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THE EFFECT OF STRAY DIRECT CURRENT AT
VARIOUS CURRENT DENSITIES ON THE
CORROSION OF STEEL

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Electrode potentials and IR drop
Intermediate electrode (bipolar anode and bipolar cathode)   (Continues)

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

   Stray current corrosion has been of major concern to the Navy over the past few years. Serious corrosion attributable to stray current has occurred in seawater or brackish water on several occasions where the possibility of the corrosion being from improper welding was precluded. The experimental technique used isolates the bipolar anodes and bipolar cathodes so that stray current corrosion parameters can be studied and quantized. Data are presented on the effect of various stray dc densities on the corrosion rates and the electrode potentials of

                                                                    (Continues)

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Current density, effect, on steel
Theoretical metal-loss rate
Corrosion rate
Corrosion characteristics

20.

steel both as common electrodes and as bipolar (or intermediate) electrodes. The metal-loss rates have also been compared to the theoretical values based on the reaction $Fe-2e=Fe^{+2}$.

The mean dissolution potential for steel in 0.6M (3.5%) NaCl solution was approximately -0.7 V to the Ag/AgCl reference electrode, and was essentially independent of the current density. Similar values were observed for anodes, bipolar anodes and freely corroding control specimens. Steel could not be polarized cathodically to a mean potential more negative than -1.015 volts to the Ag/AgCl reference electrode. Mean potentials either more positive than -0.7 V or more negative than -1.015 V were observed only when the measurement included an IR drop.

Potential measurement can be used to detect stray current on steel only at relatively high current densities. The corrosion characteristics of steel anodes and bipolar anodes were similar at any one current density, but varied with current density.

CONTENTS

THE EFFECT OF STRAY DIRECT CURRENT AT VARIOUS CURRENT DENSITIES ON THE CORROSION OF STEEL

INTRODUCTION

There have been several incidences of very severe corrosion on naval ship hulls in the past few years. In at least some of these cases, the possibility of the corrosion being caused by improper welding techniques has been eliminated. Field studies have been made in which the recorded hull potential intermittently showed large fluctuation in the positive direction indicating that stray currents do exist at some naval berthing sites. The source of these stray currents, however, was not established.

As part of a continuing effort to gain further insight into stray current corrosion and mitigation, personnel of the Naval Research Laboratory have been conducting laboratory experiments to quantify the corrosion caused by stray currents. Parameters that may be useful in stray current detection are also being studied.

Stray electrical currents can flow through multiple paths which generally result in a very complex network. For stray direct currents on steel, the primary concern is the corrosion at the anodes and bipolar (or intermediate) anodes.

A bipolar or intermediate electrode exists when a metal, other than the primary anode and cathode, is in an electrolytic cell and the metal has no metallic contact with the current source or return to the source, i.e., the metal is an electrically isolated, floating electrode. A ship in an electrical direct-current field is a bipolar or intermediate electrode if it is not metallically connected to the source or return for the current. Figure 1 shows a ship (Ship 2) in a stray-current field as a bipolar or intermediate electrode. This ship would receive current at one location on the hull and discharge current into the water from some other area on the hull. The location where the current leaves the hull would be a bipolar anode and would corrode at an accelerated rate.

The location on the steel hull where the current was received from the solution would be a bipolar or intermediate cathode. There should be no concern about accelerated corrosion of steel bipolar cathodes because at these points the steel would receive at least partial cathodic protection. The electrochemical reactions at the bipolar cathode should also produce an alkaline condition which would tend to further reduce the corrosion of the steel. Similar to intentional cathodic protection, the possibility of hydrogen embrittlement on susceptible steels and hydrogen discharge into a confined space would be of concern.

This report presents data obtained on low-carbon steel in stray direct-current fields of various intensities. In order to minimize variables, these studies were conducted on
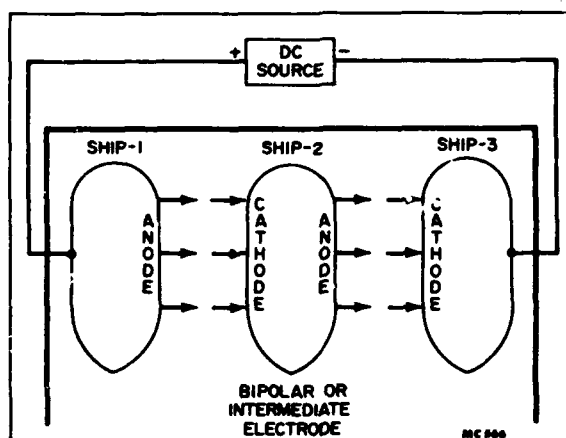
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Fig. 1 — Stray currents and bipolar
or intermediate electrodes

laboratory scale models. The solution used in all experiments was 0.6M (3.5%) NaCl in
tap water with a resistivity of 19 ohm-cm.

EXPERIMENTAL TECHNIQUE

A planar bipolar electrode would pick up current on one side (or surface) and dis-
charge the current into the water from the opposite side. To quantify stray-current
corrosion parameters, it is necessary to have two separate metal specimens to simulate a
bipolar electrode; one specimen being the bipolar cathode and the second the bipolar
anode. These experiments were designed so that quantitative data could be obtained
on anodes, bipolar anodes, cathodes, and bipolar cathodes.

Individualizing the bipolar cathode and the bipolar anode was achieved by the experi-
mental technique shown in Fig. 2. An anode and bipolar cathode were positioned in one
acrylic tank and a bipolar anode and cathode were in a second acrylic tank. The anode
and cathode were electrically connected to the direct-current power source. The bipolar
cathode and the bipolar anode were electrically connected to each other, but were not
electrically connected to the power source or to the metallic return to the power source.
An electrically isolated, floating, bipolar electrode was thus obtained, and each half of
the bipolar electrode could be studied independently. Each electrode measured 6×8×1/32
in. The cross section of the tank was 6×8 in. and the internal length of the acrylic tanks
was approximately 21 in. The cross section of the solution in the tank was 6 × 6 3/4 in. The
electrodes were positioned at the extreme ends of the tanks. A constant area of each specimen
was in contact with the solution so the apparent current density could be controlled at selected
levels.

