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A Laboratory Simulation of the Galvanic Corrosion of a Ship Hull Plate by Shaft Grounding Systems

by

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ABSTRACT

The use of modern impressed current cathodic protection and shaft grounding systems have substantially reduced the corrosion of the underwater hull and propellers of HMC Ships. However, there have been circumstances in which the shaft grounding system has been left on while the cathodic protection system has been turned off. This has led to increased corrosion of the hull plate, both because of the inherent difference in potential between the steel hull and bronze propellers and because of the differences in the rates of delivery of oxygen to these surfaces. A laboratory simulation has been developed in an effort to determine the extent of galvanic corrosion that occurs under these circumstances.

The effects of different relative velocities of impinging natural sea water on the galvanic corrosion of hull steel (350WT) coupled to a bronze propeller were quantified with a zero resistance ammeter data acquisition system. The effects of relative surface area and different propeller materials were also measured. The results were extrapolated to estimate the length of time the cathodic protection system could be shut off before hull perforation could occur.



INTRODUCTION

Metal corrosion or oxidation is a natural phenomenon, as illustrated by the fact that ores are the most common source of metals. The abundance of ores indicates that these metals are more stable as cations than in their elemental state. Since the natural tendency of anything is to spontaneously move to a lower energy state, there is an intrinsic (or inherent) driving force for metals to corrode. This is an unfortunate situation for the Navy.

Metals and alloys exhibit varying physical, chemical, and mechanical properties. When constructing ships, we take advantage of this by utilizing materials which are well-suited to a particular purpose.

For example, when choosing materials for propellers, high tensile strength and resistance to various forms of corrosion rank high in importance. In addition the material must be readily cast in heavy sections. To satisfy these criteria bronzes, such as nickel aluminum bronze, are usually employed.

Hull materials are chosen based mostly on cost, strength, and toughness properties with much less regard to corrosion-resistance. Steels, such as 350WT, which is a tough, weldable steel are used for this purpose.

The most important criteria when choosing heat exchanger materials are resistance to a number of types of corrosion (general, localized, selective), high thermal conductivity, and high ductility. Copper-nickel alloys, such as 70-30 or 90-10, are usually used for heat exchangers.

In order to construct our ships with the most appropriate materials, we encounter an unavoidable situation of having different alloys in contact with each other in seawater, which is a corrosive environment. Thus, in addition to the occurrence of inherent corrosion, we have the perfect setting for what is known as galvanic corrosion.

A definition of galvanic corrosion is corrosion which occurs as a result of dissimilar metals in contact in a corrosive solution. This is exactly what we have with hull steel and bronze propellers which are in contact via the shafts.

When the metals or alloys are not in contact with each other but are immersed in a corrosive solution, both will undergo inherent corrosion. However, when in a corrosive solution and in contact with each other, we observe different behaviour. As the metals or alloys are dissimilar, one will be more reactive (less noble) than the other. The more reactive of the couple acts as an anode, while the less reactive material behaves as a cathode. Current flows from the anode to the cathode.

In the hull/propeller case, the hull acts as an anode and the steel is oxidized to produce ferrous ions and electrons (see Figure 1). The current flows to the propellers where the major cathodic reaction is oxygen reduction, which consumes the electrons and produces hydroxide ions.

The galvanic couple causes the steel to suffer accelerated corrosion, while the bronze is protected by the preferential corrosion of the steel. The driving force of the galvanic corrosion is the potential difference and the rate determining step is usually O_2 reduction.

It is obvious that we are unable to avoid circumstances which lead to galvanic corrosion, so we must employ methods which eliminate or at least reduce the extent of corrosion. Several methods, including those known as cathodic protection methods, are used to accomplish just that.

The simplest is the use of sacrificial anodes. This involves electrically connecting a more reactive metal to the material to be protected. The more reactive species corrodes preferentially, resulting in cathodic protection.

Another method which is slightly more complicated is known as impressed current cathodic protection (ICCP). This is the method which is used on the frigates. Current from a DC source is supplied to the ship via the hull and serves to decrease the potential of the ship as a whole. The aim is to lower the potential of all components such that they have the same or similar potentials, thereby reducing the driving force for current flow. With all components being held at a more negative potential than their respective free corrosion potentials, all act as cathodes.

A very site-specific method is the shaft grounding system, which maintains an electrical connection between the shaft and the hull. The shaft grounding system consists of metal brushes firmly connected to the hull, which surround the shaft and maintain contact with it, even when the shaft is rotating. The current flows from the ICCP anode, through the hull, and out through the shaft back to the anode via the seawater (see Figure 2).

When properly maintained, these methods are highly effective in eliminating or least significantly diminishing galvanic corrosion, however, there are occasions when the cathodic protection must be turned off. If each time the cathodic protection is turned off care is taken to ensure that it is turned back on as soon as possible, there will not be a problem in the short term. Unfortunately there is always the chance that the requirement to turn the cathodic protection back on may be forgotten.

