B	N	--	N	--
					C	IP	--	IF	--
					D	N	--	N	--
					E	N	--	N	--
					G	P, IP	--	P (E)	--

Table III. (cont'd.)

System	Stainless Steel	Treatment	Type of Specimen	Coupled to	Test Site	Exposed 1 yr (a) Exposed surfaces	Exposed 1 yr (a) Crevice areas	Exposed 2 yrs (a) Exposed surfaces	Exposed 2 yrs (a) Crevice areas
30	26 Cr-6.5 Ni	--	U	--	A	N	--	N	--
					B	IP (E)	--	N	--
					C	IP	--	P, IP	--
					D	N	--	N	--
					E	N	--	IF	--
					G	P, IP	--	N	--
33	26 Cr-1 Mo	--	U	Zn	A	N	--	N	--
					B	N	--	N	--
					C	P (F, E), IP	--	P	--
					D	RS, IP	--	RS	--
					E	N	--	N	--
					G	P (E)	--	P (E), RS	--
34	26 Cr-1 Mo	--	U	Mg	A	N	--	N	--
					B	N	--	N	--
					C	IP	--	Bl, RS	--
					D	N	--	RS	--
					E	Bl	--	Bl	--
					G	P, IP	--	RS, IP	--
35	26 Cr-1 Mo	--	U	Steel	A	N	--	Et (sli)	--
					B	N	--	N	--
					C	ET (sli), IP	--	Et, P, IP	--
					D	N	--	N	--
					E	N	--	N	--
					G	IF	--	IP, RS	--
36	26 Cr-6.5 Ni	--	U	Zn	A	N	--	N	--
					B	N	--	N	--
					C	IP	--	Et, P, IP	--
					D	N	--	N	--
					E	N	--	Et (sli)	--
					G	P (F, E), IP	--	P (E), IP, Et (sli)	--
37	26 Cr-6.5 Ni	--	U	Mg	A	Et (sli)	--	N	--
					B	N	--	N	--
					C	P (F, E), IP	--	Bl, P, IP	--
					D	N	--	N	--
					E	IP	--	N	--
					G	P (F, E), IP	--	P, IP	--
38	26 Cr-6.5 Ni	--	U	Steel	A	P	--	N	--
					B	P	--	N	--
					C	P (F, E), IP	--	P, IP	--
					D	N	--	N	--
					E	N	--	P	--
					G	P (F, E), IP	--	P, IP, RS	--
42	26 Cr-6.5 Ni	--	Unstressed	Cu	A	Et (sli), A (E)	--	N	--
					B	IP	--	N*	--
					C	P, IP	--	N	--
					D	N	--	N	--
					E	N	--	N	--
					G	P, IP	--	N	--

* One specimen not recovered
(a) Abbreviations used:

A- general corrosion attack
AW- adjacent to weld
E- edge
Et- etch
F- face
IF- irridescent film
IP- incipient pitting
N- no apparent corrosion
P- pitting corrosion
RS- rust stain
m- moderate
sev- severe
sli- slight
T- tunneling corrosion
W- weld

Table IV. Summary of results obtained from stressed 1-in by 12-in stainless steel alloy specimens after exposure for one and two years at the six NBS soil corrosion test sites.

System	Stainless Steel	Treatment (a)	Stressed Specimen (b)	Number of Specimens Failed											
				Site A Toppenish, Washington		Site B Loch Raven, Maryland		Site C Cape May, New Jersey		Site D Wildwood, New Jersey		Site E Wildwood, New Jersey		Site G Patuxant, Maryland	
				Exposure Time Years		Exposure Time Years		Exposure Time Years		Exposure Time Years		Exposure Time Years		Exposure Time Years	
				1	2	1	2	1	2	1	2	1	2	1	2
Exposed in 1970															
67	Type 301	1/2-Hard	U	0	0	0	0	0	1(d)	0	0	0	0	0	0
68	Type 301	1/2-Hard	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
69	Type 301	1/2-Hard+S	UU	1(c)	1	1(c)	0	2(c)	2	2	2	2	2	1	1
70	Type 301	Full Hard	U	0	0	0	0	0	0	0	0	0	0	0	0
71	Type 301	Full Hard	(UU)	0	0	0	0	0	0	0	0	0	0	0	1(c)
72	Type 304	-	U	0	0	0	0	0	0	0	0	0	0	0	0
73	Type 304	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
74	Type 304	1/2-Hard	U	0	0	0	0	0	0	0	0	0	0	0	0
75	Type 304	1/2-Hard	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
76	Type 304	S	UU	0	0	0	0	0	1-1(c)	0	0	1	0	0	0
77	Type 316	-	U	0	0	0	0	0	0	0	0	0	0	0	0
78	Type 316	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
79	Type 316	S	UU	0	0	0	0	0	0	0	0	0	0	0	0
80	Type 434	-	U	0	0	0	0	0	0	0	0	0	0	0	0
81	Type 434	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
Exposed in 1971															
20	26Cr-1Mo	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
21	26Cr-1Mo	-	U	0	0	0	0	0	0	0	0	0	0	0	0
22	20Cr-24Ni-6.5Mo	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
23	20Cr-24Ni-6.5Mo	-	U	0	0	0	0	0	0	0	0	0	0	0	0
24	20Cr-24Ni-6.5Mo	S	UU	0	0	0	0	0	0	0	0	0	0	0	0
25	18Cr-2Mo	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
26	18Cr-2Mo	-	U	0	0	0	0	0	0	0	0	0	0	0	0
27	18Cr-8Ni(N)	-	(UU)	0	0	0	0	0	0	0	0	0	0	0	0
28	18Cr-8Ni(N)	-	U	0	0	0	0	0	0	0	0	0	0	0	0
30	26Cr-6.5Ni	-	U	0	0	0	0	0	0	0	0	0	0	0	0