The area of metal exposed to the solution was 26.25 sq in., i.e., 5×5-1/4 in. on the
one flat surface of each specimen facing the bulk solution. The other areas on the specimens
were masked with 15-mil-thick vinyl tape. The masking also served to eliminate possible
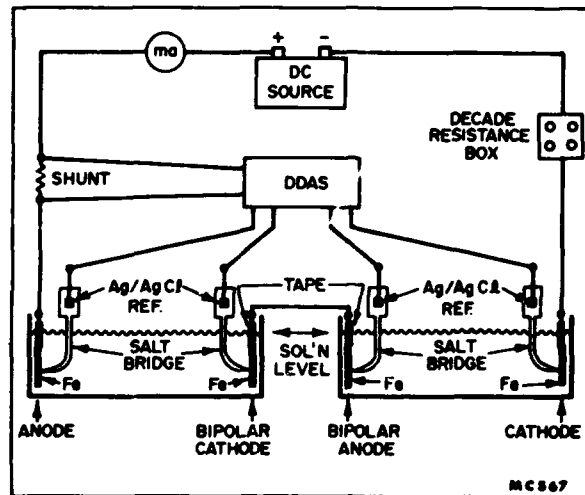
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Fig. 2 — Stray current experimental technique

edge and water line effects. Each specimen was weighed to 0.01 g before and after the experiment to permit metal-loss rates (corrosion rates) to be calculated.

The potential of each specimen was measured relative to a Ag/AgCl reference electrode. The Ag/AgCl reference electrodes were located in inverted polyethylene bottles to which a polystyrene capillary tube was attached. The plastic bottle and capillary were filled with 0.6M (3.5%) NaCl solution, and served as a salt bridge from the Ag/AgCl reference electrode to the specimen. The tip of the capillary was positioned essentially in contact with the metal electrodes being studied in order to eliminate as much voltage (IR) drop from the potential measurement as possible.

The time between potential measurements was programmed and the potentials were recorded on a Digital Data Acquisition System (DDAS). The potentials were measured both with the current on and the current off. The current-off potentials were obtained by manually interrupting the electrical current flow in the system for less than 5 s. The current-off potentials completely excluded the IR drop from the potential measurements and therefore are better values for the potential at the metal surfaces.

The source of the direct current was a 12-V lead-acid storage battery. A milliammeter in the circuit indicated the current flow and the current was recorded on the DDAS by measuring the potential drop across a precision resistor (shunt). The current was controlled at preselected levels by a decade resistance box in series in the circuit.

At the conclusion of each experiment, the tape used for masking the selected areas was removed from the specimens and the electrodes were cleaned with ethyl alcohol to remove any remaining adhesive. Prior to the final weighing, the specimens were cleaned at room temperature by brushing in HCl containing 40 g/l of Sb_2O_3; rinsed in distilled water; and dried with ethyl alcohol and a jet of dry nitrogen gas.

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DATA AND DISCUSSION

Electrode Potentials vs Time

Figures 3 — 6 show the potential vs time data for steel at direct-current densities of 5, 10, 100 and 1000 mA per square foot (mA/sq ft), respectively, after an initial stabilization period of approximately 1 hr. The potentials of freely corroding steel are shown for the entire time periods. At the three highest current densities, the same range of potentials has been used on the ordinate axis, i.e., —0.3 to —1.3 V to the Ag/AgCl reference electrode.
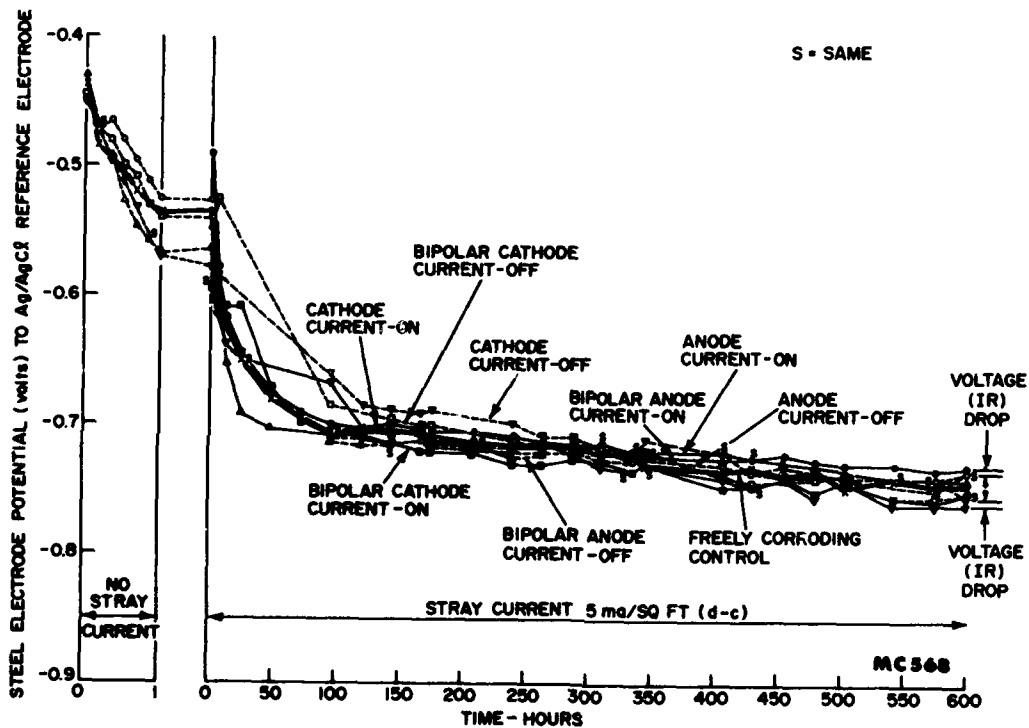

Fig. 3 — The effect of stray direct current on steel electrodes in 0.6M (3.5%) NaCl solution. Potential vs time data at a current density of 5 mA/sq ft.