The aim of this project was to determine the time for hull perforation under the circumstances in which the cathodic protection has been turned off and the shaft grounding system is functioning well. If the cathodic protection system is off and the shaft is not grounded, then the circuit is not complete; there will be no galvanic corrosion due to hull/propeller coupling.

EXPERIMENTAL

In order to estimate the time for hull perforation, the rate of corrosion of hull steel must be determined. The true corrosion rate of the steel is a combination of the rate due to galvanic corrosion and that of inherent corrosion. Experimentally the galvanic and inherent corrosion rates must be determined independently, but the experimental setup is similar.

The metal specimens used in the experiments are thin 1"x8" plates. To simulate the hull, 350WT, the actual hull steel, was used, while the propellers were simulated using Al bronze alloy D, a typical propeller bronze.

Surface preparation of the bronze samples involved blasting, while the steel samples were surface ground to a 25 - 30 μin finish. Early experiments, in which the

steel samples were only blasted, resulted in an inconsistent surface area, as indicated by the data, so although this is how actual hull steel is treated, a more consistent finish was desired for these experiments. The specimens were then painted with an insulating paint such that only a nominal 1 in² (6.45 cm²) of metal was exposed to seawater.

The seawater is natural seawater, pumped directly from the Strait of Juan de Fuca, which is less than 40 m from the lab, and used on a once through basis. The temperature of the water varies from 7 - 13 °C throughout the year, and was approximately 9 °C during the experiments discussed today.

The intake of the pump system is shown in Figure 3; there are two pumps, each with its own basket filter used to exclude large particles. Once in the lab, the water is filtered again through a 30 mesh filter to remove smaller particles. The intake is nowhere near any sewage or freshwater outlets, thus the seawater used for these experiments is very representative of natural open seawater.

Figure 4 shows the experimental setup. The manifold has 6 lines, each with its own pressure regulating valve, and calibrated pinch clamp. The velocity of seawater travelling through each line can be adjusted independently. One experiment requires two lines, one for the steel and one for the bronze, so this manifold can handle three experiments running simultaneously. Since the experimental conditions, such as T and [O₂], vary with time it is important to be able to run several at the same time in order to be able to compare the data.

A close-up of the samples immersed in the seawater tank is shown in Figure 5. Each water line ends with a small glass tube which fits into the sample holder such that the water is impinging on the sample from the same distance for each one.

The water velocities chosen for impinging on the samples were based on information obtained from crew on one of the frigates. The low end of slow cruising speed is 10 knots, with the shaft rotating at a frequency of 63 rpm. This translates roughly to a ship velocity of 17 ft/s (5.2 m/s), and a maximum velocity of 50 ft/s (15.2 m/s) at the tip of the propeller blade. Most of the hull would not experience direct impingement at 17 ft/s, nor would the entire propeller blade experience 50 ft/s. Moreover, there were limitations to the maximum velocity obtainable in the lab, so a velocity of 5 ft/s (1.5 m/s) was chosen as the slow ship velocity, and 20 ft/s (6.1 m/s) was chosen as the fast propeller velocity.

DATA & CALCULATIONS

Galvanic Corrosion Rate

For determining the galvanic corrosion rate, the steel and bronze specimens were electrically connected through a zero-resistance ammeter (ZRA, see Figure 6), which determines the current flow without altering the current. The ZRA is connected to a computer which initiates data acquisition at preset time intervals, and stores the current-time data. The ZRA is capable of acquiring current-time data for several experiments running simultaneously. In addition, the ZRA also measures the potential between each specimen and its own SSC electrode.

Figure 7 shows a typical current-time plot. The data were acquired every 30 min for ca. 1 week. The current increases to a maximum and then remains at ca. the same value. The oscillations reflect how the oxygen concentration fluctuates with demand by biological activity. The average current is obtained by averaging the data from where the current appears to have reached a maximum to the end of the experiment. For this experiment shown the average current was determined to be 2815 μA .

In order to calculate the galvanic corrosion rate, the following equation (derived from Faraday's Law) is used:

$$\frac{W}{t} = \frac{I(EW)}{F} \quad 1$$

where W is mass lost (g), t is time (s), I is current (A), EW is equivalent weight of the material (g/mol e⁻), and F is Faraday's constant (96487 C/mol e⁻). The average current determined in the ZRA experiment used for I , EW of iron used for EW , since 350WT is more than 98.5% Fe.