(a) All specimens were in the annealed condition unless noted otherwise. S - sensitized.
(b) U - single U-bend specimen; UU - double U-bend specimen; (UU) - double U-bend specimen, joined by a spot weld.
(c) Microcrack on edge, specimen considered failed.
(d) Microcrack on face, specimen considered failed.

Table V. Summary of galvanically coupled stressed and unstressed 1-in by 12-in stainless steel alloy specimens after exposure for 1 and 2 years at the six NBS soil corrosion test sites.

System	Alloy Designation	Treatment	Years Exposed	Stressed Specimen (b)	Coupled to	Site A Toppenish, Washington		Site B Loch Raven, Maryland		Site C Cape May, New Jersey		Site O Wildwood, New Jersey		Site E Wildwood, New Jersey		Site G Patuxant, Maryland	
						No. of Failures (c)	Percent Dissipation of Couple Material (d)	No. of Failures (c)	Percent Dissipation of Couple Material (d)	No. of Failures (c)	Percent Dissipation of Couple Material (d)	No. of Failures (c)	Percent Dissipation of Couple Material (d)	No. of Failures (c)	Percent Dissipation of Couple Material (d)	No. of Failures (c)	Percent Dissipation of Couple Material (d)
Exposed in 1970																	
82	Type 301	1/2-Hard	1	U	Zn	0	<1	0	<2	2	<5	1	<2	2	<2	2	15-20
	" "	"	2	U	Zn	0	2	1(f)	5-10	2	20-100	1	2	2	<5	2	25-35
83	" "	"	1	U	Mg	1	50-85	2	5	2	40-50	2	2	2	50	2	100
	" "	"	2	U	Mg	1-1(f)	10	2	20-25	2	100	2	10-20	2	70	2	100
84	" "	"	1	U	Steel	0	<5	0	<2	0	<2	0	<5	0	<2	0	<5
	" "	"	2	U	Steel	0	5-10	0	5	2(f)	5	0	5	0	5	0	30-40
85	" "	Full-Hard	1	U	Zn	0	<1	1-1(f)	<2	2	<5	2	<2	2	<2	2	10-15
	" "	"	2	U	Zn	1	2	2	5	2	15-20	2	2	2	5	2	15-20
86	" "	"	1	U	Mg	2	65-75	2	5	2	30-50	2	5	2	40-50	2	100
	" "	"	2	U	Mg	1	20-30	2	20	2	100	2	20	2	50-60	2	100
87	" "	"	1	U	Steel	0	<5	0		2	<2	0	<5	0	<2	0	<5
	" "	"	2	U	Steel	0	5-10	0	5	2	5	0	5	0	5	2	35-40
88	Type 304	-	1	U	Zn	0	<1	0	<2	0	<5	0	<2	0	<2	0	15-20
	" "	-	1	U	Zn	0	2-5	0	5	0	10-30	0	2	0	5	0	70-75
89	" "	-	1	U	Mg	0	50-85	0	5	0	40-60	0	<5	0	40-50	0	100
	" "	-	2	U	Mg	0	20-80	0	20-25	0	100	0	10-20	0	50	0	100
90	" "	-	1	U	Steel	0	<5	0	<2	0	<2	0	<5	0	<2	0	<5
	" "	-	2	U	Steel	0	10	0	5	0	5	0	<5	0	<5	0	35-40
91	Type 304	-	1	Unstressed	Cu	-	<1	-	<2	-	<2	-	<2	-	<2	-	<2
	" "	-	2	"	Cu	-	<2	-	<2	-	<5	-	<2	-	<5	-	<5
92	Type 409	-	1	Unstressed	Cu	-	<1	-	<2	-	<2	-	<2		<2		<2
	" "	-	2	"	Cu	-	<2	-	<2	-	<5	-	<2	-	<2	-	<2
Exposed in 1971																	
33	26Cr-1Mo	-	1	U	Zn	0	2	0	5	0	15	0	<2	0	<5-10	0	10
	"	-	1	U	Zn	0		0	10	0	20	0	5	0	<5	0	10
34	"	-	1	U	Mg	0	60	0	10	0	60-70	0	10	0	40-50	0	40-60
	"	-	2	U	Mg	0		0	10	0	50	0	10	0	50	0	60
35	"	-	1	U	Steel	0	5-10	0	5	0	5	0	5	0	<5	0	5
	"	-	2	U	Steel	0		0	5	0	5	0	5	0	5	0	5-10
36	26Cr-6.5Ni	-	1	U	Zn	0	2	0	5	0	10	0	<2	0	5-10	0	20
	"	-	2	U	Zn	0		0	10	0	20	0	<5	0	<5	0	10
37	"	-	1	U	Mg	0	40-50	0	20	0	70-75	0	5-10	0	50	0	50-70
	"	-	2	U	Mg	0		0	10	0	50	0	10-15	0	60	0	60-70
38	"	-	1	U	Steel	0	5-10	0	5	0	<5	0	5	0	5	0	<5-10
	"	-	2	U	Steel	0		0	5	0	5	0	5	0	<5-10	-	10
42	"	-	1	Unstressed	Cu	-	2	-	<2	-	<2	-	<1	-	<2	-	<2
	"	-	2	"	Cu	-		-	10(e)	-	<5	-	<5	-	5	-	<5