For a current density of 5 mA/sq ft, the ordinate axis covers the potential range from —0.4 to —0.9 V. The same time scale has been used for the abscissa at all the current densities except for the data at a current density of 1000 mA/sq ft, where an expanded time scale has been used because the experiment at this current density lasted only 48 hrs.

Figure 3 shows that at a stray direct-current (dc) density of 5 mA/sq ft or less it would not be possible to detect stray currents by measuring the potentials of the electrodes.

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Fig. 4 — The effect of stray direct current on steel electrodes in 0.6M (3.5%) NaCl solution. Potential vs time data at a current density of 10 mA/sq ft.

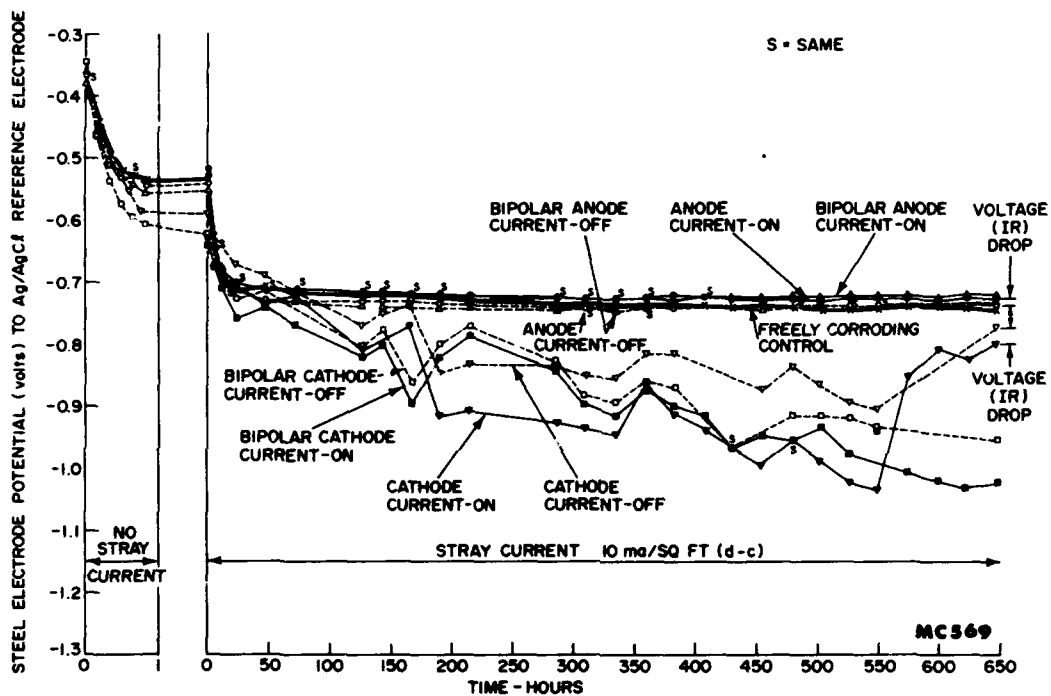Fig. 5 — The effect of stray direct current on steel electrodes in 0.6M (3.5%) NaCl solution. Potential vs time data at a current density of 100 mA/sq ft.
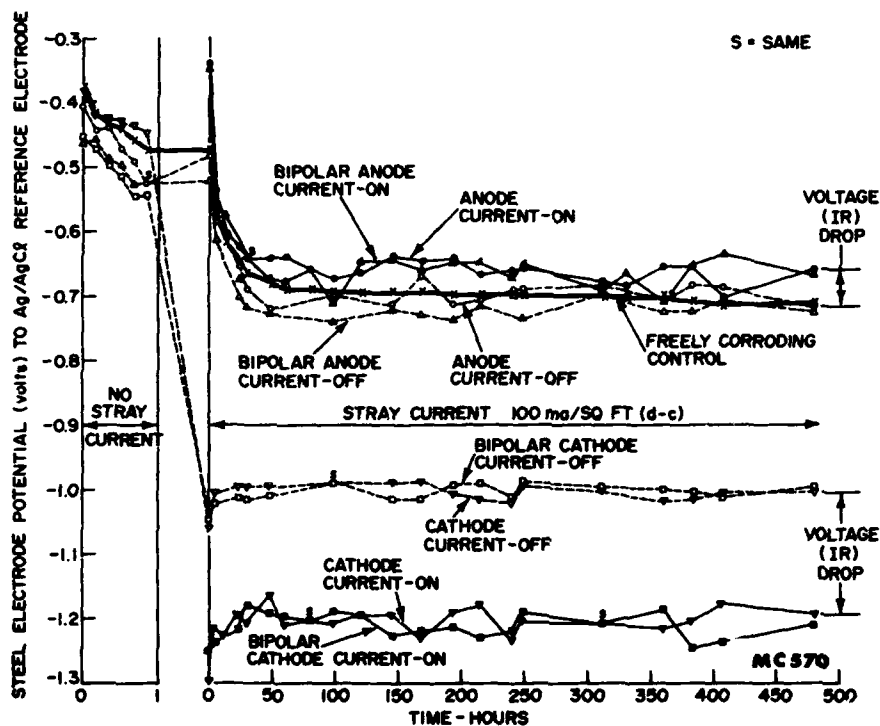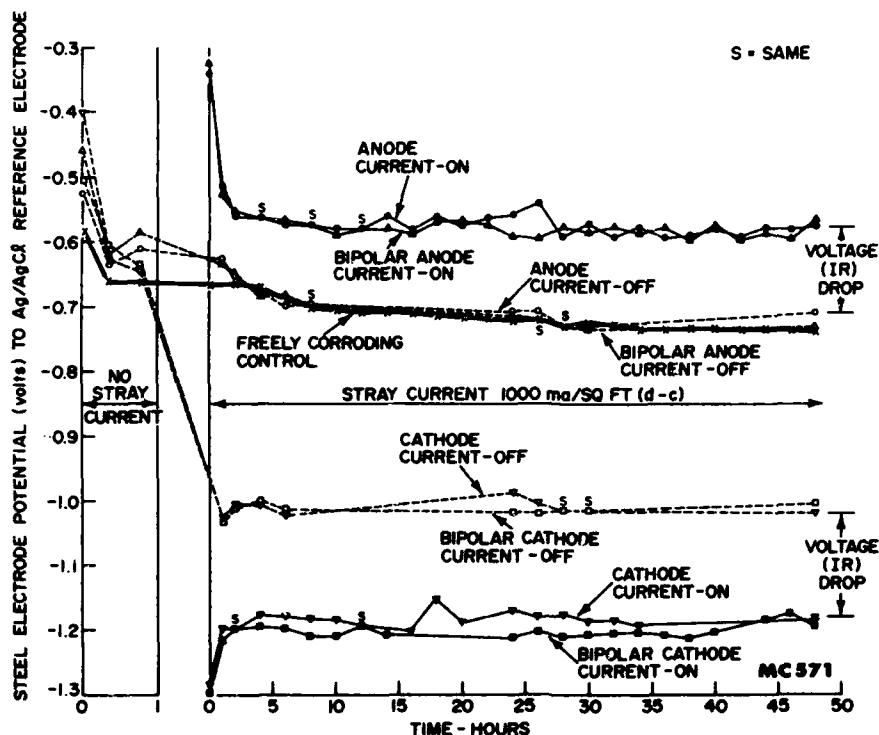
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Fig. 6 — The effect of stray direct current on steel electrode in 0.6M (3.5%) NaCl
solution. Potential vs time data at a current density of 1000 mA/sq ft.

