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Technical Report

FIELD TESTING OF ELECTRICAL GROUNDING RODS

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FIELD TESTING OF ELECTRICAL GROUNDING RODS

Technical Report R-660

YF 38.534.006.01.001

by

Richard W. Drisko and A. E. Hanna

ABSTRACT

In cooperation with the National Association of Corrosion Engineers, NCEL conducted a 7-year program of field testing metal rods for electrical grounding. Single rods of galvanized steel, copper-clad steel, Ni-Resist cast iron, type 302 stainless steel, type 304 stainless-clad steel, zinc, magnesium, and aluminum were tested along with couples of these to mild steel rods. Sets of both single and coupled rods were removed, cleaned, and weighed after 1, 3, and 7 (or 5) years. Potential, resistance, and current measurements were made monthly as far as practicable. Weight losses and electrical data were analyzed for correlations. It was concluded that type 302 stainless steel and type 304 stainless-clad steel rods were the best choices for general use.

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FOREWORD

The Naval Civil Engineering Laboratory prepared the following report to meet the requirements of the National Association of Corrosion Engineers (NACE) Program. The other participating agencies will submit their findings to NACE as soon as they complete their work. NACE will then evaluate all the information and will prepare a summary report.

INTRODUCTION

Grounding in electrical installation and other construction is important for at least six reasons:[1]

1. To protect personnel from electrocution in case they accidentally ground a circuit whose potential is different from the structure or earth with which the person is in contact.
2. To equalize potentials among components of electrical systems.
3. To decrease the potential difference between the earth and structures that may accumulate static electric charges.
4. To provide a path to ground for electric currents produced by lightning.
5. To provide a low impedance connection through the earth between parts of an electric power system.
6. To minimize interference with or radiation from communications systems.

In the past it has been a standard practice to use water piping systems for electrical grounding. Now many water companies object to their piping systems being used as a ground for electrical systems, and at least one company has a regulation that holds the customer responsible for any damage resulting from ground wire attachment.[2]

A physical limitation associated with grounding to water piping systems is the increased use of cement, plastic, and wrapped pipe, as well as metal pipe with neoprene joints, in water mains. Also, many water systems install an insulating bushing between the house lines and meter or street mains, thus reducing the size of the grounding network. Several years ago gas companies started a program of installing an insulated meter swivel on the inlet side of meters to prevent an arc or spark when removing a gas meter from the service line.

National, state, and local safety codes usually specify that electrical grounding be made to a continuous metallic underground piping system when such is available. Where this is not available, the grounding connections may be made to other local metallic underground piping systems or plate, pipe, or metal ground rods.

The Navy is especially concerned about the extensive buried grounding networks required for power transformer stations, radar installations, and radio stations. Copper rod or wire or copper-clad steel rods are the ones most commonly used for this purpose. When copper is connected underground to steel pipes, lead cable sheaths, etc., the copper receives cathodic protection from the other less noble (less corrosion-resistant) metals connected to it, at the expense of these other metallic structures. The damage to a large area of steel when a small area of copper is connected to it is not very great. However, a small area of steel connected to a large area of copper will promote rapid corrosion of the steel.[3] Because of its interest in the corrosion problems associated with ground rods, the Naval Facilities Engineering Command (NAVFAC) directed the Naval Civil Engineering Laboratory (NCEL) to conduct a field testing investigation in this area. This investigation was coordinated with a 1-, 3-, 7-year test program of the National Association of Corrosion Engineers (NACE). This report describes the installation and testing of driven electrical grounding rods conducted by NCEL.

NACE TEST PROGRAM[2,4,5]

In 1960 a proposal for a "Driven Ground Rod Program" was first formulated by NACE. The purpose of this program was "to find a metal that (a) can be readily driven into the ground at or near the electric service entrance to a residential or commercial building to provide a satisfactory ground electrode; (b) will have the property of adequate underground corrosion resistance; and (c) will not cause serious galvanic corrosion to other metals or pipes buried nearby and connected to the grounding rod and electric neutral network." Fourteen sponsors, including NCEL, with 21 test sites agreed to participate in the program.

Three complete sets totaling 33 driven ground rods were to be buried at each location for removal after 1, 3, and 7 years. Each set of 11 were to consist of single rods of SAE Grade 1060 mild steel (I), galvanized steel (G), copper-clad steel (C), Ni-Resist cast iron (N), and type 302 stainless steel (S) and couples of mild steel to copper-clad steel (I-C), mild steel to Ni-Resist cast iron (I-N), and mild steel to type 302 stainless steel (I-S). The Ni-Resist cast iron and type 302 stainless steel rods were to be furnished by the International Nickel Company, the copper-clad steel rods by the Copper-weld Steel Corporation, the galvanized steel rods by U. S. Steel, Tennessee Coal and Iron Division, and the mild steel rods by the individual sponsors. The coupled rods were to be used to simulate buried steel pipes connected to corrosion-resistant ground rods.

Each rod was to be a single piece 8 feet in length and 5/8 inch in diameter. Pointed tips would permit easier driving into the earth with either a hand-held or a power-driven hammer. Three inches of the rod were to extend above the ground to permit coupling to other rods (for the three coupled pairs in each set) and to make electrical measurements periodically. Care was to be taken during driving of the ground rods to prevent vibrations that might make a hole in the ground larger than needed. Tests by the National Bureau of Standards and others indicate that driven steel ground rods have a longer service life than rods buried in disturbed or excavated soil; driving the rods seems to limit the amount of oxygen on their surfaces.

A 6-foot minimum separation was chosen to allow a variation of plot designs that should be free of stray currents. The coupled rods were to be connected with a No. 10 TW wire and a split-bolt type connector; the connections were then to be covered with a putty-type insulating material.

Each single test rod or couple was to be weighed to the nearest gram before installation and after removal and cleaning so that corrosion losses could be calculated. Also, the following electrical measurements indicating changes in corrosion rates were to be made on the ground rods monthly when practical and as permitted by weather conditions:

1. Potential of single rods and sets of coupled rods to a copper—copper sulfate reference electrode.
2. Resistance of single rods and sets of coupled rods to earth using two auxiliary reference electrodes with a sensitive resistance meter.
3. Current flow in coupled sets using a small shunt that was permanently installed and joined only during measurements.

Electronegative potentials of metals and current flow are directly related to corrosion rates. A buildup of corrosion products, causing a decrease in corrosion rates, may be detected by an increase in resistance.

NCEL TEST PROGRAM

The NCEL test program was an expanded form of the NACE test program. Thirty-one rods of eight different metal systems (Figure 1) comprised each group. In addition to the five metal systems in the NACE program, high-purity zinc (Z), AZ31B magnesium alloy (M), and 6061-T6 aluminum alloy (A) rods were used. Single rods of all eight metal systems were tested; single rods of mild steel coupled to rods of the seven other metal systems and two mild steel rods coupled to rods of copper-clad steel, magnesium, and zinc were also tested. The latter couples were used to obtain data on corrosion losses with different anode-to-cathode area ratios.

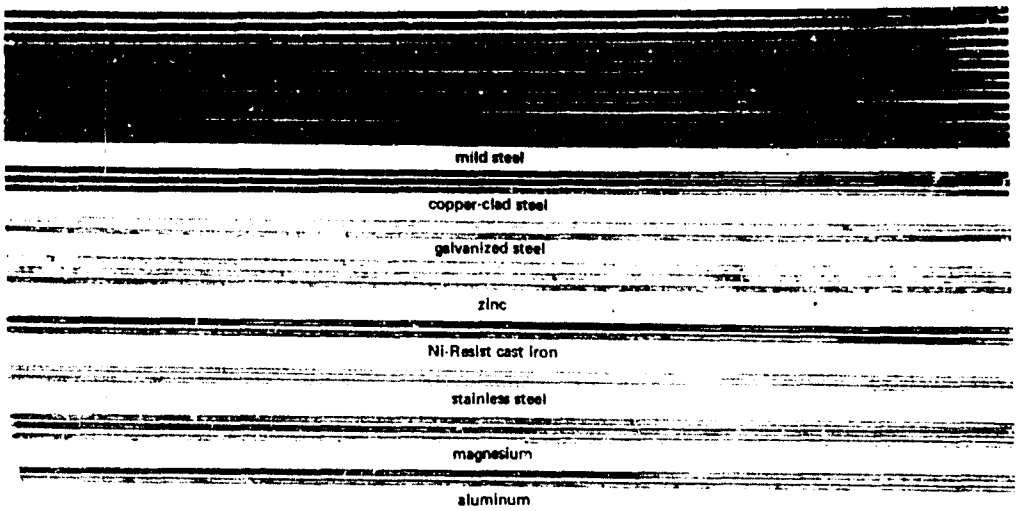


Figure 1. Typical group of electrical grounding rods.

Two years after initiation of the test program, sets of type 304 stainless-clad steel rods (B) were included for 1-, 3-, and 5-year exposures. The 1- and 3-year sets had one single stainless-clad steel rod and one coupled to a mild steel rod; the 5-year set had these plus two stainless-clad steel rods coupled to a mild steel rod.

The rods were installed in the NCEL test site located at the southeast corner of the main Laboratory compound (Figure 2). The site was approximately 200 feet long and 20 feet wide, with two reference electrodes for resistance measurements permanently installed 50 and 100 feet from the edge of the site area on a line perpendicular to the length of the site and located at its center. The site paralleled the south boundary fence and ocean, with the first row of test rods 6 feet from the fence.

The soil in the test site consisted of a 3-foot layer of crushed sandstone fill covering a 5-foot layer of sand and gravel hydraulic fill and a natural deposit of sand and gravel of undertermined thickness. The resistivity of the soil to an 8-foot depth averaged 1,200 ohm-cm.

Rods were installed in the rectangular pattern on 6-foot centers, as shown in Figure 3. An air hammer with a special driving head (Figure 4) was used to drive the rods into the soil after they had been started with a sledge hammer. A 5/8-inch-diameter steel rod was used to make pilot holes for the aluminum, magnesium, and Ni-Resist cast iron rods. The first two rods are relatively soft and tend to mushroom when driven; the third is quite brittle and might break if driven into rocks present in the fill. A slightly larger pilot hole was drilled for the zinc rods which were so soft that even slight resistance to driving might cause them to bend above ground. After the rods were inserted, these holes were backfilled carefully with fine sand to insure good contact between the rods and the soil.

Figure 2. Ground rod test site at NCEL. Breakwater and boundary fence are at left with the test area in the center foreground.

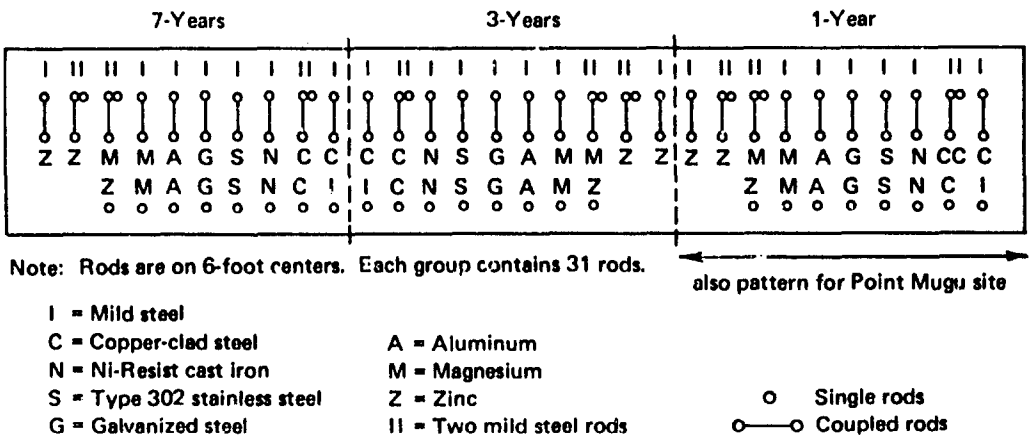


Figure 3. Arrangement of test rods at NCEL test site.

A separate set of ground rods was also driven into a very aggresive soil at the Naval Air Station, Point Mugu, for a 1-year exposure. The test pattern is shown in the right-hand portion of Figure 3. It was hoped that these rods would show accelerated corrosion when compared to the test rods in the less aggressive soil at NCEL. The Point Mugu site (shown in Figure 5) was located in an area sometimes covered with water at high tide and during the rainy season. The site was approximately 70 feet in length and 20 feet in width. Two reference electrodes were located 50 and 100 feet from the

edge of the site area and on a line perpendicular to the length of the site and located at its center. The top soil consisted of a fine, silt-like material to a depth of 28 inches, overlying a 2-inch layer of a sand-silt mixture and a 6-inch layer of brown sand. Below the 36-inch depth, the sand was blue gray in color, and sea shells were present in the sand below the 4-foot depth. The resistivity of the soil to an 8-foot depth averaged 85 ohm-cm. A chemical analysis of the soil at the Point Mugu site is given in Table 1. At Point Mugu the rods were hand-pushed into the ground until the sand layer was contacted and then driven the rest of the way with a light hammer (Figure 6). Pilot holes were not needed for any of the rods.

Figure 4. Installing rods with air hammer at NCEL test site.

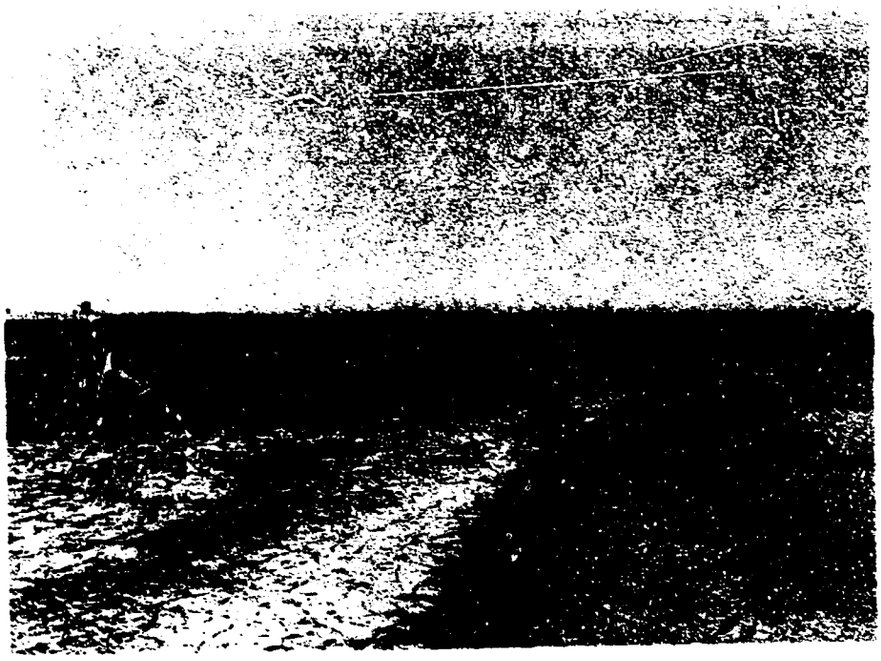


Figure 5. Point Mugu ground rod test site.

Figure 6. Installing rods with light hammer at Point Mugu test site.

Table 1. Chemical Analysis of Soil at Point Mugu Site

Sample No.	Depth (in.)	Soluble Constituents (ppm)							Insoluble Constituents (ppm)					pH
		CO_3	HCO_3	TDS[a]	Cl	SO_4	Mg	Ca	Organic	Acid Insolubles	Al_2O_3	Fe_2O_3	$CaCO_3$	
1-1	0-18	0	120	16,750	7,500	1,250	280	20	122,700	739,300	10,600	60,800	33,200	7.9
-2	29-47	0	216	57,000	26,200	4,750	560	170	29,700	934,100	3,300	9,100	7,500	7.4
-3	49-69	0	80	70,000	34,600	7,250	650	200	24,300	942,900	1,200	10,700	11,400	7.1
-4	69-88	0	119	52,500	26,400	5,000	450	110	22,100	922,100	4,200	10,800	12,300	7.2
2-1	0-18	20	160	25,000	10,600	1,450	310	15	88,600	748,400	2,500	74,000	33,900	8.4
-2	29-47	0	130	47,500	20,700	3,750	450	60	22,300	947,700	900	13,900	7,200	7.3
-3	49-68	0	180	134,000	53,500	9,000	1,100	240	33,400	919,800	1,300	6,500	8,800	7.0
-4	69-85	0	160	89,000	36,500	6,500	780	220	23,400	935,700	1,700	8,700	15,700	7.0
3-1	0-18	0	140	19,000	8,000	1,375	295	25	104,000	839,000	5,000	25,000	26,100	7.8
-2	30-46	0	142	44,000	20,800	4,100	360	40	18,600	964,000	1,400	7,100	3,500	7.5
-3	49-69	0	156	87,500	45,800	8,500	740	190	28,000	944,300	1,300	6,300	5,700	7.0
-4	70-88	0	185	81,000	39,400	6,750	750	160	31,700	946,800	1,500	7,800	15,700	7.0
average														
-1	–	7	140	20,250	8,700	1,358	295	20	105,100	775,600	6,000	53,300	31,100	8.0
-2	–	0	163	49,500	22,900	4,200	457	90	23,500	948,600	1,900	10,000	6,100	7.4
-3	–	0	139	97,170	41,300	8,250	830	210	28,600	935,700	1,300	7,800	8,600	7.0
-4	–	0	161	74,170	34,100	6,080	660	163	25,700	934,900	2,500	9,100	14,600	7.1
seawater[b]	–	–	140	35,000[c]	18,980	2,649	1,272	400	–	–	–	–	–	7.5-8.3[d]

[a] Total dissolved solids.

[b] Reference 6, page 1111.

[c] Approximate value.

[d] Reference 6, page 1118.

At the conclusion of each phase of the 1-, 3-, and 7-year program, the ground rods for that phase were removed from the ground. At NCEL a forklift truck similar to that shown in Figure 4 was used, while at Point Mugu the rods were pulled up by hand. If the ground rods broke during extraction because of weakness from excessive corrosion (for example, magnesium and zinc rods) or because of inherent brittleness (for example, Ni-Resist cast iron rods), a hole was dug to expose the broken end and the remainder of the rod was again pulled.

The test rods at both sites were cleaned in a similar manner after removal from testing. The dirt and loosely adhering corrosion products were brushed off with a stiff-bristle scrub brush. The remaining corrosion products were removed by a combination of scrubbing and chemical cleaning, as indicated in Table 2.

The cleaned rods were weighed to the nearest gram on the platform of a laboratory top-loading counter balance. Each rod was placed on the balance so that its center of gravity was directly over the center of the platform.