(a) All specimens in the annealed condition unless otherwise noted.
(b) U - Single U-bend.
(c) Two specimens were exposed at each site.
(d) Zinc, magnesium, steel, or copper. Based on visual determination.
(e) One specimen lost (not recovered).
(f) Microcrack at edge, specimen considered failed.

Table VI. Maximum couple current and corresponding potential* of Cu-SS couples (two-year exposure).

Specimen		Site A Washington		Site B Loch Raven		Site C Cape May		Site D Wildwood (Dry Sand)		Site E Wildwood (Wet Sand)		Site D Patuxent	
Stainless Steel	No.	SS Anodic μA (V)	SS Cathodic μA (V)	SS Anodic μA (V)	SS Cathodic μA (V)	SS Anodic μA (V)	SS Cathodic μA (V)	SS Anodic μA (V)	SS Cathodic μA (V)	SS Anodic μA (V)	SS Cathodic μA (V)	SS Anodic μA (V)	SS Cathodic μA (V)
304	91-10	- -	0.2 (-0.115)	- -	193 (+0.054)	0.85 (-0.100)	134 (-0.065)	56 (-0.29)	1.2 (-0.062)	46 (-0.327)	56 (-0.055)	100 (-0.404)	7 (-0.370)
	91-12	0.015 (-0.041)	0.01 (-0.002)	0.96 (-0.016)	0.82 (-0.025)	2.0 (-0.084)	170 (-0.152)	8.2 (-0.201)	167 (+0.039)	16.5 (-0.034)	64 (+0.014)	5.2# (-0.449)	50 (-0.690)
	91-18	0.01 (-0.045)	0.4 (-0.129)	- -	52 (+0.020)	56 (-0.149)	170 (-0.152)	23.4 (-0.230)	32 (-0.034)	10 (-0.112)	46 (-0.012)	250 (-0.493)	24 (-0.435)
	91-20	0.01 (-0.105)	0.7 (-0.151)	0.03 (-0.007)	4.5 (-0.007)	1.8 (-0.144)	14 (-0.49)	43 (-0.290)	2.5 (-0.049)	5.5 (-0.133)	15.4 (-0.046)	9# (-0.500)	13.5 (-0.466)
409	92-10	0.2 (-0.112)	0.02 (-0.004)	0.1 (-0.048)	117 (+0.018)	770 (-0.306)	82 (-0.061)	42 (-0.302)	1.8 (-0.080)	92 (-0.351)	30 (-0.136)	950 (-0.512)	- -
	92-12	6.0 (-0.133)	0.06 (-0.002)	3.5 (-0.143)	1.7 (-0.031)	64 (-0.676)	2 (-0.124)	56 (+0.047)	132 (+0.024)	91 (-0.342)	30 (-0.137)	470 (-0.556)	200 (-0.532)
	92-18	6.1 (-0.103)	- -	- -	172 (+0.071)	360 (-0.134)	- -	28 (-0.266)	42 (-0.030)	130 (-0.259)	17.5 (-0.150)	200 (-0.469)	2.3 (-0.444)
	92-20	5.3 (-0.084)	1.1 (-0.023)	1.1 (-0.023)	1.9 (0.006)	71 (-0.089)	3 (-0.104)	22 (-0.232)	38 (-0.042)	78 (-0.299)	32 (-0.025)	805 (-0.566)	67 (-0.474)
26Cr-6.5Ni	42-10	0.035 (-0.144)	0.1 (-0.176)	40 (-0.016)	28 (+0.025)	18 (-0.151)	0.96 (-0.111)	92 (-0.080)	0.62 (-0.562)	- -	1350 (-0.166)	- -	18# (-0.450)
	42-12	0.024 (-0.020)	0.02 (-0.086)	53 (-0.039)	66 (+0.029)	3.1 (-0.164)	600 (-0.260)	0.4 (-0.146)	50 (+0.111)	0.2 (-0.095)	260 (+0.049)	3 (-0.457)	10# (-0.460)
	42-18	0.24 (-0.224)	0.10 (-0.189)	54 (-0.046)	52 (+0.018)	6.4 (-0.115)	3.5 (-0.107)	46 (-0.167)	22 (-0.087)	37 (-0.137)	772 (+0.050)	- -	11# (-0.440)
	42-20	0.32 (-0.101)	3 (-0.041)	40 (-0.054)	71 (+0.021)	450 (-0.094)	3.5 (-0.104)	4 (-0.137)	1.25 (-0.163)	- -	425 (+0.037)	7.5# (-0.410)	4500 (-0.421)

