CORROSION AND CATHODIC PROTECTION OF IRON IN DIFFERENTIAL TEMPERATURE CELLS

by

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Submitted in Partial Fulfillment of the Requirements
for the Degree of Bachelor of Science
from
Massachusetts Institute of Technology
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Signature of Author: Signature redacted

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Dept. of Chemical Engineering
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Cambridge 39, Mass.
May 18, 1950

Professor Joseph S. Newell
Secretary of the Faculty
M. I. T.
Cambridge 39, Mass.

Dear Sir:

The thesis entitled, "Corrosion and Cathodic Protection of Iron in Differential Temperature Cells," is hereby submitted in partial fulfillment of the requirements for the degree of Bachelor of Science in Chemical Engineering.

Respectfully submitted,

Signature redacted

Vinson R. Simpson Jr.

ACKNOWLEDGEMENT

The author wishes to express his appreciation to Dr. H. H. Uhlig, the staff of the M.I.T. Corrosion Laboratory, and to the staff of Building 12.

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SUMMARY

When two pieces of the same metal at different temperatures are placed in an electrolyte a thermogalvanic current is produced. The object of this thesis is to determine whether such a thermogalvanic current between two steel electrodes can be used to cathodically protect one of the electrodes from corrodingand how such factors as anode-to-cathode area ratio and resistance affect the thermogalvanic current.

The experimental cell shown in Figure 1 consisted of a ten-gallon earthenware crock containing 3% NaCl and equipped with cooling coils, an air bubbler, a stirrer, and a thermometer. Three "U" shaped electrodes were constructed from 1/4 inch steel tubing. One was used to measure the normal corrosion rate of steel in the cell solution and it will be termed the neutral electrode. The other two electrodes were outfitted with electrical means of shorting through a "zero-resistance" ammeter, care being taken to avoid thermocouple effects. A steam line was constructed to pass steam through one of these electrodes and this electrode will be termed the hot electrode, the remaining one being termed the cold electrode. A thermometer, installed at the exit of the steam from the hot electrode, completed the experimental apparatus.

Though the cold electrode was predicted to be the cathode and thus cathodically protected from corrosion, it was found that the current reverses after about an hour and a half with the hot electrode becoming the cathode. Figure 2 shows how the thermogalvanic current varied with time for the one such run made in this work. Cathodic protection from corrosion of the hot electrode for a thermogalvanic driving force of 68 C^o is not obtained.

The thermogalvanic current is reduced to the same degree whether the cathode area or the anode area is changed by a given amount. The anode and cathode areas are equally controlling the thermogalvanic current. Both the resistance of the leads and the resistance of the solution were proven negligable and, since the resistance of the "zero-resistance" ammeter is zero, in this respect the resistance of the electrode film is controlling the thermogalvanic current.

Recommendations are to execute confirmatory runs for the above results. In addition insight into the reason for heavy corrosion loss of the hot electrode, even when it is under predicted adequate cathodic protection, may be had by employing in future tests a second neutral electrode to measure the corrosion rate of steel at the hot electrode temperature. This data would throw light on the theory that the higher temperature of the hot electrode causes a greatly increased rate of corrosion reaction.

INTRODUCTION

Previous work by H. H. Uhlig and O. F. Noss Jr. (15) has led to the prediction that a cold steel electrode will be cathodically protected by a hot steel electrode of the same area. This thesis is for the purpose of examining Uhlig and Noss's prediction.

Heat exchangers, condensers, evaporators, and many other similar types of equipment are commonly employed to handle corrosive fluids while maintaining temperature differences between various areas of the metal. To designers of such equipment, corrosion is a very important consideration. Therefore it is desirable to be able to predict where corrosion will occur and how great a cathode area can be protected by a given anodic area. For the use of designers, engineering handbooks in the future will probably contain a section covering the phenomenon of thermogalvanic corrosion. This thesis materially contributes to the accumulation of information from which such a section in engineering handbooks will be made.

An examination of past studies of thermogalvanic corrosion reveals that cathodic protection by differential temperature cells has never been looked into. In fact, any information concerning the field of thermogalvanic corrosion of steel is lacking. This is probably due to the fact that no theory yet proposed for the mechanism of galvanic corrosion has been applicable to all the common metals.

The first report of corrosion due to temperature difference, according to Wesley, Trebler, and LaQue (18), was made by A. Walker (16) in 1825. More recent work concerning thermogalvanic corrosion was made a quarter of a century ago by Carl Benedicks who studied the corrosion by severe pitting of boiler tubes. Bubbles which form on the walls of such tubes cause local superheating because they prevent the cooling water from reaching the wall. This local superheating was postulated to "give rise to a local, purely thermal pitting of the metal wall." There is no evidence in the literature that Benedicks followed up his well-aimed assumption.

In 1926 E. D. Eastman (4) of the University of California made a thermodynamic study of what he termed "thermocells". Actually he was the first American to study thermogalvanic corrosion. Although he revised his original analysis two years later, Eastman's (5) work was obscure to the practical engineer because it was directed primarily to calculating the entropy of transfer of ions.

From a study of the corrosion of nickel equipment in a milk-purifying plant, Wesley, Trebler, and LaQue (18) stated in 1932 that "galvanic corrosion can occur, due solely to a difference in temperature of identical metal surfaces exposed to a given solution." Their work represents the first study of practical significance to the design engineer.

Results were at first confusing until the three men discovered that differential aeration of their experimental cell could be of much greater importance than the temperature differential. The hot electrode was found to be the anode.

Further practical study of thermogalvanic corrosion has been made on copper in two separate laboratories since 1943. First A. H. Maude (9) observed that with hydrochloric acid solutions "where copper is slightly hotter it will dissolve away and deposit as a sponge in other spots." In addition he stated that hot silver electrodes immersed in hydrochloric acid solutions will also be anodic. On this point H. J. V. Tyrrell (13) discovered in 1948 that silver electrodes in acidified silver nitrate solutions exhibit just the reverse effect; the anode is the cold electrode.

The other study of copper was made by N. E. Berry (2) and R. M. Buffington (3). Using a copper sulfate solution they found that the cold electrode was the anode. Agreement of their experimental results within about one percent of the theory is recorded. However no check of their theory was made with other metals until Noss's (11) study was made at M.I.T.