Table 2. Cleaning Procedures for Test Rods

Test Rods	Chemical Treatment	Method[a]
Mild steel	10% ammonium citrate (heated to 120°F)	Rods immersed and scrubbed
Galvanized steel	10% ammonium chloride (heated to 120°F)	Rods immersed and scrubbed
Copper-clad steel	18% hydrochloric acid	Acid swabbed on cladding only
Ni-Resist cast iron	10% ammonium citrate (heated to 120°F)	Rods immersed and scrubbed
Type 302 stainless steel	concentrated nitric acid	Acid swabbed on rods
High purity zinc	10% ammonium chloride (heated to 120°F)	Rods immersed and scrubbed
AZ31B magnesium	6.5% chromic acid	Rods immersed and scrubbed
6061-T6 aluminum	concentrated nitric acid	Acid swabbed on rods
Type 304 stainless-clad steel	concentrated nitric acid	Acid swabbed on cladding only

[a] After cleaning, all rods were rinsed with deionized water.

RESULTS

1-Year Rods

During a routine inspection about 2 months after installation of the ground rods at Point Mugu, it was found that the coupled magnesium rods had corroded to complete separation at the ground level. Both these and the mild steel rods coupled to them were removed at this time. The single magnesium rod at Point Mugu corroded to complete separation 4 months after installation, and it was removed from the test.

The 1-year group of test rods at NCEL and the remaining test rods at Point Mugu were removed about 13 months after installation. The coupled magnesium rods in the 3- and 7-year program were so badly corroded that they and the mild steel rods coupled to them were also removed at this time. As shown in Figures 7a and 7b, there was relatively little corrosion damage to most of the rods when compared with the magnesium rods. With the exception of the magnesium rods and the mild steel rods coupled to them, the rods from Point Mugu generally looked as good as or better than those from the NCEL site. The weight losses for the rods from both test sites are given in Table A-1 and the electrical measurements on these rods in Tables B-1, B-2, C-1, and C-2.

3-Year Rods

The 3-year group of rods was removed about 36 months after installation. As expected they were noticeably more corroded than the 1-year rods. Their weight losses are given in Table A-2 and their electrical measurements in Tables B-3 through B-5 and C-3 through C-5.

7-Year Rods

The 7-year group of rods was removed almost exactly 7 years from the date of installation. The 5-year group of stainless-clad steel rods and the mild steel rods coupled to them were also removed at this time. Both the 5- and 7-year rods were generally most corroded at the tip. The corroded tips of the single and selected coupled rods are shown in Figures 8a and 8b respectively. The same rods after cleaning are shown in Figures 9a and 9b. The weight losses for all of the rods removed at this time are given in Table A-3 and their electrical measurements in Tables B-6 through B-12 and C-6 through C-12. The two Ni-Resist cast iron rods were broken during removal, but all of the broken pieces were recovered. The single magnesium rod was also broken during removal, but only four pieces, totaling 40-1/2 inches in length and 274 grams in weight, were recovered. The condition of the individual 5- and 7-year rods after removal is described below.

Single Rods	Comments
Mild steel	There was nonuniform rusting and pitting. Some of the pits were quite broad. The rust scale adhered very tightly.
Galvanized steel	Most of the galvanizing had been lost. Rusting of steel was greatest near the surface of the ground. Pitting was worst here and near the tip.
Copper-clad steel	The copper cladding was virtually free of corrosion, but the steel core had corroded at the tip to a point 2 inches inside the cladding.
Ni-Resist cast iron	The rod broke into four pieces during removal. It had rather light corrosion somewhat worse near the surface of the ground.
Type 302 stainless steel	There was very little corrosion except for localized deep pitting near the tip and near the surface of the ground.
6061-T6 aluminum	There were 3/16-inch deep, broad pits near the tip and near the surface of the ground. These pits were filled with a bluish-white corrosion product. In other areas there was much less corrosion.
AZ31B magnesium	The rod was very badly pitted and reduced in diameter so that only four pieces, totaling 40-1/2 inches in length, were recovered. The rest of the rod was too deeply buried for easy recovery. The pits were filled with a thick, white, tightly adhering corrosion product.
High purity zinc	There was deep pitting near the tip and near the surface of the ground. The rod was covered with a tight film of white corrosion product.
Type 304 stainless-clad steel	The cladding was free of corrosion, but at the tip the steel core had corroded to a point about 1 inch inside the cladding.

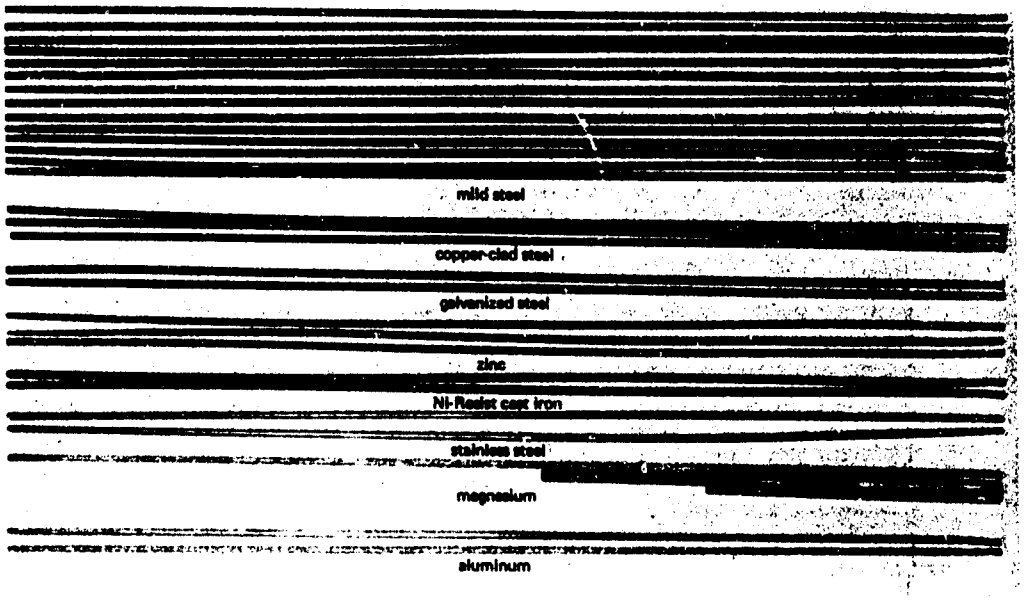
Coupled Rods	Comments
Galvanized steel to mild steel	Most of the galvanizing had been lost, and there was nonuniform rusting and pitting of the underlying steel.
Copper-clad to mild steel	The copper cladding was virtually free of corrosion, but at the tip the steel core had corroded to a point about 1 inch inside the cladding.
Ni-Resist cast iron to mild steel	The rod broke into two pieces during removal. It had light corrosion and no pitting.
Stainless steel to mild steel	This rod was virtually free of corrosion.
Aluminum to mild steel	There was extensive corrosion with deep, broad pits along the entire length. The rod was covered with a bluish-white, tightly adhering corrosion product. A green corrosion product occurred in many of the pits. At the tip there was considerable reduction in diameter and a 3/4-inch reduction in length.
Zinc to mild steel	There was extensive corrosion with scattered broad, deep pits, and it was reduced in diameter and length at the tip. There was a layer of white, tightly adhering corrosion product.
Stainless-clad steel to mild steel	The cladding was free of corrosion, but at the tip the steel core had corroded to a point about 5/8 inch inside the cladding.
Mild steel to galvanized steel	There was nonuniform rusting and pitting. At the tip there was considerable reduction in diameter and a 1-1/2-inch reduction in length.
Mild steel to stainless steel	There was extensive nonuniform rusting and pitting. At the tip there was a considerable reduction in diameter and a 1-1/2-inch reduction in length.
Mild steel to aluminum	There was only slight corrosion. The rod was covered with a tight, hard film.

Mild steel to zinc	There was only lightly scattered rusting near the surface of the ground. The rod was covered with a tough, tightly adhering film.
Mild steel to stainless-clad steel	There was considerable nonuniform rusting and pitting. Some pits were quite broad.
Copper-clad to two mild steel	The copper cladding was virtually free of corrosion, but at the tip the steel core had lost about 1/8 inch from corrosion.
Zinc to two mild steel	The rod had been severed into two pieces by corrosion about 2 feet underground. There was extensive corrosion and pitting, and it was considerably reduced in diameter and length at the tip. The rod was covered with a thick layer of white, tightly adhering corrosion product.
Two mild steel to copper-clad steel	Both rods had general nonuniform rusting. At the tip they were considerably reduced in diameter and had 1-inch reductions in length.
Two mild steel to zinc	Both rods had only lightly scattered rusting, mostly above ground. They were covered with tough, tightly adhering films.
Two stainless-clad steel to mild steel	The claddings were free of corrosion, but at the tips the steel cores had corroded to points 3/8 inch and 5/8 inch inside the claddings.
Mild steel to two stainless-clad steel	There was considerable nonuniform rusting and pitting. At the tip there was a considerable reduction in diameter and a 1/2-inch reduction in length.

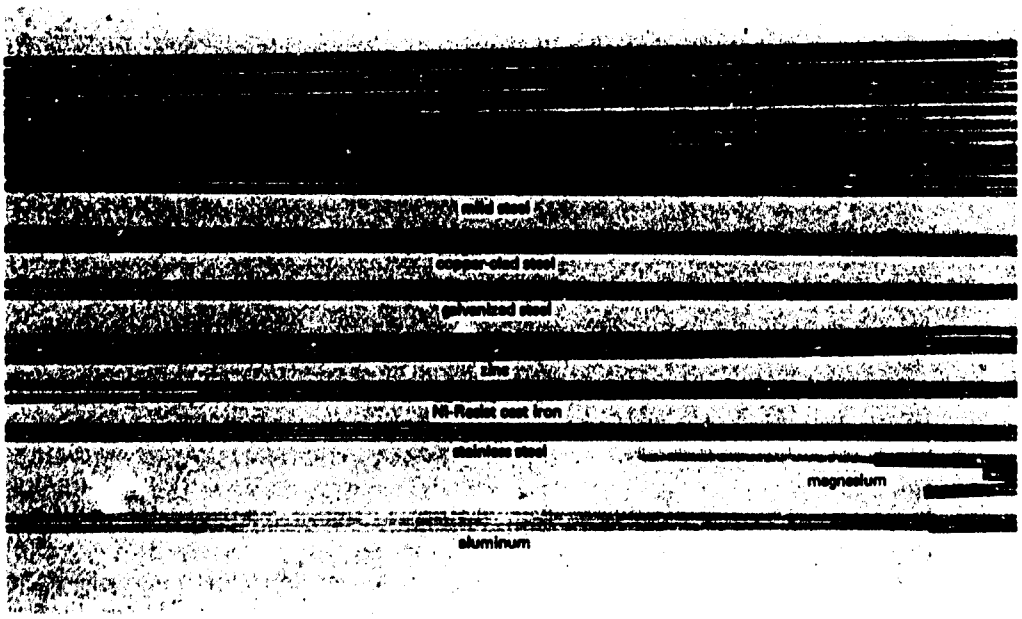
DISCUSSION

Tables 3, 4, and 5 list the percent weight losses of the 1-, 3-, and 7-year ground rods at NCEL. These data were extracted from Tables A-1, A-2, and A-3. Since the different test metals vary greatly in density, percent losses rather

than actual weight losses are given. For both single and coupled rods the relative orders of weight losses were quite similar after 1, 3, and 7 (or 5) years. The losses per year, however, decreased with time as the buildup of passive films of corrosion product tended to mitigate further corrosion.

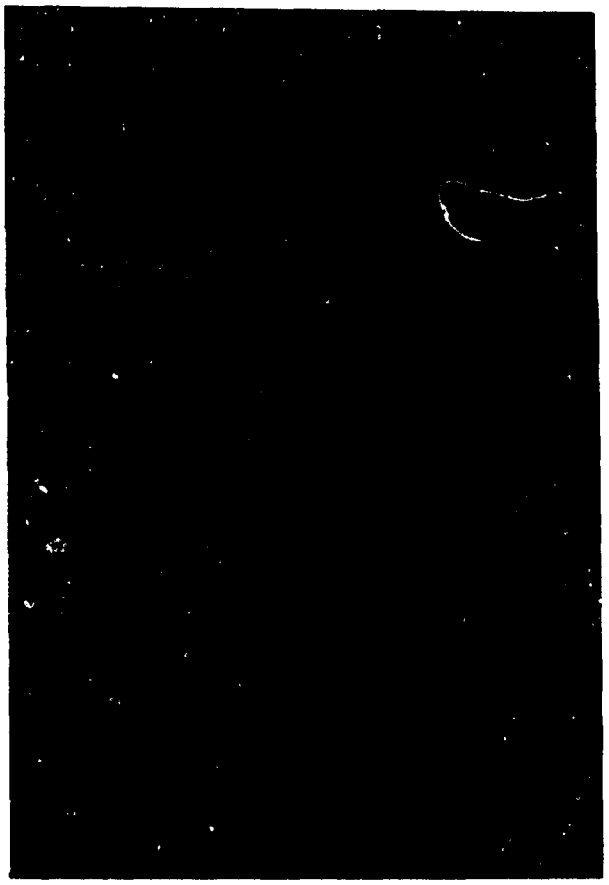


(a) NCEL site.



(b) Point Mugu site.

Figure 7. Cleaned 1-year test rods.



mild steel

galvanized steel

copper-clad steel

Ni-Resist cast iron

stainless steel

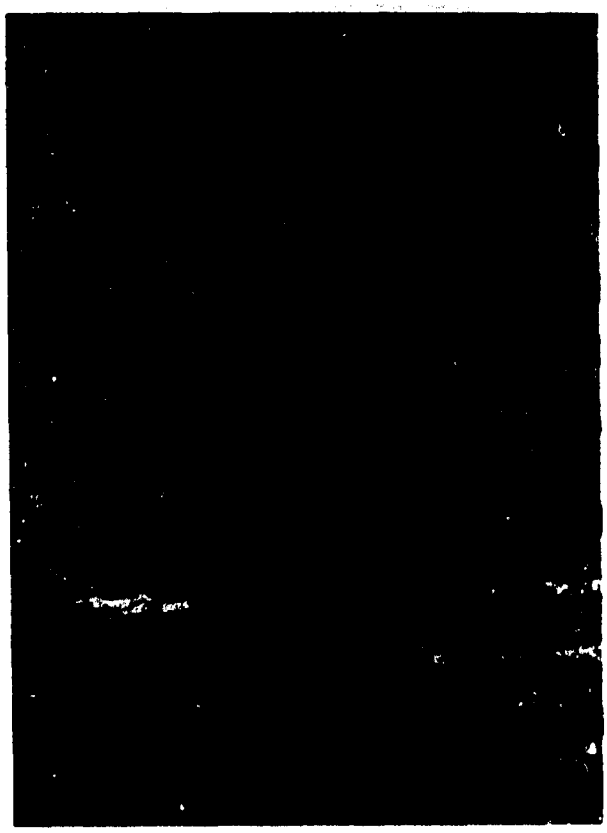
aluminum

magnesium

zinc

stainless-clad steel

(a) Single rods.



mild steel (as anode)

mild steel (as cathode)

galvanized steel

copper-clad steel

Ni-Resist cast iron

stainless steel

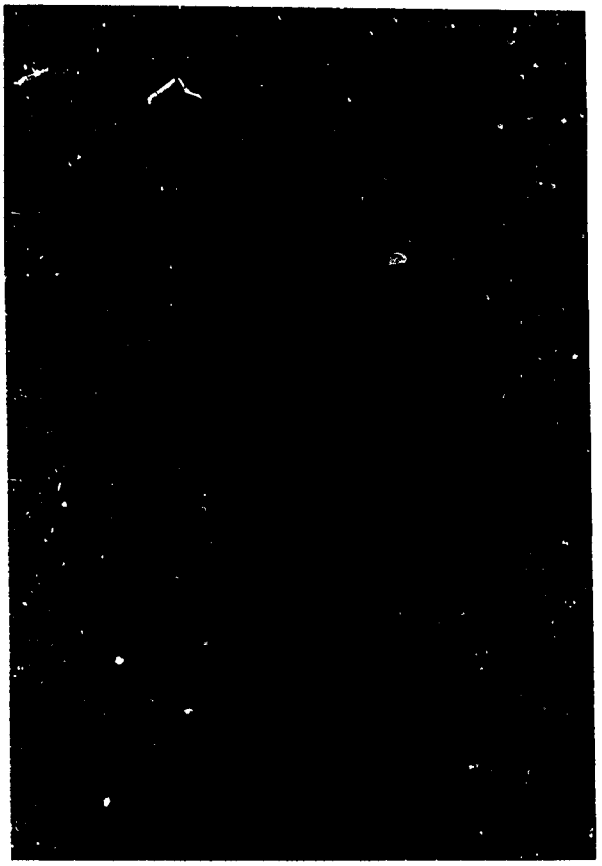
aluminum

zinc

stainless-clad steel

(b) Coupled rods.

Figure 8. Seven-year rods after removal from ground.



mild steel

galvanized steel

copper-clad steel

Ni-Resist cast iron

stainless steel

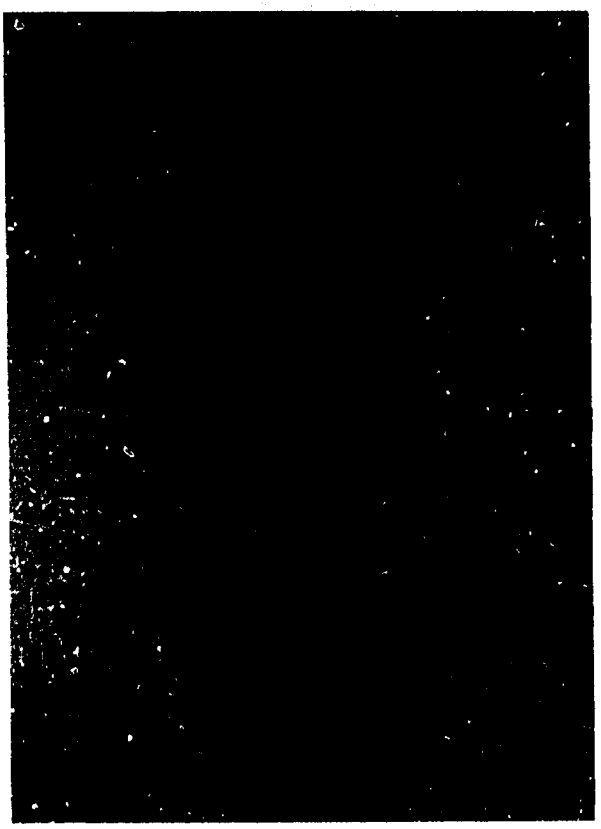
aluminum

magnesium

(a) Single rods.

zinc

stainless-clad steel



mild steel (as anode)

mild steel (as cathode)

galvanized steel

copper-clad steel

Ni-Resist cast iron

stainless steel

aluminum

(b) Coupled rods.

zinc

stainless-clad steel

Figure 9. Seven-year rods after cleaning.