Thus for an average current of 2815 μA , the corrosion rate was calculated to be 8.147×10^{-7} g/s per 6.45 cm^2 bronze. The surface area of the bronze is critical to the overall corrosion rate for galvanic corrosion. When the steel is coupled to two propellers (each with a surface area of 9.5 m^2 or 95000 cm^2), the corrosion rate is calculated to be 2.400×10^{-2} g/s. Converting to volume per unit time, using the density of steel ($d = 7.8 \text{ g/cm}^3$) yields a corrosion rate of $3.077 \times 10^{-3} \text{ cm}^3/\text{s}$. The calculation may be halted at this point since we can combine the galvanic corrosion rate with the inherent corrosion rate, which will be discussed next.

Inherent Corrosion Rate

A technique known as linear polarization was used to determine the inherent corrosion rate. The technique involves measuring the polarization resistance of the steel. The polarization resistance is the slope of a potential versus current plot. To obtain this type of data a potentiostat holds the potential of the sample at a range of values slightly removed from the free corrosion potential (within $\pm 20 \text{ mV}$). The potentiostat also measures the current at each of the potential values, and a potential-current plot can then be constructed.

The experiment was set up concurrently with ZRA experiments, so that the conditions would be the same, and the polarization resistance was measured periodically. The polarization resistance values were plotted versus time, and the average R_p was determined by averaging the data which had reached a stable value (see Figure 8). The average R_p was determined to be 67.9Ω .

The polarization resistance, R_p , is inversely proportional to the corrosion current, according to:

$$I_{\text{corr}} = \frac{B}{R_p} \quad 2$$

where: B is a constant (which depends on electrolyte, material, temperature, time, *etc.*), I_{corr} is the corrosion current, and R_p is the polarization resistance. Using a B value of 21.7 mV (corresponding to cathodic and anodic Tafel constants of 100 mV), the corrosion current was calculated to be 319.6 μA per 6.45 cm^2 of exposed steel (49.6 $\mu\text{A}/\text{cm}^2$ of exposed steel). Unlike the galvanic corrosion rate, which depends only on the propeller surface area, the inherent corrosion rate depends only on the surface area of exposed steel.

Using the loss rate equation (equation 1), the inherent corrosion rate was calculated to be 1.435×10^{-8} g/s per cm^2 exposed steel, or 1.840×10^{-9} cm^3/s per cm^2 exposed steel.

TIME TO PERFORATION CALCULATION

In order to calculate the time to perforation, the area of exposed steel must be known. The time to perforation was calculated for 1 m^2 to 20 m^2 , and the data presented in the form of a plot of time to perforation, in months, versus exposed steel area, in m^2 (see Figure 9).

The calculations were based on a hull thickness of 3/8" (0.9525 cm). For each exposed steel area, the inherent corrosion rate for a given area is the product of the area and the inherent rate per cm^2 exposed steel (calculated from the polarization resistance). The true corrosion rate is simply the sum of the inherent corrosion rate for a given area and the galvanic corrosion rate. To calculate the time to perforation, the volume (product of area and hull thickness) is simply divided by the rate of corrosion. The mass of steel lost may also be calculated (product of volume and density).

For example, for 10 m^2 of exposed steel,

$$\text{inherent corrosion rate} = 1.84 \times 10^{-4} \text{ cm}^3/\text{s}$$

$$\text{true corrosion rate} = 1.84 \times 10^{-4} \text{ cm}^3/\text{s} + 3.077 \times 10^{-3} \text{ cm}^3/\text{s}$$

$$= 3.261 \times 10^{-3} \text{ cm}^3/\text{s}$$

$$\text{mass lost} = 743.0 \text{ g steel}$$

$$\text{time to perforation} = 11.1 \text{ months}$$

CONCLUSIONS

There are several assumptions which were made when calculating the time to perforation which result in overestimating the time to perforation dramatically. One of the major assumptions is that the rate of corrosion is consistent across the exposed surface. In reality, there will be areas which suffer accelerated corrosion, while other areas corrode at rates less than calculated. Although the calculated time to perforation is based on consistent thinning, it is highly unlikely that the hull will not perforate until almost all of the exposed area has corroded.

Another assumption made is that the exposed area remains constant. That is, there is no buildup of corrosion products on the exposed steel. The buildup of corrosion products serves to decrease the effective surface area, which decreases the inherent rate of loss but has no effect on the loss rate due to galvanic. The inherent loss rate is

significantly less than the galvanic loss rate (an order of magnitude), even at exposed steel areas as great as 15 m^2 , so the reduction in surface area has little effect on the true corrosion rate. However, the time to perforation is directly proportional to the exposed area, so any reduction in surface area will have a dramatic effect on the time to perforation. For example, if the effective exposed steel area is 5 m^2 , the calculated time to perforation is 5.7 months.

