ATMOSPHERIC POLLUTANTS AND THEIR EFFECTS ON CORROSION

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ATMOSPHERIC POLLUTANTS AND THEIR EFFECTS ON CORROSION

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SUMMARY

It is a well known fact that steels used in the manufacture of everything from buildings to ocean going vessels experience corrosion when exposed to the marine air environment. A combination of marine and industrial air environments is believed to be even more corrosive. It has been hypothesized that oxygen replenishment in the thin film near metal surfaces is often a determining factor for the corrosion rate of metals. It is the purpose of this investigation to compare the influence of various environments on corrosion rates; this was simulated by exposing metal to a sodium chloride aerosol in the presence of sulfur dioxide. The oxygen adsorbed onto the aerosol was reduced by using a surfactant in the aerosol solution. Also a comparison between various metals utilized in a marine-industrial environment was examined. The variables examined were time of exposure, aerosol conditions, and material exposed.

It was found that by decreasing oxygen adsorption onto the aerosol the corrosion rate of the metals was decreased. The effect of sulfur dioxide in conjunction with sodium chloride aerosol increased the corrosion rate. Finally a comparison of weight loss measurements on various materials yielded an order of corrosion resistance.

CHAPTER I

INTRODUCTION

One of the conditions under which corrosion occurs is exposure to the atmospheric environment. When a metal is exposed to a bulk solution the rate of oxygen replenishment is often the corrosion rate determining factor, but when the same metal is exposed to the atmosphere above or near the bulk solution other factors have been shown to be crucial. These factors are as follows: 1) the length of time the material is wet, 2) the composition of the atmosphere, and 3) the effect of the corrosion products. The wet time is a factor worth considering because the solution in contact with the metal provides the media for ion transport.

The composition of the atmosphere is important because various gases in the air will affect the pH, and the particulate matter will affect the erosion and porosity of the corrosion products. Particulate matter has been arranged by Evans (1) into three categories: 1) the harmless, 2) the intrinsically corrosive, and 3) the indirectly corrosive. The latter is referred to as indirectly corrosive because it in itself is not corrosive, but through its ability to adsorb gases and water vapor from the air it increases the wet time and alters the local pH.

The effect of the corrosion product must also be considered. Although corrosion products usually inhibit future corrosion by limiting the oxygen and water transfer to the metal surface, atmospheric conditions may alter this effect by erosion and porosity due to particulate matter and solubility due to pH variations.

One of the sources of an indirectly corrosive particle is the ocean. Two methods by which a salt particle is introduced into the air are the tearing of the ocean surface, as occurs at the crest of a wave, and the ocean bursting of the surface by a rising bubble (2). The latter is the most accepted and studied theory (3,4). An estimated two to ten billion tons of sea salt per year is believed to be transferred to the atmosphere (5,6).

The purpose of this investigation was to examine the effect of marine aerosols and industrial atmospheric pollutants on the corrosion rate of metals. This has been accomplished by exposing carbon-steel to simulated atmospheric conditions near the ocean and industry on the shore. The variables examined were time of exposure, atmospheric composition, and type of metal.

CHAPTER II

APPARATUS

The apparatus used for this investigation was chosen for its residence time characteristics. The salt spray test is an accelerated test, and its results have been used as standard values. The relationship between an accelerated test and actual corrosion tests may be made only when both are conducted under similar conditions and compared.

The salt spray test was first described in 1914 by J.A. Capp (7) as follows:

> As now used, the test consists in exposing the articles in any convenient chamber into which there is projected an atomized spray of water saturated with common salt in solution, care being taken to avoid placing the test specimens directly in the path of the jet.

Uhlig (8), Romans (9), and ASTM method B117 (10) describe suitable apparatus which may be used to meet these conditions.

The apparatus employed here consisted of a fog chamber; a bulk solution constant head reservoir; a supply of compressed air and means to humidify it; an aerosol generator; a specimen rack; a supply of sulfur dioxide and nitrogen; and means to measure pressures, flow rates, and concentrations of incoming gases. A schematic representation of the apparatus is presented in Figure 1.

Dimensions of fog chambers employed by others have varied from a few cubic feet to a small room (11). That they be constructed of a