There was less than a 0.020-V potential difference between the freely corroding specimens,
the anodes and bipolar anodes that were corroding, and the cathodes and bipolar cathodes
which should be at least partially protected. These small differences in potential were
evident even when the potential measurement was made with the current on, i.e., any
IR drop was included in the measurement.

Figure 4 shows the potential as a function of time for steel electrodes at a stray dc
density of 10 mA/sq ft. As in the case at a current density of 5 mA/sq ft, the potentials
for the anodes and bipolar anodes at a current density of 10 mA/sq ft are similar to
the freely corroding potentials. Therefore, stray direct currents at a current density of
10 mA/sq ft still could not be detected from potential measurements even if the current
interrupter technique was used, i.e., by comparing the current-off to the current-on
potential.

At a current density of 10 mA/sq ft, definite potential changes with time occurred
on both the cathode and bipolar cathode. These potential changes show that both the
cathode and bipolar cathode were being protected because the specimens had polarized
to a potential more negative than —0.8 V to the Ag/AgCl reference electrode after

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approximately 175 hr. However, these cathodic potential changes could not be used to detect stray currents because they are similar to the potential changes that would be obtained from intentionally applied cathodic protection.

Figure 5 shows that, at a stray dc density of 100 mA/sq ft, an appreciable IR drop exists in the electrode potentials measured at both the anodes and the bipolar anodes of steel. Therefore, if current-on and current-off potential measurements can be made, the existence of stray currents of this current density can be detected from the potential observed. Even if current-on and current-off potential measurements could not be made, the existence of stray currents of this magnitude could be detected by comparing the potential of the bipolar anode with the potential of the same steel in the freely corroding condition. This is possible because a potential difference of approximately 0.05 V would exist. Surges of stray direct currents with a current density of 100 mA/sq ft could also be detected by continuously recording the potential over a period of several days.

Figure 5 also shows that both the cathode and the bipolar cathode polarized to a potential of approximately -1.0 V to the Ag/AgCl reference electrode when the current density was 100 mA/sq ft. This degree of polarization, a change in potential from -0.7 V for the freely corroding specimen to -1.0 V for the cathode and bipolar cathode, also indicates that the cathodes were completely protected. The existence of a stray dc density of 100 mA/sq ft could perhaps be inferred from the extremely negative potentials although a cathodic protection system could also produce negative potentials in the same range. If the current from the cathodic protection system was turned off and the potential remained at extremely negative values over a portion of the hull, the existence of stray currents would be definitely indicated.

Figure 6 shows that with a stray dc density of 1000 mA/sq ft a sizeable IR drop exists at all the steel electrodes. The potentials of the anodes and bipolar anodes with the current on is sufficiently distinct from the freely corroding potential of low-carbon steel that stray currents at a density of 1000 mA/sq ft can be readily detected from potential measurements. The stray current in this instance could be detected either by a direct comparison of the current-on potential to the freely corroding potential or by continuously recording the potential to observe any changes that would be caused by current surges.

At all the stray dc densities studied, the potentials of the anodes and bipolar anodes measured with the current off were essentially identical to the freely corroding potential of low-carbon steel. This indicates that steel does not show appreciable anodic polarization even at a current density of 1000 n.A/sq ft. Any anodic potential change observed on steel in 0.6M (3.5%) NaCl solution was a result of an IR drop in the measurement due to the flow of electrical current through the solution.

The potential data for low-carbon steel also indicates that steel cannot be cathodically polarized more negatively than approximately -1.06 V to the Ag/AgCl reference electrode in 0.6M (3.5%) NaCl solution. Cathode potential measurements more negative than -1.06 V can be observed only if a large IR drop is included in the potential measurement.

The significance of the limits of the range of potentials that steel will assume is that the more positive value (approximately −0.7 V) is the potential at which steel will corrode. Regardless of the current density, the potential under anodic conditions (i.e., when steel is dissolving) will remain essentially constant until all the steel has dissolved. The most negative potential (approximately −1.06 V) apparently is the potential at which hydrogen is discharged at both the cathode and bipolar cathode. Potentials this negative, if caused by a cathodic protection system, would indicate that a substantial amount of current is being wasted.