Other experiments, under similar experimental conditions, resulted in lower average galvanic currents (approximately $2100 \mu\text{A}$). As mentioned previously, the experimental conditions vary, especially with respect to oxygen concentration, and this substantially affects the current flow since the rate-determining step is oxygen reduction. For a 10 m^2 exposed steel area, a current of $2100 \mu\text{A}$ results in a galvanic corrosion rate of $2.295 \times 10^{-3} \text{ cm}^3/\text{s}$, and a calculated time to perforation of 14.2 months. This again is highly overestimated due to the assumptions outlined above.

In conclusion it is absolutely critical that the cathodic protection remain on as much as possible, and if it must be turned off, care must be taken to ensure that it is turned back on as soon as possible.

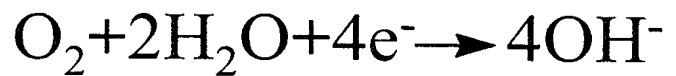
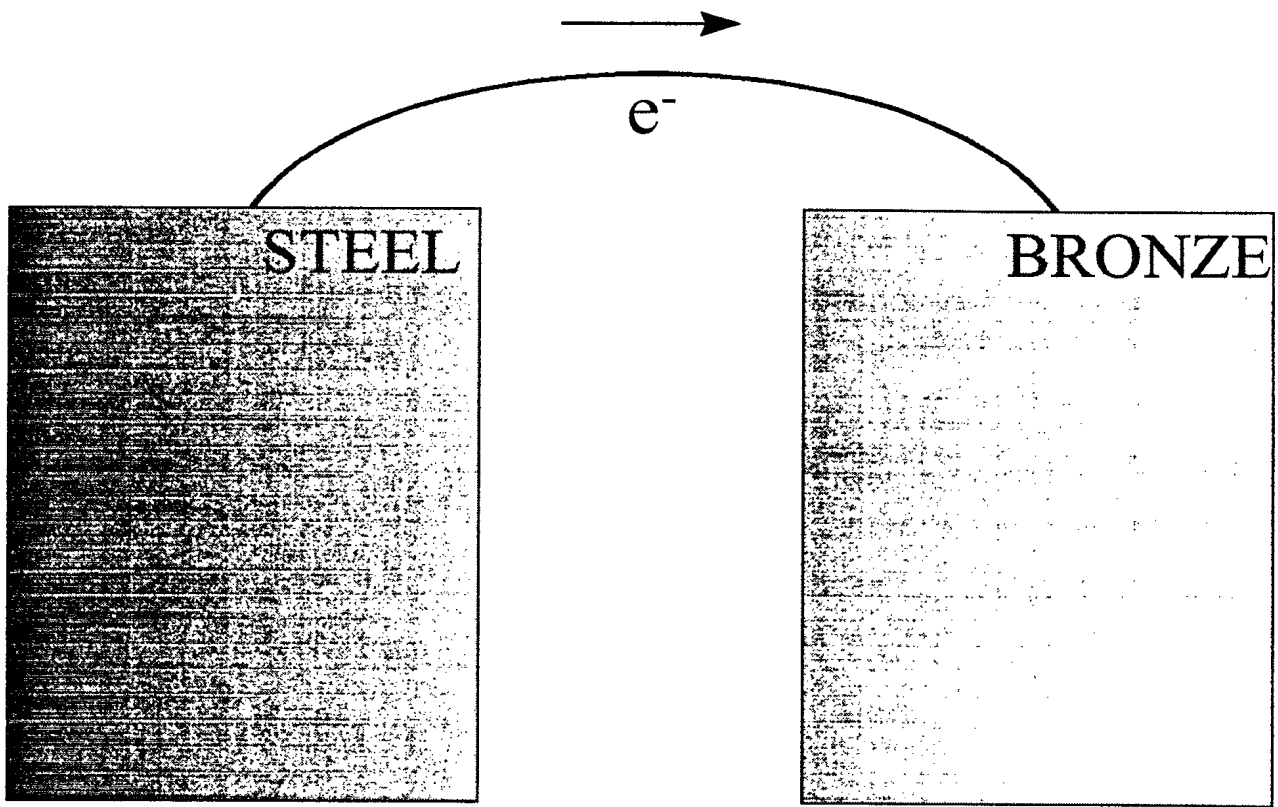