From Buffington's (3) theoretical work Noss predicted for iron a thermogalvanic potential gradient of -0.00093 volts per degree centigrade for the following half cell:

$$Fe \quad = \quad Fe^{++}\text{(in solution)} \quad + \quad 2e^{-} \qquad (1)$$

This would indicate that the low temperature electrode in ferrous ion solutions would be the anode. Using sodium chloride solutions Noss obtained just the reverse condition, recording a value of +0.00032 volts per degree centigrade, the hot electrode being the anode.

Thus the prediction of whether the hot or cold electrode will be the anode is clearly seen to be dependent to some degree on the solution utilized. When handbook data are eventually compiled they will have to include this consideration.

The background for the work in this thesis lies in Noss's (11) results with 3% aerated sodium chloride solutions using a constant temperature differential of 75°C. between identical steel electrodes. Noss found that "there is a definite reproducible corrosion potential" of 24 ± 3 millivolts. The corresponding current density for equal area anode and cathode was 0.425 milliamperes per square inch with a corresponding corrosion rate of 0.0306 inches penetration per year. The ordinary long exposure corrosion rate of steel in sea water at "atmospheric temperature" (14) is 0.005 inch penetration per year.

If the current density associated with a given cathode is great enough to polarize the cathode to the open circuit potential of the anode then cathodic protection is complete.

Data of J. M. Pearson (14) indicate that the minimum current density required for the protection of steel in sea water is of the "order of magnitude" of 0.1 milliamperes per square inch. Thus Noss's value of 0.4 milliamperes per square inch predicts that a hot steel anode should cathodically protect a cold steel cathode. Noss made no extensive runs, however, in which current was measured, merely recording the initial corrosion conditions.

The information of this thesis is qualitative in nature but it is nevertheless of practical significance to the designer of steel equipment which is exposed to corrosive fluids and a temperature diference. Under specified conditions of concentration, aeration, and temperature difference, the possibility is investigated of the cathodic protection, for example, of the hot section of a heat exchanger by the cold section. With this information the designer of such a heat exchanger, by reducing the thickness of the hot steel area, can materially reduce the cost of the installation.

PROCEDURE

Construction of Cell

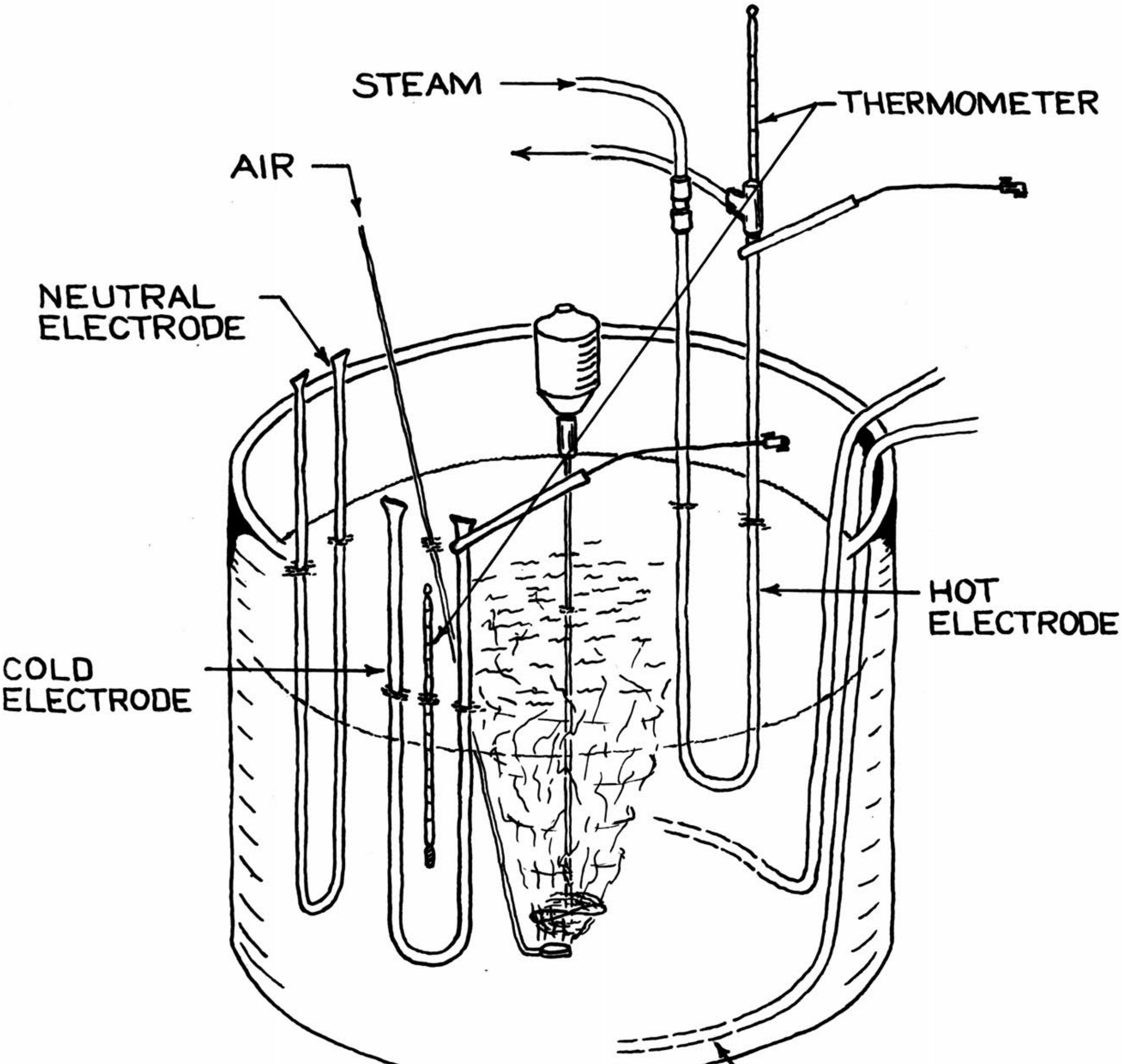
A ten-gallon earthenware crock was mounted on a marble laboratory desk top to insulate it in case of electrical seepage. Placed on top of the crock was a wooden harness painted with a glyptal resin and equiped with slotted cross bars to which the hot and cold electrodes were clamped. The crock also contained rubber tubing cooling coils, an air bubbler, a stirrer, and a thermometer to measure the temperature of the 3% NaCl solution in the crock.