Steel Metal Loss vs Mean Electrode Potential

Figure 7 shows the steel metal loss in mils per year (mpy) as a function of the mean potential for each type of electrode in the presence or absence of stray direct currents. The mean potential of the anodes and bipolar anodes with the current off was approximately −0.7 V to the Ag/AgCl reference electrode regardless of the anodic current density. However, when the IR drop at the higher current density levels is included in the potential measurement, potential values more positive than −0.7 V were observed.

The mean potentials of the anodes and bipolar anodes at the low current densities were similar to each other and to the mean potential of the freely corroding control specimens. This was true whether the potential measurements were made with the current on or current off. Even without a noticeable change in the mean potential of the anodes and bipolar anodes, a stray dc density of 5 mA/sq ft increased the metal loss rate from 3 to 5 mpy. A current density of 10 mA/sq ft increased the metal loss rate from 3 to 8 mpy. Increases in corrosion of this magnitude would not be catastrophic, but would decrease the life of the steel proportionately.

The metal-loss rate for steel anodes and bipolar anodes was 50 mpy at a current density of 100 mA/sq ft, and approximately 500 mpy at a current density of 1000 mA/sq ft. In both instances the current-off electrode potentials were −0.7 V. Metal loss rates of 50 and 500 mpy would be catastrophic.

Figure 7 also shows that a current density of 5 mA/sq ft was not sufficient to cause any apparent polarization on either the cathodes or bipolar cathodes. This magnitude of current density, however, reduced the rate of steel metal loss from 3 to 1.6 mpy on the bipolar cathode. A current density of 10 mA/sq ft or higher was sufficient to produce significant cathodic polarization and to eliminate essentially all the corrosion on the steel cathodes and bipolar cathodes.

Increase in metal-loss rates at the anodes or bipolar anodes was accompanied by a reduction in the corrosion on the cathodes and bipolar cathodes. This effect would not be practically beneficial, however, because the anodes and bipolar anodes corroded at an accelerated rate.
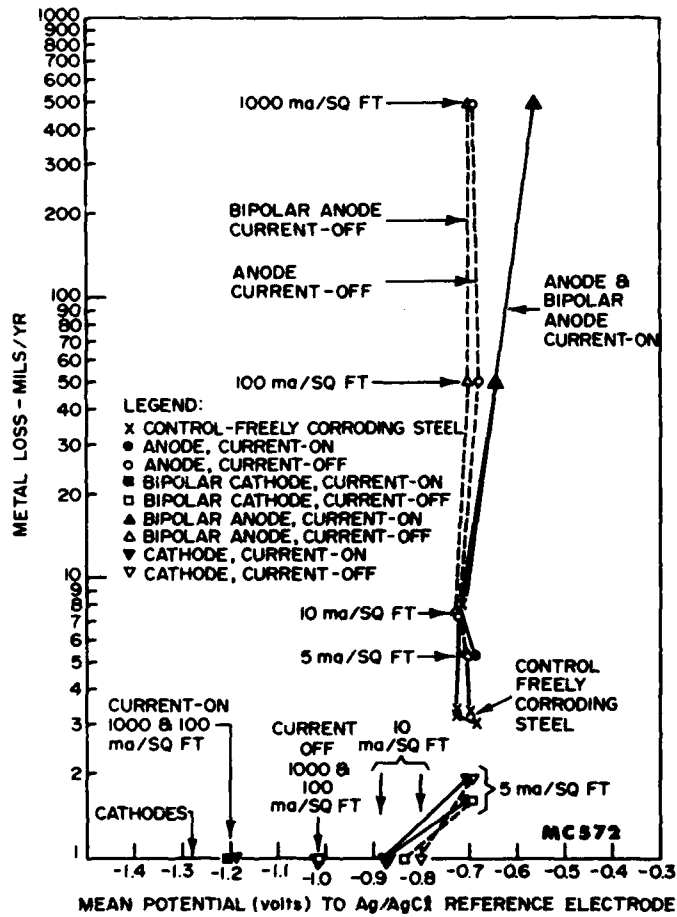
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Fig. 7 — Steel metal loss vs mean potential to Ag/AgCl reference electrode in the presence of stray direct current in 0.6M (3.5%) NaCl solution.
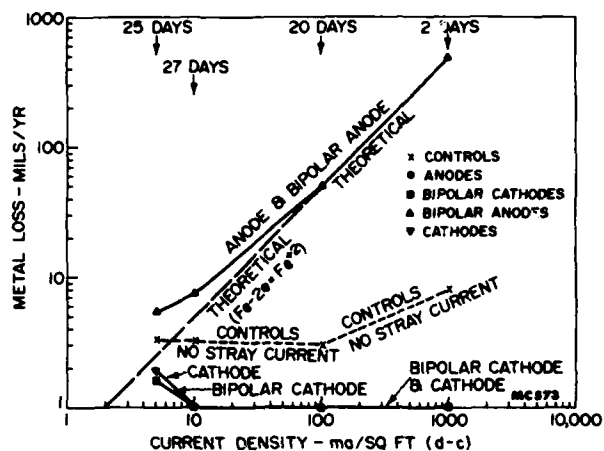
Fig. 8 — Steel metal loss vs current density in the presence of stray direct current in 0.6M (3.5%) NaCl solution

Steel Metal Loss vs Current Density

Figure 8 shows the theoretical values of steel metal loss in mpy as a function of current density. Data for anodes, bipolar anodes, cathodes, bipolar cathodes and freely corroding control specimens are included in Fig. 8.

The anodes and bipolar anodes at a current density of 100 and 1000 mA/sq ft had a metal-loss rate that was equivalent to the theoretical values for the reaction $Fe-2e=Fe^{+2}$. At a current density of 10 mA/sq ft and less, the metal-loss rates of the anodes and bipolar anodes increased compared to the theoretical values. At a current density of 5 mA/sq ft, the metal-loss rate was approximately 100% greater than the theoretical and 60% greater than for the freely corroding steel.