Figure 1: Galvanic Current Flow

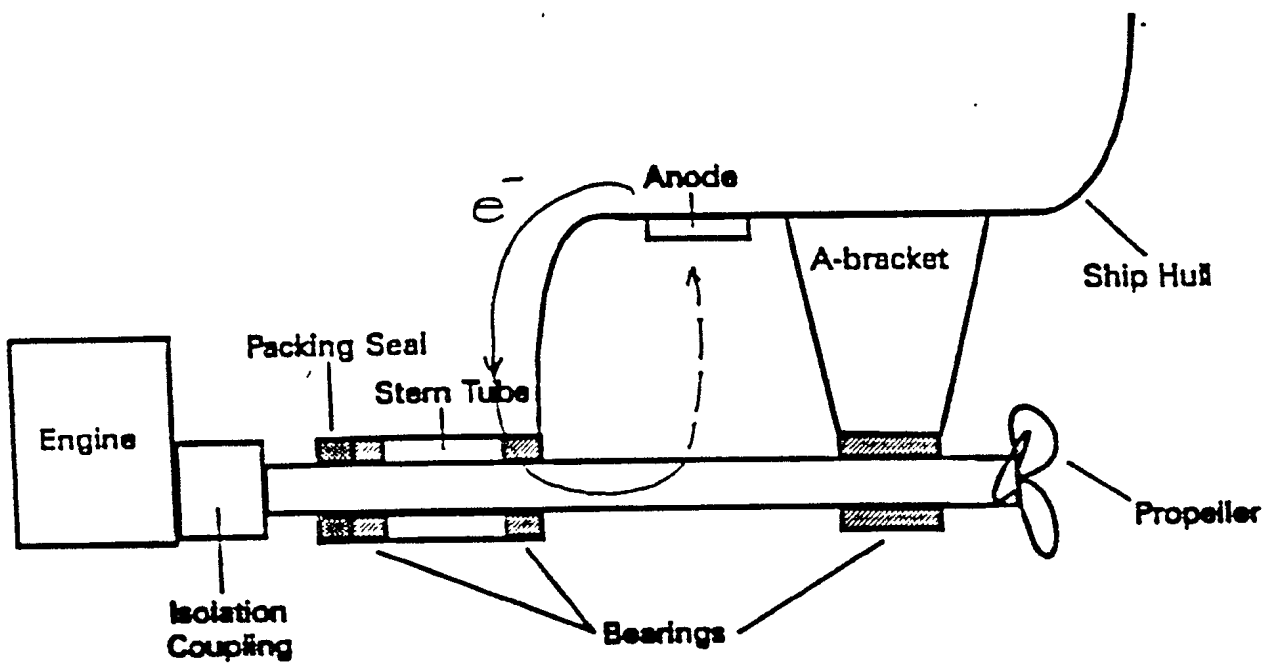


Figure 2: Ship Diagram