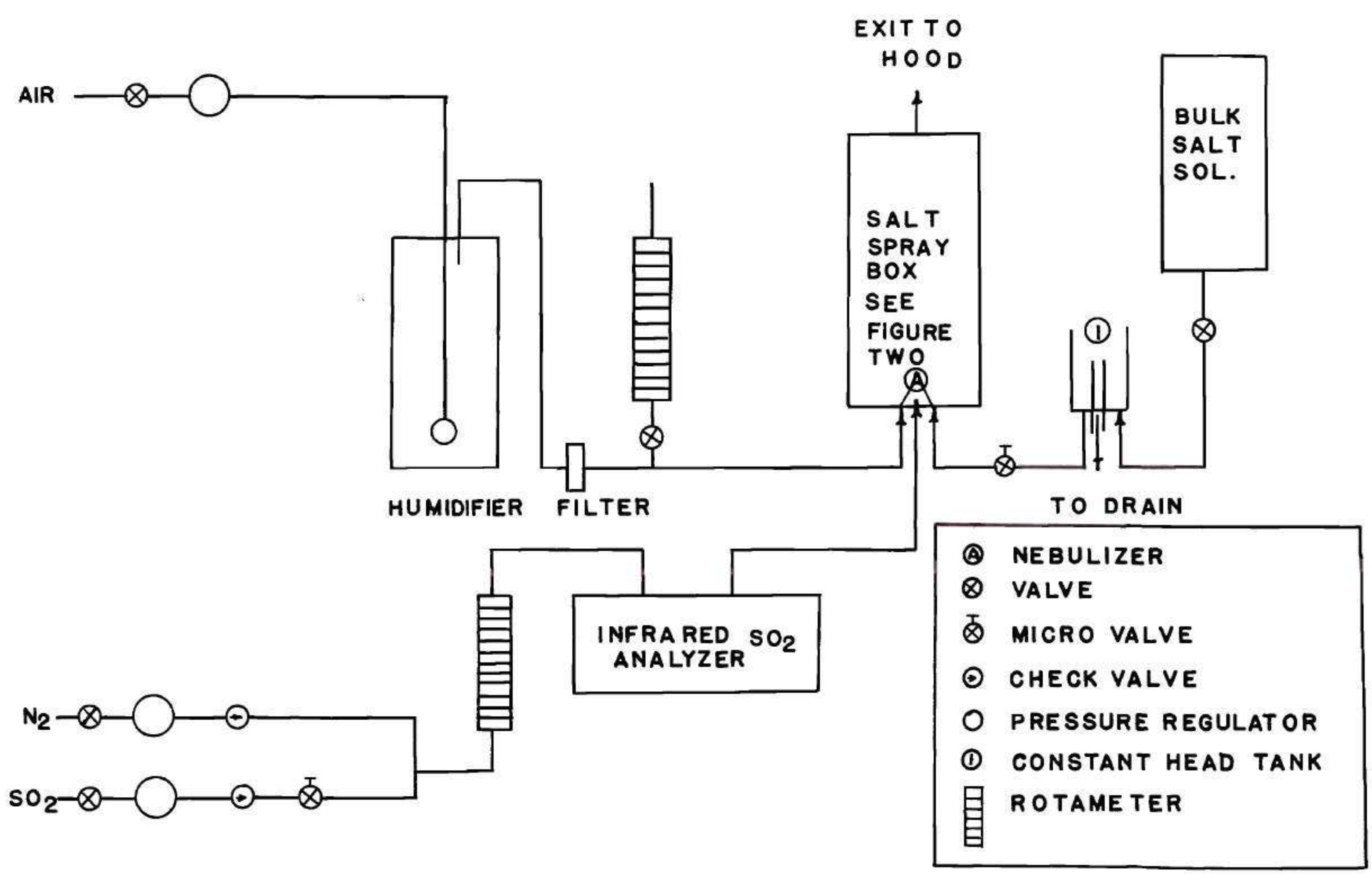

Figure 1. Schematic of Apparatus

non-corrosive material with respect to the environment being tested is of major importance. In this investigation 3/8-inch plexiglass was chosen both for its transparency and corrosion resistance. The dimensions were as given in Figure 2. The top of the chamber was removable to allow access to the samples; it was sealed with a rubber gasket.

A baffle was installed directly in front of the aerosol generator. This was to prevent direct impaction of the aerosol with any of the samples. It also allowed for a more uniform aerosol size distribution in that it separated the larger particles from the air stream.

Exits in the bottom on both sides of the baffle allowed for removal of excess deposited aerosol, since this solution should not be allowed to come in contact with the bulk solution because it contains corrosion products. An additional exit on the end opposite from the aerosol generator was needed as a vent for the aerosol.

The aerosol generator should simulate the natural production of marine aerosols. MacIntyre (2) used a glass plate manifold placed into the bulk solution to simulate the bubble burst mechanism; but Glass (12) reported the use of such an apparatus required approximately eight hours to produce an effective amount of aerosol. Therefore another method should be chosen. The generator used in this investigation was a nebulizer. The passage of humid air through a nozzle reduces the pressure at the tip of a second nozzle. This allows the drawing of the bulk solution up into the second nozzle. Here the air tears the liquid simulating the natural production at the crest of a wave. The heavier particles impact against a bend in the neck of the nebulizer and are

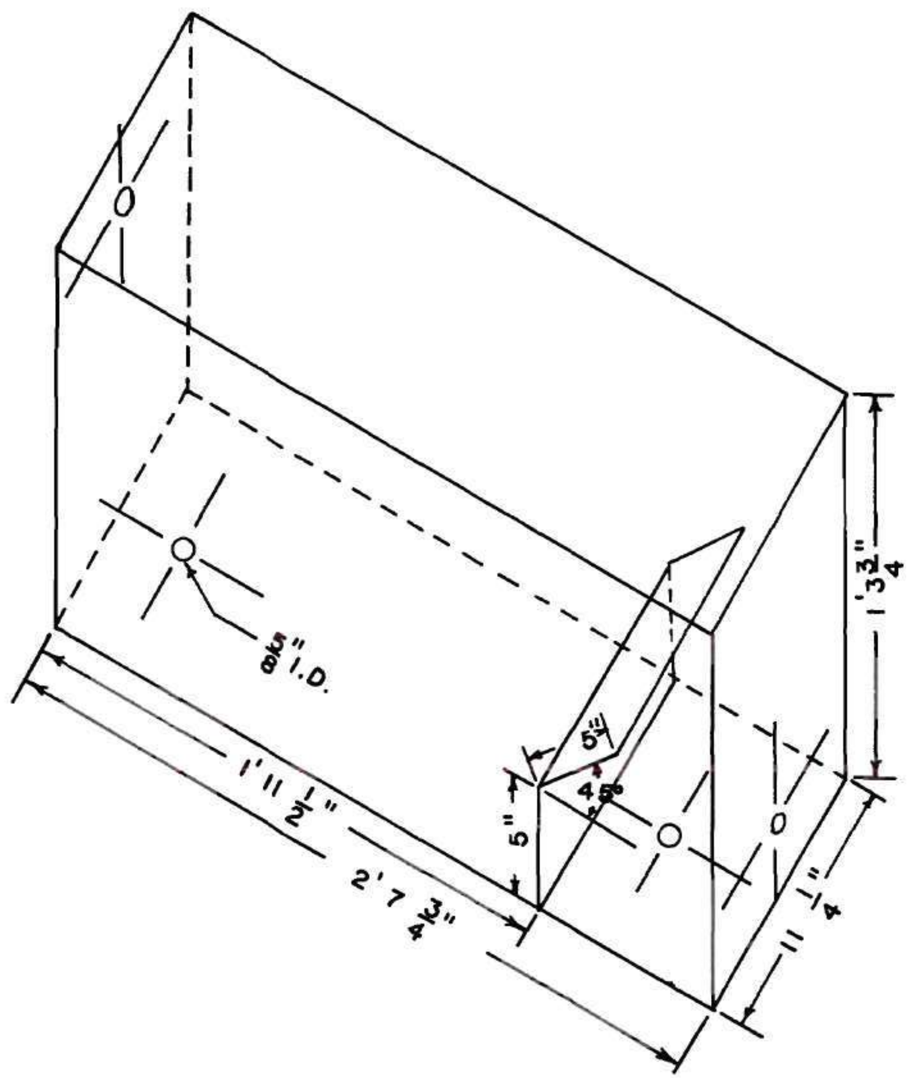

Figure 2. Isometric View of Salt Spray Box

removed from the aerosol stream.

Because of removal from the nebulizer reservoir and the return of the larger particles the concentration alters over a period of time; therefore, a supply of the initial concentration bulk solution is needed to maintain an equilibrium concentration. This was obtained by using a constant head reservoir attached to a number 22G hypodermic needle with a flattened tip. The needle was inserted through a rubber stopper in a port in the side of the nebulizer body.

The air supplied to the nebulizer was passed through a 47-mm diameter Millipore filter with an average 0.45μm pore size to prevent any particles entering the nebulizer and plugging the air nozzle. Air flow was controlled by a pressure regulator and control valve; the rate was measured by a Matheson rotameter, Number 604.

The prepared samples were placed on a rack to keep them free of the condensed aerosol on the floor of the box, and to ensure reproduceable placement of the samples for the different tests. The rack prevented contact of the exposed sample and any corrosive material. It also ensured free runoff of the aerosol deposit from the sample. The rack used in this investigation was constructed from plexiglass. Two pieces of 3/8-inch plexiglass were separated seven inches by 3/8-inch diameter plexiglass rods such that a sample would rest on three rods, two behind and one at the bottom, at a 30 degree angle with the horizontal.

For the condition requiring the presence of sulfur dioxide, an additional inlet to the box was provided. Sulfur dioxide and nitrogen were supplied from tanks and were regulated by means of pressure regulators and valves. Check valves were installed to prohibit the flow of one into the supply tank of the other. The flow of the mixture was measured with a rotameter. A Beckman Infrared Analyzer, Model 215A, was used to measure the sulfur dioxide concentration and a Coleman Hitachi strip chart recorder, Number 165, was used to monitor the analyzer's output.