A stray current density of 100 mA/sq ft increased the metal-loss rate by more than an order of magnitude compared to the freely corroding control exposed for the same time period. A stray current density of 1000 mA/sq ft caused a metal-loss rate increase of almost 2 orders of magnitude compared to the control exposed for the same time period. This latter increase in corrosion is conservative because it is based on control specimens that were exposed for only 2 days; the duration of the experiment at this current density. The metal-loss rate of the control specimens in the 2-day experiment was high compared to the longer term experiments. The high metal loss rate for the freely corroding steel in the shorter term experiments is not uncommon as will be discussed later in this report. Based on the metal-loss rate of the controls in the longer term experiments, steel at a current density of 1000 mA/sq ft would have a metal-loss rate approximately 2-1/2 orders of magnitude greater than the control.

The metal-loss rate is essentially reduced to zero when the current density on either a steel cathode or a bipolar steel cathode is 10 mA/sq ft or greater.
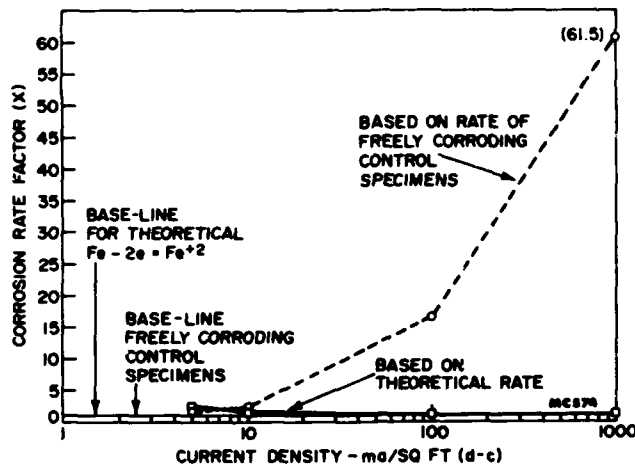
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Fig. 9 — Corrosion rate factor (X) vs stray direct-current
density for anodes and bipolar anodes of steel

Corrosion Rate Factor vs Current Density

Figure 9 shows corrosion-rate factors for steel anodes and bipolar anodes as a function of current density. Data have been shown for corrosion-rate factors based on both the theoretical rates and on the rates for freely corroding control specimens. As an example in the use of this graph, at a dc density of 100 mA/sq ft, steel anodes and bipolar anodes would have a corrosion-rate factor of 1 based on the theoretical corrosion rate. Therefore, the corrosion rate would be equivalent to the theoretical. Based on the freely corroding control specimens, the corrosion-rate factor for the steel anodes and bipolar anodes would be approximately 16.5 at a current density of 100 mA/sq ft. Therefore, if a freely corroding specimen had a corrosion rate of 3 mpy, the corrosion rate of the steel anodes and bipolar anodes would be 3 X 16.5 = 49.5 mpy at a current density of 100 mA/sq ft.

A graph of this type is a useful guide in estimating the increased amount of corrosion that could be expected on steel in 0.6M (3.5%) NaCl solution. Similar graphs developed for other metals and other environments would be useful in estimating the increased corrosion that could be expected from stray direct currents.

Percent Reduction in Corrosion Rate vs
   Current Density

Figure 10 shows the percent reduction in corrosion rates for steel cathodes and bipolar cathodes as a function of current density. Both the cathodes and bipolar cathodes showed approximately the same percentage reduction in corrosion rates at a particular current density. This was especially true at current densities of 10 mA/sq ft and above, where essentially complete protection was obtained. At a current density of
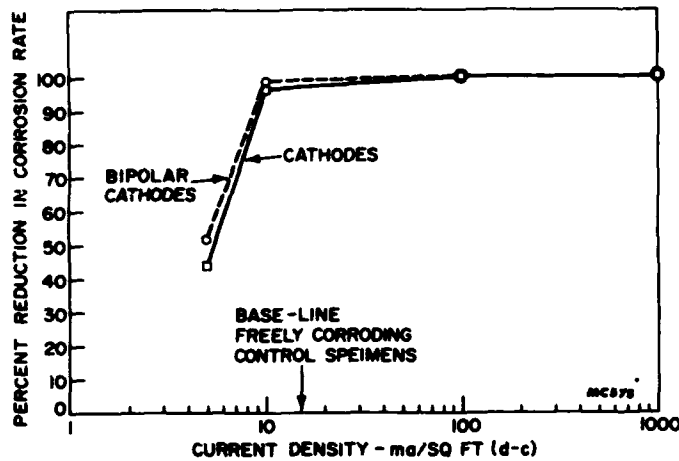
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Fig. 10 — Percent reduction in corrosion rate vs stray direct
current density for cathodes and bipolar cathodes of steel

5 mA/sq ft, the reduction in corrosion rate was 44% for the cathode and 52% for the
bipolar cathode. As discussed earlier, these reductions in corrosion rate occurred without
any detectable potential changes.

Corrosion Rates, Potential Data, and Corrosion Characteristics

Tables 1, 2, and 3 each summarize the corrosion rates, mean electrode potentials and
corrosion characteristics for low-carbon steel at various dc densities and in the absence
of stray current.

Table 1 shows data for the freely corroding control specimens in the absence of
stray currents. The corrosion rate on these specimens ranged from approximately 3 to
8 mpy. With an exposure time of 20 days or more, the corrosion rate was relatively
constant at approximately 3 mpy. At the shorter exposure time of 2 days the corrosion
rate was approximately 8 mpy. The relatively high corrosion rate in the short exposure
time is not unexpected. It is generally agreed that the corrosion rate of unprotected
steel decreases with exposure time. The reason for this is that apparently a partially
protective film develops on corroding steel with time. The longer term rate is, therefore,
lower than the rate in the shorter term experiments where the protective film has not
had sufficient time to develop.

The mean electrode potential for the freely corroding steel specimens varied from
—0.680 V to —0.726 V in these experiments that ranged from 2 days to 27 days duration.
The mean potential of the freely corroding specimens for the four time periods was —0.704 V.
For any one time period, the mean potential was within ±0.025 V of this value. The range
of potentials were between —0.421 and —0.747 V. The least negative potentials were

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observed in the early stages of the experiments, before the steel specimens had stabilized in the environment, and therefore are not indicative of the actual electrode potentials.