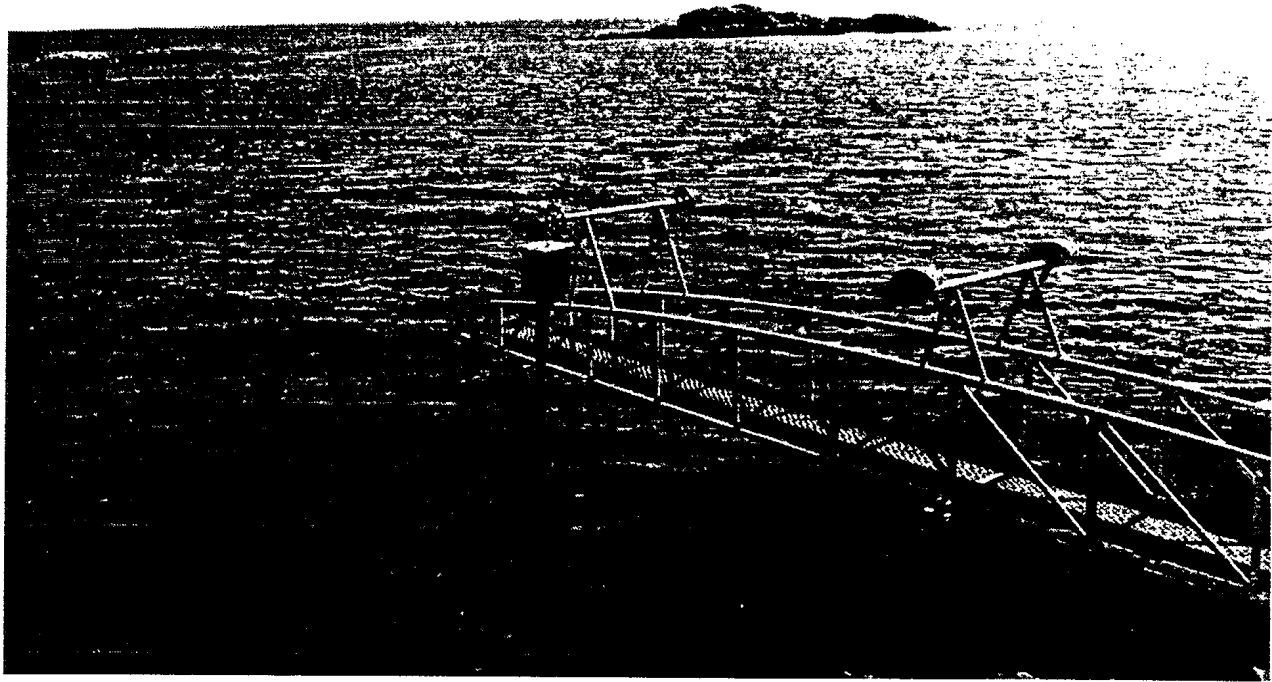


Figure 3: Seawater Intake

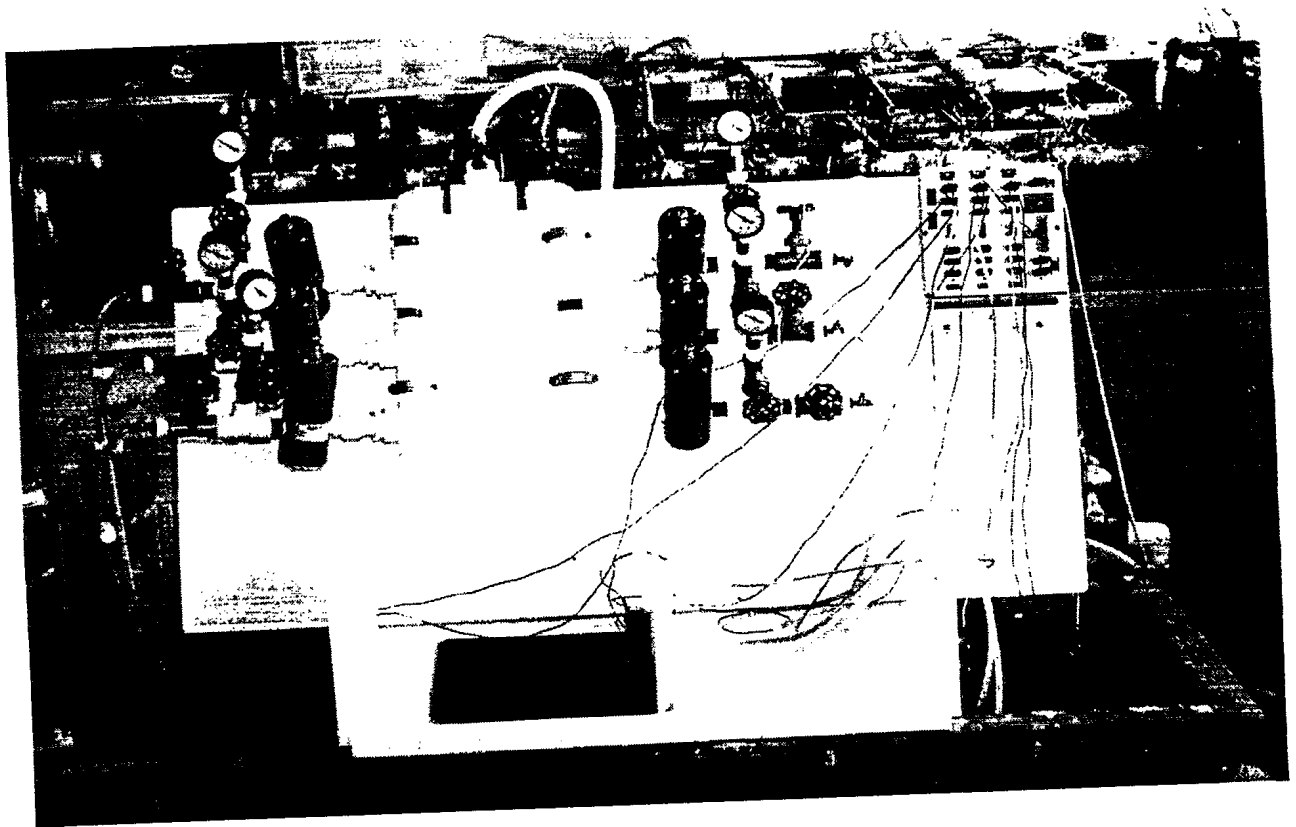


Figure 4: Experimental Setup