An Anderson Non-viable Sampler, No. 21-000, was used to measure the aerosol size distribution. This device is an eight stage cascade impactor allowing an aerodynamic diameter distribution to be obtained.

The pH and potential measurements were performed using a TROPHY pH meter with a combination pH electrode. A Keithley Model 600B Electrometer, and a miniature silver-silver chloride electrode were used to measure the corrosion potential.

CHAPTER III

PROCEDURE

Sample Preparation

Samples of cold rolled carbon steel were cut from a 1/16-inch thick sheet to pieces 2.0 by 3.75-inches. The sample was then cleaned with acetone to remove oils from the surface. A protective coating was then applied to the back side and edges. The material used for this purpose in this investigation was Ellac, an enamel-type material produced by H. Struers Chemiske Labortorium. This left only one exposed side to the corrosive environment. For identification purposes, roman numerals were painted on the back side with enamel. The exposed surface was then roughly polished and washed with 3N hydrochloric acid to remove any previously acquired corrosion product and to give the surface a standardized starting point. The sample was then placed in a dessicator and allowed to dry prior its initial weighing.

A trial sample piece of the metal was prepared as above to determine the weight loss of the metal itself during cleaning. It was found to be small in comparison to the weight lost by other cleaning methods, such as mechanical, and to the observed weight loss measurements obtained, subsequently.

In the final test series, various metals were examined under the conditions of the first test. These metals were nickel, type 304L stainless steel, type 384 stainless steel, cold rolled carbon steel, 60/40 brass, 5052 aluminum, 5005 anodized aluminum, and HRA copper. These samples were also cleaned as above except for the aluminum. Aluminum, being soluble in hydrochloric acid, was washed with 3N nitric acid instead.

Bulk Solution Preparation

It has been reported by Uhlig (8) that a saline solution concentration between 3 and 20% yields approximately the same corrosion results at constant temperature. For all tests a basic 10%, by weight, saline solution was prepared. Using a density of 0.998 g/cc for distilled, deionized water at room temperature, 20°C, and a specific gravity of 1.0726 for a 10% saline solution, 10,705g of reagent grade sodium chloride per 10ℓ of solution was required. After the preparation of the solution a freezing point depression test indicated a concentration of 11.5%.

For the second set of conditions, a surfactant was added to the solution for the purpose of retarding oxygen adsorption. The surfactant used in this investigation was dodecylsodiumsulfate ($CH_3(CH_2)_{10}CH_2NaSO_3$), having a molecular weight of 272.42g. An amount of 0.38184g was added to 14ℓ of saline solution yielding a 10^{-4} molar concentration.

Experimental Procedure

After a steady aerosol flow was established in the chamber the prepared samples were weighed and placed on the rack. They were arranged with an inch separation between samples and between the outer samples and the walls of the rack.

The rack was then placed in the salt spray chamber and the test was begun. The samples were removed after exposure of 6, 12, 24, 48, 96, and 192 hours. They were immediately placed in a dessicator and allowed to dry for 24 hours. Weight gain measurements were then taken.

The samples were next placed in a bath of 3N hydrochloric acid (3N nitric acid for the aluminum) for three minutes to clean the corrosion products from them. Each sample was then washed with deionized water to remove excess acid, and then washed with technical-grade methyl alcohol to remove the water. Each sample was then weighed.

The air entering the nebulizer had a relative humidity of 100% after passing through the humidifier. It was supplied to the humidifier at 14 psig and regulated to 23.6 SCFH at 70°F and 14.7 psia on the rotameter (10 cm reading with the stainless steel ball) before entering the nebulizer. This reading was taken in parallel with the nebulizer, but when the rotameter was in the circuit it was assumed that the resistance to flow through the nebulizer was high enough to divert all flow through the rotameter.

The nitrogen - sulfur dioxide mixture entering the chamber was dry so it could be analyzed using infrared absorption. The flow rate of this mixture was measured, using a Fisher-Porter rotameter number FP 1/4-20-P-3/37, at 2 SCFH. The sulfur dioxide concentration was measured at 650 $\pm$ 50 ppm, using the Beckman Infrared Analyzer.

Particle Size Analysis

In an attempt to determine the particle size actually depositing on the samples, a particle size analysis was performed on both the bulk solution and the bulk solution plus surfactant. An eight stage cascade impactor with a range of 11.0- to 0.43-μm aerodynamic diameter was used in this investigation. The impactor plates are calibrated such that the diameter of particle given for that plate is a 50% impaction efficiency diameter at a flow rate of 1.0 CFM. The aerodynamic diameter is the diameter of a sphere of unit density with a settling velocity equal to that of the particle in question. The 1.0 CFM flow rate was obtained using a vacuum pump calibrated with a wet test flow meter.

Potential and pH Measurements

To estimate the acidity of the aerosol in the presence of sulfur dioxide, bulk saline solution was saturated with sulfur dioxide, and the pH determined using a calibrated pH meter and a combination pH electrode.

Drops of both the neutral and the acidified solution were placed on a clean iron sample and the corrosion potentials were measured using a reference electrode and an eletrometer. The potential of the miniature silver-silver chloride electrode was measured with respect to a standard calomel electrode and found to be +0.003 volts. Considering the potential of +0.242 volts for the saturated calomel electrode vs. a standard hydrogen electrode, the measured potentials were adjusted by adding +0.245 to obtain values on the hydrogen scale.

CHAPTER IV

PRESENTATION OF RESULTS

Four different conditions were considered during this investigation. They were: (A) cold-rolled, carbon steel exposed to an aerosol produced from an 11.5% saline bulk solution, (B) the same as (A) with a 10^{-4} molar addition of a surfactant, (C) the same as (A) with sulfur dioxide added at the rate of 650 ppm, and (D) eight different metals exposed to the environmental conditions in (A). The average results of these examinations are presented in Figure 3, 4, 5, and 6, respectively.

Condition (A) was designed as a control for this investigation. The initial stages of this condition yielded evidence of very localized corrosion, i.e. pitting. An initial corrosion rate of 1.64μg/hr. was obtained under these conditions. After 96 hours exposure, however, the rate was no longer linear (Figure 3). At this time the corrosion visible to the eye showed a large area of coverage. When measuring the weight gained on this sample, it was noticed that the sample was hygroscopic. On the last sample taken in this series the corrosion products showed what appeared to be large scale-type formation.

The second set of conditions yielded a very similar set of results to those of the first (Figure 4). The observations pertaining to hygroscopy and form of the corrosion and corrosion products are also the same. One noticeable difference between the two was in the initial corrosion rate, this being 1.64μg/hr. and 1.275μg/hr. for the conditions

(A) and (B), respectively. Another difference is that in condition (B) the corrosion rate was linear over 200 hrs.

A major departure from the above results occured when sulfur dioxide was introduced into the system. By the time the incoming sulfur dioxide and the air producing the aerosol were mixed the concentration of sulfur dioxide dropped, but was still above the range commonly found in an industrial environment; it was approximately 50 ± 5 ppm based on the dilution ratio.