Table 3. Percent Weight Loss of Single Rods

Type of Rod	Percent Weight Loss for—		
	1-Year Rod	3-Year Rod	7-Year Rod
Mild steel	2.6	6.11	7.61
Galvanized steel	1.5	2.4	2.2
Copper-clad steel	0.52	0.93	1.4
Ni-Resist cast iron	0.68	1.2[a]	1.9
Type 302 stainless steel	0.2	0.53	1.4
6061-T6 aluminum	0.92	1.6	2.3
AZ31B magnesium	6.3	[b]	25[c]
High purity zinc	1.2	1.2	4.11
Type 304 stainless-clad steel	0.29	0.63	0.87[d]

[a] Different manufacture for 1- and 7-year rods.

[b] Undetermined length of rod recovered.

[c] Percent weight loss for 40-1/2 inches of recovered rod.

[d] Value for 5-year rod.

Corrosion is an electrochemical oxidation process in which an electron loss corresponding to 96,500 coulombs (1 faraday) of electricity is accompanied by loss of one gram equivalent weight of metal. Thus by knowing the average current flow of the test couples in which a pure elementary metal of known equivalent weight serves as the anode, it is possible to calculate the weight losses of the anode rods that result from coupling. By adding to these the weight losses that occur to the corresponding single (uncoupled) rods, it is possible to estimate the total weight losses of these rods when coupled. The average current flow in the couples of high purity zinc and those in couples where mild steel rods served as anodes (mild steel was assumed to be pure iron) were determined from the 3- and 7-year data in Tables C-3 through C-12. These values were used for the weight loss calculations shown in Table 6. It can be seen that calculated and actual weight losses were quite close, especially with the couples where anode weight losses were greatest and the corresponding current flows could be measured with much more accuracy.

Table 4. Percent Weight Loss of Rods Coupled to Mild Steel Rods (I)

Coupled Metal	Couple Design	Percent Weight Loss for—		
		1-Year Rod	3-Year Rod	7-Year Rod
Galvanized steel (G)	G-I	3.72	6.24	5.66
Copper-clad steel (C)	C-I	0.38	0.35	0.73
Copper-clad steel (C)	C-2I	0.35	0.32	0.1
Ni-Resist cast iron (N)	N-I	0.26	0.35	0.29
Ni-Resist cast iron (N)[a]	N-I	–	0.95	–
Type 302 stainless steel (S)	S-I	0.05	0.01	0.05
6061-T6 aluminum (A)	A-I	7.4	20.5	22.7
AZ31B magnesium (M)	M-I	55.8	b	b
AZ31B magnesium (M)	M-I	69.2	b	b
High purity zinc (Z)	Z-I	6.88	13.0	29.66
High purity zinc (Z)	Z-ZI	8.32	20.1	30.11
Type 304 stainless-clad steel (B)	B-I	0.1	0.1	0.58[c]
Type 304 stainless-clad steel (B)	2B-I	–	–	0.58[c]
Type 304 stainless-clad steel (B)	2B-I	–	–	0.40[c]

[a] Of different manufacture than above rod.

[b] Rod previously removed.

[c] Value for 5-year rod.

Table 5. Percent Weight Loss of Coupled Mild Steel Rods (I)

Rods Coupled to Steel Rods	Couple Design	Percent Weight Loss for—		
		1-Year Rod	3-Year Rod	7-Year Rod
Galvanized steel (G)	G-I	1.2	2.85	5.95
Copper-clad steel (C)	C-I	4.83	14.8	25.9
Copper-clad steel (C)	C-2I	3.83	10.3	17.2
Copper-clad steel (C)	C-2I	3.85	13.4	16.9
Ni-Resist cast iron (N)	N-I	2.4	7.46	10.9
Ni-Resist cast iron (N)[a]	N-I	–	4.89	–
Type 302 stainless steel (S)	S-I	2.5	6.79	11.8
6061-T6 aluminum (A)	A-I	1.0	0.53	0.38
AZ31B magnesium (M)	M-I	0.85	[b]	[b]
AZ31B magnesium (M)	M-2I	0.80	[b]	[b]
AZ31B magnesium (M)	M-2I	0.88	[b]	[b]
High purity zinc (Z)	Z-I	0.88	0.82	0.2
High purity zinc (Z)	Z-2I	0.88	0.91	0.1
High purity zinc (Z)	Z-2I	0.89	0.77	0.1
Type 304 stainless-clad steel (B)	B-I	2.3	5.56	6.84[c]
Type 304 stainless-clad steel (B)	2B-I	–	–	7.72[c]

[a] Of different manufacture than above rod.

[b] Rod previously removed.

[c] Value for 5-year rod.

Table 6. Calculated and Actual Weight Losses for Coupled Rods

Rod Weighed[a]	Couple Design	Calculated Weight Loss for Couple Rods (g)	Actual Weight Loss for Single Rod (g)	Calculated Total Weight Loss (g)	Actual Total Weight Loss (g)
3-Year Rods					
Z	Z-I	381	42	423	442
Z	Z-2I	582	42	624	687
I	C-I	320	229	549	556
I	C-2I	241	458	699	887
I	N-I	73	229	302	279
I	S-I	38	229	267	255
I	B-I	25	229	254	207
7-Year Rods					
Z	Z-I	782	142	924	1,010
Z	Z-2I	782	142	924	1,027
I	C-I	672	285	967	970
I	C-2I	667	570	1,237	1,278
I	N-I	96	285	381	412
I	S-I	96	285	381	443

[a] Z = zinc
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
B = stainless-clad steel

Table 7. Weight Changes Due to Coupling for 1-, 3-, and 7-Year Rods

Description of Rods	Weight Changes (g) for—		
	1-Year Rod	3-Year Rod	7-Year Rod
Galvanized steel to mild steel	-82	-145	-128
Copper-clad steel to mild steel	+5	+20	+24
Copper-clad steel to two mild steel	+6	+21	+45
Ni-Resist cast iron to mild steel	+16	+10[a]	+61
Type 302 stainless steel to mild steel	+5	+15	+50
6061-T6 aluminum to mild steel	-84	-245	-265
AZ31B magnesium to mild steel	-420	[b]	[b]
AZ31B magnesium to two mild steel	-538	[b]	[b]
High purity zinc to mild steel	-194	-400	-868
High purity zinc to two mild steel	-243	-645	-885
Type 304 stainless-clad steel to mild steel	+6	+7	+11[c]
One of two type 304 stainless-clad steel to mild steel	–	–	+11[c]
One of two type 304 stainless-clad steel to mild steel	–	–	+18[c]
Mild steel to galvanized steel	+50	+122	+64
Mild steel to copper-clad steel	-85	-327	-685
One of two mild steel to copper-clad	-48	-155	-364
One of two mild steel to copper-clad	-38	-274	-344
Mild steel to Ni-Resist cast iron	+6	-50	-127
Mild steel to stainless steel	+1	-26	-158
Mild steel to aluminum	+58	+209	+271
Mild steel to magnesium	+64	[b]	[b]
One of two mild steel to magnesium	+66	[b]	[b]
One of two mild steel to magnesium	+63	[b]	[b]
Mild steel to zinc	+63	+198	+278
One of two mild steel to zinc	+63	+195	+280
One of two mild steel to zinc	+69	+200	+281
Mild steel to stainless-clad steel	+10	+22	+29[c]
Mild steel to two stainless-clad steel	–	–	-3[c]

[a] The 3-year Ni-Resist cast iron rods were of different manufacture than the 1- and 7-year rods.

[b] Coupled magnesium rods previously removed.

[c] The 5-year stainless-clad steel rods were removed at the same time as the 7-year rods.

Table 7 lists the changes in weight loss of each type of ground rod due to coupling. These data were derived by subtracting the weight loss of each coupled rod from the weight loss of the corresponding single (uncoupled) rod.

It can be seen that positive changes of one rod of a coupled pair were accompanied by negative changes of the other rod of the pair. Exceptions occurred with some of the couples of mild steel to stainless-clad steel rods where weight loss changes were relatively small. With coupled rods the rod with the more electronegative potential (the anode) cathodically protected the other rod of less electronegative potential (the cathode) from corroding. This was accomplished by a sacrifice in weight loss by the rod serving as the anode. The greater the differences of open circuit potentials of the coupled rods, generally the greater was the current flow and thus the corrosion of the anode rod. Electron flow in coupled rods was always from the rod of higher to the rod of lower electronegative potential.

As expected, doubling the number of mild steel rods coupled to individual magnesium and zinc rods increased the weight loss of these latter rods, but the increase was considerably less than twofold. Conversely, doubling the number of mild steel rods coupled to copper-clad steel rods reduced the weight loss of each of the mild steel rods by about one-half.

Table 8 summarizes weight loss and average potential, resistance, and current measurements for the 1-, 3-, and 7-year rods. From this table (or from Tables B-3 through B-12 and C-3 through C-12 from which the averages of electrical measurements were derived), it can be seen that there was a general overall decrease in electronegative potential and current and an increase in resistance with time. Considerable periodic variations also occurred in electrical measurements in addition to the general trends. These variations were frequently associated with rainfall which initially decreased electrical resistance and thus increased electronegative potential and current flow. Continued rainfall sometimes had the opposite effects by leaching from the soil conductive, water soluble salts introduced by salt spray.

Appropriately selected columns of Table 8 were treated statistically on a computer to obtain the correlation coefficients listed in Table 9. A correlation of 1 would indicate a perfect direct correlation, while one of -1 would indicate a perfect inverse correlation, and 0 would indicate no correlation. For single rods, there was only a fair overall correlation of percent weight loss and electronegative potential measurements. A similar correlation for the coupled rods was much better. Percent weight loss and electrical resistance did not correlate well with either the single or coupled rods. As might be expected from the previous discussion of Table 6, the best overall correlation occurred between the average current of couples and the weight loss of the rod coupled to the mild steel rod. There was only a fair inverse correlation between weight loss of mild steel rods and that of the rods coupled to them. Obviously there were many factors that contributed to irregularities in measurements and consequently less correlation. Two factors not previously discussed are localized variations in the soil substrate at different depths and locations in the test plot and localized anode and cathode areas on the same rod, especially on the galvanized rods and those with cladding.

Table 8. Data

Rod[a]	Single Rods		
	Percent Weight Loss	Average Electronegative Potential (v)	Av Res (c
M	6.3	1.539	1
I	2.6	0.618	1
G	1.5	0.845	
Z	1.2	1.065	1
A	0.92	0.776	
N	0.68	0.509	1
C	0.52	0.331	1
B	0.29	0.516	
S	0.2	0.092	
I	6.11	0.664	
G	2.4	0.728	
Z	1.2	1.068	1
A	1.6	0.776	
N	1.2	0.554	
C	0.93	0.353	
B	0.63	0.407	
S	0.53	0.133	
I	7.61	0.647	1
G	2.2	0.685	2
Z	4.11	1.048	1
A	2.3	0.768	
N	1.9	0.537	1
C	1.4	0.328	
B[c]	0.87	0.322	
S	1.4	0.080	

[a] M = magnesium
I = mild steel
G = galvanized steel
Z = zinc
A = aluminum
N = Ni-Resist cast ir

[b] Minus indicates flow of current from, rather than to, mild s

[c] The stainless-clad steel rods were exposed for only 5 years.

Table 8. Data Summary for 1-, 3-, and 7-Year Rods at NCEL

Single Rods			Couple of One Rod to One Mild Steel Rod				
Weight ıss	Average Electronegative Potential (v)	Average Resistance (ohms)	Percent Weight Loss		Average Electronegative Potential (v)	Average Resistance (ohms)	Average Current[b] (ma)
			Mild Steel Rod	Other Rod			
			1-Year Rods				
3	1.539	10.1	0.85	55.8	1.147	3.1	38.6
6	0.618	11.1	–	–	–	–	–
5	0.845	8.3	1.2	7.4	0.651	4.5	8.7
2	1.065	11.3	0.88	6.88	0.924	3.9	16.8
92	0.776	8.1	1.0	3.72	0.725	2.8	9.3
68	0.509	12.7	2.4	0.26	0.559	7.8	-2.1
52	0.331	10.9	4.83	0.38	0.550	4.0	-10.5
29	0.516	5.7	2.3	0.1	0.608	6.5	-0.4
2	0.092	5.6	2.5	0.05	0.581	5.7	-1.9
			3-Year Rods				
11	0.664	6.0	–	–	–	–	–
4	0.728	7.8	2.85	6.24	0.660	4.4	4.5
2	1.068	17.2	0.82	13.0	0.966	4.0	12.3
6	0.776	5.5	0.53	20.5	0.733	2.7	9.6
.2	0.554	8.3	7.46	0.35	0.632	3.2	-2.6
.93	0.353	5.1	14.8	0.35	0.584	2.6	-11.7
.63	0.407	5.7	5.56	0.1	0.584	19.9	-0.9
.53	0.133	5.3	6.79	0.1	0.621	3.2	-1.4
			7-Year Rods				
.61	0.647	10.0	–	–	–	–	–
.2	0.685	29.1	5.98	5.66	0.639	6.5	2.2
.11	1.048	16.5	0.2	29.66	0.915	6.4	10.4
.3	0.768	8.1	0.38	22.7	0.793	4.0	5.0
.9	0.537	13.4	10.9	0.29	0.616	4.6	-1.5
.4	0.328	8.2	25.9	0.73	0.549	3.9	-10.5
.87	0.322	7.5	6.84	0.58	0.549	16.9	-1.4
.4	0.080	8.5	11.8	0.05	0.596	3.8	-1.5

Z = zinc
A = aluminum
N = Ni-Resist cast iron
C = copper-clad steel
B = stainless-clad steel
S = stainless steel

teel

flow of current from, rather than to, mild steel rod.

d steel rods were exposed for only 5 years.

Table 9. Correlation of Corrosion Measurements

Measurements Correlated	Correlation Coefficient for—		
	1-Year Rods	3-Year Rods	7-Year Rods
Percent weight loss and average electronegative potential of single rods	0.815	0.297	0.508
Percent weight loss and average resistance of single rods	0.277	-0.101	0.532
Percent weight loss of single rods and of these rods coupled to one mild steel rod	0.996	0.482	0.872
Percent weight losses of mild steel rods and of other rods coupled to them	-0.445	-0.740	-0.695
Percent weight loss of coupled rods other than mild steel and average electronegative potentials	0.876	0.687	0.977
Percent weight loss of coupled rods other than mild steel and average resistance of couples	-0.471	-0.305	-0.176
Percent weight loss of coupled rods other than mild steel and average current of couples	0.896	0.818	0.833

All test ground rods met the requirements of the National Electrical Code[7] Section 250-83 that (1) the rods be driven to a depth of at least 8 feet, (2) the iron or steel rods be at least 5/8 inch in diameter, and (3) the nonferrous rods be at least 1/2 inch in diameter. Section 250-84 of the National Electrical Code requires that ground rods have a resistance to ground, as measured for single rods in this report, not to exceed 25 ohms. When the resistance is not this low, it is necessary to connect in parallel two or more rods. It is also suggested that resistive measurements be repeated at intervals of a few months to determine whether conditions have changed due to corrosion of the rods or drying out of the soil. Resistances measured at the Point Mugu site for 1 year were usually less than 1 ohm. At the NCEL site resistance measurements were several times higher than those of Point Mugu, but usually less than 25 ohms. Notable exceptions (resistances above 25 ohms), especially after several years of exposure, were single rods of zinc, magnesium, and galvanized steel.

NAVFAC Specification 9Yi[8] specifies that grounding shall be in accordance with the National Electrical Code except for the following values of resistance to ground:

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	Ohms
For grounding generating stations	1
For grounding main substations, and switching stations on primary distribution system	3
For grounding metal enclosures of electrical and electrically operated equipment and cable sheaths of connecting cables	3
For grounding systems to which portable electrical utilization equipment or appliances are connected .	3
For grounding secondary distribution systems (neutral), non-current carrying metal parts associated with distribution systems, and enclosures of electrical equipment not normally within reach of other than authorized and qualified electrical operating and maintenance personnel	10
For individual transformer and lightning arrester grounds on a distribution system	10
For equipment not covered above	10

When grounding rods are used because buried metal water piping is not practicable, NAVFAC Specification 9Yi states that the rods shall be of the sectional type and of cone-pointed, copper-encased steel or solid copper.

The previously stated criteria for a superior ground rod were that it (1) could be easily driven, (2) would have adequate corrosion resistance, and (3) would not cause serious galvanic corrosion to metals or pipes buried nearby. The magnesium, aluminum, zinc, and galvanized steel rods do not meet requirement 2. The copper-clad steel rod does not meet requirement 3. The Ni-Resist cast iron, type 302 stainless steel, and type 304 stainless-clad steel rods meet requirements 2 and 3, but the Ni-Resist cast iron rods are difficult to drive because of their inherent brittleness. The necessity of making pilot holes and backfilling would contribute appreciably to costs associated with their use. Types 302 and 304 stainless steel are quite similar in composition. Other stainless steels in the 300 series might have performed well, but types 302 and 304 are among the least expensive and are more readily available. Thus type 302 stainless steel and type 304 stainless-clad steel ground rods are the logical choices based on results of the NCEL study.

In 1965, the city of Los Angeles Department of Water and Power initiated a program using type 304 stainless-clad steel ground rods for such installations as transformer mounts. Mild steel ground rods could be used satisfactorily if they were cathodically protected. Thus magnesium anodes were installed to protect mild steel ground rods at Bethlehem Steel's Fairless Works near Morristown, Pennsylvania.[9] It would appear more economical for general use, however, to utilize rods requiring no cathodic protection.

FINDINGS AND CONCLUSIONS

1. The relative orders of percent weight loss of different types of ground rods were quite similar after 1, 3, and 7 years.

2. Weight losses per year decreased with time.

3. Weight losses of selected coupled rods calculated from current measurements compared well with the actual weight losses.