*Vs $Cu-CuSO_4$ reference half cell.
#Potential based on average of two readings.

Table VII. Average Couple Current$^{\Delta}$ vs Failure (Two-Years' Exposure).

Specimen No.	Specimen	Coupled to	Site A Washington µA/cm²	Site A Failures	Site B Loch Raven µA/cm²	Site B Failures	Site C Cape May µA/cm²	Site C Failures	Site D Wildwood (Dry Sand) µA/cm²	Site D Failures	Site E Wildwood (Wet Sand) µA/cm²	Site E Failures	Site G Patuxent µA/cm²	Site G Failure
82	301HH	Zn	2.78	0	1.67	2	21.2	2	0.74	1	1.61	2	11.5	2
83	"	Mg	20.6	2	6.17	2	115	2	3.68	2	52.0	2	223	2
84	"	Fe	0.03	0	0.45	0	1.91	2	0.21	0	0.57	0	4.13	0
85	301FH	Zn	4.84	1	1.84	2	25.2	2	1.02	2	1.39	2	16.8	2
86	"	Mg	25.4	2	9.04	2	123	2	3.49	2	47.3	2	231	2
87	"	Fe	0.04	0	0.59	0	1.70	2	0.21	0	0.58	0	4.46	2
88	18Cr-8Ni(N)	Zn	3.16	0	2.41	0	29.7	0	41.7	0	0.98	0	13.4	0
89	"	Mg	31.3	0	8.07	0	112	0	4.65	0	36.4	0	242	0
90	"	Fe	0.08	0	0.48	0	1.29	0	0.14	0	0.37	0	8.72	0
33	26Cr-1Mo	Zn	7.30	0	1.48	0	33.1	0	1.37	0	2.76	0	19.3	0
34	"	Mg	19.9	0	3.57	0	128	0	3.57	0	25.4	0	344	0
35	"	Fe	5.85	0	0.57	0	0.54	0	0.26	0	2.68	0	0.30#	0
36	26Cr-6.5Ni	Zn	7.25	0	1.72	0	27.6	0	1.36	0	5.61	0	15.1	0
37	"	Mg	30.0	0	4.01	0	130	0	4.39	0	30.4	0	362	0
38	"	Fe	0.32	0	0.98	0	1.64	0	0.30	0	1.0	0	6.65	0

Δ Average of 2 specimens, 14 readings.
Specimen anodic to Fe.

TABLE VIII. Average,≠ Max-min corrosion current, μA and corresponding potential (V)* of SS specimens. Two year exposure.