As shown in Figure 5 there was a rapid period of corrosion followed by a slower corrosion rate after 16 hrs. In the first period this rate was $10.0 \mu g/hr.$, while in the second it was $0.75 \mu g/hr.$

A noticeable discoloration of the samples occured as early as in less than one hour. The exposed surface began to turn brown at this time. The localized pitting observed with the 6 hr. samples in the previous two conditions was not present here; instead the surface gave evidence of a green film-type corrosion product. With the 192 hr. sample the pitting had still not appeared. Instead more uniform corrosion was present.

In the last series of tests various metals were compared during exposure to the environment in condition (A). These results are presented in Figure 6. A time of 96 hrs. was chosen because this was the midpoint of the scale used above. The order of corrosion resistance observed was as follows, from best to worse: anodized aluminum, nickel, type 384 stainless steel, aluminum, type 304L stainless steel, copper, brass, and cold rolled steel. Actual data points obtained from this investigation are presented in Table 1 in the Appendix.

The size distribution of the aerosol depositing on the samples was also obtained. The aerodynamic diameters were obtained from the calibration charts supplied with the impactor. The distribution for the bulk solution was a geometric mean diameter (D_g) of 1.20μm and a geometric standard deviation (σ_g) of 1.83 on the dried aerosol. D_g was obtained from Figure 7 at the 50% point, while σ_g is the diameter at the 84.13 percentile divided by that at the 50.0 percentile. The actual data points are presented in Table 2 in the Appendix.

A distribution was also obtained for the aerosol produced from the bulk solution containing the surfactant. These results may be seen in Figure 8 and Table 3 in the Appendix. The geometric mean diameter was 1.28μm and the geometric standard deviation was found to be 1.74 on the dry aerosol.

An aerosol concentration of approximately $3 \times 10^5 \mu g/m^3$ was found from total weight of aerosol deposited, flow rate, and time of deposition in the impactor.

The pH of the bulk solution in condition (A) was found to be 7.1. It was assumed that the pH in condition (B) was the same as in (A). In condition (C), the pH was found to be 0.9.

The corrosion potentials in conditions (A) and (C) were -0.335 and -0.285 volts (SHE), respectively.

CHAPTER V

DISCUSSION OF RESULTS

Uhlig (8) has reported that the oxygen replenishment under conditions similar to those of the first set of conditions of this investigation is the determining factor for the corrosion rate. This can be understood by examining the corrosion reactions. Generally, dissolution is, in the simplest case, an anodic reaction of the type:

$$Me \rightarrow Me^{z+} + ze^{-}, \tag{1}$$

where z is the valency. The electrons are transferred via the metal to cathodic sites and consumed in a cathodic reaction. In the presence of oxygen, as in these tests, the dominant cathodic reaction will be the reduction of dissolved oxygen:

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}. \tag{2}$$

For corrosion of iron in aqueous environments, the potential pH diagram (13) indicates that at neutral pH and in the presence of oxygen the iron surface will be covered with a layer of an oxide or hydroxide, which provides some protection to the metal. However, in the presence of chloride ions in the solution the protective layer is disturbed and localized corrosion in the form of pitting occurs.

This above situation apparently existed in the first series of tests in which pitting was observed on the samples. The time of exposure was the only variable studied in this series. As would be expected, the weight lost by a sample increased with time.

The observed decrease in the corrosion rate shown as a change of slope of the curve in Figure 3 can be explained by a buildup of corrosion products, which hinder the reactions.

In the second set of conditions, where the surfactant dodecylsodium sulfate was added to the bulk saline solution, slight variations from the results of condition (A) were observed. The first, and most significant, was the reduction of the corrosion rate from 1.64 to 1.275 μg/hr.

A possible explanation for this decrease is the reduction of oxygen available for the cathodic reaction. This reduction is a result of the surfactant inhibiting the adsorption of oxygen onto the aerosol droplet. With the surface occupied by the surfactant there exists an added resistance thereby reducing the amount of adsorbed oxygen.

The lack of deviation from the straight line in Figure 4, as compared to Figure 3, indicates the lack of a sufficient corrosion product layer. This may be due to a lower corrosion rate in condition (B).

In condition (C), the initial bulk solution with sulfur dioxide present, a most apparent deviation has taken place from condition (A).

The initial corrosion rate of 10μg/hr. is considerably higher than under conditions (A), 1.64, and (B), 1.275μg/hr., and the decrease in the rate occurs earlier.

Adsorption of sulfur dioxide onto a growing droplet of deionized water was studied by Giardina (14). Adsorption was dependent on the exposed surface area of the droplet. The adsorption of sulfur dioxide reduces the pH of the aerosol; in the tests performed in this investigation the acidity of the droplets of the solution saturated with sulfur dioxide was about pH 1. At the same time, the corrosion potential of iron in contact with the film was found to be -0.285 volts (SHE), as compared to -0.335 volts for the neutral condition. According to the potential pH diagram, the iron-water system under these conditions is in the region of corrosion, and the protective corrosion products (oxides and hydroxides) dissolve. In addition, another cathodic reaction can take place:

$$H^{+} + e^{-} \rightarrow \tfrac{1}{2}H_{2}. \tag{3}$$

This results in a higher corrosion rate, as observed in Figure 5. The reduction in the corrosion rate after approximately 20 hrs. seems to be caused by formation of a different type of a corrosion product (dark green color); this was not identified.

Corrosion under acidic conditions is more uniform because pitting as a result of the breakdown of a passive film does not take place. This explains the absence of pitting observed in the previous conditions, despite the localized contact in the early stages of exposure.

In condition (D), the exposure of different metals to that of condition (A) was performed to yield a comparison of corrosion resistance. All eight metals are frequently found in industrial marine environments. Examples of this would be ships in port, buildings, and industrial sites. As stated in the previous chapter the order found for the resistance to corrosion was: (1) anodized aluminum, (2) nickel, (3) type

384 stainless steel, (4) aluminum, (5) type 304L stainless steel, (6) copper, (7) brass, and (8) cold rolled carbon steel. The order may be different in an acidic environment.

Visual observations provided some confirmation of the results. Corrosion products were observed on the samples in the reverse order mentioned above (see Table 1). A discoloration of the brass was also observed upon removal of the corrosion product. The final color of this sample was very similar to that of copper. This supports the hypothesis that dezincification occurs in copper-zinc systems in corrosive environments.

The effect of the aerosol size distribution was not investigated. As reported in the previous chapter, size analyses were performed on the two different bulk solutions. Although the D_g for the bulk solution plus surfactant is slightly larger than for the bulk solution alone, it is believed that, within experimental errors, these two analyses may be assumed identical for purposes of this investigation.

CHAPTER VI

CONCLUSIONS

The conclusions obtained from this investigation are summarized as follows:

1) The presence of a surfactant on a wet NaCl aerosol reduces the rate of iron corrosion from the case where no surfactant is present.

2) The presence of sulfur dioxide in the environment in conjunction with marine aerosols greatly enhances the corrosion rate.

3) The resistance to corrosion in a marine-industrial environment has been shown to be in the following order: anodized aluminum, nickel, type 384 stainless steel, aluminum, type 304L stainless steel, copper, brass, and carbon steel, the first being the most resistant.