4. For the coupled rods, an increased weight loss for one rod was accompanied with a decreased weight loss for the other.

5. Doubling the number of cathode rods in a couple increased the weight loss of the anode, while doubling the number of anode rods decreased the weight loss of each anode rod.

6. There was a general overall decrease in electronegative potential and current measurements and an increase in resistance measurements with time.

7. The direct correlation between percent weight loss and electronegative potential was only fair for the single rods but good for the coupled rods.

8. Percent weight loss and resistance measurements did not correlate well.

9. There was a good direct correlation between current measurements and weight loss of rods coupled to mild steel.

10. Magnesium, aluminum, zinc, mild steel, and galvanized steel rods did not have the desired corrosion resistance.

11. Copper-clad steel rods caused appreciable galvanic corrosion to coupled mild steel rods.

~~12. Ni-Resist cast iron rods performed well, but required special installation~~ procedures because of their brittleness.

13. Type 302 stainless steel and type 304 stainless-clad steel rods performed the best overall and are the best choice of the different types of ground rods tested.

RECOMMENDATIONS

It is recommended that type 302 stainless steel or type 304 stainless-clad steel rods be used throughout the Naval Shore Establishment where driven ground rods are required.

Appendix A

WEIGHT CHANGES FOR TEST RODS

Table A-1. Weight Changes for 1-Year Ground Rods

Description of Test Rod	NCEL Site			Point Mugu Site		
	Initial Weight (g)	Weight Loss (g)	Weight Loss (%)	Initial Weight (g)	Weight Loss (g)	Weight Loss (%)
Single mild steel rod	3,751	96	2.6	3,776	52	1.4
Single galvanized steel rod	3,629	56	1.5	3,662	90	2.5
Single copper-clad steel rod	3,449	18	0.52	3,381	19	0.56
Single Ni-Resist cast iron rod	3,819	26	0.68	3,560	14	0.39
Single type 302 stainless steel rod	3,822	7	0.2	3,803	2	0.05
Single 6061-T6 aluminum rod	1,303	12	0.92	1,306	4	0.3
Single AZ31B magnesium rod	857	54	6.3	852	*a*	*a*
Single high purity zinc rod	3,416	41	1.2	3,412	40	1.2
Single type 304 stainless-clad steel rod	3,785	11	0.29	–	–	–
Galvanized rod coupled to mild steel rod	3,713	138	3.72	3,619	94	2.6
Copper-clad steel rod coupled to mild steel rod	3,442	13	0.38	3,392	6	0.2
Ni-Resist cast iron rod coupled to mild steel rod	3,814	10	0.26	3,557	4	0.1
Stainless steel rod coupled to mild steel rod	3,832	2	0.05	3,811	2	0.05
Aluminum rod coupled to mild steel rod	1,307	96	7.4	1,340	20	1.5
Magnesium rod coupled to mild steel rod	849	474	55.8	852	*b*	*b*
Zinc rod coupled to mild steel rod	3,415	235	6.88	3,419	105	3.07
Stainless-clad steel rod coupled to mild steel rod	3,783	5	0.1	–	–	–
Mild steel rod coupled to galvanized rod	3,748	46	1.2	3,782	33	0.87
Mild steel rod coupled to copper-clad steel rod	3,749	181	4.83	3,776	65	1.7
Mild steel rod coupled to Ni-Resist cast iron rod	3,754	90	2.4	3,777	86	2.3
Mild steel rod coupled to stainless steel rod	3,752	95	2.5	3,775	76	2.0
Mild steel rod coupled to aluminum rod	3,743	38	1.0	3,771	37	0.98
Mild steel rod coupled to magnesium rod	3,748	32	0.85	3,768	*b*	*b*
Mild steel rod coupled to zinc rod	3,749	33	0.88	3,781	29	0.72
Mild steel rod coupled to stainless-clad steel rod	3,660	86	2.3	–	–	–
Copper-clad steel rod coupled to two mild steel rods	3,461	12	0.35	3,393	5	0.2
Magnesium rod coupled to two mild steel rods	856	592	69.2	847	*b*	*b*
Zinc rod coupled to two mild steel rods	3,413	284	8.32	3,415	161	4.72
One of two mild steel rods coupled to copper-clad steel rod	3,764	144	3.83	3,769	70	1.9
One of two mild steel rods coupled to copper-clad steel rod	3,757	134	3.57	3,775	86	2.3
One of two mild steel rods coupled to magnesium rod	3,746	30	0.80	3,781	*b*	*b*
One of two mild steel rods coupled to magnesium rod	3,752	33	0.88	3,768	*b*	*b*
One of two mild steel rods coupled to zinc rod	3,743	33	0.89	3,782	61	1.6
One of two mild steel rods coupled to zinc rod	3,751	27	0.72	3,785	37	0.98

[a] Rod removed after 4 months.

[b] Rod removed after 8 weeks.

Table A-2. Weight Changes for 3-Year Ground Rods at NCEL

Description of Test Rod	Initial Weight (g)	Weight Loss (g)	Weight Loss (%)
Single mild steel rod	3,749	229	6.11
Single galvanized steel rod	3,625	86	2.4
Single copper-clad steel rod	3,451	32[a]	0.93
Single Ni-Resist cast iron rod[b]	3,536	44	1.2
Single type 302 stainless steel rod	3,833	20	0.53
Single 6061-T6 aluminum rod	1,302	21	1.6
Single AZ31B magnesium rod	851	c	c
Single high purity zinc rod	3,423	42	1.2
Single stainless-clad steel rod	3,785	24	0.63
Galvanized rod coupled to mild steel rod	3,702	231	6.24
Copper-clad steel rod coupled to mild steel rod	3,452	12[d]	0.35
Ni-Resist cast iron rod coupled to mild steel rod	3,992	14	0.35
Ni-Resist cast iron rod coupled to mild steel rod[e]	3,595	34	0.95
Stainless steel rod coupled to mild steel rod	3,795	5	0.1
Aluminum rod coupled to mild steel rod	1,300	266	20.5
Magnesium rod coupled to mild steel rod[f]	–	–	–
Zinc rod coupled to mild steel rod	3,413	442	13.0
Stainless-clad steel rod coupled to mild steel rod	3,783	5	0.1
Mild steel rod coupled to galvanized steel rod	3,760	107	2.85
Mild steel rod coupled to copper-clad steel rod	3,761	556	14.8
Mild steel rod coupled to Ni-Resist cast iron rod	3,740	279	7.46
Mild steel rod coupled to Ni-Resist cast iron rod[e]	3,744	183	4.89
Mild steel rod coupled to stainless steel rod	3,735	255	6.79
Mild steel rod coupled to aluminum rod	3,749	20	0.53
Mild steel rod coupled to magnesium rod[f]	–	–	–
Mild steel rod coupled to zinc rod	3,760	31	0.82
Mild steel rod coupled to stainless-clad steel rod	3,728	207	5.56
Copper-clad steel rod coupled to two mild steel rods	3,481	11[g]	0.32
Magnesium rod coupled to two mild steel rods[f]	–	–	–
Zinc rod coupled to two mild steel rods	3,417	687	20.1
One of two mild steel rods coupled to copper-clad steel rod	3,744	384	10.3
One of two mild steel rods coupled to copper-clad steel rod	3,757	503	13.4
One of two mild steel rods coupled to magnesium rod[f]	–	–	–
One of two mild steel rods coupled to magnesium rod[f]	–	–	–
One of two mild steel rods coupled to zinc rod	3,751	34	0.91
One of two mild steel rods coupled to zinc rod	3,752	29	0.77

[a] 1-3/16 inch of steel core lost by corrosion.

[b] Original rod broken during driving; this rod of different manufacture.

[c] Rod only partially recovered.

[d] 1/4 inch of steel core lost by corrosion.

[e] Similar to single Ni-Resist cast iron rod described in *b*.

[f] Previously removed from test.

[g] 1/8 inch of steel core lost by corrosion.

Table A-3. Weight Changes for 7-Year Ground Rods at NCEL

Description of Test Rod	Initial Weight (g)	Weight Loss (g)	Weight Loss (%)
Single mild steel rod	3,746	285	7.61
Single galvanized steel rod	3,650	82	2.2
Single copper-clad steel rod	3,451	49	1.4
Single Ni-Resist cast iron rod	3,859	72	1.9
Single type 302 stainless steel rod	3,849	52	1.4
Single 6061-T6 aluminum rod	1,310	30	2.3
Single AZ31B magnesium rod	855	[a]	25.[b]
Single high purity zinc rod	3,457	142	4.11
Single type 304 stainless-clad steel rod[c]	3,781	33	0.87
Galvanized steel rod coupled to mild steel rod	3,710	210	5.66
Copper-clad steel rod coupled to mild steel rod	3,432	25	0.73
Ni-Resist cast iron rod coupled to mild steel rod	3,816	11	0.29
Stainless steel rod coupled to mild steel rod	3,845	2	0.05
Aluminum rod coupled to mild steel rod	1,302	295	22.7
Magnesium rod coupled to mild steel rod[d]	–	–	–
Zinc rod coupled to mild steel rod	3,405	1,010	29.66
Stainless-clad steel rod coupled to mild steel rod[c]	3,782	22	0.58
Mild steel rod coupled to galvanized steel rod	3,693	221	5.98
Mild steel rod coupled to copper-clad steel rod	3,747	970	25.9
Mild steel rod coupled to Ni-Resist cast iron rod	3,766	412	10.9
Mild steel rod coupled to stainless steel rod	3,740	443	11.8
Mild steel rod coupled to aluminum rod	3,697	14	0.38
Mild steel rod coupled to magnesium rod[d]	–	–	–
Mild steel rod coupled to zinc rod	3,775	7	0.2
Mild steel rod coupled to stainless-clad steel rod[c]	3,743	256	6.84
Copper-clad steel rod coupled to two mild steel rods	3,472	4	0.1
Magnesium rod coupled to two mild steel rods[d]	–	–	–
Zinc rod coupled to two mild steel rods	3,411	1,027	30.11
One of two mild steel rods coupled to copper-clad steel rod	3,769	649	17.2
One of two mild steel rods coupled to copper-clad steel rod	3,763	629	16.7
One of two mild steel rods coupled to magnesium rod[d]	–	–	–
One of two mild steel rods coupled to magnesium rod[d]	–	–	–
One of two mild steel rods coupled to zinc rod	3,720	5	0.1
One of two mild steel rods coupled to zinc rod	3,693	4	0.1
One of two stainless-clad steel rods coupled to mild steel rods[c]	3,785	15	0.42
One of two stainless-clad steel rods coupled to mild steel rods[c]	3,784	22	0.58
Mild steel rod coupled to two stainless-clad steel rods[c]	3,732	288	7.72

[a] The 40-1/2 inches of rod recovered weighed 274 grams.

[b] The 40-1/2 inches of rod recovered had lost 25% of its weight.

[c] Five-year rods removed at same time 7-year rods were removed.

[d] Rods previously removed from test.

Appendix B

ELECTRICAL MEASUREMENTS FOR SINGLE TEST RODS

Table B-1. Electrical Measurements for Single 1-Year Rods (NCEL)

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.618	-0.599	-0.596	-0.587	-0.597	-0.587	-0.631	–	-0.701	-0.625	-0.622	-0.635	-0.618
G	-1.020	-1.085	-0.882	-0.827	-0.772	-0.772	-0.743	–	-0.742	-0.741	-0.733	-0.985	-0.845
C	-0.397	-0.370	-0.329	-0.330	-0.336	-0.308	-0.282	–	-0.307	-0.353	-0.315	-0.320	-0.331
N	-0.500	-0.472	-0.501	-0.488	-0.495	-0.481	-0.532	–	-0.518	-0.530	-0.521	-0.567	-0.509
S	-0.055	-0.087	-0.061	-0.078	-0.106	-0.092	-0.026	–	-0.104	-0.137	-0.150	-0.118	-0.092
Z	-1.085	-1.060	-1.060	-1.055	-1.035	-1.050	-1.100	–	-1.060	-1.070	-1.075	-1.065	-1.065
A	-0.792	-0.773	-0.765	-0.759	-0.793	-0.758	-0.790	–	-0.770	-0.792	-0.795	-0.751	-0.776
M	-1.585	-1.540	-1.540	-1.530	-1.540	-1.525	-1.535	–	-1.520	-1.540	-1.535	-1.545	-1.539
B	-0.537	-0.543	-0.541	-0.530	-0.540	-0.519	-0.525	-0.495	-0.523	-0.458	–	-0.465	-0.516
	Resistance to Ground (ohms)												
I	12.1	13.1	12.0	12.7	13.1	13.0	7.4	–	10.5	10.8	12.2	5.1	11.1
G	5.6	5.8	6.5	8.2	8.9	9.7	8.8	–	10.2	11.3	11.2	5.5	8.3
C	10.2	11.0	11.6	12.8	12.8	13.8	9.1	–	11.9	12.2	12.3	2.5	10.9
N	10.9	11.7	12.1	13.9	14.5	15.6	11.0	–	16.1	16.7	16.2	1.9	12.7
S	5.3	5.5	5.8	6.2	6.2	6.5	5.0	–	6.9	6.7	6.2	1.6	5.6
Z	10.6	11.8	12.2	12.9	11.1	12.8	8.8	–	14.8	14.7	12.2	2.6	11.3
A	8.4	9.0	9.4	9.9	9.4	10.2	5.7	–	8.1	8.6	8.5	2.2	8.1
M	10.1	10.8	11.8	12.6	11.8	13.0	7.6	–	9.4	10.2	10.1	3.0	10.0
B	6.9	7.6	7.0	7.4	7.4	7.4	6.5	7.1	1.5	2.0	–	2.0	5.7

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-2. Electrical Measurements for Single 1-Year Rods (Point Mugu)

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.706	-0.679	-0.661	-0.671	-0.663	-0.653	-0.663	–	-0.673	–	-0.555	-0.440	-0.636
G	-1.155	-1.125	-1.075	-1.090	-1.075	-1.070	-1.068	–	-1.015	–	-0.620	-0.488	-0.978
C	-0.580	-0.490	-0.461	-0.548	-0.531	-0.506	-0.470	–	-0.554	–	-0.453	-0.510	-0.510
N	-0.610	-0.603	-0.567	-0.585	-0.587	-0.579	-0.598	–	-0.578	–	-0.597	-0.600	-0.590
S	-0.290	-0.308	-0.218	-0.260	-0.268	-0.147	-0.250	–	-0.240	–	-0.120	-0.202	-0.230
Z	-1.182	-1.135	-1.125	-1.095	-1.095	-1.090	-1.110	–	-1.075	–	-1.085	-1.075	-1.104
A	-0.853	-0.826	-0.808	-0.834	-0.837	-0.832	-0.830	–	-0.817	–	-0.822	-0.824	-0.828
M	-1.630	-1.610	-1.560	-1.580	–	–	–	–	–	–	–	–	-1.595
B	–	–	–	–	–	–	–	–	–	–	–	–	–
	Resistance to Ground (ohms)												
I	0.52	0.55	0.56	0.39	0.70	0.37	0.54	–	–	–	10.5	6.5	0.59
G	0.58	0.63	0.92	0.84	0.68	0.67	0.79	–	–	–	–	30.1	4.40
C	0.52	0.48	0.50	0.44	0.50	0.36	0.47	–	–	–	0.37	0.34	0.44
N	0.56	0.62	0.53	0.37	0.59	0.35	0.59	–	–	–	0.42	0.41	0.49
S	0.51	0.64	0.55	0.42	0.61	0.41	0.69	–	–	–	0.34	0.44	0.51
Z	0.50	0.64	0.78	0.98	0.89	0.72	0.81	–	–	–	4.5	3.0	1.42
A	0.69	0.57	0.60	0.49	0.61	0.49	0.62	–	–	–	0.49	0.41	0.55
M	0.66	0.84	0.84	–	–	–	–	–	–	–	–	–	0.78
B	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-3. Electrical Measurements for Single 3-Year Rods

First Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.648	-0.618	-0.630	-0.620	-0.623	-0.615	-0.792	–	-0.663	-0.683	-0.667	-0.678	-0.657
G	-0.987	-0.873	-0.819	-0.770	-0.747	-0.725	-0.983	–	-0.705	-0.712	-0.692	-1.010	-0.820
C	-0.406	-0.357	-0.347	-0.332	-0.332	-0.313	-0.340	–	-0.340	-0.358	-0.308	-0.420	-0.350
N	-0.548	-0.507	-0.512	-0.538	-0.550	-0.540	-0.559	-0.549	-0.597	-0.595	–	-0.590	-0.553
S	-0.267	-0.239	-0.281	-0.250	-0.151	-0.253	-0.052	–	0.024	-0.061	-0.035	-0.137	-0.153
Z	-1.085	-1.070	-1.083	-1.092	-1.085	-1.070	-1.105	–	-1.025	-1.060	-1.060	-1.085	-1.072
A	-0.810	-0.781	-0.789	-0.783	-0.808	-0.877	-0.810	–	-0.752	-0.812	-0.802	-0.797	-0.802
M	-1.575	-1.545	-1.545	-1.535	-1.545	-1.530	-1.555	–	-1.525	-1.547	-1.525	-1.545	-1.542
B	-0.526	-0.542	-0.550	-0.540	-0.548	-0.591	-0.543	-0.516	-0.560	-0.510	–	-0.520	-0.540
	Resistance to Ground (ohms)												
I	5.7	5.7	7.7	9.6	6.5	9.4	7.0	–	5.7	7.2	7.3	1.7	6.7
G	7.3	8.5	9.0	9.9	9.8	12.5	9.2	–	10.3	10.7	10.4	4.3	9.3
C	5.7	5.8	6.4	6.8	7.0	7.5	4.6	–	5.4	5.9	6.1	1.8	5.7
N	8.2	9.3	8.2	10.2	9.0	8.5	6.9	7.2	1.8	2.1	–	2.0	6.6
S	6.3	6.3	6.4	6.9	6.6	7.4	4.6	–	6.7	7.1	7.1	1.8	6.1
Z	32.5	35.5	35.5	34.5	29.5	41.0	15.3	–	36.5	37.0	24.5	2.5	29.2
A	6.3	6.0	6.7	7.2	6.9	7.7	5.2	–	6.6	6.8	6.4	2.4	6.2
M	6.1	6.4	7.1	7.6	7.7	8.4	6.4	–	8.6	7.7	6.7	3.1	6.9
B	6.8	7.3	6.0	6.4	6.5	6.6	5.3	6.2	1.4	1.8	–	1.8	5.1