Specimen		Site A Washington		Site B Loch Raven		Site C Cape May		Site D Wildwood (Dry Sand)		Site E Wildwood (Wet Sand)		Site G Patuxent	
Designation	No.	Maximum Current μA (V)	Minimum Current μA (V)	Maximum Current μA (V)	Minimum Current μA (V)	Maximum Current μA (V)	Minimum Current μA (V)	Maximum Current μA (V)	Minimum Current μA (V)	Maximum Current μA (V)	Minimum Current μA (V)	Maximum Current μA (V)	Minimum Current μA (V)
301HH	67	0.28 (-0.094)	0.06 (-0.065)	1.5 (+0.091)	0.16 (-0.076)	13.1 (-0.010)	0.07 (-0.050)	3.8 (-0.317)	0.61 (-0.045)	6.1 (-0.188)	0.26 (-0.098)	3.2 (-0.508)	1.6 (-0.405)
301FH	70	0.26 (-0.078)	0.10 (-0.034)	2.6 (+0.15)	0.37 (-0.08)	12.2 (+0.016)	0.51 (-0.260)	2.0 (-0.017)	0.73 (+0.004)	10.5 (-0.124)	0.66 (-0.172)	21.8 (-0.440)	1.7 (-0.471)
304	72	0.32 (-0.073)	0.06 (+0.027)	3.1 (+0.184)	0.41 (-0.107)	14.3 (-0.061)	0.37 (-0.144)	2.7 (+0.016)	0.48 (+0.003)	6.4 (+0.100)	0.36 (-0.098)	10.3 (-0.440)	1.7 (-0.282)
316	77	0.17 (-0.1)	0.04 (+0.018)	2.4 (+0.169)	0.16 (-0.055)	10.4 (+0.104)	0.72 (-0.126)	2.2 (-0.341)	0.48 (-0.008)	9.5 (-0.003)	0.25 (-0.129)	15.2 (-0.436)	1.6 (-0.283)
436	80	0.21 (-0.10)	0.04 (+0.06)	4.6 (+0.172)	0.16 (-0.056)	14.5 (+0.051)	0.78 (-0.185)	3.0 (-0.302)	0.40 (-0.019)	7.0 (-0.061)	0.23 (-0.111)	7.2 (-0.491)	1.8 (-0.357)
26Cr-1Mo	21	0.105 (-0.032)	0.065 (-0.069)	0.621 (-0.002)	0.078 (+0.115)	1.86 (-0.343)	0.30 (-0.326)	1.83 (-0.520)	0.32 (-0.117)	31.4^Δ (+0.268)	0.15 (-0.040)	9.81 (-0.480)	1.02 (-0.349)
20Cr-24Ni-6.5Mo	23	0.127 (-0.067)	0.091 (-0.050)	0.702 (+0.042)	0.101 (+0.326)	8.83^Δ (-0.298)	0.61 (-0.288)	1.15^Δ (-0.294)	0.38 (-0.038)	17.9^Δ (+0.251)	.914 (-0.127)	20.5 (-0.510)	0.85 (-0.424)
18Cr-2MO	26	0.130 (-0.070)	0.084 (-0.083)	0.632 (-0.075)	0.101 (0.268)	12.75 (-0.446)	0.65 (-0.194)	2.33 (-0.262)	0.60 (-0.480)	24.4^Δ (+0.139)	0.13 (-0.033)	18.5 (-0.512)	1.39 (-0.429)
18Cr-8Ni(N)	28	0.111 (-0.110)	0.093 (-0.037)	0.896 (-0.008)	0.360 (+0.193)	4.35^Δ (-0.266)	0.46 (-0.053)	2.01 (-0.262)	0.41 (-0.388)	25.5^Δ (+0.168)	0.16 (-0.063)	18.5 (-0.505)	0.87 (-0.412)
26Cr-6.5Ni	30	0.251 (-0.068)	0.164 (-0.073)	0.528 (+0.473)	0.184 (+0.362)	8.62^Δ (-0.240)	1.52 (-0.052)	3.78^Δ (-0.0259)	0.32 (-0.075)	33.6^Δ (0.227)	0.74 (0.063)	28.3 (-0.532)	0.714 (-0.366)

* vs Cu-$CuSO_4$ reference half cell.
≠ Average of four specimens.
Δ Average of less than four specimens.