CHAPTER VII

RECOMMENDATIONS

1. It is recommended that additional studies be performed with other gases such as ammonia, the oxides of nitrogen, and carbon monoxide.

2. A further study utilizing different nitrogen-oxygen mixtures should be undertaken to shed more light on the effect of oxygen adsorption by the aerosol.

3. A study using a different exposure cycle should be undertaken. Where this study utilized a continuous exposure to the environment, a cycle of wet and dry periods should be examined also.

4. A more detailed study of the various industrial metals under a wider range of environmental conditions should be undertaken.

APPENDICES

Table 1. Results of Experimentation

A. Carbon Steel 11.5% NaCl Bulk Solution

Time (Hrs.)	Weight Gained[1] (Gms.)	Weight Lost[2] (Gms.)	Comments
6	0.01684 0.02232	0.01382 0.01320	Localized Pitting
12	0.04622 0.04765	0.02514 0.01760	
24	0.08703 0.07680	0.05616 0.03884	
48	0.12477 0.14905	0.07353 0.07958	Corrosion Products Hygroscopic
96	0.24444 0.23340	0.14634 0.14761	
192	0.33656 0.33543	0.25283 0.24956	Scale Formation

B. Carbon Steel 11.5% NaCl+10^{-4}M $CH_3(CH_2)_{11}NaSO_3$

Time (Hrs.)	Weight Gained (Gms.)	Weight Lost (Gms.)	Comments
6	0.02417 0.03546	0.00966 0.00588	
12	0.05015 0.06346	0.01572 0.02026	
24	0.09340 0.07448	0.04013 0.03338	
48	0.12882 0.11459	0.07174 0.05943	
96	0.22142 0.20368	0.14367 0.11049	
192	0.32336 0.40840	0.24496 0.22810	

Table 1. (continued)

C. Carbon Steel 11.5% NaCl 650ppm SO_2

Time (Hrs.)	Weight Gained (Gms.)	Weight Lost (Gms.)	Comments
6	0.05008 0.07169	0.05466 0.06482	Corrosion Products Green in Color no Pitting
12	0.09450 0.12411	0.09533 0.09864	
24	0.14168 0.21570	0.11858 0.13983	
48	0.21652 0.34565	0.13161 0.18010	
96	0.19213 0.50413	0.16597 0.23759	Pitting still not present to the eye
192	0.20985 0.61498	0.20176 0.33316	Areas showing signs of corrosion are slower in removal of corrosion products

D. Ninety-six Hours 11.5% NaCl

Metal			
Nickel	0.01407 0.01042	0.00207 0.00000	Corrosion Product "Rust" Colored
304L Stainless	0.01132 0.01214	0.00581 0.00659	Corrosion 35 Hrs.
384 Stainless	0.01229 0.01806	0.00026 0.00216	Corrosion 35 Hrs.
Cold-Rolled	0.22519	0.14037	Corrosion Products Corrosion 5 Hrs.
C-Steel	0.22809	0.12960	Hygroscopic Pitting

Table 1. (continued)

Metal	Weight Gained (Gms.)	Weight Lost (Gms.)	Comments
60-40 Brass	0.11597 0.12545	0.06242 0.06143	Corrosion Products Hygroscopic, Color Change After Removal of Corrosion Products Approximately that of Copper, Pitting
5052 Aluminum	0.07350 0.07345	0.00436 0.00662	Pitting
5005 Anodized Aluminum	0.02120 0.02603	0.00000 0.00000	
HRA Copper	0.01771 0.02148	0.02023 0.03551	Pitting Corrosion 21 Hrs.

[1]Before the removal of corrosion products.

[2]After the removal of corrosion products.

Table 2. Aerosol Size Distribution of Bulk Solution

Impactor Plate Number	Average Net Weight (mg)	Percent	Cumulative Percent	Aerodynamic Diameter (μm)
1	0.35	0.81	100.00	11.00
2	0.31	0.72	99.19	7.00
3	1.34	3.11	98.47	4.70
4	6.58	15.29	95.36	3.30
5	12.77	29.68	80.07	2.10
6	15.79	36.70	50.39	1.10
7	4.06	9.44	13.69	0.65
8	1.18	4.25	4.25	0.43

Geometric Standard Deviation (σ_g) = 1.83

Geometric Mean Diameter (D_g) = 1.2μm

Table 3. Aerosol Size Distribution

Of Bulk Solution and Surfactant

Impactor Plate Number	Average Net Weight (mg)	Percent	Cumulative Percent	Aerodynamic Diameter (μm)
1	0.16	0.36	100.00	11.00
2	0.09	0.20	99.64	7.00
3	1.75	3.89	99.44	4.70
4	8.49	18.88	95.55	3.30
5	14.15	31.47	76.67	2.10
6	15.44	34.34	45.20	1.10
7	3.71	8.26	10.86	0.65
8	1.17	2.60	2.60	0.43