Each of the three electrodes, hot, cold, and neutral, consisted of a two-and-one-half foot length of 1/4 inch O.D. seamless steel tubing bent into a "U" shape. The hot and cold electrodes were made from the same piece of stock to insure that no thermocouple effects would be present. A six inch section of this same tubing was split lengthwise and a piece of this flattened tubing was spotwelded to the end of both the hot and cold electrodes. A piece of iron wire was spotwelded to the end of the flattened tube to provide a means of electrical connection. Spotwelding was employed to further prevent the occurance of any thermocouple effects.

Copper tubing and fittings were used to handle the

FIGURE 1

SKETCH OF EXPERIMENTAL CELL



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steam which was passed through the hot electrode to maintain its temperature near one hundred degrees centigrade. There was zero potential difference between the steam line and the hot electrode. At the exit of the steam from the electrode a thermometer was placed. The cold and neutral electrodes were closed off at their ends to prevent moisture from collecting inside and rendering the determination of metal weight loss inaccurate. A "zero-resistance" ammeter (14) was constructed to accurately measure the current flowing between the electrodes.

Preparation for Run

Thirty-four liters of distilled water were added to the crock along with 120 grams of NaCl to make a 3% solution. Before each run the electrodes were washed, pickled in acid which contained inhibitor, washed with scalding water, and dried in air. The hot electrode which was not sealed shut was flushed clean by passing air through it. All three electrodes were weighed to an accuracy of ±0.003 gram.

Procedure During Run

During each run steam was passed through the hot electrode and its temperature was maintained at about ninety-five degrees. Cold tap water was passed through the cooling coils and the bath or solution temperature was maintained at about thirty degrees. Both the air bubbler and stirrer were operated throughout each run to keep the solution saturated with air and well mixed. Recorded during each run were: the time, the solution temperature, the exit steam temperature, and the milliamperes of current flowing between the electrodes. When the "zero-resistance" ammeter was not being used to obtain a reading, the electrodes were shorted together by means of a copper connector.

Immediately following each run, the three electrodes were washed, pickled, dried in air, and weighed.

RESULTS AND DISCUSSION OF RESULTS

Phenomenon of Current Reversal

In every test run made in this study (five), of the current produced between two identical steel electrodes immersed in stirred aerated 3% NaCl, shorted, and maintained at a 68°C. temperature difference, the hot electrode is at first the anode but after about an hour and a halfthe current reverses and the cold electrode becomes the anode. Furthermore, the plot of current vs. time, Figure 2, shows that there is no tendancy for the cell to reverse again but that even after eight days the thermogalvanic current is still increasing negatively.

The results shown in Figure 2 are the results of only one run. No confirmatory run has yet been made. However the data for this one extensive run, in the early stages of the run, closely correspond to the data recorded for several other runs of about a days duration. During the extensive run there was nothing observed to indicate that the run would not be easily reproducible.

Lack of Adequate Cathodic Protection

Since the phenomenon of the reversal of polarity immediately eliminates the possibility of extended cathodic protection of the cold electrode, cathodic protection