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-4. Electrical Measurements for Single 3-Year Rods

Second Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (volts) to $Cu/CuSO_4$													
I	–	-0.700	-0.672	-0.670	-0.678	-0.678	-0.672	-0.680	-0.677	-0.665	-0.665	-0.630	-0.672
G	–	-0.697	-0.687	-0.673	-0.675	-0.700	-0.690	-0.685	-0.687	-0.675	-0.680	-0.680	-0.684
C	–	-0.395	-0.441	-0.365	-0.300	-0.340	-0.345	-0.350	-0.358	-0.365	-0.345	-0.319	-0.356
N	–	0.590	-0.623	-0.620	-0.623	-0.625	–	–	-0.565	-0.540	–	-0.513	-0.587
S	–	-0.193	-0.130	-0.133	-0.144	-0.134	-0.109	-0.107	-0.047	-0.085	-0.103	-0.139	-0.120
Z	–	-1.110	-1.100	-1.080	-1.082	-1.100	-1.085	-1.080	-1.090	-1.080	-1.090	-1.095	-1.090
A	–	-0.828	-0.795	-0.780	-0.778	-0.770	-0.778	-0.795	-0.798	-0.785	-0.790	-0.780	-0.789
M	–	-1.580	-1.550	-1.530	-1.535	-1.520	-1.525	-1.525	-1.540	-1.530	-1.520	-1.500	-1.532
B	–	-0.510	-0.525	-0.441	-0.337	-0.327	–	–	-0.190	-0.225	–	-0.290	-0.356
Resistance to Ground (ohms)													
I	–	1.8	2.7	8.5	5.0	4.5	8.8	6.0	6.0	6.2	6.2	5.8	5.6
G	–	4.3	5.0	4.7	5.0	7.0	7.3	8.8	8.8	8.8	8.8	7.6	6.9
C	–	1.7	2.8	1.9	1.8	3.2	5.2	6.0	6.2	6.3	6.5	6.2	4.3
N	–	2.3	1.7	2.5	4.8	4.4	6.6	–	7.8	9.3	–	13.7	5.9
S	–	1.7	2.9	2.0	1.9	3.2	5.3	5.8	5.8	6.0	6.3	6.2	4.3
Z	–	2.9	2.1	3.4	3.1	6.3	12.5	15.0	16.8	16.8	16.8	14.3	10.0
A	–	2.2	3.8	2.5	2.4	4.5	5.3	5.6	5.7	5.6	6.0	5.8	4.5
M	–	3.0	20.0	32.0	38.0	30.0	39.0	45.0	37.0	45.0	52.0	58.0	33.3
B	–	2.0	1.4	1.9	3.0	2.9	4.2	–	4.7	6.9	–	10.0	4.1

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-5. Electrical Measurements for Single 3-Year Rods

Third Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.647	-0.651	-0.650	-0.658	-0.667	-0.658	-0.667	-0.663	-0.680	-0.666	-0.677	-0.682	-0.663
G	-0.675	-0.686	-0.302	-0.707	-0.787	-0.700	-0.701	-0.697	-0.751	-0.704	-0.720	-0.720	-0.679
C	-0.330	-0.330	-0.348	-0.353	-0.368	-0.346	-0.348	-0.350	-0.358	-0.330	-0.395	-0.380	-0.353
N	-0.520	-0.533	-0.537	-0.530	-0.524	–	-0.520	-0.505	-0.500	-0.473	-0.580	-0.521	-0.522
S	-0.155	-0.181	-0.220	-0.119	–	-0.036	-0.076	-0.083	-0.055	-0.078	-0.166	-0.220	-0.126
Z	-1.085	-1.090	-0.522	-1.105	-1.115	-1.085	-1.075	-1.070	-1.120	-1.089	-1.075	-1.100	-1.042
A	-0.778	-0.783	-0.480	-0.790	-0.792	-0.753	-0.760	-0.758	-0.775	-0.760	-0.777	-0.652	-0.738
M	-1.485	-1.490	-1.421	-1.530	-1.495	-1.480	-1.490	-1.530	-1.520	-1.475	-1.455	-1.485	-1.488
B	-0.334	-0.421	-0.355	-0.372	-0.363	–	-0.310	-0.325	-0.330	-0.340	-0.252	-0.193	-0.326
	Resistance to Ground (ohms)												
I	6.2	6.1	6.5	6.9	5.0	5.9	6.1	6.5	4.8	10.1	1.8	3.3	5.7
G	7.4	7.6	7.3	8.5	7.6	8.7	8.7	8.2	7.5	7.7	3.4	3.3	7.2
C	6.5	6.7	6.8	7.4	5.5	5.6	5.6	5.7	4.8	5.3	1.7	2.1	5.3
N	12.5	7.9	9.5	12.2	12.7	–	14.0	13.0	12.5	12.0	15.5	14.2	12.4
S	6.5	6.8	6.3	6.2	6.9	6.2	6.3	6.3	4.2	5.7	1.9	2.3	5.5
Z	14.2	14.7	12.0	14.8	11.5	21.0	23.5	12.8	8.0	11.8	3.0	3.2	12.5
A	5.9	6.1	6.2	6.9	5.3	7.2	7.4	7.5	5.2	6.7	2.3	2.8	5.8
M	65.0	70.0	32.0	51.0	47.0	69.0	77.0	39.5	40.0	68.0	88.0	87.0	61.1
B	6.9	4.5	6.2	5.9	7.4	–	9.9	10.1	10.0	9.4	8.3	8.2	7.9

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-6. Electrical Measurements for Single 7-Year Rods

First Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.638	-0.624	-0.604	-0.607	-0.619	-0.620	-0.650	–	-0.661	-0.662	-0.662	-0.663	-0.637
G	-1.035	-0.977	-0.901	-0.849	-0.826	-0.790	-0.877	–	-0.788	-0.764	-0.751	-1.020	-0.870
C	-0.409	-0.380	-0.350	-0.350	-0.340	-0.346	-0.383	–	-0.350	-0.330	-0.351	-0.417	-0.364
N	-0.532	-0.570	-0.494	-0.498	-0.508	-0.501	-0.577	–	-0.547	-0.539	-0.538	-0.595	-0.536
S	-0.157	-0.156	-0.124	-0.017	-0.120	-0.175	-0.110	–	-0.019	-0.075	-0.083	-0.113	-0.102
Z	-1.080	-1.080	-1.030	-1.038	-1.030	-1.025	-1.046	–	-1.030	-1.035	-1.080	-1.080	-1.046
A	-0.829	-0.813	-0.796	-0.799	-0.803	-0.790	-0.800	–	-0.787	-0.793	-0.812	-0.793	-0.801
M	-1.590	-1.565	-1.540	-1.538	-1.545	-1.535	-1.545	–	-1.535	-1.540	-1.555	-1.555	-1.549
B	-0.540	-0.546	-0.560	-0.540	-0.551	-0.540	-0.560	-0.535	-0.571	-0.570	–	-0.548	-0.549
	Resistance to Ground (ohms)												
I	8.3	5.8	6.4	6.6	8.1	9.5	6.1	–	5.8	6.1	6.1	1.6	6.4
G	9.0	9.7	11.4	16.6	17.5	19.5	19.8	–	23.5	23.0	23.5	5.4	16.2
C	6.2	6.6	7.1	7.6	7.5	8.4	5.1	–	7.2	7.5	7.6	1.6	6.6
N	7.9	8.4	8.9	9.7	9.9	12.5	5.7	–	8.4	9.1	9.4	1.6	8.3
S	7.0	7.2	7.3	8.2	8.0	8.9	5.5	–	7.4	7.5	7.2	1.5	6.8
Z	14.2	15.5	17.5	18.3	16.7	20.5	14.6	–	18.2	17.7	16.8	3.1	15.6
A	6.1	6.4	6.9	7.3	7.1	8.0	6.3	–	6.6	7.6	7.2	2.1	6.5
M	6.9	6.6	7.4	7.8	7.9	8.9	6.6	–	9.2	8.7	8.8	3.2	7.5
B	6.5	7.2	7.6	13.4	6.3	6.3	4.8	5.8	1.4	1.8	–	1.8	5.7

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-7. Electrical Measurements for Single 7-Year Rods

Second Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (volts) to $Cu/CuSO_4$													
I	–	-0.697	-0.670	-0.652	-0.652	-0.640	-0.628	-0.646	-0.646	-0.640	-0.630	-0.647	-0.650
G	–	-0.900	-0.748	-0.690	-0.690	-0.700	-0.690	-0.685	-0.687	-0.670	-0.660	-0.650	-0.679
C	–	-0.385	-0.445	-0.318	-0.390	-0.300	-0.335	-0.310	-0.311	-0.305	-0.295	-0.280	-0.334
N	–	-0.610	-0.582	-0.560	-0.568	-0.562	-0.543	-0.538	-0.537	-0.515	-0.505	-0.480	-0.545
S	–	-0.184	-0.148	-0.125	-0.175	-0.122	-0.082	-0.086	-0.084	-0.080	-0.072	-0.139	-0.108
Z	–	-1.100	-1.050	-1.080	-1.070	-1.050	-1.070	-1.080	-1.055	-1.050	-1.095	-1.035	-1.083
A	–	-0.823	-0.790	-0.780	-0.780	-0.782	-0.780	-0.788	-0.790	-0.780	-0.775	-0.780	-0.786
M	–	-1.595	-1.545	-1.540	-1.540	-1.540	-1.510	-1.520	-1.530	-1.520	-1.510	-1.505	-1.532
B	–	-0.510	-0.517	-0.437	-0.297	-0.290	–	–	-0.097	-0.135	-	-0.166	-0.306
Resistance to Ground (ohms)													
I	–	1.7	4.4	8.0	2.0	3.3	8.0	8.0	6.1	6.0	6.2	5.7	5.0
G	–	6.4	9.0	12.0	11.2	15.7	18.8	24.0	23.5	24.0	24.0	23.0	17.4
C	–	1.7	2.6	2.3	1.9	3.6	6.3	7.4	7.5	7.5	7.8	7.1	5.1
N	–	1.8	2.3	2.3	2.0	4.0	7.3	8.0	8.0	8.3	8.3	7.9	5.5
S	–	1.6	2.1	2.0	1.7	3.0	5.5	6.3	6.3	6.5	6.8	6.1	4.4
Z	–	4.2	20.0	3.4	3.0	5.8	9.0	11.8	11.2	[illegible]	12.8	12.6	9.6
A	–	2.3	2.7	2.5	2.4	3.6	5.5	6.3	6.5	[illegible]	6.5	6.2	4.6
M	–	3.3	4.5	4.3	3.7	5.5	10.8	11.8	11.8	[illegible]	12.2	11.9	8.5
B	–	2.3	1.5	2.1	3.1	3.1	4.3	–	4.7	6.9	–	10.2	4.2

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-8. Electrical Measurements for Single 7-Year Rods

Third Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (volts) to $Cu/CuSO_4$													
I	-0.635	-0.641	-0.650	-0.645	-0.658	-0.654	-0.667	-0.660	-0.683	-0.658	-0.675	-0.682	-0.659
G	-0.651	-0.662	-0.133	0.677	-0.642	-0.670	-0.677	-0.669	-0.752	-0.657	-0.720	-0.665	-0.648
C	-0.293	-0.302	-0.322	-0.322	-0.316	-0.300	-0.305	-0.318	-0.347	-0.282	-0.350	-0.295	-0.312
N	-0.498	-0.501	-0.420	-0.510	-0.517	-0.525	-0.538	-0.530	-0.570	-0.543	-0.542	-0.565	-0.522
S	-0.081	-0.112	-0.112	-0.115	-0.118	-0.076	-0.074	-0.059	-0.023	-0.084	-0.155	-0.140	-0.095
Z	-1.050	-1.090	-0.396	-1.055	-1.050	-1.065	-1.045	-1.035	-1.065	-1.040	-1.045	-1.080	-1.001
A	-0.782	-0.793	-0.813	-0.800	-0.800	-0.780	-0.797	-0.790	-0.807	-0.783	-0.783	-0.793	-0.793
M	-1.510	-1.515	-1.520	-1.535	1.530	-1.515	-1.535	-1.525	-1.535	1.510	-1.530	-1.540	-1.525
B	-0.295	-0.403	-0.295	-0.282	-0.193	—	-0.145	-0.187	-0.205	-0.353	-0.385	-0.189	-0.265
Resistance to Ground (ohms)													
I	5.9	5.9	6.2	6.9	5.0	5.6	5.7	5.8	4.8	5.5	1.8	2.1	5.1
G	22.5	22.0	18.3	22.2	18.3	24.0	23.5	21.5	25.5	24.5	13.2	13.0	20.7
C	7.4	7.4	7.8	8.5	6.6	6.5	6.7	7.2	6.4	7.0	1.6	1.9	6.2
N	8.0	8.1	7.9	8.3	9.4	7.3	7.8	8.4	6.1	8.0	1.7	2.0	6.9
S	6.3	6.2	6.3	7.1	4.8	5.1	5.2	5.4	4.5	5.2	1.9	1.8	5.0
Z	12.8	13.1	10.1	14.5	13.2	14.0	13.7	12.8	12.2	13.0	5.2	5.4	11.6
A	6.2	6.3	6.5	7.3	5.9	6.0	6.0	5.9	5.1	5.8	2.1	2.6	5.4
M	12.2	12.8	12.0	14.2	10.8	11.6	13.2	13.2	8.6	11.0	5.5	7.2	11.0
B	6.3	4.4	6.2	7.1	8.3	—	10.3	10.5	10.3	9.7	9.4	9.5	8.3

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-9. Electrical Measurements for Single 7-Year Rods

Fourth Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	–	-0.680	-0.680	-0.718	-0.700	-0.700	-0.711	–	–	-0.680	-0.673	–	-0.692
G	–	-0.672	-0.695	-0.772	-0.700	-0.687	-0.727	–	–	-0.640	-0.655	–	-0.693
C	–	-0.313	-0.338	-0.475	-0.400	-0.390	-0.380	–	–	-0.297	-0.251	–	-0.355
N	–	-0.568	-0.572	-0.606	-0.597	-0.592	-0.602	–	–	-0.550	-0.535	–	-0.577
S	–	-0.176	-0.183	-0.180	-0.214	-0.149	-0.177	–	–	-0.058	-0.046	–	-0.147
Z	–	-1.075	-1.080	-1.095	-1.050	-1.050	-1.075	–	–	-1.015	-1.030	–	-1.058
A	–	-0.800	-0.815	-0.821	-0.795	-0.772	-0.790	–	–	-0.738	-0.737	–	-0.783
M	–	-1.545	-1.555	-1.545	-1.508	-1.495	-1.495	–	–	-1.450	-1.450	–	-1.505
B	-0.257	-0.297	-0.198	-0.177	-0.169	-0.173	-0.167	-0.193	-0.228	-0.267	-0.245	-0.218	0.219
	Resistance to Ground (ohms)												
I	–	4.1	2.5	2.0	3.0	4.7	4.7	6.5	–	7.7	15.4	–	5.6
G	–	12.2	10.2	7.3	11.4	15.1	16.5	29.0	–	26.5	29.3	–	17.5
C	–	2.1	2.2	1.6	2.6	4.2	4.3	6.7	–	8.4	11.2	–	4.8
N	–	2.1	2.4	1.7	2.8	5.0	5.0	7.4	–	9.6	11.3	–	5.3
S	–	1.7	1.9	1.4	2.2	3.4	3.4	4.9	–	6.6	8.9	–	3.8
Z	–	6.5	6.5	5.2	6.1	8.7	8.9	12.6	–	16.2	21.3	–	10.2
A	–	2.8	3.0	2.2	3.0	4.2	4.2	6.6	–	7.3	9.4	–	4.7
M	–	9.2	6.5	5.2	6.1	8.7	17.3	23.5	–	25.5	26.2	–	14.2
B	9.3	5.3	6.7	8.2	8.7	8.9	9.7	10.7	11.2	10.8	10.2	–	8.9

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-10. Electrical Measurements for Single 7-Year Rods

Fifth Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.650	-0.650	-0.650	-0.717	-0.695	-0.688	–	-0.677	-0.675	-0.660	-0.625	-0.615	-0.663
G	-0.633	-0.648	-0.667	-0.683	-0.697	-0.690	–	-0.692	-0.635	-0.630	-0.646	-0.637	-0.659
C	-0.233	-0.250	-0.305	-0.469	-0.475	-0.448	–	-0.300	-0.284	-0.273	-0.227	-0.213	-0.316
N	-0.532	-0.527	-0.522	-0.611	-0.644	-0.625	–	-0.542	-0.576	-0.520	-0.485	-0.477	-0.551
S	0.032	0.00	-0.102	-0.109	-0.105	-0.085	–	0.00	-0.021	-0.010	-0.001	-0.005	-0.037
Z	-1.055	-1.055	-1.055	-1.065	-1.040	-1.025	–	-1.015	-1.020	-1.030	-1.020	-1.015	-1.035
A	-0.735	-0.739	-0.769	-0.792	-0.785	-0.778	–	-0.760	-0.722	-0.715	-0.710	-0.714	-0.747
M	-1.455	-1.455	-1.460	-1.465	-1.460	-1.475	–	-1.480	-1.445	-1.435	-1.420	-1.425	-1.452
B	-0.293	-0.297	-0.261	-0.302	–	-0.259	-0.068	-0.322	-0.382	-0.273	-0.278	–	-0.273
	Resistance to Ground (ohms)												
I	24.5	19.5	6.7	1.8	5.8	17.6	–	37.0	8.5	9.1	10.3	15.3	14.2
G	32.0	29.5	23.5	25.5	27.5	29.0	–	31.5	31.0	31.5	32.5	41.9	30.5
C	14.8	10.3	6.1	7.7	8.4	10.2	–	12.3	9.7	10.4	11.7	14.9	10.6
N	14.9	14.4	9.7	8.8	10.3	11.4	–	13.9	16.5	17.0	18.5	13.7	13.6
S	12.5	10.0	5.0	7.9	9.5	8.8	–	10.1	31.0	31.5	32.5	41.9	18.2
Z	28.5	21.2	13.8	17.6	18.4	18.7	–	19.2	20.7	21.2	23.5	21.8	20.4
A	11.6	11.7	6.2	11.4	11.7	11.3	–	11.2	11.4	11.1	11.1	10.9	10.9
M	29.0	24.5	32.5	32.5	31.0	31.5	–	32.0	32.5	33.5	33.5	32.4	31.3
B	4.6	6.1	6.8	9.7	6.4	7.2	14.3	14.9	15.0	14.5	13.5	–	10.3