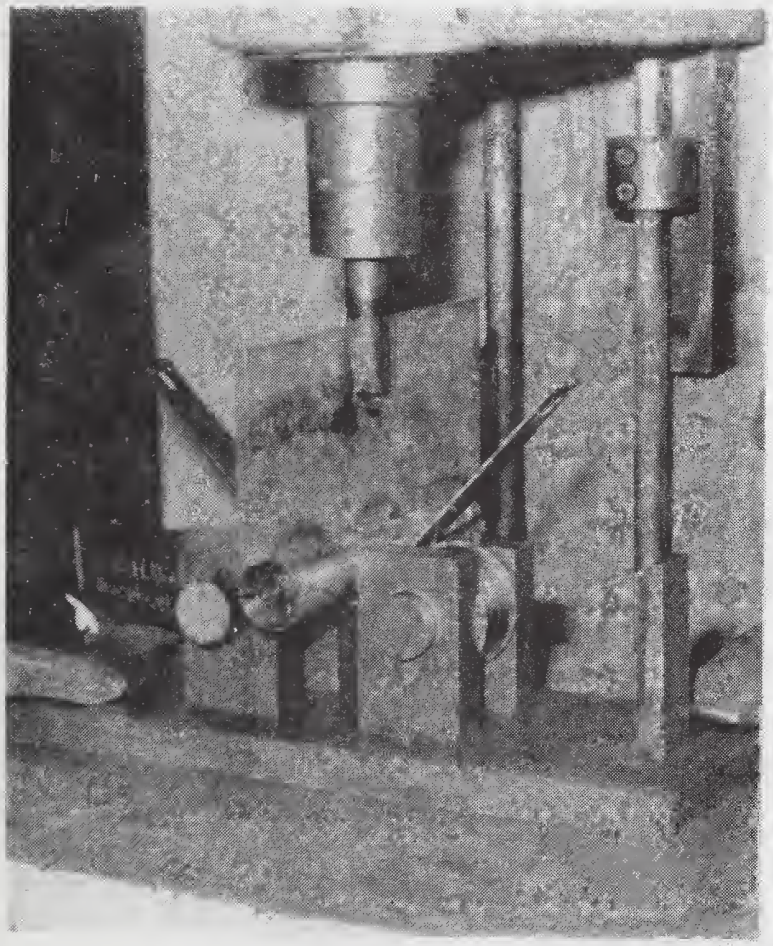


Figure 1. Die for forming U-bend specimens.