CURRENT FLOW VS. TIME BETWEEN TWO EQUAL AREA STEEL ELECTRODES HELD 68°F APART

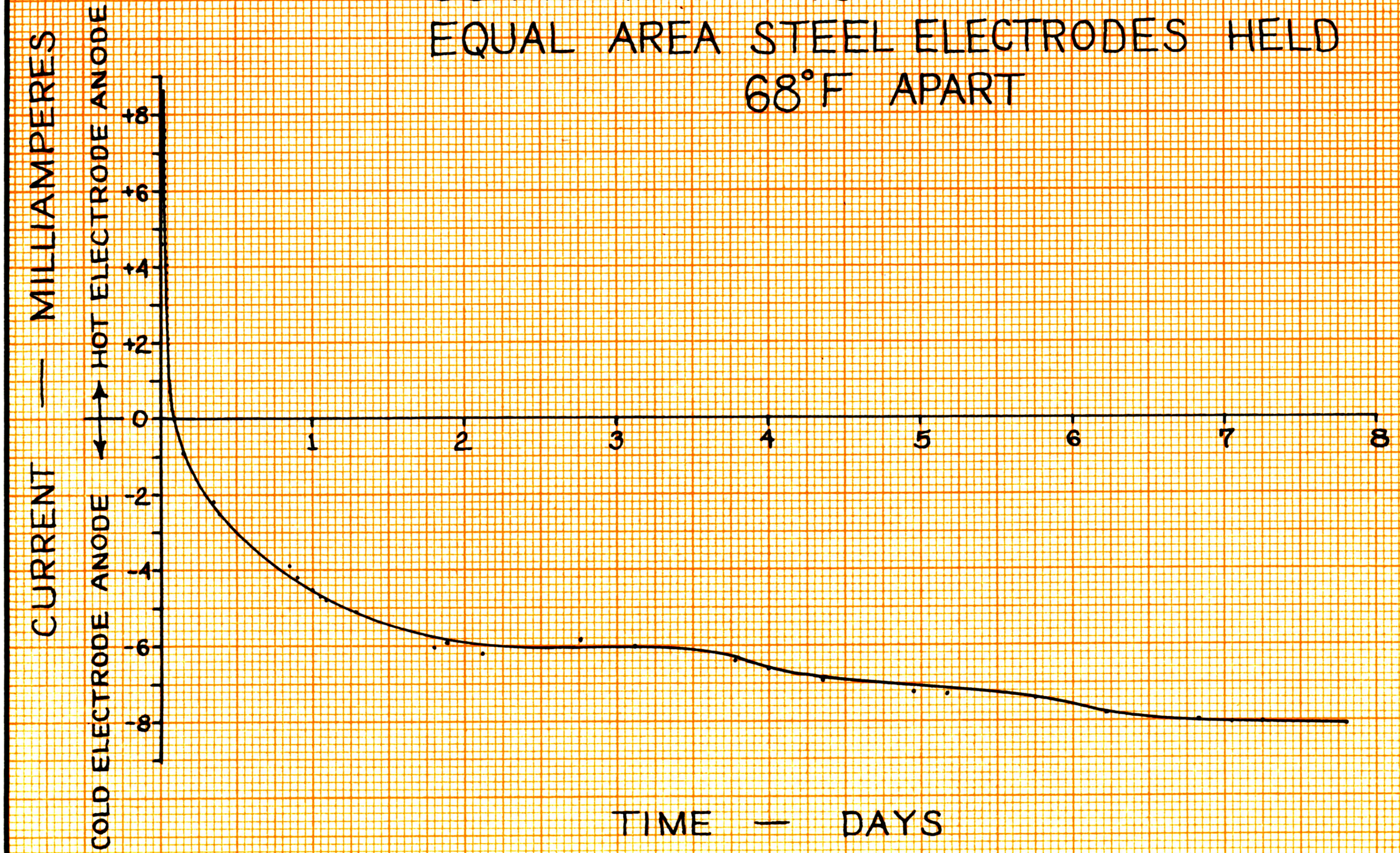

FIGURE 2

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of the hot electrode was investigated. From data in the "Corrosion Handbook" (14) p. 920, the minimum protective current was predicted to be (see appendix for calculation) 1.36 milliamperes for the electrodes used in this study, under the above specified conditions.

Two runs were planned and executed. The first (Run #4) was to last until the current had reversed and reached 1.36 milliamperes. The second (Run #5) was to last until the current had increased considerably beyond this minimum requirement. In both runs the weight loss of the electrodes would be measured. The quanitative results are shown below in Table I.

Table I

Loss in Weight of Electrodes

	Loss in Grams Run #4 (1 hour, 50 min.)	Loss in Grams Run #5 (7 days, 19 hours, 45 min.)
Hot electrode	0.096	9.442
Cold electrode	0.023	2.736
Neutral electrode	0.052	2.041

(weight loss accuracy: ± 0.006 grams)

It is clearly seen that the hot electrode has suffered a heavy corrosion loss and has not been cathodically protected when past the predicted point of minimum required cathodic protection current. Even if the predicted protection current were somewhat incorrect, the fact remains that the hot electrode corroded much more than the neutral electrode. This indicates that the conditions are much more corrosive at the hot electrode than they are at either the cold or neutral electrode, so much so that they overshadow a 6.74 milliampere excess of cathodic protection current. It may be that the higher temperature at the hot electrode increases the rate of the corrosion reaction until it does overshadow the effect of cathodic protection.

Anode and Cathode Areas Equally Controlling

Data regarding the effect of changing the ratio of the anode area to the cathode area would be of interest. To do this properly, extensive runs should be made for each area ratio. This was not done in this work but an investigation was made of this area factor using the electrodes which had been in the cell for already eight days. By dipping in the 3% NaCl (aerated and stirred) only a portion of the normal area of an electrode the data of Table II were recorded.

Table II

(next page)

Table II

Effect of Anode-to-cathode Area Ratio

Area Ratio Anode to Cathode	Electrode Area Arrangement	Thermogalvanic Current Milliamperes	Time Waited Before Taking Reading Minutes
3	1/3 hot in 1 cold in	4.85	10
1.5	2/3 hot in 1 cold in	7.20	10
1.0	1 hot in 1 cold in	8.10	9
0.67	1 hot in 2/3 cold in	7.25	10
0.33	1 hot in 1/3 cold in	4.80	9

(cold is anode; hot is cathode)

The time waited before recording the current reading was arbitrary. In each case, the current reading shown above registered on the "zero-resistance" ammeter in less than half a minute after the electrode area relationship was fixed. Thereafter the reading was constant with no fluctuations.

It is seen that the reading is the same whether only one-third of the cathode area is in the solution or whether one-third of the anode area is in the solution. Thus the anode and cathode appear to be equally controlling with regard to the thermogalvanic current.

Electrode Film Resistance Controlling

The resistance of the cell may be considered to consist of three parts: the resistance of the leads, the resistance of the solution, and the resistance of the film. The "zero-resistance" ammeter has as its name implies, zero resistance. The resistance of the leads was proven to be negligable by introducing leads of three times the resistance of the original leads and observing no change in the current reading. The resistance of the cell solution was also proven to be negligable by moving the electrodes close together and observing no change in the current reading. The conclusion is that the film resistance is controlling for the cell studied.

CONCLUSIONS

Two steel electrodes, immersed in stirred aerated 3% NaCl solution and maintained at a temperature difference of 68 C^{o}, produce at first a current flow with the hot electrode the anode: however, after about an hour and a half this current reverses and from then on appears to steadily increase with the cold electrode the anode. It is concluded that in such steel thermogalvanic cells the cold electrode is the anode after about an hour and a half.

Though this latter reversed current flow becomes several times the magnitude of the minimum predicted cathodic protection current, the hot electrode instead of being protected suffers a heavier corrosion loss than either the cold or neutral electrode. It is concluded therefore that the thermogalvanic current is inadequate to prevent the corrosion of the hot electrode which is probably due to an increased reaction rate caused by the higher temperature. Thus cathodic protection of neither the cold or hot electrode is obtained by a thermogalvanic driving force over an extensive period of time.

The thermogalvanic current is reduced to the same degree whether the the anode or cathode area is reduced by a given amount. The conclusion is that the anode and cathode areas are equally controlling the thermogalvanic current.

An examination of the resistances in the cell leads to the conclusion that in this respect the film resistance controls the thermogalvanic current.

RECOMMENDATIONS

It is definately recommended that several extensive runs be made, similar to the one eight day run of this work, to confirm the data of Figure 2. The cell should be allowed to operate until an equilibrium current is reached. Figure 2 indicates that such runs would not be much longer than eight days, however this should be investigated.

Several improvements may be incorporated into these runs. First, two neutral electrodes should be used, one at the solution temperature as was done in this work, and another at the same temperature as the hot electrode. Comparing the weight loss of these two electrodes would yeild factual information as to how the temperature affects the normal exposure corrosion rate. This information in turn would give insight into the actual reason for the heavy corrosion loss suffered by the hot electrode even though it is being cathodically protected by the thermogalvanic current. Another improvement would be to obtain some very thin wall rubber tubing to use for an improved and more easily controlled cooling coil.