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-11. Electrical Measurements for Single 7-Year Rods

Sixth Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.630	-0.630	-0.628	-0.722	-0.710	-0.695	-0.701	-0.715	-0.710	-0.705	-0.678	-0.656	-0.681
G	-0.645	-0.657	-0.653	-0.675	-0.687	0.695	-0.714	-0.697	-0.635	-0.625	-0.643	-0.656	-0.665
C	-0.247	-0.255	-0.298	-0.457	-0.464	-0.454	-0.465	-0.374	-0.279	-0.215	-0.203	-0.246	-0.329
N	-0.467	-0.473	-0.503	-0.619	-0.656	-0.637	-0.613	-0.607	-0.625	-0.510	-0.478	-0.493	-0.556
S	-0.017	-0.025	-0.013	-0.013	-0.014	-0.010	-0.037	-0.015	-0.012	-0.005	0.000	-0.020	-0.015
Z	-1.025	-1.005	-1.015	-1.020	-1.015	-1.025	-1.025	-1.020	-1.025	-1.030	-1.015	-1.010	-1.019
A	-0.727	-0.730	-0.753	-0.772	-0.762	-0.769	-0.785	-0.769	-0.729	-0.725	-0.718	-0.731	-0.747
M	-1.430	-1.435	-1.450	-1.460	-1.450	-1.465	-1.460	-1.465	-1.450	-1.425	-1.415	-1.420	-1.443
B	—	—	—	—	—	—	—	—	—	—	—	—	—
	Resistance to Ground (ohms)												
I	17.6	10.8	6.3	1.9	6.2	6.8	6.4	7.2	9.1	9.4	10.6	11.1	8.6
G	53.0	49.0	51.0	57.0	62.0	57.0	62.0	62.0	59.0	63.0	62.0	67.0	58.6
C	15.3	11.8	7.4	9.3	10.2	11.1	10.8	14.1	10.1	10.6	11.8	14.8	11.4
N	14.8	15.7	13.2	11.7	14.8	13.9	13.2	14.6	16.8	17.5	18.8	13.9	14.9
S	13.1	10.3	8.4	8.3	10.7	9.2	8.7	11.3	11.0	11.3	11.7	12.8	10.5
Z	22.1	19.3	12.4	14.7	21.2	19.3	16.8	20.2	21.2	22.6	24.7	22.3	19.7
A	10.9	11.3	9.4	12.7	14.8	15.2	15.7	15.1	16.1	15.9	14.7	12.2	13.6
M	33.4	36.5	41.5	42.7	39.9	41.5	47.0	43.0	46.0	49.0	53.0	52.7	43.9
B	—	—	—	—	—	—	—	—	—	—	—	—	—

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Table B-12. Electrical Measurements for Single 7-Year Rods

Seventh Year

Test Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
	Potential (volts) to $Cu/CuSO_4$												
I	-0.625	-0.610	-0.613	-0.588	-0.685	-0.500	-0.739	-0.380	-0.232	-0.418	-0.608	-0.550	-0.545
G	-0.649	-0.647	-0.554	-0.625	-0.675	-0.185	-0.272	-0.694	-0.667	-0.680	-0.669	-0.665	-0.581
C	-0.287	-0.305	-0.313	-0.232	-0.477	-0.199	-0.259	-0.310	-0.261	-0.238	-0.259	-0.261	-0.283
N	-0.482	-0.475	-0.517	-0.459	-0.593	-0.195	-0.458	-0.542	-0.520	-0.405	-0.504	-0.560	-0.475
S	-0.068	-0.082	-0.064	-0.068	-0.015	–	-0.046	-0.059	-0.119	-0.065	-0.052	-0.002	-0.058
Z	-1.015	-1.010	-1.010	-1.000	-1.005	-1.650	-1.125	-1.390	-1.030	-1.020	-1.050	-1.030	-1.111
A	-0.747	-0.753	-0.768	-0.720	-0.815	-0.480	-0.644	-0.750	-0.739	-0.742	-0.743	-0.750	-0.720
M	-1.410	-1.400	-1.415	-1.410	-1.395	-1.640	-1.478	-1.440	-1.410	-1.400	-1.410	-1.390	-1.433
B	–	–	–	–	–	–	–	–	–	–	–	–	–
	Resistance to Ground (ohms)												
I	–	12.5	6.9	11.2	11.1	17.5	13.0	17.5	30.5	100.0	18.2	40.0	25.3
G	–	17.0	18.3	26.0	57.0	60.0	45.0	49.0	49.0	52.0	49.0	45.0	42.5
C	–	6.2	7.7	9.1	10.5	16.0	12.0	14.6	15.8	17.5	17.4	13.8	12.8
N	–	6.1	9.4	6.7	14.2	52.5	30.0	42.5	54.0	66.0	76.0	72.0	39.0
S	–	4.9	7.6	7.2	–	9.6	9.6	13.2	10.5	15.8	15.5	12.0	10.6
Z	–	16.3	10.1	19.7	20.5	15.6	10.8	45.0	46.0	47.5	44.0	39.0	28.6
A	–	5.9	6.2	7.9	14.8	12.0	10.7	13.5	13.2	13.5	12.5	11.5	11.0
M	–	160.0	–	180.0	41.0	40.0	35.0	125.0	145.0	165.0	180.0	180.0	94.5
B	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel
I = mild steel
C = copper-clad steel
N = Ni-Resist cast iron
S = stainless steel
Z = zinc
A = aluminum
M = magnesium
B = stainless-clad steel

Appendix C

ELECTRICAL MEASUREMENTS FOR COUPLED TEST RODS

Table C-1. Electrical Measurements for 1-Year Coupled Rods (NCEL)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.830	-0.724	-0.671	-0.613	-0.620	-0.600	-0.639	–	-0.605	-0.617	-0.603	-0.639	-0.651
C	-0.563	-0.556	-0.542	-0.537	-0.550	-0.537	-0.542	–	-0.537	-0.553	-0.545	-0.593	-0.550
C[b]	-0.558	-0.554	-0.548	-0.546	-0.565	-0.551	-0.584	–	-0.538	-0.560	-0.558	–	-0.556
N	-0.552	-0.540	-0.538	-0.520	-0.550	-0.532	-0.567	–	-0.557	-0.570	-0.590	-0.637	-0.559
S	-0.598	-0.579	-0.573	-0.567	-0.583	-0.572	-0.590	–	-0.560	-0.567	-0.567	-0.642	-0.581
Z	-0.910	-0.907	-0.893	-0.890	-0.899	-0.882	-0.952	–	-0.937	-0.936	-0.965	-0.995	-0.924
Z[b]	-0.850	-0.833	-0.820	-0.820	-0.837	-0.822	-0.916	–	-0.862	-0.863	-0.835	–	-0.845
A	-0.741	-0.721	-0.712	-0.704	-0.713	-0.700	-0.738	–	-0.731	-0.750	-0.737	-0.728	-0.725
M	-1.335	-1.308	-1.295	-1.280	-1.290	-1.270	-1.235	–	-1.155	-0.913	-0.837	-0.708	-1.147
M[b]	-1.340	-1.315	-1.300	-1.275	-1.270	-1.245	-1.175	–	-1.135	-1.147	-1.070	–	-1.229
B	-0.583	-0.575	-0.575	-0.576	-0.590	-0.580	-0.622	-0.605	-0.672	-0.662	–	-0.648	-0.608
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	3.3	3.8	4.2	7.4	4.5	4.4	4.4	–	4.8	4.7	–	3.1	4.5
C	3.6	3.4	3.7	4.1	4.1	4.4	4.6	–	5.2	5.5	5.0	1.2	4.0
C[b]	3.5	3.4	3.6	3.9	3.9	4.2	3.6	–	5.0	5.0	4.3	–	4.0
N	6.9	7.3	8.0	8.9	8.9	10.0	6.2	–	9.3	10.6	8.9	1.3	7.8
S	4.9	5.4	5.9	6.3	6.2	6.3	4.8	–	7.1	7.5	7.1	1.1	5.7
Z	3.8	3.9	4.0	4.6	4.2	4.5	3.2	–	4.6	4.8	2.9	2.5	3.9
Z[b]	4.1	3.85	4.3	4.5	4.3	4.6	3.1	–	4.6	4.8	3.3	–	4.1
A	2.7	2.6	2.8	2.9	3.0	3.1	2.6	–	3.3	3.4	3.2	1.1	2.8
M	2.8	2.5	2.7	3.2	3.2	3.3	3.1	–	3.5	4.0	4.2	1.9	3.1
M[b]	3.3	3.4	3.6	4.1	3.8	4.1	4.0	–	5.5	5.5	4.3	–	4.1
B	4.1	4.3	4.4	13.0	13.9	4.3	5.8	3.7	–	–	–	5.3	6.5
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	21.7	15.3	11.1	7.5	6.8	6.2	–	–	4.5	4.8	5.8	3.0	8.7
C	11.8	11.9	10.9	11.3	9.8	9.3	–	–	8.1	9.9	10.3	11.9	10.5
C[b]	11.5	11.3	9.9	8.8	8.7	8.2	–	–	6.1	6.1	8.3	–	8.8
N	3.6	2.9	2.1	1.6	1.8	1.5	–	–	1.6	1.5	1.9	2.2	2.1
S	2.5	2.3	2.1	1.8	1.7	1.6	–	–	1.3	1.5	1.9	1.8	1.9
Z	22.0	19.8	20.3	18.8	16.9	15.9	–	–	12.0	12.5	15.3	14.0	16.8
Z[b]	25.3	23.5	22.8	20.8	21.8	19.1	–	–	16.1	17.1	19.4	–	20.7
A	14.1	10.9	10.5	9.4	8.8	8.3	–	–	5.7	6.4	7.8	11.2	9.3
M	64.2	51.8	55.0	48.2	46.7	44.7	–	–	30.8	18.2	16.3	10.4	38.6
M[b]	71.6	68.6	65.7	57.3	55.5	51.5	–	–	28.0	30.5	35.0	–	51.5
B	0.6	0.5	0.3	0.4	0.1	0.2	0.5	0.8	0.3	0.7	–	0.5	0.4
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-2. Electrical Measurements for 1-Year Coupled Rods (Point Mugu)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-1.125	-1.110	-1.000	-0.875	-0.795	-0.723	-0.768	–	-0.710	–	-0.717	-0.713	-0.853
C	-0.692	-0.683	-0.658	-0.662	-0.670	-0.657	-0.678	–	-0.690	–	-0.690	-0.680	-0.676
C[b]	-0.692	-0.683	-0.648	-0.660	-0.663	-0.664	-0.680	–	-0.650	–	-0.675	-0.681	-0.669
N	-0.690	-0.697	-0.665	-0.675	-0.678	-0.661	-0.675	–	-0.662	–	-0.687	-0.680	-0.667
S	-0.695	-0.699	-0.670	-0.678	-0.681	-0.673	-0.678	–	-0.670	–	-0.685	-0.691	-0.682
Z	-1.120	-1.105	-1.065	-1.085	-1.092	-1.080	-1.105	–	-1.060	–	-1.080	-1.065	-1.085
Z[b]	-1.110	-1.100	-1.060	-1.080	-1.085	-1.075	-1.100	–	-1.050	–	-0.807	-1.060	-1.052
A	-0.838	-0.823	-0.810	-0.825	-0.833	-0.833	-0.827	–	-0.815	–	-0.844	-0.813	-0.826
M	-1.465	-1.320	–	–	–	–	–	–	–	–	–	–	-1.392
M[b]	-1.455	-1.280	–	–	–	–	–	–	–	–	–	–	-1.367
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	0.45	0.47	0.52	0.47	0.63	0.56	0.55	–	–	–	–	–	0.52
C	0.40	0.55	0.43	0.29	0.42	0.26	0.35	–	–	–	0.42	0.23	0.37
C[b]	0.37	0.50	0.41	0.27	0.39	0.26	0.31	–	–	–	0.47	0.22	0.35
N	0.44	0.46	0.42	0.57	0.55	0.26	0.54	–	–	–	0.78	0.27	0.47
S	0.48	0.47	0.43	0.29	0.44	0.27	0.41	–	–	–	0.30	0.18	0.36
Z	0.44	0.77	0.53	0.47	0.60	0.59	0.58	–	–	–	1.25	0.47	0.63
Z[b]	0.36	0.50	0.48	0.38	0.52	0.36	0.36	–	–	–	3.30	0.48	0.74
A	0.47	0.47	0.44	0.32	0.48	0.29	0.31	–	–	–	0.33	1.40	0.50
M	0.43	0.68	–	–	–	–	–	–	–	–	–	–	0.55
M[b]	0.38	0.56	–	–	–	–	–	–	–	–	–	–	0.47
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	26.1	9.1	3.8	0.8	0.5	1.0	0.6	–	0.5	–	0.5	0.4	4.5
C	4.1	4.6	1.9	1.8	1.6	2.5	1.2	–	0.4	–	0.4	0.3	1.9
C[b]	4.8	6.7	5.7	3.1	5.6	1.5	1.3	–	2.8	–	1.5	1.0	3.4
N	3.0	2.0	1.0	0.6	0.5	0.7	0.5	–	0.8	–	0.3	0.3	1.0
S	1.6	2.0	0.4	0.2	0.2	0.7	0.5	–	0.5	–	0.4	0.1	0.7
Z	34.0	11.0	6.4	3.4	4.7	4.1	2.4	–	5.6	–	2.0	3.7	7.7
Z[b]	66.5	16.5	8.3	5.3	8.0	6.6	4.6	–	9.8	–	4.3	10.4	14.0
A	3.6	5.2	4.4	1.8	2.2	1.2	0.48	–	1.1	–	–	0.5	2.3
M	1.1	0.5	–	–	–	–	–	–	–	–	–	–	0.8
M[b]	1.1	0.4	–	–	–	–	–	–	–	–	–	–	0.8
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-3. Electrical Measurements for 3-Year Coupled Rods (First Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.884	-0.752	-0.747	-0.692	-0.683	-0.658	-0.690	–	-0.698	-0.648	-0.645	-0.667	-0.706
C	-0.594	-0.560	-0.569	-0.551	-0.558	-0.551	-0.613	–	-0.569	-0.583	-0.600	-0.633	-0.580
C[b]	-0.608	-0.571	-0.578	-0.560	-0.571	-0.561	-0.637	–	-0.582	-0.596	-0.613	-0.650	-0.593
N	-0.627	-0.606	-0.626	-0.606	-0.617	-0.609	-0.655	–	-0.616	-0.637	-0.639	-0.695	-0.630
S	-0.631	-0.610	-0.631	-0.625	-0.631	-0.623	-0.650	–	-0.625	-0.644	-0.670	-0.667	-0.637
Z	-0.910	-0.877	-0.895	-0.873	-0.890	-0.877	-0.920	–	-0.845	-0.850	-0.951	-1.035	-0.902
Z[b]	-0.840	-0.805	-0.817	-0.802	-0.816	-0.820	-0.780	–	-0.804	-0.818	-0.793	-1.035	-0.830
A	-0.777	-0.735	-0.747	-0.727	-0.742	-0.730	-0.760	–	-0.734	-0.747	-0.733	-0.764	-0.745
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.551	-0.562	-0.610	-0.590	-0.598	-0.588	-0.624	-0.606	-0.682	-0.680	–	-0.665	-0.614
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	2.9	3.2	3.4	3.6	4.0	3.8	3.6	–	4.1	3.8	4.5	1.8	3.5
C	2.5	2.6	2.5	2.9	2.9	3.0	2.1	–	3.2	3.3	2.9	0.9	2.6
C[b]	2.1	2.2	2.6	2.5	2.5	2.9	1.8	–	2.8	2.9	2.2	1.0	2.3
N	3.0	3.1	3.4	3.5	3.5	3.9	2.5	–	3.8	3.8	3.5	1.3	3.2
S	2.8	2.8	2.7	2.7	2.9	3.2	2.4	–	4.1	4.6	2.6	1.1	2.9
Z	3.3	3.4	3.7	4.1	4.0	4.5	3.7	–	5.6	4.9	2.5	1.7	3.8
Z[b]	2.5	2.5	2.6	2.6	2.8	2.9	2.4	–	3.3	3.3	3.5	2.6	2.8
A	2.6	2.7	2.9	3.1	3.0	3.3	2.4	–	3.4	3.3	2.5	1.0	2.7
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	4.4	12.2	4.0	11.1	8.6	11.2	10.5	6.4	9.3	1.1	–	28.0	9.7
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	15.7	11.7	10.7	8.2	7.0	6.2	–	–	4.0	3.5	4.1	2.3	7.3
C	13.8	15.9	13.4	13.0	15.8	12.2	–	–	11.6	12.2	15.6	12.1	13.5
C[b]	19.2	18.1	17.7	16.4	15.9	15.6	–	–	14.5	17.4	20.5	16.1	17.1
N	5.6	4.5	4.1	3.5	3.2	2.6	–	–	1.7	2.4	3.5	4.4	3.5
S	2.6	2.1	2.1	1.9	1.7	1.6	–	–	1.6	1.4	1.9	1.1	1.8
Z	21.7	19.4	20.4	16.7	18.2	15.2	–	–	13.3	13.5	19.5	13.9	17.1
Z[b]	30.1	31.0	31.0	27.5	26.8	26.0	–	–	23.8	24.5	35.3	19.3	27.5
A	9.7	9.1	9.9	8.9	8.8	8.4	–	–	8.6	8.9	10.8	7.2	9.0
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	1.1	0.7	0.9	0.6	0.6	0.5	0.7	0.7	0.5	0.8	–	0.8	0.7
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-4. Electrical Measurements for 3-Year Coupled Rods (Second Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	–	-0.690	-0.657	-0.650	-0.658	-0.630	-0.615	-0.613	-0.618	-0.615	-0.620	-0.632	-0.636
C	–	-0.643	-0.632	-0.608	-0.618	-0.595	-0.573	-0.575	-0.573	-0.560	-0.560	-0.562	-0.590
C[b]	–	-0.657	-0.650	-0.635	-0.640	-0.610	-0.593	-0.590	-0.592	-0.580	-0.575	-0.572	-0.608
N	–	-0.685	-0.659	-0.650	-0.655	-0.640	-0.605	-0.615	-0.618	-0.610	-0.610	-0.620	-0.633
S	–	-0.718	-0.680	-0.665	-0.670	-0.618	-0.595	-0.605	-0.611	-0.595	-0.595	-0.590	-0.631
Z	–	-1.060	-1.040	-1.040	-1.030	-0.985	-0.890	-0.905	-0.908	-0.905	-0.935	-0.972	-0.970
Z[b]	–	-1.055	-1.045	-1.020	-1.045	-0.915	-0.828	-0.878	-0.872	-0.880	-0.900	-0.948	-0.944
A	–	-0.793	-0.770	-0.755	-0.755	-0.735	-0.715	-0.795	-0.798	-0.727	-0.720	-0.715	-0.752
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	-0.650	-0.690	-0.663	-0.655	-0.655	–	-0.532	-0.557	-0.519	–	-0.489	-0.601
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	–	2.0	2.0	5.5	2.4	2.2	3.0	3.7	6.6	5.3	5.3	5.5	3.9
C	–	1.0	2.0	1.4	1.3	2.1	2.6	3.2	3.2	3.2	3.3	2.9	2.4
C[b]	–	0.9	1.9	1.2	1.4	1.6	2.2	2.6	2.7	2.8	2.6	2.4	2.0
N	–	1.3	2.1	1.6	1.9	2.0	3.0	3.3	3.7	3.8	3.9	3.9	2.8
S	–	1.2	1.7	1.4	1.4	2.0	3.4	4.2	4.1	4.4	4.8	4.6	3.0
Z	–	1.1	3.3	2.9	1.6	3.5	3.5	4.3	4.8	4.7	4.8	4.1	3.5
Z[b]	–	1.9	1.8	1.7	1.7	1.9	3.6	2.8	5.5	5.0	4.5	3.2	3.0
A	–	1.0	3.3	1.3	1.5	1.9	2.6	3.0	3.1	3.0	3.1	2.8	2.4
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	12.5	10.5	46.0	28.0	47.0	2.6	24.0	30.0	26.0	–	27.5	25.1
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	–	2.5	2.1	1.1	1.6	3.6	5.1	5.0	3.5	5.0	4.8	4.5	3.5
C	–	15.7	8.8	14.4	9.5	11.2	13.6	12.5	11.8	12.2	12.2	12.8	12.2
C[b]	–	20.8	10.8	22.5	11.2	15.8	18.6	16.3	16.1	16.5	16.6	19.1	16.7
N	–	3.9	2.8	2.4	2.0	2.9	5.6	3.6	2.2	3.1	2.8	1.9	3.0
S	–	1.3	0.5	1.9	0.9	1.0	1.3	1.3	1.3	1.4	1.4	1.5	1.2
Z	–	20.8	13.7	16.0	7.5	16.2	19.2	13.6	13.6	15.0	14.8	14.6	15.0
Z[b]	–	23.5	17.8	22.5	13.2	29.0	28.5	25.0	21.7	11.1	9.2	7.8	19.0
A	–	9.0	6.3	3.8	4.8	7.4	13.3	14.0	12.8	19.5	18.0	15.0	11.2
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	1.0	0.8	0.8	0.9	0.6	1.2	1.2	0.8	1.0	–	1.2	0.9
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-5. Electrical Measurements for 3-Year Coupled Rods (Third Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.625	-0.633	-0.549	-0.641	-0.642	-0.623	-0.634	-0.642	-0.662	-0.645	-0.682	-0.680	-0.638
C	-0.550	-0.557	-0.630	-0.567	-0.578	-0.541	-0.548	-0.571	-0.592	-0.570	-0.638	-0.640	-0.581
C[b]	-0.560	-0.563	-0.604	-0.578	-0.594	-0.560	-0.569	-0.585	-0.610	-0.584	-0.612	-0.663	-0.594
N	-0.610	-0.618	-0.662	-0.628	-0.633	-0.608	-0.615	-0.628	-0.651	-0.628	-0.663	-0.668	-0.634
S	-0.572	-0.577	-0.658	-0.607	-0.591	-0.588	-0.592	-0.632	-0.646	-0.626	-0.682	-0.680	-0.595
Z	-0.970	-0.982	-1.020	-1.020	-1.085	-0.990	-0.985	-1.060	-1.075	-1.020	-1.050	-1.055	-1.026
Z[b]	-0.948	-0.963	-0.965	-0.942	-0.975	-0.919	-0.972	-1.045	-1.020	-0.976	-1.065	-1.065	-0.987
A	-0.717	-0.723	-0.658	-0.641	-0.642	-0.718	-0.732	-0.735	-0.750	-0.730	-0.690	-0.697	-0.702
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.501	-0.538	-0.525	-0.510	-0.518	–	-0.522	-0.520	-0.510	-0.502	-0.665	-0.617	-0.538
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	5.7	5.0	6.0	9.7	4.2	11.0	8.8	4.4	4.5	7.5	1.2	1.3	5.7
C	3.3	3.3	3.7	3.6	2.9	3.6	4.0	3.1	2.5	2.8	1.2	1.2	2.9
C[b]	2.8	2.8	3.0	2.7	2.4	3.1	2.8	2.7	2.2	2.7	1.1	1.3	2.4
N	3.9	3.9	4.7	4.0	4.2	4.4	4.2	3.8	3.2	3.8	1.7	1.5	3.6
S	4.5	3.2	4.5	4.6	3.6	4.8	4.9	3.8	3.0	3.8	1.2	1.3	3.6
Z	4.4	4.5	5.0	4.5	4.0	6.7	6.8	4.0	5.0	6.4	1.6	4.6	4.7
Z[b]	4.4	4.8	6.3	6.0	4.0	4.7	4.6	3.2	3.8	3.8	1.3	3.2	4.2
A	2.9	3.3	3.1	6.6	3.1	3.5	3.4	3.1	2.8	3.1	1.1	1.3	3.1
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	12.5	2.7	3.9	18.5	33.5	–	55.0	47.0	8.6	5.9	43.0	42.6	24.8
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	4.3	4.0	4.5	3.6	3.4	3.4	2.4	2.1	2.2	1.8	0.2	0.1	2.6
C	14.6	12.4	10.4	11.9	9.8	9.5	6.8	8.9	9.4	10.4	4.1	5.9	9.5
C[b]	12.4	19.2	18.4	17.2	15.0	14.0	10.1	12.1	13.8	15.0	3.8	6.5	13.1
N	1.8	1.8	2.0	1.6	1.0	0.9	0.9	1.0	1.0	1.3	0.8	0.9	1.3
S	1.5	1.5	1.5	1.4	1.7	1.6	1.0	1.3	1.6	1.6	0.5	0.8	1.3
Z	6.5	6.0	13.9	5.7	3.3	3.8	2.8	2.9	2.7	5.2	2.3	2.9	4.8
Z[b]	12.9	11.4	12.0	9.5	7.0	7.2	5.0	7.6	6.1	7.6	2.9	4.3	7.8
A	13.7	12.8	13.2	11.0	8.3	9.2	6.3	7.1	7.4	7.9	2.5	3.7	8.5
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	1.2	1.2	1.2	1.2	1.2	–	0.6	0.8	0.9	1.2	1.1	0.8	1.0
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-6. Electrical Measurements for 7-Year Coupled Rods (First Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.817	-0.728	-0.658	-0.643	-0.640	-0.628	-0.742	–	-0.623	-0.621	-0.643	-0.667	-0.673
C	-0.596	-0.565	-0.540	-0.541	-0.550	-0.541	-0.585	–	-0.548	-0.545	-0.570	-0.622	-0.563
C[b]	-0.651	-0.617	-0.600	-0.591	-0.598	-0.591	-0.665	–	-0.603	-0.597	-0.627	-0.670	-0.610
N	-0.626	-0.607	-0.507	-0.588	-0.598	-0.591	-0.637	–	-0.620	-0.620	-0.641	-0.671	-0.609
S	-0.643	-0.623	-0.607	-0.599	-0.603	-0.596	-0.652	–	-0.623	-0.623	-0.634	-0.667	-0.624
Z	-0.948	-0.920	-0.897	-0.887	0.902	-0.893	-0.991	–	-0.910	-0.905	-0.910	-1.035	-0.927
Z[b]	-0.886	-0.823	-0.795	-0.823	-0.835	-0.833	-0.891	–	-0.824	-0.835	-0.837	-1.000	-0.852
A	-0.763	-0.740	-0.717	-0.721	-0.730	-0.719	-0.765	–	-0.730	-0.734	-0.747	-0.770	-0.739
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.472	-0.570	-0.617	-0.592	-0.608	-0.600	-0.621	-0.609	-0.708	-0.690	–	-0.687	-0.615
B[c]	-0.553	-0.573	-0.627	-0.551	-0.582	-0.581	-0.605	-0.581	-0.685	-0.682	–	-0.670	-0.608
Resistance to Ground (ohms)													
G	3.1	3.2	4.4	4.0	4.0	4.7	3.6	–	5.0	4.9	2.6	1.5	3.7
C	2.5	2.5	2.6	2.8	2.8	3.0	2.4	–	3.1	3.3	2.9	1.1	2.6
C[b]	2.4	2.6	2.7	2.9	2.9	2.9	2.5	–	3.2	3.4	3.2	1.1	2.7
N	2.6	2.8	3.0	3.3	3.3	3.8	2.4	–	3.4	3.8	3.6	1.1	3.0
S	2.4	2.6	2.8	3.2	3.3	3.5	2.2	–	3.4	3.5	3.4	0.9	2.8
Z	2.7	2.7	3.0	3.3	3.0	3.4	3.2	–	4.4	8.2	3.0	1.6	3.5
Z[b]	2.2	2.9	3.2	2.6	2.6	3.0	2.2	–	4.3	6.0	4.6	3.2	3.3
A	2.2	2.3	2.7	2.6	3.1	2.7	2.1	–	2.8	2.9	2.6	1.0	2.4
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	4.3	10.8	7.6	13.4	7.6	12.0	6.7	26.0	7.0	1.6	–	10.1	9.7
B[c]	5.3	10.2	4.9	12.5	5.6	11.0	8.7	26.0	7.0	1.0	–	45.0	12.4
Current Flow Between Coupled Rods (ma)													
G	18.7	14.0	9.0	7.0	5.7	4.5	–	–	2.2	2.2	2.4	8.3	7.4
C	16.1	14.9	15.5	15.3	15.1	14.8	–	–	14.6	15.5	21.5	18.6	16.2
C[b]	14.5	13.6	13.3	12.5	12.1	11.6	–	–	14.4	14.5	17.6	21.8	14.6
N	5.2	3.3	2.7	2.3	2.3	1.5	–	–	1.7	1.4	1.9	2.9	2.5
S	2.1	1.8	1.5	1.2	1.1	1.0	–	–	0.9	0.9	1.1	1.2	1.3
Z	30.3	28.9	27.9	26.9	26.9	24.3	–	–	16.8	9.5	27.3	13.8	23.2
Z[b]	34.8	24.8	26.8	29.7	31.6	29.0	–	–	17.2	25.8	30.3	23.0	27.2
A	19.0	15.2	14.7	13.1	11.8	10.7	–	–	9.4	10.6	11.5	7.0	12.3
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	1.1	0.3	1.0	1.7	1.3	0.9	2.2	1.9	0.7	1.3	–	1.0	1.2
B[c]	0.1	0.5	1.5	4.4	3.2	2.1	4.2	2.9	1.3	3.2	–	3.4	2.4