General corrosion was observed on all the freely corroding steel specimens. On some specimens the corrosion was relatively uniform while on others the corrosion occurred on approximately 75% of the exposed area.

Table 2 shows the data for the anodes and the bipolar anodes of low-carbon steel in the presence of stray direct currents. The corrosion rates for the anodes and bipolar anodes were essentially the same at any one current density. The corrosion rates ranged from 5.3 mpy at a current density of 5 mA/sq ft to 492 mpy at a current density of 1000 mA/sq ft.

The mean potentials for all the time periods measured with the current off (IR drop excluded from the measurement) was −0.700 V for the steel anodes and −0.709 V for the bipolar anodes. This difference cannot be considered a real difference in potential because for both the anodes and bipolar anodes the mean potentials varied by more than 0.01 V from one current density to another. However, the mean potentials of all the anodes and bipolar anodes measured with the current off were within ±0.005 V of the freely corroding mean potential (compare Tables 1 and 2).

Table 1
Corrosion Rates, Potential Data and Corrosion Characteristics for Low Carbon Steel Controls: No Stray Current; Freely Corroding in 0.6M (3.5%) NaCl Solution

Controls For Current Density at mA/sq ft Shown	Test Duration (days)	Corrosion Rate (mpy*)	Potential†				Corrosion Characteristics
			Mean		Range		
			Current On	Current Off	Current On	Current Off	
1000	2	8.1	—	−0.714	—	−0.666 to −0.738	General and relatively uniform corrosion
100	20	3.1	—	−0.680	—	−0.473 to −0.730	General and relatively uniform corrosion
10	27	3.2	—	−0.726	—	−0.534 to −0.746	General corrosion on 75% of exposed area
5	25	3.3	—	−0.696	—	−0.421 to −0.747	General corrosion on 75% of exposed area
			Mean =	−0.704			

*mpy = mils penetration per year, 1 mil = 0.001 in.
†Potentials measured to Ag/AgCl reference electrode.

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Table 2
Corrosion Rates, Potential Data and Corrosion Characteristics for Low
Carbon Steel: Anodes and Bipolar Anodes; Stray Direct Currents Present in 0.6M (3.5%) NaCl Solution

Current Density (mA/sq ft)	Test Duration (days)	Corrosion Rate (mpy*)	Potential†				Corrosion Characteristics
			Mean		Range		
			Current On	Current Off	Current On	Current Off	
Anode							
1000	2	491	−0.563	−0.694	−0.340 to −0.594	−0.628 to −0.730	Channeled by corrosion at tape edges; uniform corrosion other areas
100	20	50	−0.642	−0.678	−0.339 to −0.702	−0.483 to −0.722	Very sharp corroded channels at some locations of taped edges; some areas uncorroded or very small amount of corrosion
10	27	7.3	−0.714	−0.724	−0.518 to −0.730	−0.538 to −0.741	General corrosion entire exposed areas and some areas under tape
5	25	5.3	−0.690	−0.705 Mean = −0.700	−0.489 to −0.736	−0.527 to −0.742	General corrosion entire exposed area
Bipolar Anode							
1000	2	492	−0.567	−0.699	−0.323 to −0.595	−0.633 to −0.734	Channeled by corrosion at tape edges; uniform corrosion other areas
100	20	50	−0.643	−0.699	−0.347 to −0.710	−0.520 to −0.741	Channeled by corrosion at some location of taped edges; some areas uncorroded or very small amount of corrosion
10	27	7.6	−0.714	−0.726	−0.528 to −0.728	−0.550 to −0.745	General corrosion entire exposed area
5	25	5.4	−0.702	−0.710 Mean = −0.709	−0.547 to −0.741	−0.563 to −0.748	General corrosion entire exposed area

*mpy = mils penetration per year, 1 mil = 0.001 in.
†Potentials measured to Ag/AgCl reference electrode.

Table 3
Corrosion Rates, Potential Data and Corrosion Characteristics for Low
Carbon Steel: Cathodes and Bipolar Cathodes; Stray Direct Currents
Present in 0.6M (3.5%) NaCl Solution

| Current Density (mA/sq ft) | Test Duration (days) | Corrosion Rate (mpy*) | Potential† | | | | Corrosion Characteristics |
| | | | Mean | | Range | | |
			Current On	Current Off	Current On	Current Off	
Cathode							
1000	2	0	−1.190	−1.011	−1.152 to −1.284	−0.987 to −1.028	No corrosion but some small areas with peened appearance
100	20	0	−1.208	−1.010	−1.154 to −1.325	−0.988 to −1.059	No corrosion
10	27	0.12	−0.872	−0.802	−0.602 to −1.034	−0.556 to −0.904	Slight general corrosion on <10% of exposed area
5	25	1.9	−0.705	−0.694	−0.595 to −0.760	−0.577 to −0.757	General corrosion on 35-40% of exposed area
Bipolar Cathode							
1000	2	0	−1.207	−1.015	−1.175 to −1.314	−1.001 to −1.033	No corrosion but some small areas with peened appearance
100	20	0	−1.211	−1.014	−1.178 to −1.250	−0.987 to −1.047	No corrosion
10	27	0.04	−0.873	−0.836	−0.629 to −1.041	−0.607 to −0.978	Slight general corrosion on <10% of exposed area
5	25	1.6	−0.703	−0.694	−0.592 to −0.758	−0.524 to −0.756	General corrosion on 45-50% of exposed area

*mpy = mils penetration per year, 1 mil = 0.001 in.
†Potentials measured to Ag/AgCl reference electrode.

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The mean potentials in Table 2 also show that at current densities of 5 and 10 mA/sq ft, there was less than 0.015 V difference between the current-on and the current-off potentials for both the anodes and bipolar anodes. The existence of stray current could not be readily detected from current-on and current-off potential measurements at these current densities because of the small IR drop. At current densities of 100 and 1000 mA/sq ft, sufficient IR drop was evident so that stray currents could be readily detected from current-on and current-off potential measurements. The range of potentials for the anodes and bipolar anodes were similar when the current-on and current-off potentials are viewed at a particular current density.