Extensive runs should be made for various anode-to-cathode area ratios to confirm the indications reported in this work. Also the effect of varying the temperature difference between the electrodes should be studied. To do this a very cold cooling liquid should be available for better control of the solution temperature. A recirculating reservoir apparatus that might very effectively be used is described by Wesley, Trebler, and La Que (18).

APPENDIX

IDENTIFICATION AND CHARACTERISTICS OF INSTRUMENTS USED

Instruments Used in "Zero-resistance" Ammeter

Portable Galvenometer R.L.A.C. #91
Central Scientific Company
Sensitivity- 3 to 4 megohms
Period - 3/4 second
Resistance - 750 ohms

Direct Current Milliammeter C.E.D. #266
Triplett Model 321
Range - 0 - 1 mamp. (gradations in 0.02 mamp.)
0 - 10 mamps. (gradations in 0.2 mamp.)
Resistance - 26.12 ohms

Instrument Used to Calibrate "Zero-resistance" Ammeter Circuit

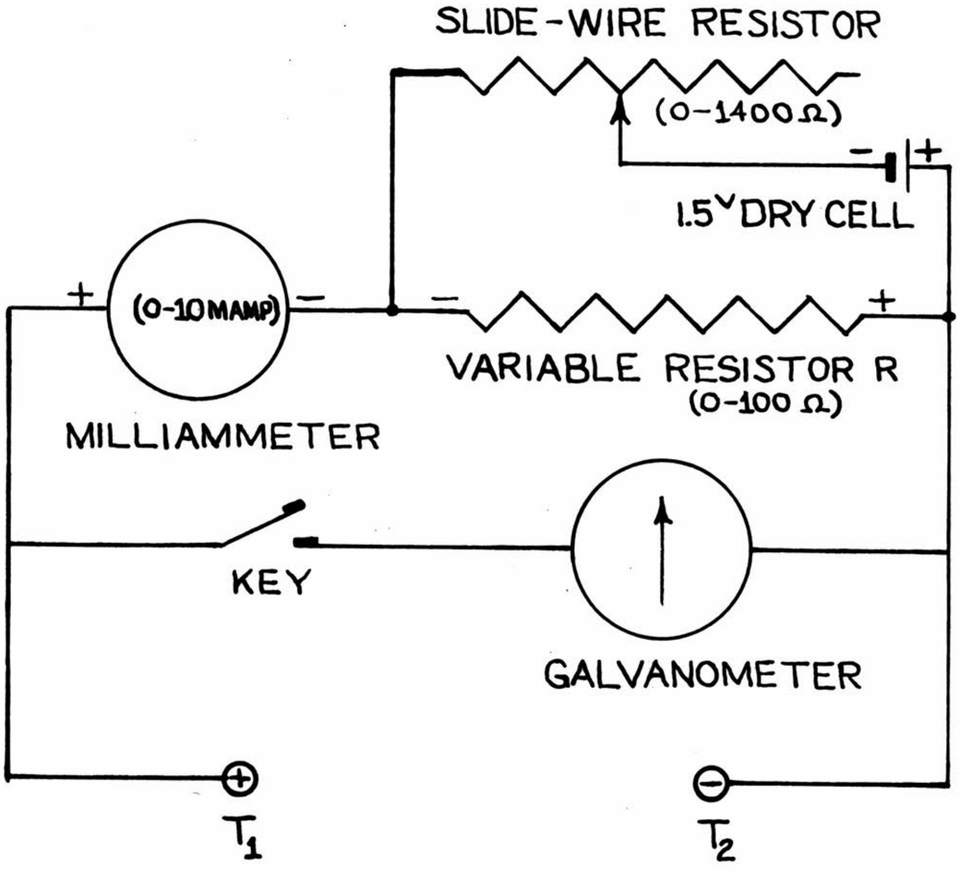
Direct Current Milliammeter C.E.D. #265
Triplett Model 321
Range - 0 - 25 mamps. (gradations in 0.5 mamp.)
0 - 250 mamps. (gradations in 5 mamps.)

Instrument Used to Verify Polarity of the Electrodes

Millivoltmeter # 203969
Weston
Range - 0 - 50 mvolts. (gradations in 1 mvolt.)

FIGURE A1

CIRCUIT OF "ZERO-RESISTANCE AMMETER



A drop in voltage across the terminals T_1 and T_2 is opposed by an equal voltage drop across resistance R, such that the net drop across T_1 and T is reduced to zero. (<u>14</u>) p. 1039.