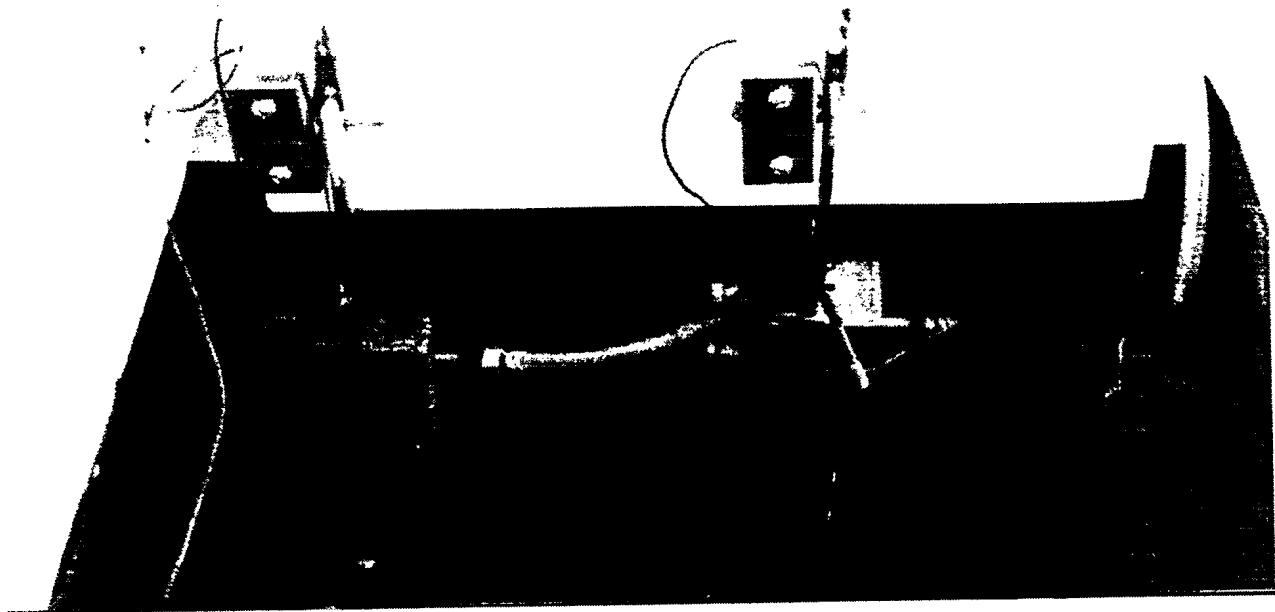


Figure 5: Immersed Samples

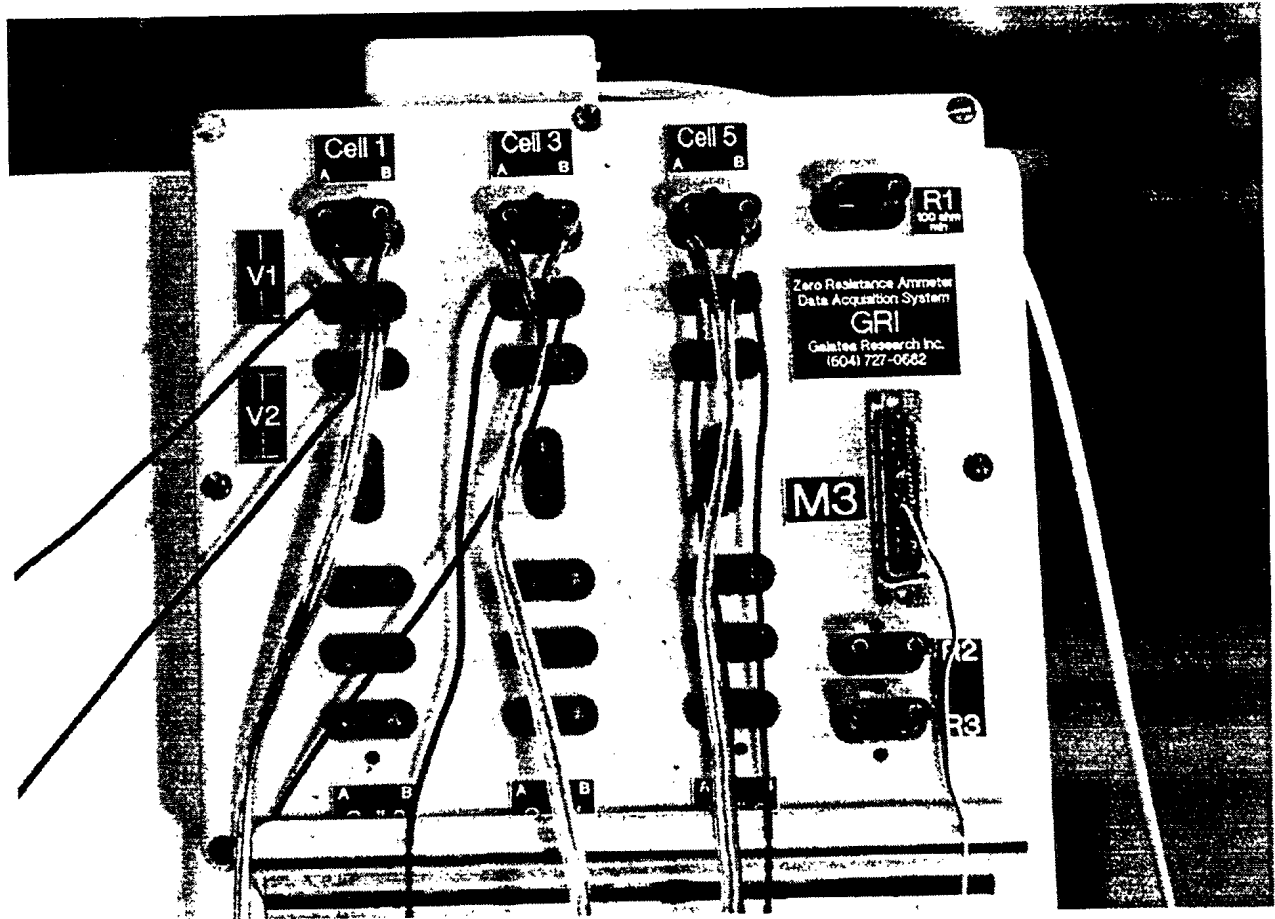