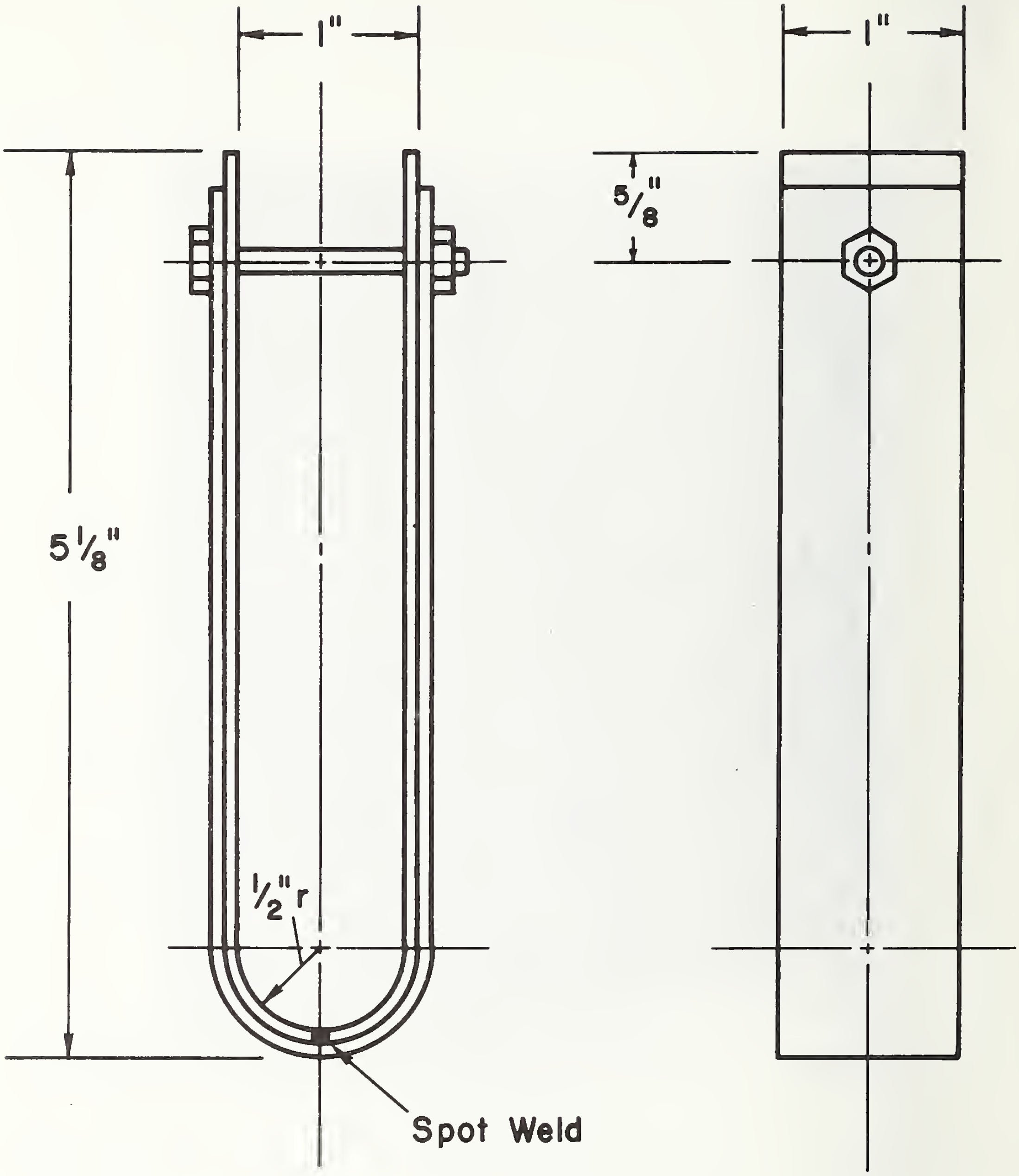
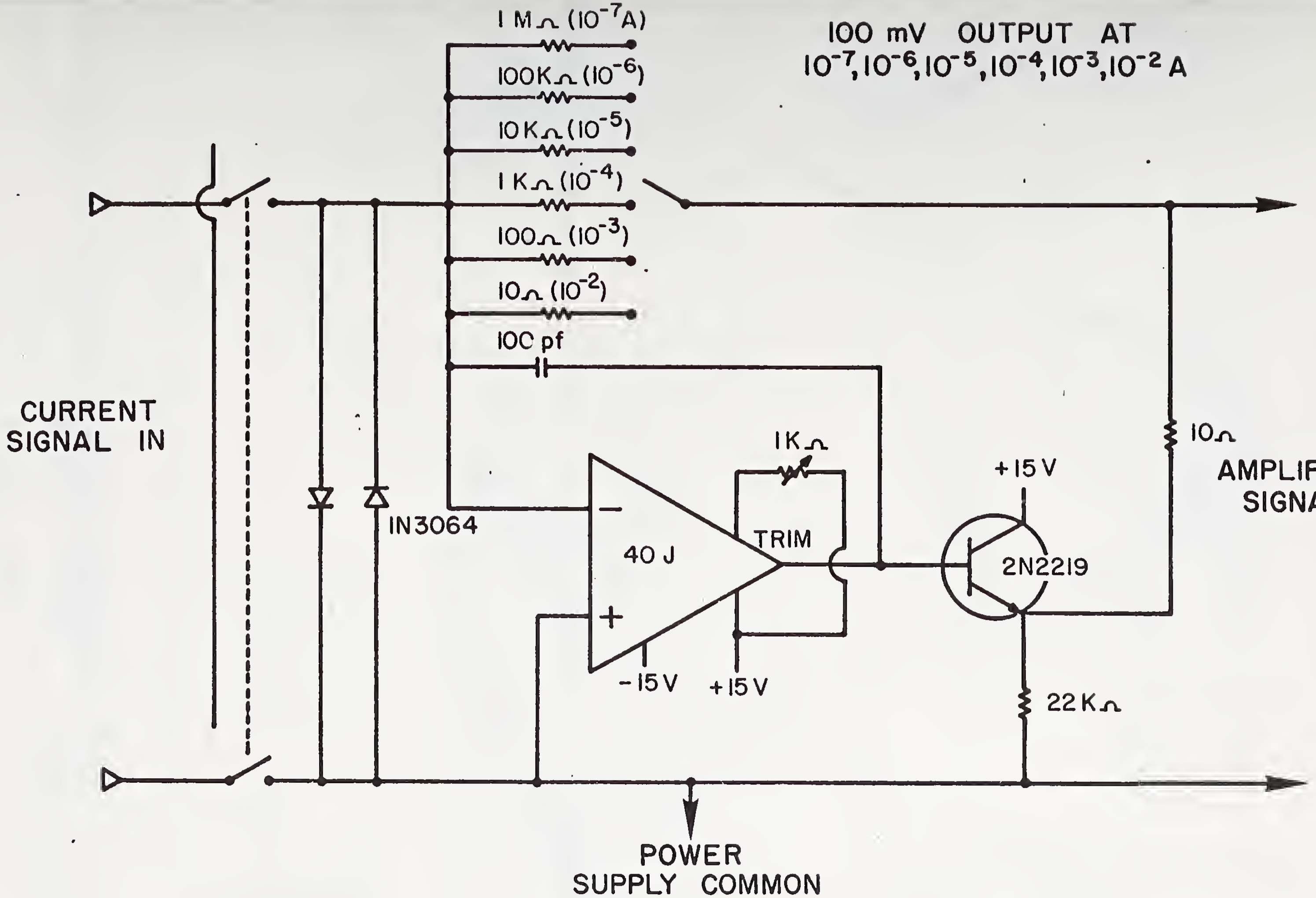


Figure 2. Double or crevice U-bend specimen for underground exposure.



Suggested by R.J. Carpenter
Electronics Instrumentation Section, NBS

Figure 3. Solid state zero resistance amplifier.