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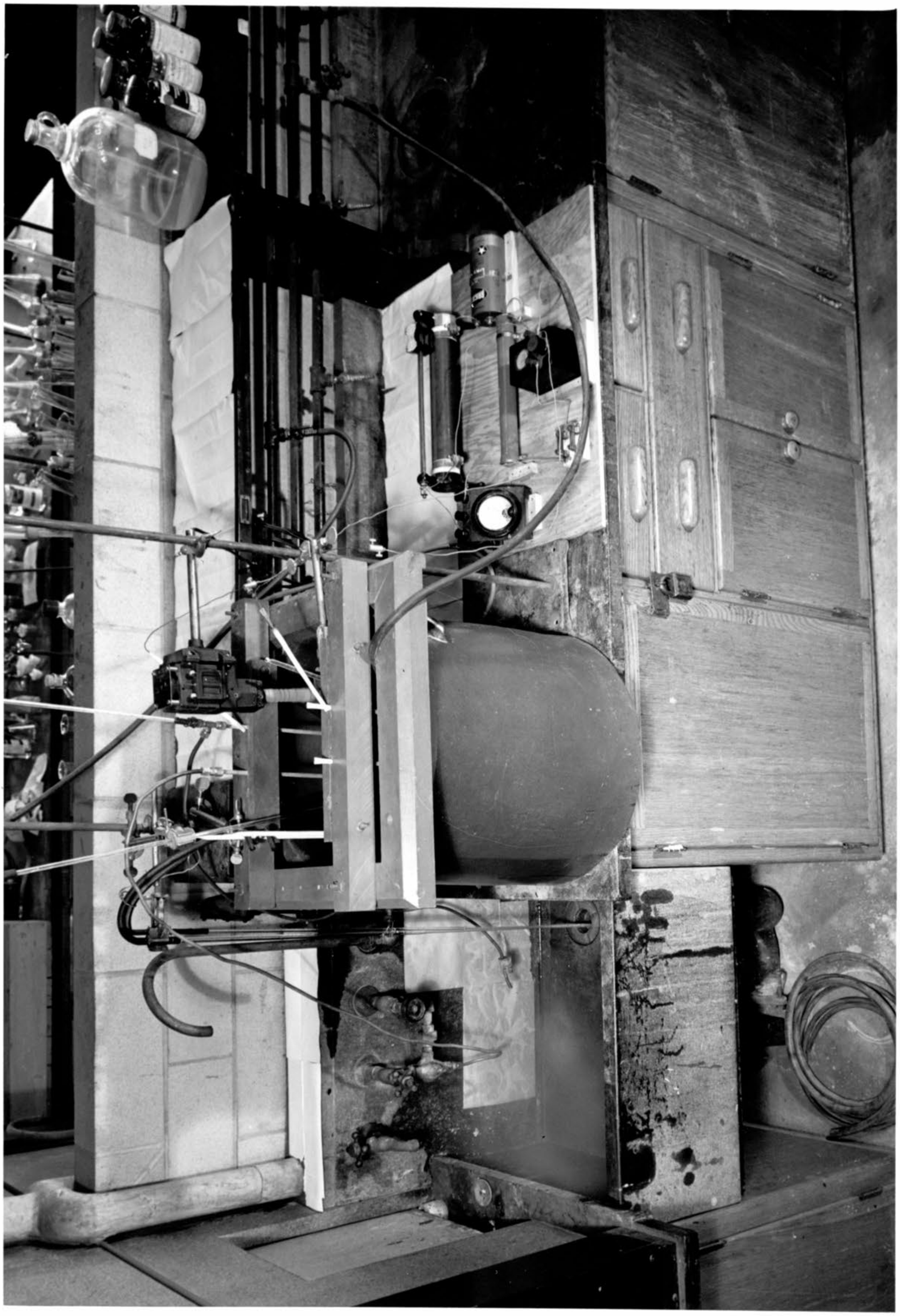
FIGURE A2

EXPERIMENTAL APPARATUS



DETAILS OF PROCEDURE

Design of Electrodes

From a single piece of 1/4 inch outside diameter steel tubing, two two-and-one-half foot lengths were cut. A third piece of steel tubing of the same dimensions was also obtained. Each of these three lengths was bent into a "U" shape such that the diameter of the semicircle at the bend was about three inches with each arm of the "U" approximately twelve-and-one-half inches in length. The two "U" shapes from the same piece of stock were used as the hot and cold electrodes; the other "U" shape was used as a dummy or neutral electrode to determine the normal corrosion rate in the cell.

Precaution was taken to prevent corrosion of the electrodes above the solution. A three inch length of tight-fitting rubber tubing was slipped over each arm of each electrode. During a test this tubing extended one-half inch below the surface of the cell solution. Equal area steel surfaces were to be exposed by the electrodes in the cell solution and careful orientation of the rubber tubing met this requirement. In each case 15.5 inches of steel tubing was exposed corresponding to an area of 90.9 square centimeters.

The open ends of the cold and neutral electrodes were heated and hammered shut to prevent any foreign matter, especially moisture, from entering the electrode during a test. A six inch piece of steel tubing was split lengthwise and a piece of this flattened tubing was spotwelded to an end of both the hot and cold electrodes. To the end of the flattened tubing an eight inch iron wire was spotwelded. Electrical connections to the electrodes were all made at the extreme end of the iron wires by means of copper conectors. Spotwelding was employed in forming the permanent unions in order to prevent the occurence of any stray electrothermic effects.

To prevent corrosion of the electrodes on the above-solution areas, these areas were given two coats of "Unichrome" Quick-dry Stop-off Lacquer #324.

Construction of Cell

A ten-gallon earthenware crock was placed on a marble laboratory desk top to insulate it in case of electrical seepage. Placed on top of the crock was a wodden harness painted with glyptal resin and equiped with slotted cross bars to which the hot and cold electrodes were clamped. Ringstands were utilized to support an air bubbler and AC moter stirrer, both of which were located in the center of the crock or cell. Approximately forty feet of rubber tubing cooling coils was located in the bottom of the crock. In addition a thermometer was placed in the cell with its bulb between the arms of the cold electrode and approximately four inches below the solution level.

Installation of Electrodes

Copper tubing and fittings were used to handle the steam which was passed through the hot electrode. Just at the exit of the steam from the electrode a thermometer was placed to determine the approximate temperature of the electrode. The potential of the steam line was checked and found to be zero with respect to the water line as ground. Both the hot and cold electrodes were supported by pressure between two pieces of wood which had been treated with glyptal resin. The neutral electrode was insulated by placing rubber tubing over the fingers of the clamp which supported it.

Preparation of Solution

Before each test a new solution was prepared and the crock and contents were thoroughly cleaned. Forty liters of distilled water and 120 grams of sodium chloride was added to the crock to make up the 3% NaCl solution. After the sodium chloride was dissolved the solution was mixed and aerated for at least a half hour before beginning a test.

Weighing of Electrodes

Prior to each weighing of the electrodes they were washed by hand and then pickled for five minutes in a twenty percent sulfuric acid solution containing one milliliter of Monsanto Hibitite L per liter of pickling liquor. Following this, the electrodes were washed with scalding water and let dry in air. The hot electrode which was not sealed shut was flushed clean inside by passing a stream of air through it for at least five minutes. The accuracy of the balance used was ±0.003 gram~~s~~. Loss in weight during pickling due to dissolution of the metal was measured by pickling a clean electrode and determining the corresponding weight loss. This correction was incorporated into all the weight measurements.

Procedure During Run

During each run steam was passed through the hot electrode and its temperature was maintained at approximately 100°C. by holding the temperature of the exit steam at 100°C. This was done by adjusting the valve to the steam line. The bath temperature was maintained as low as possible, about thirty degrees, by using as great a cooling water flow rate as the water line could supply. An air bubbler was located at the very bottom of the crock with its porous plate directly under the axis of the stirrer.

The electrodes were weighed, immersed in the cell solution, and the time recorded. During each run the solution temperature, the exit steam temperature, the milliamperes of current flowing between the electrodes, and the time were recorded. When the zero resistance ammeter circuit was not being used the electrodes were shorted by connecting their iron wire extensions with a copper conector. Immediately following each run the three electrodes were washed, pickled, dried in air, and weighed.