The corrosion characteristics of steel anodes and bipolar anodes were similar at any one current density. At current densities of 5 and 10 mA/sq ft, general corrosion was evident over the entire exposed areas. At current densities of 100 and 1000 mA/sq ft, very accelerated corrosion was evident at the edges of the tape used to mask certain areas from the solution. This corrosion occurred in the form of deep channels. At a current density of 1000 mA/sq ft, this type corrosion occurred along all the tape edges, but at a current density of 100 mA/sq ft occurred only at some locations along the tape. The areas distant from the tape edges were uniformly corroded at a current density of 1000 mA/sq ft, but at a current density of 100 mA/sq ft, some areas away from the tape were essentially uncorroded.

Table 3 shows the summary data for the cathodes and bipolar cathodes of steel in the presence of stray direct currents. The corrosion rate at any one current density is similar for the cathode and bipolar cathode except at a current density of 10 mA/sq ft. At this current density, the bipolar cathode had a lower corrosion rate than the cathode. The lower corrosion rate for the bipolar cathode in this instance was undoubtedly the result of the bipolar cathode being slightly more polarized than the cathode. This additional polarization was indicated by the mean current-off potential measurements; -0.802 V for the cathode and -0.836 V for the bipolar cathode. As noted earlier, at a current density of 5 mA/sq ft the corrosion rate of both the cathode and bipolar cathode was reduced approximately 50% compared to the freely corroding control specimen, although no noticeable polarization of these electrodes was evident from the electrode potential measurements.

Current densities above 5 mA/sq ft caused varying degrees of cathodic polarization. The mean current-off potentials show that for both the cathodes and bipolar cathodes -1.015 V was the most negative mean potential to which steel cathodes could be polarized in 0.6M (3.5%) NaCl solution. More negative mean potentials were not true polarization potentials because the value included an IR drop.

The change to more negative potentials shown by the ranges of potentials for both the cathodes and bipolar cathodes with the current off and above a current density of 10 mA/sq ft is indicative of cathodic polarization. At a current density of 100 mA/sq ft and above, polarization of the cathodes and bipolar cathodes occurred almost immediately on applying the current. The immediate cathodic polarization at these high current densities was evident from the instantaneous current-off potentials which were approximately -1 V (Figs. 5 and 6).

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The corrosion characteristics of the cathodes and the bipolar cathodes were the same at any one current density. As expected, no corrosion occurred at current densities of 100 and 1000 mA/sq ft, although at the latter current density some small areas had a peened appearance. The cathode and bipolar cathode at a current density of 10 mA/sq ft had only slight general corrosion on less than 10% of the exposed area, and the corrosion rate had been reduced by more than 96% (Fig. 10). At a current density of 5 mA/sq ft, general corrosion occurred on 35 to 40% of the exposed area of the cathode and 45 to 50% of the exposed area of the bipolar cathode.

CONCLUSIONS

1. An experimental technique has been developed which makes it possible to individualize bipolar anodes and bipolar cathodes so that stray-current corrosion parameters can be studied and quantized.

2. Low-carbon steel had a mean potential range of from -0.700 V to -1.015 V to the Ag/AgCl reference electrode in 0.6M (3.5%) NaCl solution under the conditions of these experiments. The least negative potential was measured on anodes, bipolar anodes and freely corroding control specimens. Regardless of the anode current density, steel corroded at a potential of approximately -0.7 V. Any more positive potential measured on steel was caused by an IR drop in the potential measurement as a result of the dc flow through the solution. The most negative potential was the potential to which steel was polarized cathodically. The most negative potential with the current off is undoubtedly the potential at which the only cathodic reaction occurring is hydrogen discharge. A mean potential more negative than -1.015 V to the Ag/AgCl reference electrode was obtained only when the measurement included an IR drop.

3. At stray dc densities of 5 and 10 mA/sq ft on steel, the IR drop was too small to detect stray currents from potential measurements.

4. Stray direct-current densities of 100 and 1000 mA/sq ft were readily detected from potential measurements because there was an appreciable IR drop at the bipolar anodes. The stray currents of this magnitude were detectable by either measuring the potential changes that occurred with the current on and the current off or by comparing the potentials measured with the current on to the potentials of the freely corroding control specimens.

5. The metal-loss rate for steel anodes and bipolar anodes was 50 mpy at a current density of 100 mA/sq ft and approximately 500 mpy at a current density of 1000 mA/sq ft. These increases in metal-loss rate would be catastrophic.

6. Even without a noticeable potential change at the anodes and bipolar anodes of steel, a stray direct current of 10 mA/sq ft increased the metal-loss rate from 3 to 8 mpy. This increase in metal-loss rate would not be catastrophic but would proportionately shorten the life of the steel.

7. A current density of 5 mA/sq ft was not sufficient to cause any apparent cathodic polarization, but reduced the metal-loss rate by approximately 50%. A current density of 10 mA/sq ft produced significant cathodic polarization and essentially eliminated corrosion on the steel cathodes and bipolar cathodes.

8. The anodes and bipolar anodes at current densities of 100 and 1000 mA/sq ft had a metal-loss rate equivalent to the theoretical values for the reaction $Fe-2e=Fe^{+2}$. At current densities of 5 and 10 mA/sq ft, the metal-loss rates increased compared to the theoretical values.

9. General corrosion was observed on all the freely corroding steel specimens.

10. The corrosion characteristics of steel anodes and bipolar anodes were similar at any one current density. At current densities of 5 and 10 mA/sq ft, general corrosion occurred over the entire exposed areas. At current densities of 100 and 1000 mA/sq ft, highly localized corrosion in the form of deep channels occurred at the edges of the tape used for masking specific areas from the solution. At a current density of 100 mA/sq ft, some areas away from the tape were essentially uncorroded.