Geometric Standard Deviation (σ_g) = 1.74

Geometric Mean Diameter (D_g) = 1.28μg

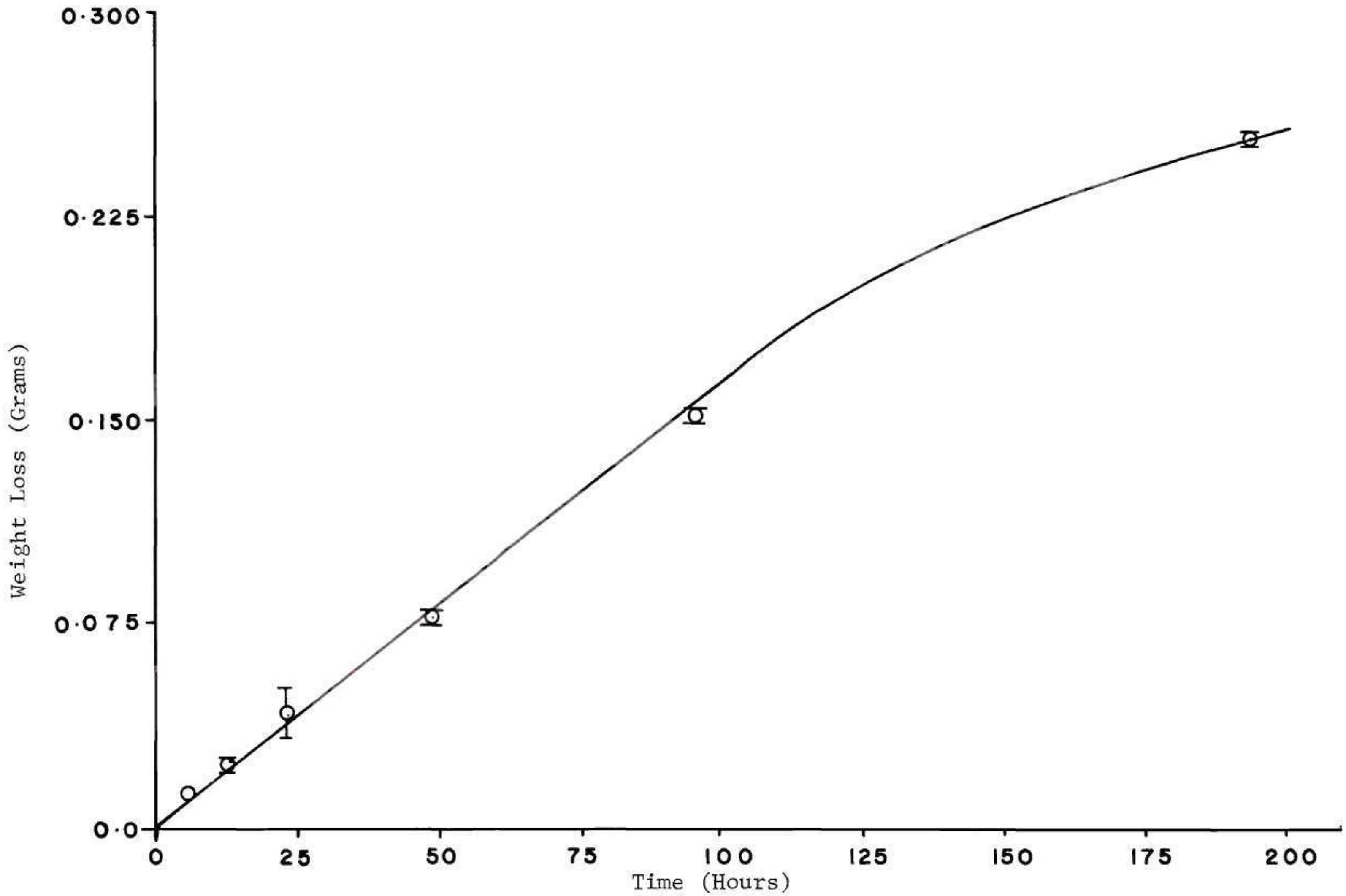

Figure 3. Weight Loss vs. Time

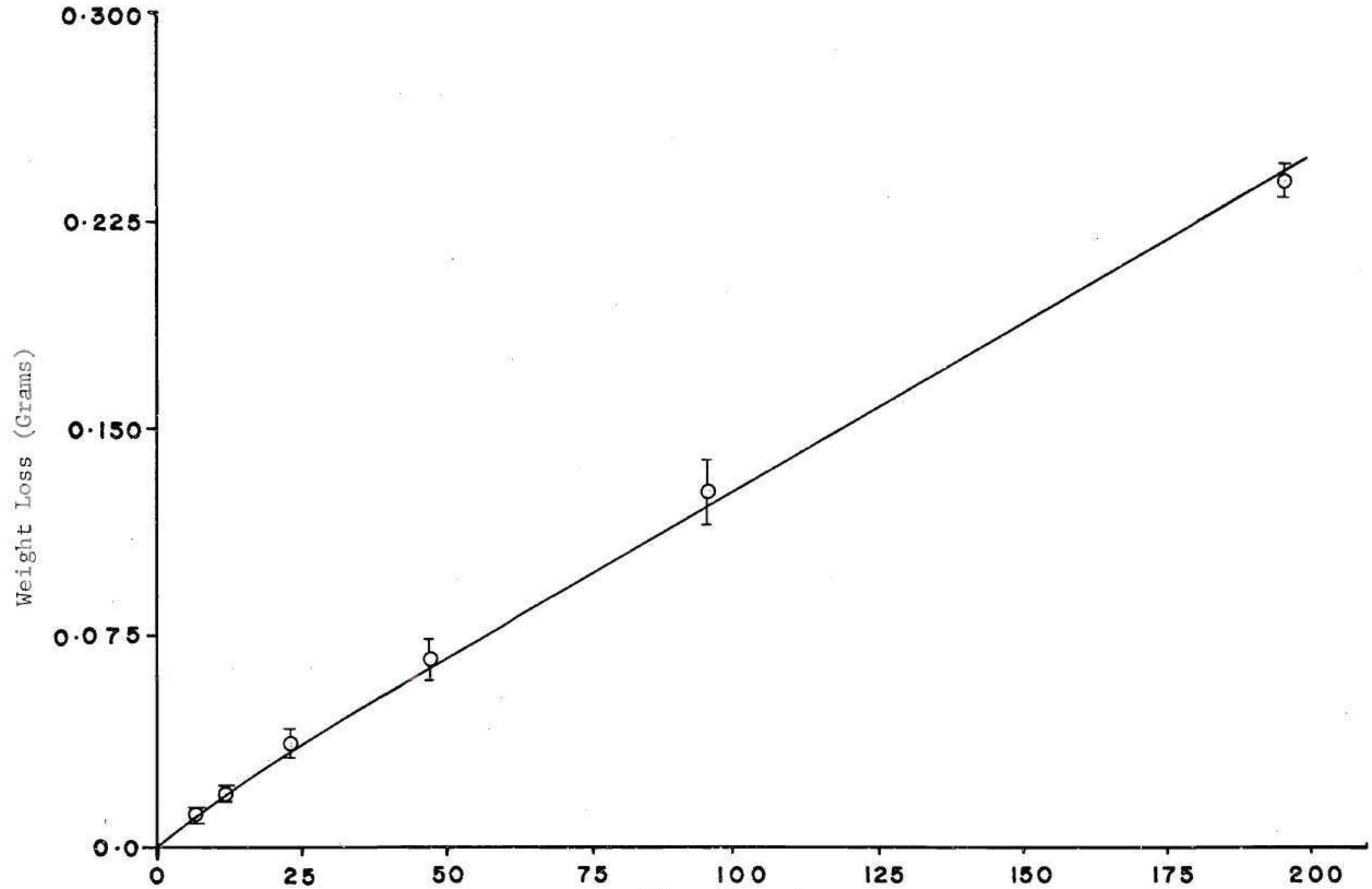