DATA RUN #2

Determination of Relative Importance of Aeration, Stirring, and Temperature Difference to the Potential Difference and Current Flow Between the Hot and Cold Electrodes.

Note: Throughout this run the electrodes were shorted except for brief moments when the millivot readings were taken. The solution is 3% NaCl. Initially, there is no stirring or aeration. Elapsed time is the time since the electrodes were shorted.

Elapsed Time hours - minutes	Mamps.	Mvolts.	Temperature Difference degrees centigrade
0 - 0	2.6	1.6	0
0 - 8	(stirrer turned on)		
0 - 11	1.3	5.0	0
0 - 13	(stirrer turned off; air turned on)		
0 - 19	1.1	4.5	0
0 - 22	(stirrer turned on; air kept on)		
0 - 25	1.5	5.2	0
0 - 32	(steam turned on; air and stirrer kept on)		
0 - 33	2.9	10.0	72
0 - 36	2.95	10.2	76.8
0 - 40	3.1	10.8	73.3
0 - 45	3.3	11.4	70.8
0 - 50	3.45	11.4	69.2
0 - 55	3.45	11.4	67.2
1 - 0	3.42	10.9	65.6
1 - 5	3.3	10.9	64.8
1 - 10	3.2	10.5	63.7

DATA RUN #4

Determination of Weight Loss Encountered by the Electrodes When Allowed to Run Until Theoretical Protection of the Hot Electrode

Note: The hot and cold electrodes were allowed to come to the same potential. At zero elapsed time, the air, stirrer and steam were turned on. Throughout the test the electrodes were shorted via the "zero-resistance" ammeter. Positive current readings mean that the hot electrode was the anode.

Initial Weight of the Electrodes:

Hot	165.828 ± 0.003 grams
Cold	148.227 ± 0.003 grams
Neutral	85.618 ± 0.003 grams

Elapsed Time minutes	Mamps.	Temperature Difference degrees centigrade
0		
15.5	9.4	69.1
17	9.0	68.5
18	8.5	68.0
19.5	8.0	67.8
20	7.8	67.4
21.3	7.45	67.0
22	6.8	66.8
23	6.7	66.5
25	6.2	66.0
27	5.7	65.9
29	5.25	65.3
31	4.7	64.4
33	4.25	65.3
35	3.85	63.9
37	3.5	63.1
40	3.0	62.6
42.5	2.5	63.0
48	1.9	61.7

Elapsed Time minutes	Mamps.	Temperature Difference degrees centigrade
50.5	1.75	61.3
52	1.65	60.6
55	1.25	60.8
58	0.9	60.1
60.7	0.75	59.7
62.5	0.7	60.5
64	0.5	60.2
65.5	0.45	60.4
68	0.2	60.3
70	0.2	60.5
71.5	0.1	59.9
73	0.05	60.1
75	-0.05	60.4
77	-0.2	60.4
79	-0.3	60.3
81	-0.4	60.3
83	-0.55	60.3
85.5	-0.55	60.1
86	-0.6	60.2
88	-0.7	60.2
90.5	-0.7	60.0
92	-0.9	59.5
93	-0.8	59.7
94	-0.85	59.6
96	-0.9	59.1
98.5	-1.1	59.1
101	-1.1	59.1
104.5	-1.1	60.3
106	-1.1	60.1
108	-1.15	60.3
110	-1.25	60.8
110.5	(took out electrodes)	

Loss In Weight During Run

Hot electrode	0.096 ± 0.006 grams
Cold electrode	0.023 ± 0.006 grams
Neutral electrode	0.052 ± 0.006 grams

DATA RUN #5

Performance of Electrodes When Cell Is Allowed to Operate Over a Week Period

Note: The hot and cold electrodes were allowed to come to the same potential. At zero elapsed time the air, stirrer, and steam were turned on. During the test the electrodes were shorted directly by means of a copper conector except when readings were taken, then they were shorted through the zero-resistance ammeter. Positive current readings indicate that the hot electrode was the anode.

Elapsed Time day-hour-min.	Mamps.	Temperature Difference degrees centigrade
0		
2	4.6	62.6
3	5.2	66
4.2	6.5	70.7
5	7.0	68.6
5.5	7.4	69.0
6.2	7.6	69
7	7.8	68.4
8.8	8.0	68
9.5	8.3	67.6
10	8.6	67.7
11.3	8.6	67.2
12.7	8.3	66.7
13.2	8.35	66.7
14	8.35	66.6
16	8.25	65.5
18.2	7.8	64.6
19.5	7.7	
20	7.55	
20.5	7.45	
21	7.35	
21.5	7.30	
22	7.20	

Elapsed Time day-hour-min.	Mamps.	Temperature Difference degrees centigrade
22.7	6.90	
23.5	6.65	
24	6.65	
24.5	6.70	
25	6.7	70.9
26	6.2	
26.5	6.25	
27	6.25	
27.5	6.20	
28	6.20	
28.5	6.1	
29	6.05	
29.5	6.00	
30	5.90	69.5
31	5.70	
32	5.65	
32.5	5.60	
33	5.50	
33.5	5.50	
34	5.30	
34.5	5.30	
35	5.25	68.7
36.5	5.00	
37	5.0-	
37.5	4.85	
38	4.80	
38.5	4.80	
39	4.55	
40	4.50	
42	4.25	
43	4.00	
43.5	3.96	
44.5	3.95	
45.5	3.90	
46.5	3.70	
47	3.70	
48.5	3.70	
49.5	3.50	61.5
51.5	3.3	
54	3.1	
55	3.1	60.8
57	3.0	
58	2.9	
59	2.9	
60	2.7	