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-7. Electrical Measurements for 7-Year Coupled Rods (Second Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	–	-0.697	-0.660	-0.655	-0.665	-0.625	-0.620	-0.620	-0.625	-0.620	-0.615	-0.620	-0.638
C	–	-0.635	-0.630	-0.608	-0.590	-0.582	-0.558	-0.550	-0.553	-0.540	-0.528	-0.523	-0.572
C[b]	–	-0.682	-0.640	-0.623	-0.610	-0.605	-0.607	-0.600	-0.600	-0.548	-0.575	-0.579	-0.606
N	–	-0.680	-0.658	-0.640	-0.645	-0.618	-0.600	-0.595	-0.595	-0.590	-0.580	-0.587	-0.617
S	–	-0.670	-0.645	-0.628	-0.630	-0.622	-0.585	-0.570	-0.570	-0.560	-0.550	-0.565	-0.599
Z	–	-1.060	-1.030	-1.040	-1.045	-1.015	-0.930	-0.940	-0.944	-0.945	-0.943	-0.963	-0.986
Z[b]	–	-0.860	-0.995	-0.805	-0.815	-0.863	-0.588	-0.745	-0.790	-0.780	-0.635	-0.807	-0.789
A	–	-0.803	-0.775	-0.760	-0.760	-0.742	-0.722	-0.730	-0.730	-0.725	-0.715	-0.730	-0.744
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	-0.673	-0.690	-0.672	-0.666	-0.663	–	-0.555	-0.575	-0.545	–	-0.490	-0.614
B[c]	–	-0.650	-0.673	-0.650	-0.650	-0.651	–	-0.537	-0.557	-0.513	–	-0.451	-0.592
Resistance to Ground (ohms)													
G	–	1.7	10.5	3.2	2.7	2.4	3.4	4.3	4.3	5.5	4.5	5.2	4.3
C	–	1.1	1.5	1.2	1.3	1.7	2.7	3.3	3.4	3.4	3.1	3.0	2.3
C[b]	–	1.2	1.6	1.5	1.5	1.9	2.5	3.2	3.1	3.3	3.2	3.0	2.3
N	–	1.1	1.6	1.4	1.4	1.8	2.9	3.6	3.6	3.8	4.2	3.3	2.6
S	–	1.0	1.5	1.3	1.3	1.6	2.6	3.2	3.4	3.4	3.5	2.9	2.3
Z	–	1.3	5.0	1.7	1.4	1.7	2.5	3.1	4.0	5.5	4.5	2.7	3.0
Z[b]	–	2.9	2.3	1.6	1.6	1.9	3.0	3.8	3.3	3.2	5.2	2.7	2.8
A	–	1.1	1.9	1.4	1.8	1.7	2.4	2.8	2.9	2.8	3.2	2.5	2.2
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	1.3	21.5	40.0	50.0	35.0	15.2	38.0	8.0	7.5	–	5.8	22.2
B[c]	–	13.5	2.0	8.1	30.0	38.0	14.0	3.2	2.2	8.3	–	12.7	13.2
Current Flow Between Coupled Rods (ma)													
G	–	1.9	1.4	2.0	0.7	1.8	2.1	2.4	1.7	2.2	2.5	2.4	1.9
C	–	21.6	8.8	11.4	12.6	15.1	17.5	16.6	15.9	17.2	17.5	19.6	15.8
C[b]	–	24.3	10.8	12.7	17.9	18.6	17.5	16.1	14.9	16.9	17.2	17.7	16.8
N	–	4.0	2.2	1.6	1.5	2.0	4.1	3.6	2.1	3.0	3.0	2.2	2.1
S	–	1.5	0.8	0.9	1.6	1.5	1.6	1.5	1.4	1.5	1.8	1.9	1.4
Z	–	30.2	17.9	9.5	14.8	19.2	28.5	23.0	20.5	19.5	19.2	17.2	19.7
Z[b]	–	40.7	25.0	15.7	2.4	20.3	8.4	28.5	27.5	22.0	18.0	24.0	20.9
A	–	8.5	5.9	5.4	3.9	8.1	12.9	13.6	13.0	13.2	12.9	10.7	9.8
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	0.9	1.6	1.3	0.6	0.6	0.5	1.1	1.3	1.2	–	1.0	1.0
B[c]	–	2.6	2.5	1.0	1.9	1.4	0.9	1.5	0.7	0.0	–	0.0	1.2

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-8. Electrical Measurements for 7-Year Coupled Rods (Third Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.624	-0.636	-0.632	-0.647	-0.643	-0.627	-0.640	-0.635	-0.664	-0.658	-0.678	-0.687	-0.647
C	-0.525	-0.536	-0.537	-0.553	-0.568	-0.535	-0.545	-0.550	-0.582	-0.564	-0.638	-0.630	-0.563
C[b]	-0.580	-0.593	-0.550	-0.608	-0.620	-0.581	-0.591	-0.594	-0.627	-0.600	-0.643	-0.653	-0.603
N	-0.590	-0.601	-0.584	-0.608	-0.610	-0.598	-0.612	-0.612	-0.643	-0.626	-0.665	-0.671	-0.618
S	-0.570	-0.579	-0.578	-0.591	-0.598	-0.573	-0.587	-0.587	-0.620	-0.599	-0.660	-0.662	-0.600
Z	-0.96[illegible]	-0.978	-0.454	-0.993	-1.085	-0.990	-1.015	-0.988	-1.050	-0.985	-1.055	-1.060	-0.967
Z[b]	-0.781	-0.781	-0.333	-0.809	-0.975	-0.798	-0.790	-0.798	-0.834	-0.840	-0.930	-0.965	-0.802
A	-0.728	-0.740	-0.508	-0.748	-0.760	-0.738	-0.752	-0.747	-0.763	-0.745	-0.850	-0.828	-0.742
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.510	-0.547	-0.553	-0.538	-0.529	–	-0.510	-0.515	-0.510	-0.482	-0.427	-0.483	-0.509
B[c]	-0.477	-0.538	-0.512	-0.500	-0.487	–	-0.478	-0.485	-0.477	-0.443	-0.477	-0.483	-0.487
Resistance to Ground (ohms)													
G	3.7	3.6	8.5	5.9	4.7	6.4	6.9	7.9	4.7	13.0	2.8	2.1	5.8
C	3.1	3.2	3.3	3.3	3.0	3.6	3.5	3.2	2.7	3.1	1.3	1.3	2.9
C[b]	3.0	3.0	3.3	3.4	3.3	3.8	3.6	3.2	2.9	3.1	1.2	1.5	2.9
N	3.9	4.0	4.1	4.2	3.7	4.6	4.1	3.7	4.0	3.7	1.3	5.5	3.9
S	3.2	3.3	3.4	3.6	3.0	3.7	3.6	3.7	2.9	3.4	0.9	1.1	3.0
Z	4.5	4.3	4.1	6.0	4.0	4.7	4.9	4.0	3.5	5.8	2.0	–	4.3
Z[b]	3.1	4.6	4.3	5.9	3.4	–	5.0	5.1	5.9	8.6	3.3	–	4.9
A	2.6	2.8	2.9	4.4	2.8	3.1	2.9	2.8	2.8	3.1	2.1	1.1	2.8
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	7.7	10.5	9.3	8.7	9.1	–	8.5	9.6	37.0	44.0	47.0	52.0	22.1
B[c]	13.2	13.9	14.8	16.7	19.2	–	24.5	26.5	28.2	31.5	51.0	54.0	26.6
Current Flow Between Coupled Rods (ma)													
G	2.5	2.5	2.8	2.2	2.0	1.9	1.3	1.4	1.2	1.2	0.1	0.7	1.7
C	20.1	19.3	17.7	16.4	14.8	13.9	10.2	12.5	15.5	15.9	5.4	6.3	14.0
C[b]	18.2	16.9	15.3	14.4	11.3	13.1	9.3	11.9	13.1	15.1	6.0	13.0	13.1
N	1.7	1.7	1.2	1.7	1.7	1.1	0.9	0.9	0.8	1.4	0.5	1.0	1.1
S	1.9	1.9	1.8	2.2	1.9	1.8	1.2	1.4	2.1	1.7	0.6	1.4	1.7
Z	17.2	16.3	26.0	13.5	9.0	9.2	8.4	7.7	7.1	5.8	6.8	4.3	10.9
Z[b]	25.0	13.5	17.0	13.8	10.8	8.3	5.8	7.9	6.9	4.2	5.5	6.1	10.4
A	11.0	9.7	10.8	8.9	6.4	7.1	4.9	5.2	5.3	6.1	0.5	1.6	6.5
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	0.9	0.3	0.3	0.5	0.7	–	0.9	1.0	1.1	1.0	1.0	0.8	0.7
B[c]	0.0	0.0	0.0	0.0	0.4	–	1.4	1.5	1.8	2.3	2.1	0.9	0.9