Figure 4. Weight Loss vs. Time with Surfactant

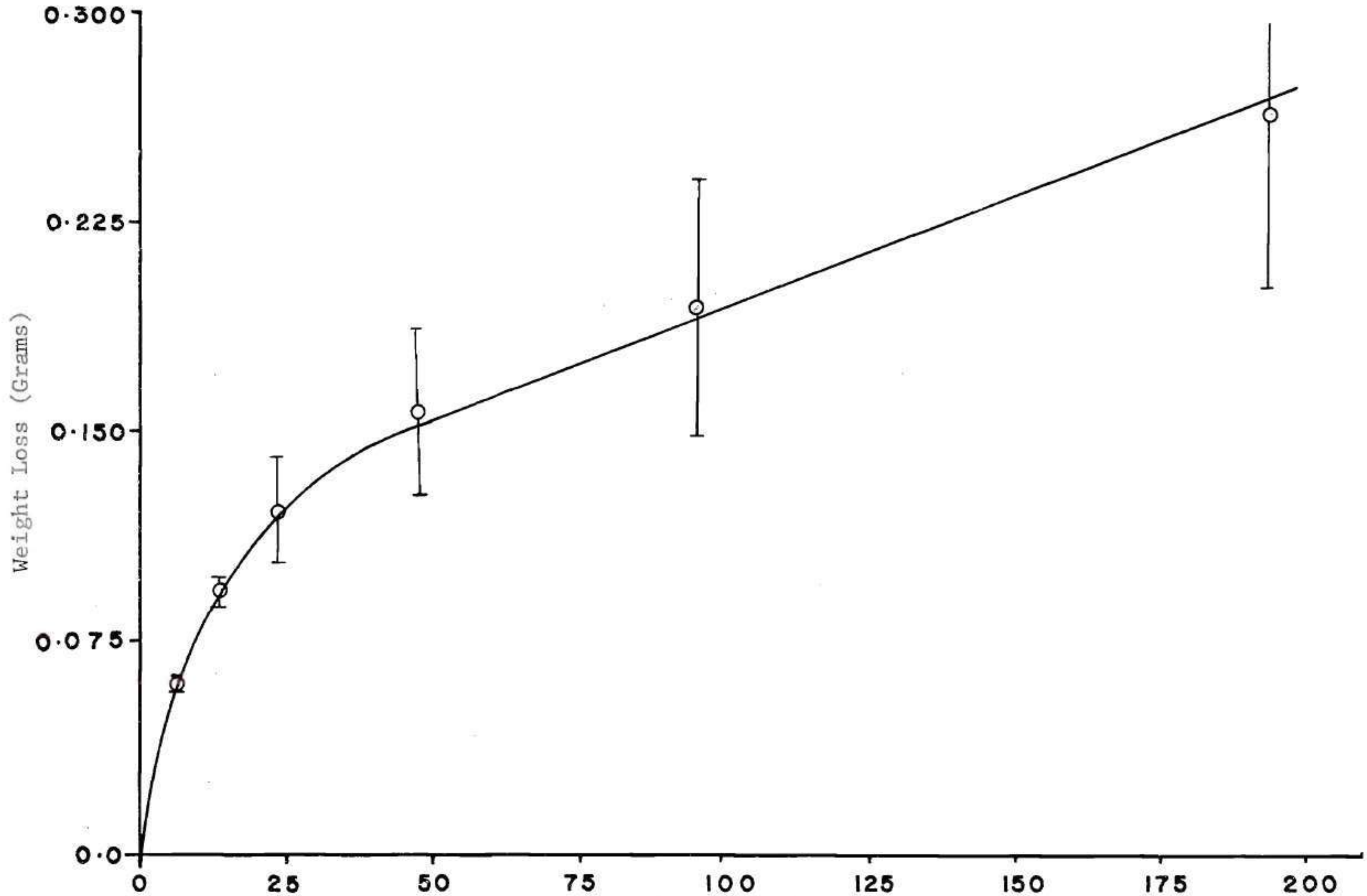

Figure 5. Weight Loss vs. Time with Sulfur Dioxide

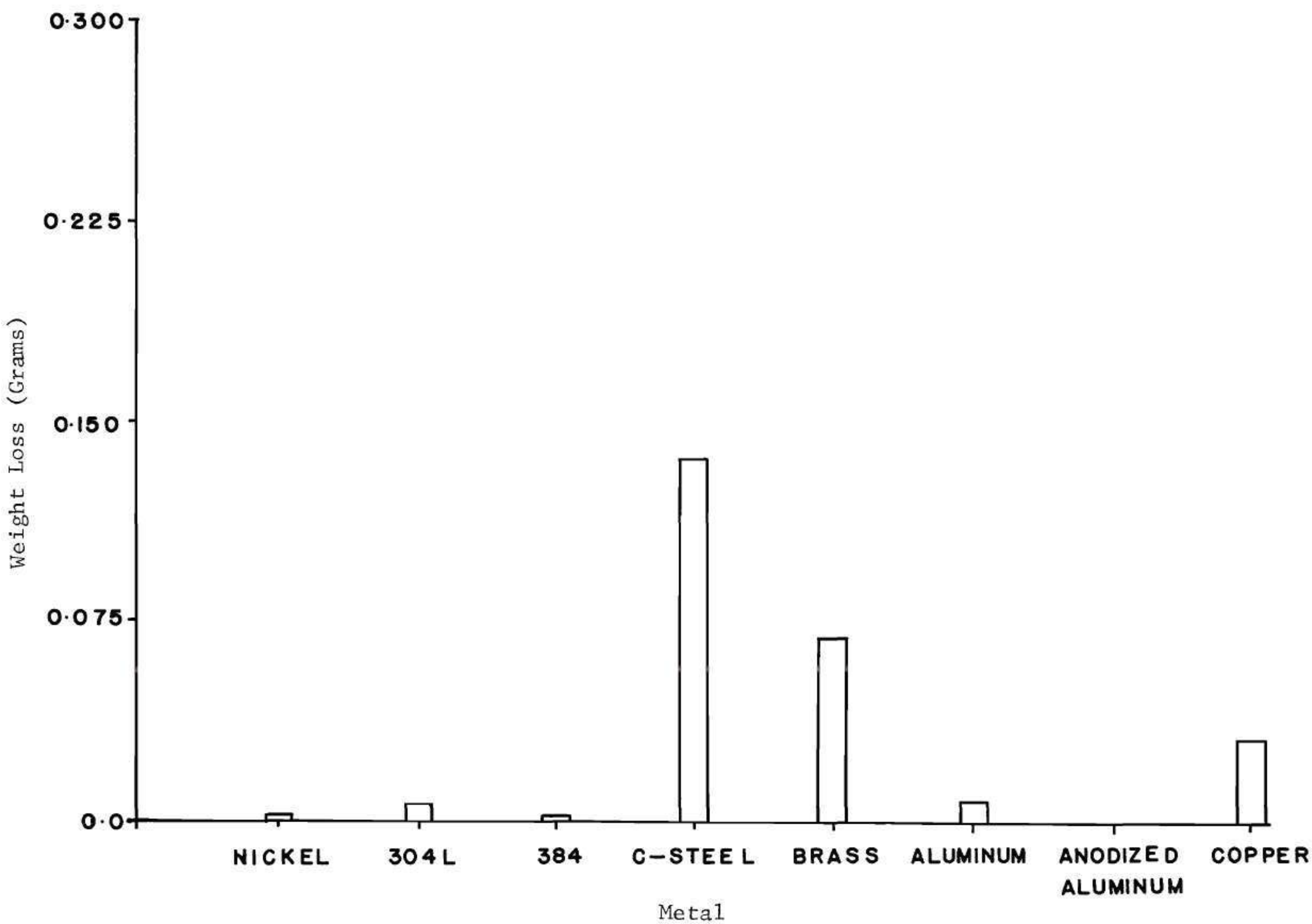

Figure 6. Corrosion at 96 Hours

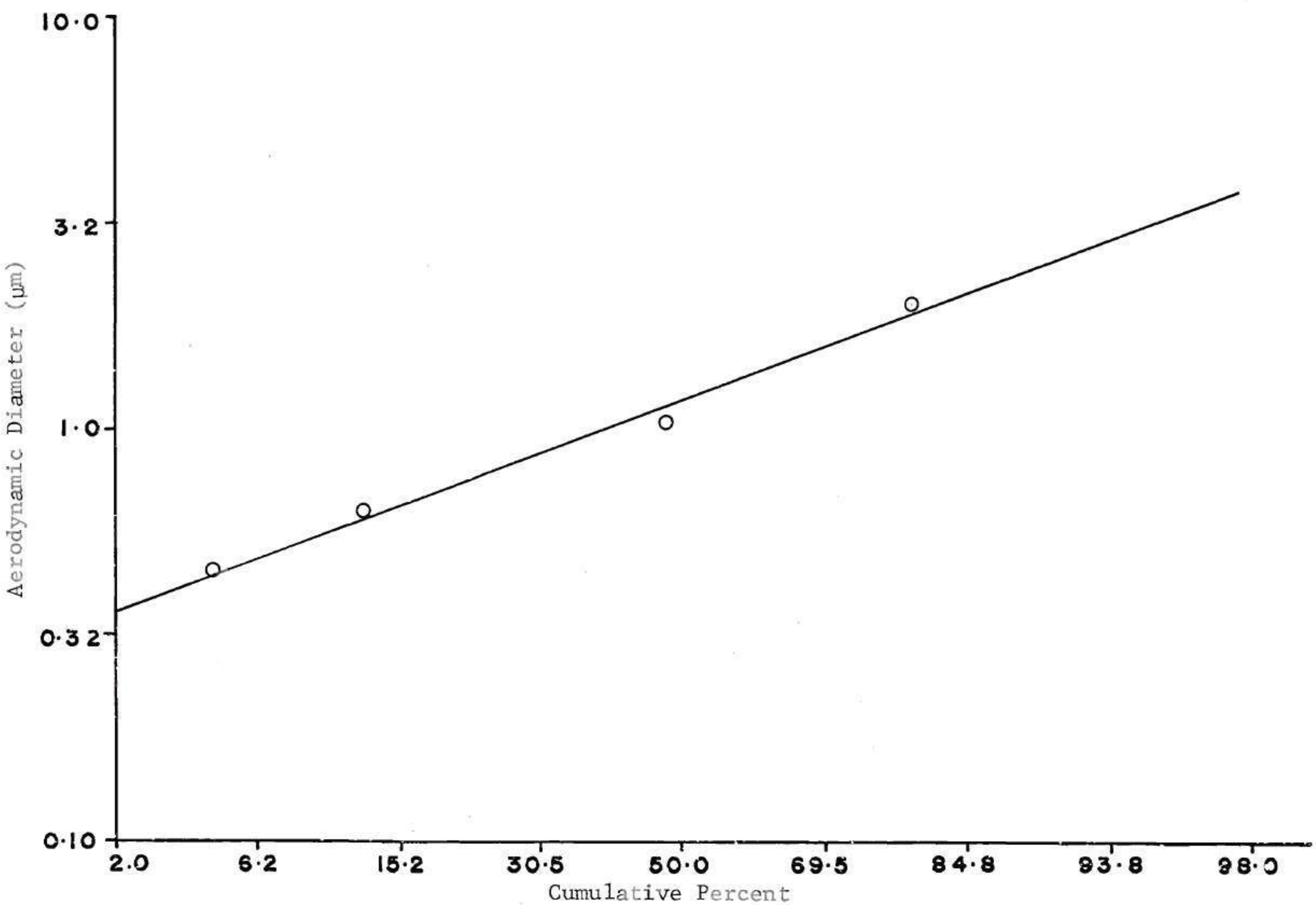