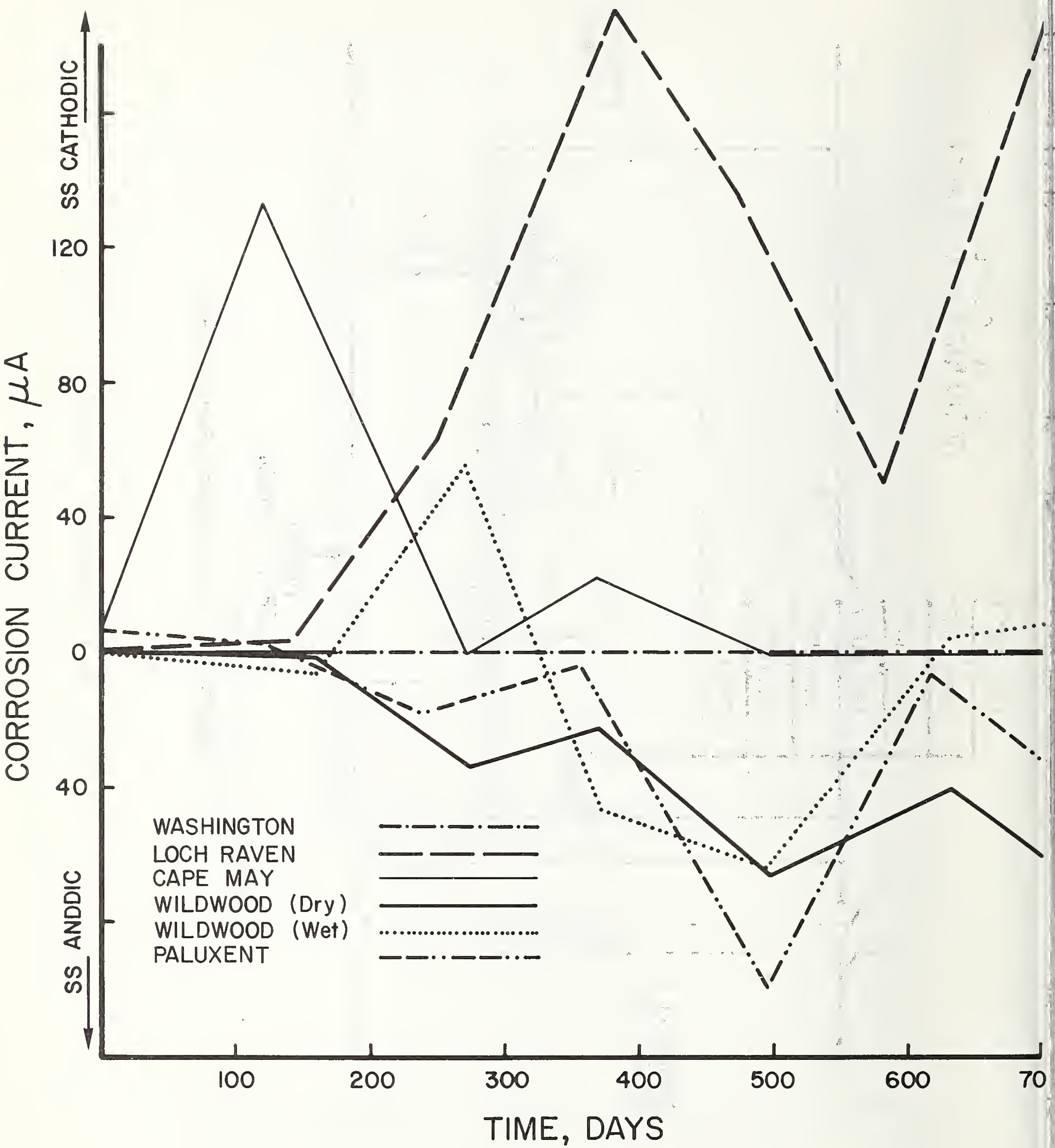


Figure 4. Type 304 stainless steel (91-10)-copper couple vs. time.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Corrosion data is presented for uncoupled stressed and galvanically coupled stressed and unstressed stainless steels exposed for up to two years in various soil environments. Systems studied were austenitic (300 series) alloys, ferritic and martensitic (400 series) alloys, and proprietary (major alloying constituents Cr or Cr-Ni) alloys. Test materials included specimens in the annealed, half-hard, full-hard, or sensitized condition. Some test specimens incorporated welds and crevices. Galvanically coupled stressed specimens were coupled to steel, zinc, or magnesium while unstressed specimens were coupled to copper. Corrosion rate data obtained by electrochemical means is presented for comparison with results obtained by visual and weight loss determinations.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Stainless steels; stress corrosion behavior; electrochemical behavior; soil environments; field tests; galvanic corrosion.

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