Elapsed Time day-hour-min.	Mamps.		Temperature Difference degrees centigrade	
1 - 1.5	2.7			
1 - 4.5	2.4			
1 - 7.5	2.2			
1 - 11.5	2.15			
1 - 14	1.90			
1 - 15	1.90			
1 - 22	1.70			
1 - 29	1.25			
1 - 31	1.20			
1 - 35	1.00			
1 - 40	0.7			
1 - 46	0.65			
1 - 50	0.50		60.5	
1 - 55	0.30			
1 - 58	0.25			
2 - 0	0.25			
3 - 36	-0.9		59.7	
8 - 9	-2.2		64.7	
8 - 25	-2.2		63.3	
8 - 36	-2.2		63.1	
8 - 56	-2.5		65.1	
9 - 3	-2.25		60.5	
9 - 21	-2.5		63.3	
18 - 13	-3.35	(doubted)	67.5	Spotweld on wire of cold electrode broke.
19 - 45	-3.4	(doubted)		
20 - 0	-3.3	(doubted)	68.2	
20 - 15	-3.95			
20 - 17	-3.95		67.3	
20 - 19	-4.00		67.3	
20 - 21	-4.00		67.1	
20 - 25	-4.05		66.4	
20 - 29	-3.95		66.2	
20 - 35	-4.10		67.3	
20 - 40	-4.10		67.4	
20 - 47	-4.10		66.7	
20 - 51	-4.10		67.0	
20 - 57	-4.20		67.0	
21 - 1	-4.20		66.7	
21 - 5	-4.20		64.7	
21 - 11	-4.15		65.3	
21 - 15	-4.20		65.6	
23 - 17	-4.50		66.4	
23 - 45	-4.50		66.4	
24 - 0	-4.50		65.7	
1 - 0 - 15	-4.60		67.0	

Elapsed Time day-hour-min.	Mamps.		Temperature Difference degrees centigrade	
1 - 0 - 30	-4.70		66.8	
1 - 1 - 15	-4.70		66.1	
1 - 2 - 20	-4.80		66.6	
1 - 6 - 0	-4.80		66.9	
1 - 7 - 5	-3.7	(doubted)	67.2	Stirrer came off.
1 - 8 - 5	-5.1		66.9	
1 - 8 - 15	-5.05		66.9	
1 -19 - 10	-6.05		67.0	
1 -20 - 15	-5.60		63.2	
1 -21 - 8	-5.90		67.2	
1 -22- 54	-6.0		66.9	
2 - 2 -45	-6.2		68.8	
2 -19 - 20	-5.8		66.8	
3 - 2 - 55	-5.95		69.4	
3 -18 - 45	-6.4		69.9	
3 -19 - 15	-6.5		69.5	
3 -19 - 30	-6.65		69.1	
3 -19 - 50	-6.6		69.1	
3 -20 - 0	-6.6		69.1	
3 -21 - 15	-6.6		68.6	
4 - 0 - 45	-6.6		69.6	
4 - 1 - 45	-6.6		68.8	
4 - 1 - 15	-6.6		69.0	
4 - 3 - 0	-6.8		69.1	
4 - 8 - 35	-6.95		68.8	
4 -23 - 0	-7.25		69.1	
5 - 4 - 0	-7.3		69.4	
5 -18 - 0	-7.45		71.9	
6 - 7 - 0	-7.8		69.4	
6 -20 - 0	-7.95		72.1	
6 -21 - 20	-7.95		70.4	
7 - 1 - 0	-8.05		69.9	
7 - 2 - 0	-8.00		70.5	
7 - 8 - 0	-8.05		70.6	
7 -19 - 30	-8.10		70.5	
7 -19 - 45	-8.10		70.1	

Loss In Weight During Run

Hot electrode	9.442 ± 0.006 grams
Cold electrode	2.736 ± 0.006 grams
Neutral electrode	2.041 ± 0.006 grams

CALCULATION OF MINIMUM CATHODIC PROTECTION CURRENT

Area of Electrodes

length: 15.5"
diameter 0.25"

Area = $(15.5)(3.14)(0.25)(2.54)^2$ cm^2.

= 90.9 cm^2.

Protective Current Density Required for Steel

Source: "Corrosion Handbook" (14) p.920

"...for steel in moving sea water and O_2-saturated hot water." $1.5 \cdot 10^{-5}$ amperes/sq.cm.

Minimum Protective Current for the Electrodes Employed

I_p = minimum protective current = $(1.5 \cdot 10^{-5})(90.9)$

= $1.364 \cdot 10^{-3}$ amperes

I_p = 1.36 milliamperes

LITERATURE CITATIONS

(1) Benedicks, Carl, Trans. Am. Inst. Mining Met. Eng. 71, 597-626 (1925).

(2) Berry, N. E., Corrosion 2, 261-272 (1946).

(3) Buffington, R. M., Corrosion 3, 613-631 (1947).

(4) Eastman, E. D., J. Amer. Chem. Soc. 48, 1482-1493 (1926).

(5) Eastman, E. D., J. Amer. Chem. Soc. 50, 292-297 (1928).

(6) International Critical Tables.

(7) Keenan, J. H. and Keyes, F. G., "Thermodynamic Properties of Steam", 1st ed., New York, John Wiley and Sons, Inc., (1936).

(8) Latimer, W. M., "Oxidation Potentials", New York, Prentice-Hall, Inc., (1938).

(9) Maude, A. H., Trans. Amer. Inst. of Chem. Engs. 39, 752-753 (1943).

(10) Millard, E. B., "Physical Chemistry for Colleges", 6th ed., New York, McGraw-Hill Book Company, Inc., (1946).

(11) Noss, O. F. Jr., "The Effects of Thermal Gradients on the Corrosion Rate", S. B. Thesis, Chem. Eng., M.I.T., (1949).

(12) Sherwood, T. K. and Reed, C. E., "Applied Mathematics in Chemical Engineering", 1st ed., New York, McGraw-Hill Book Company, Inc., (1939).

(13) Tyrrell, H. J. V., Metal Treatment 14, 243-248 (1948).

(14) Uhlig, H. H., "Corrosion Handbook", 1st ed., New York, John Wiley and Sons, Inc., (1948).

(15) Uhlig, H. H. and Noss, O. F. Jr., Corrosion 6, (1950).

(16) Walker, Adolph, Annalen der Physik und Chemie 4, 443-458 (1825).

(17) Walker, W. H., Lewis, W. K., McAdams, W. H., and Gilliland, E. R., "Principles of Chemical Engineering", 3rd ed., New York, McGraw-Hill Book Company, Inc., (1937).

(18) Wesley, W. A., Trebler, H. A., and LaQue, F. L., Trans. Amer. Electrochemical So. 61, 467 (1932).