Figure 7. Particle Size Distribution with Surfactant

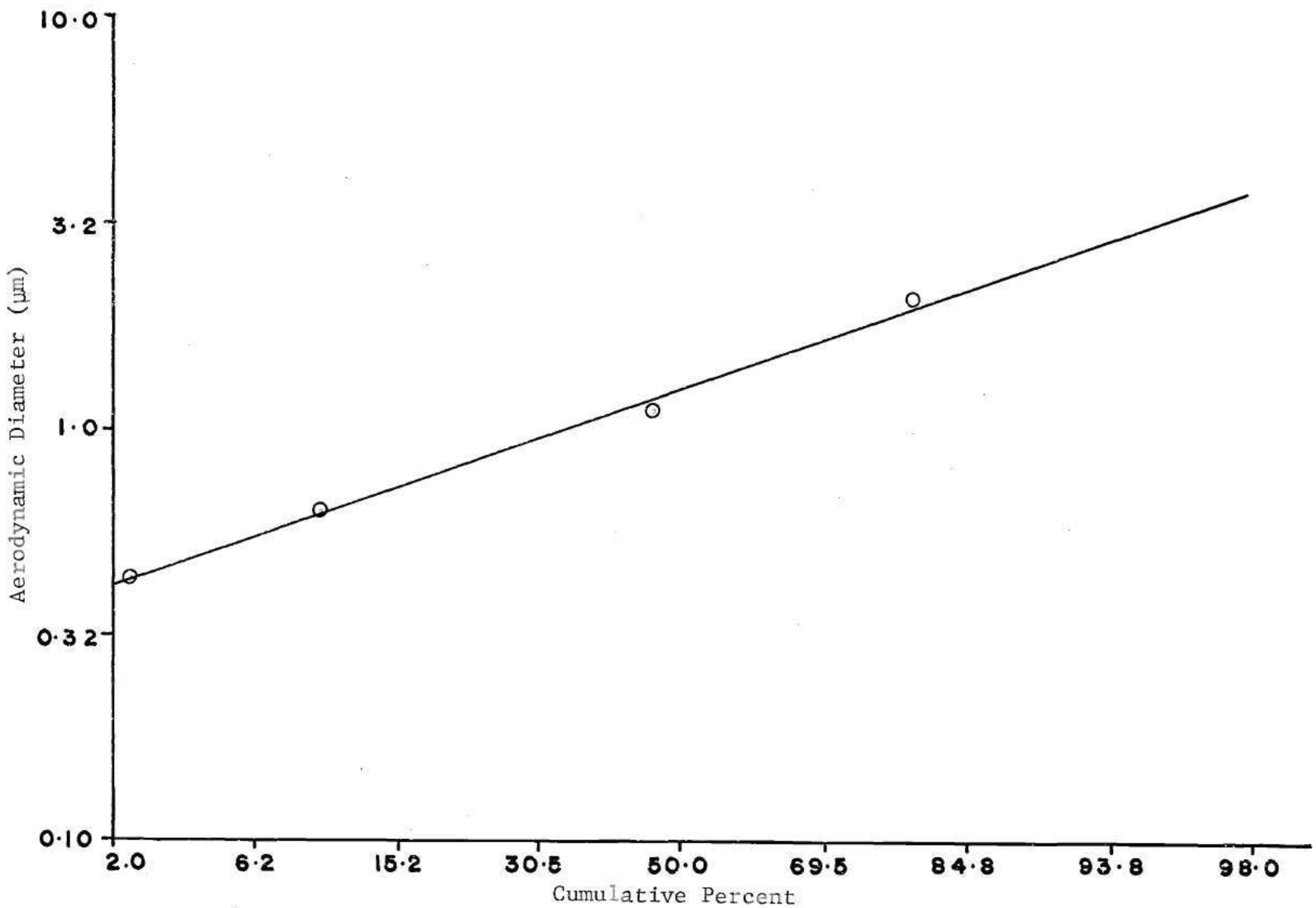

Figure 8. Particle Size Distribution with Surfactant

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