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-9. Electrical Measurements for 7-Year Coupled Rods (Fourth Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	–	-0.678	-0.679	-0.697	-0.692	-0.680	-0.687	–	–	-0.635	-0.619	–	-0.670
C	–	-0.625	-0.623	-0.653	-0.628	-0.618	-0.620	–	–	-0.542	-0.535	–	-0.605
C[b]	–	-0.650	-0.652	-0.688	-0.647	-0.645	-0.654	–	–	-0.591	-0.605	–	-0.641
N	–	-0.670	-0.673	-0.700	-0.680	-0.675	-0.683	–	–	-0.628	-0.600	–	-0.701
S	–	-0.655	-0.660	-0.689	-0.677	-0.650	-0.677	–	–	-0.618	-0.587	–	-0.655
Z	–	-1.060	-1.055	-1.090	-1.060	-1.050	-1.070	–	–	-0.970	-0.933	–	-1.036
Z[b]	–	-0.785	-0.827	-0.870	-0.841	-0.852	-0.908	–	–	-0.803	-0.763	–	-0.831
A	–	-0.790	-0.789	-0.825	-0.791	-0.772	-0.778	–	–	-0.732	-0.717	–	-0.774
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.500	-0.515	-0.537	-0.545	-0.537	-0.517	-0.508	-0.497	-0.485	-0.473	-0.413	-0.447	-0.498
B[c]	-0.489	-0.492	-0.503	-0.522	-0.501	-0.513	-0.497	-0.473	-0.461	-0.439	-0.458	-0.495	-0.487
Resistance to Ground (ohms)													
G	–	1.1	7.8	2.6	2.7	4.1	4.1	5.6	–	10.0	9.2	–	5.2
C	–	1.3	1.6	1.3	2.3	2.4	2.3	4.6	–	3.8	5.1	–	2.7
C[b]	–	4.3	1.8	1.4	2.5	2.7	3.2	5.1	–	3.7	4.4	–	3.2
N	–	5.7	7.6	1.5	2.1	2.8	2.8	4.8	–	4.1	5.3	–	4.1
S	–	1.1	1.3	1.0	1.7	2.3	1.9	3.8	–	2.7	3.4	–	2.1
Z	–	3.6	4.5	1.9	2.4	2.6	3.0	5.6	–	4.0	4.7	–	3.6
Z[b]	–	3.3	3.9	3.8	5.3	3.2	2.7	10.0	–	5.3	6.3	–	4.9
A	–	4.3	1.8	1.3	1.9	2.3	2.2	4.1	–	2.7	3.4	–	2.7
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	55.0	43.0	21.5	8.9	9.5	9.3	8.9	9.4	9.7	8.9	9.3	–	17.6
B[c]	59.0	47.0	26.0	18.9	23.5	27.1	26.0	27.0	29.2	31.1	55.0	–	33.6
Current Flow Between Coupled Rods (ma)													
G	–	1.0	1.5	1.1	0.5	0.7	0.5	0.6	–	0.4	0.3	–	0.7
C	–	12.0	11.3	9.2	6.9	6.9	5.6	6.4	–	6.1	7.1	–	7.9
C[b]	–	13.4	11.6	9.2	9.4	8.9	6.1	7.6	–	6.6	7.6	–	8.9
N	–	0.5	1.2	1.0	0.4	0.4	0.2	0.9	–	0.9	1.3	–	0.8
S	–	1.4	1.5	1.1	0.7	0.8	0.7	1.1	–	1.2	1.6	–	1.1
Z	–	10.4	8.5	4.6	5.2	5.2	3.2	5.5	–	4.1	6.3	–	5.9
Z[b]	–	3.8	8.3	5.3	4.7	1.3	2.5	3.4	–	3.8	5.4	–	4.3
A	–	2.3	2.4	1.8	0.8	0.8	0.7	1.5	–	0.8	3.3	–	1.6
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	0.6	0.6	0.5	0.5	0.5	0.6	1.6	0.9	1.0	1.0	0.9	0.8	0.8
B[c]	0.0	0.7	0.6	0.7	0.3	1.3	0.9	1.4	1.6	1.7	1.6	1.2	1.0

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-10. Electrical Measurements for 7-Year Coupled Rods (Fifth Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.602	-0.600	-0.642	-0.635	-0.630	-0.622	–	-0.608	-0.610	-0.605	-0.585	-0.590	-0.612
C	-0.515	-0.529	-0.557	-0.561	-0.585	-0.567	–	-0.505	-0.505	-0.495	-0.469	-0.483	-0.525
C[b]	-0.582	-0.559	-0.611	-0.603	-0.595	-0.585	–	-0.580	-0.587	-0.570	-0.545	-0.555	-0.579
N	-0.575	-0.581	-0.622	-0.625	-0.620	-0.605	–	-0.581	-0.615	-0.605	-0.563	-0.571	-0.597
S	-0.560	-0.573	-0.595	-0.590	-0.585	-0.572	–	-0.558	-0.602	-0.555	-0.521	-0.513	-0.566
Z	-0.875	-0.635	-0.697	-0.702	-0.715	-0.730	–	-0.753	-0.965	-0.940	-0.908	-0.895	-0.801
Z[b]	-0.625	-0.900	-0.957	-0.952	-0.960	-0.957	–	-0.940	-0.757	-0.740	-0.730	-0.730	-0.841
A	-0.708	-0.710	-0.750	-0.713	-0.725	-0.727	–	-0.732	-0.725	-0.720	-0.701	-0.710	-0.720
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	-0.543	-0.565	-0.489	-0.520	-0.550	-0.354	-0.438	-0.428	-0.619	-0.460	-0.650	–	-0.511
B[c]	-0.531	-0.522	-0.519	-0.395	-0.600	-0.400	-0.395	-0.378	-0.328	-0.415	-0.425	–	-0.446
Resistance to Ground (ohms)													
G	6.6	6.2	4.3	5.4	7.1	7.6	–	11.8	11.3	11.1	10.7	10.4	8.4
C	6.0	6.1	3.0	3.2	3.3	5.5	–	6.7	6.6	6.4	6.1	6.0	5.4
C[b]	5.5	5.2	3.3	4.1	4.7	5.8	–	6.3	6.2	6.1	5.8	5.6	5.3
N	6.2	6.5	8.0	7.5	7.9	7.6	–	7.4	7.3	7.1	6.7	6.3	7.1
S	5.3	5.4	2.7	5.8	6.1	6.8	–	7.0	7.0	6.8	6.1	5.4	5.9
Z	20.0	20.0	21.5	18.5	20.5	19.5	–	10.5	12.1	11.6	9.2	9.3	15.7
Z[b]	7.7	7.3	4.0	5.1	6.0	6.9	–	15.0	10.3	9.8	9.1	8.9	8.2
A	4.5	4.1	2.9	3.1	3.8	4.6	–	7.0	7.3	7.1	6.6	6.8	5.3
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	2.2	39.0	4.5	8.8	6.0	8.2	13.4	13.5	17.1	11.5	20.0	–	13.1
B[c]	2.2	35.0	2.7	29.5	6.0	7.6	9.9	9.6	31.5	8.1	6.6	–	13.5
Current Flow Between Coupled Rods (ma)													
G	–	1.0	1.1	1.1	1.9	1.1	–	1.3	1.3	1.4	1.6	1.4	1.3
C	8.4	8.5	8.7	7.7	7.2	7.1	–	6.2	6.9	6.8	7.4	7.1	7.5
C[b]	7.7	8.1	8.8	8.5	8.0	7.4	–	6.3	6.9	7.0	7.3	6.9	7.5
N	2.7	2.5	1.2	1.7	1.7	1.8	–	1.9	1.6	1.4	0.8	1.0	1.7
S	2.0	2.0	1.9	1.8	1.7	1.6	–	1.4	1.5	1.6	1.9	2.1	1.7
Z	9.9	8.5	7.7	6.4	5.8	5.1	–	4.1	4.2	4.7	4.9	9.1	6.4
Z[b]	6.1	4.2	0.9	1.3	1.7	1.9	–	2.8	2.5	1.6	1.0	6.1	2.7
A	4.3	4.0	1.5	1.5	1.5	1.5	–	1.5	1.5	1.5	1.5	1.7	2.0
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	0.3	0.4	–	–	–	0.6	0.5	0.8	0.8	0.8	0.7	–	0.6
B[c]	0.9	0.8	–	–	–	1.8	1.4	1.4	1.4	1.4	1.5	–	1.3

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-11. Electrical Measurements for 7-Year Coupled Rods (Sixth Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.611	-0.605	-0.627	-0.622	-0.618	-0.617	-0.612	-0.599	-0.595	-0.677	-0.633	-0.648	-0.622
C	-0.497	-0.491	-0.487	-0.417	-0.515	-0.553	-0.585	-0.527	-0.520	-0.510	-0.478	-0.492	-0.506
C[b]	-0.567	-0.570	-0.565	-0.562	-0.585	-0.571	-0.574	-0.567	-0.572	-0.563	-0.540	-0.566	-0.567
N	-0.582	-0.585	-0.597	-0.605	-0.590	-0.587	-0.582	-0.582	-0.619	-0.611	-0.569	-0.578	-0.591
S	-0.531	-0.540	-0.553	-0.567	-0.543	-0.558	-0.561	-0.541	-0.597	-0.581	-0.532	-0.543	-0.554
Z	-0.863	-0.890	-0.843	-0.836	-0.846	-0.875	-0.867	-0.893	-0.912	-0.895	-0.878	-0.893	-0.874
Z[b]	-0.695	-0.700	-0.713	-0.724	-0.737	-0.750	-0.742	-0.764	-0.766	-0.746	-0.732	-0.707	-0.731
A	-0.717	-0.708	-0.725	-0.705	-0.714	-0.715	-0.763	-0.716	-0.705	-0.703	-0.697	-0.702	-0.714
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	10.3	11.0	6.3	7.2	8.0	8.7	8.3	13.5	13.1	12.8	11.3	10.9	10.1
C	5.9	5.4	3.0	3.4	3.8	6.1	6.9	7.4	7.2	7.1	6.4	6.2	5.7
C[b]	4.7	4.8	3.0	3.0	3.3	5.3	6.1	5.9	5.7	5.8	5.6	5.7	4.9
N	5.8	5.5	7.7	6.9	6.4	6.2	5.5	6.1	6.2	6.2	6.3	6.3	6.3
S	4.7	4.9	2.6	5.1	5.4	5.9	4.7	6.2	6.1	6.0	5.7	5.5	5.2
Z	9.4	7.6	7.2	6.9	7.1	6.9	6.7	7.1	7.8	7.1	5.8	9.1	7.4
Z[b]	8.2	7.4	6.1	5.8	6.7	7.5	7.4	16.3	10.0	9.7	9.0	9.0	8.6
A	7.1	7.5	3.7	4.9	5.2	5.3	5.1	7.8	7.7	7.8	7.2	7.1	6.4
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	1.2	1.6	1.0	1.1	1.9	1.1	0.9	1.4	1.5	1.5	1.3	1.3	1.3
C	7.6	5.9	6.1	7.8	7.4	7.2	5.9	6.2	6.8	6.9	7.3	7.1	6.8
C[b]	7.1	6.2	6.3	6.1	5.9	5.8	4.8	4.9	5.2	6.9	7.3	6.9	6.1
N	0.5	0.0	1.7	1.9	2.0	2.2	0.7	2.4	2.2	1.9	0.7	1.0	1.4
S	1.7	2.3	2.3	2.3	2.2	1.9	0.9	1.7	1.7	1.8	1.5	2.0	1.9
Z	9.2	5.9	6.2	1.2	1.2	1.4	1.6	2.0	1.8	1.3	4.7	9.6	3.8
Z[b]	6.0	3.8	1.6	6.3	5.9	5.0	4.8	3.8	3.7	4.3	6.1	6.0	4.8
A	2.2	1.4	1.5	1.5	1.6	1.6	1.4	1.5	2.2	2.4	2.4	2.2	1.8
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

Table C-12. Electrical Measurements for 7-Year Coupled Rods (Seventh Year)

(Unless otherwise specified, the couple consists of the indicated rod connected to a single mild steel rod.)

Coupled Rod[a]	Monthly Measurements												Average
	1	2	3	4	5	6	7	8	9	10	11	12	
Potential (couple to $Cu/CuSO_4$)													
G	-0.628	-0.633	-0.635	-0.609	-0.710	-0.535	-0.610	-0.621	-0.573	-0.585	-0.621	-0.558	-0.610
C	-0.499	-0.527	-0.513	-0.501	-0.490	-0.520	-0.618	-0.499	-0.500	-0.482	-0.492	-0.487	-0.511
C[b]	-0.574	-0.592	-0.597	-0.564	-0.615	-0.406	-0.495	-0.594	-0.430	-0.580	-0.561	-0.565	-0.548
N	-0.597	-0.617	-0.635	-0.588	-0.600	-0.475	-0.502	-0.605	-0.545	-0.584	-0.600	-0.580	-0.577
S	-0.585	-0.597	-0.627	-0.570	-0.630	-0.490	-0.571	-0.562	-0.562	-0.568	-0.570	-0.561	-0.574
Z	-0.906	-0.930	-0.855	-0.884	-1.000	-0.430	-0.591	-0.860	-0.825	-0.828	-0.850	-0.820	-0.815
Z[b]	-0.659	-0.600	-0.687	-0.648	-0.875	-0.850	-0.985	-0.580	-0.780	-0.743	-0.533	-0.525	-0.705
A	-0.719	-0.722	-0.733	-0.702	-0.825	-0.500	-0.551	-0.740	-0.730	-0.721	-0.725	-0.720	-0.699
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Resistance to Ground (ohms)													
G	–	2.8	2.2	4.2	8.3	1.1	6.2	9.5	15.5	19.1	8.5	11.5	8.1
C	–	2.6	1.6	3.4	5.8	6.7	5.5	8.1	8.7	7.5	6.7	5.4	5.6
C[b]	–	2.8	1.6	3.8	4.8	6.1	4.8	7.3	6.8	6.8	6.6	4.8	5.1
N	–	2.4	3.4	3.3	6.1	5.4	4.7	7.6	8.2	7.6	6.3	5.8	5.5
S	–	2.1	1.5	2.8	5.8	5.1	4.8	7.5	8.0	7.5	7.0	6.0	5.3
Z	–	3.9	3.4	5.5	6.5	5.5	8.2	11.1	10.5	10.5	9.9	8.0	7.5
Z[b]	–	2.9	1.6	10.1	7.7	8.5	6.8	14.0	14.2	18.9	11.8	9.7	9.7
A	–	2.5	2.1	3.1	4.5	9.4	7.8	8.4	8.1	8.1	6.8	5.8	6.1
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–
Current Flow Between Coupled Rods (ma)													
G	1.2	–	1.0	–	–	–	1.0	1.1	1.0	1.1	1.3	–	1.1
C	6.8	–	5.7	–	–	–	5.5	5.1	5.1	5.3	5.8	–	5.6
C[b]	6.3	–	5.8	–	–	–	6.0	4.9	5.0	5.4	6.9	–	5.8
N	0.4	–	1.7	–	–	–	0.6	0.5	0.5	0.6	1.0	–	0.8
S	2.0	–	2.3	–	–	–	1.5	1.4	1.3	1.3	1.6	–	1.6
Z	9.1	–	1.7	–	–	–	3.7	3.4	0.7	0.4	0.5	–	2.8
Z[b]	5.9	–	5.9	–	–	–	1.7	1.2	1.3	1.2	0.8	–	2.6
A	2.0	–	1.4	–	–	–	0.7	0.7	0.8	0.8	1.0	–	1.1
M	–	–	–	–	–	–	–	–	–	–	–	–	–
M[b]	–	–	–	–	–	–	–	–	–	–	–	–	–
B	–	–	–	–	–	–	–	–	–	–	–	–	–
B[c]	–	–	–	–	–	–	–	–	–	–	–	–	–

[a] G = galvanized steel; C = copper-clad steel; N = Ni-Resist cast iron; S = stainless steel; Z = zinc; A = aluminum; M = magnesium; B = stainless-clad steel

[b] One rod coupled to two mild steel rods.

[c] Two rods coupled to one mild steel rod.

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13. ABSTRACT

In cooperation with the National Association of Corrosion Engineers, NCEL conducted a 7-year program of field testing metal rods for electrical grounding. Single rods of galvanized steel, copper-clad steel, Ni-Resist cast iron, type 302 stainless steel, type 304 stainless-clad steel, zinc, magnesium, and aluminum were tested along with couples of these to mild steel rods. Sets of both single and coupled rods were removed, cleaned, and weighed after 1, 3, and 7 (or 5) years. Potential, resistance, and current measurements were made monthly as far as practicable. Weight losses and electrical data were analyzed for correlations. It was concluded that type 302 stainless steel and type 304 stainless-clad steel rods were the best choices for general use.

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Type 302 stainless steel						
Type 304 stainless-clad steel						
Zinc						
Magnesium						
Aluminum						
Single rods						
Coupled rods						
Potential						
Resistance						
Current						
Field tests						

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