Figure 6: ZRA Module

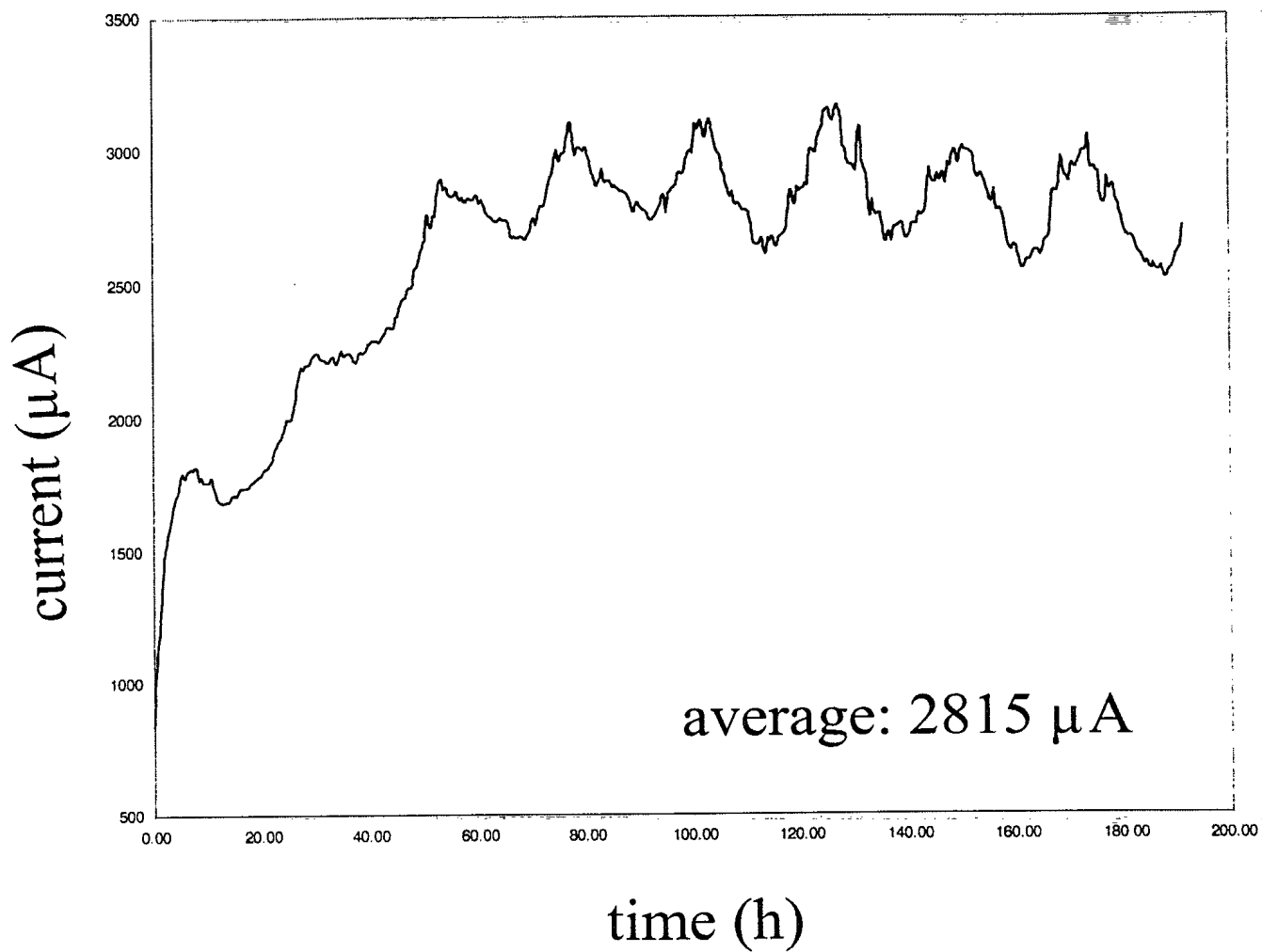


Figure 7: Plot of Current vs. Time

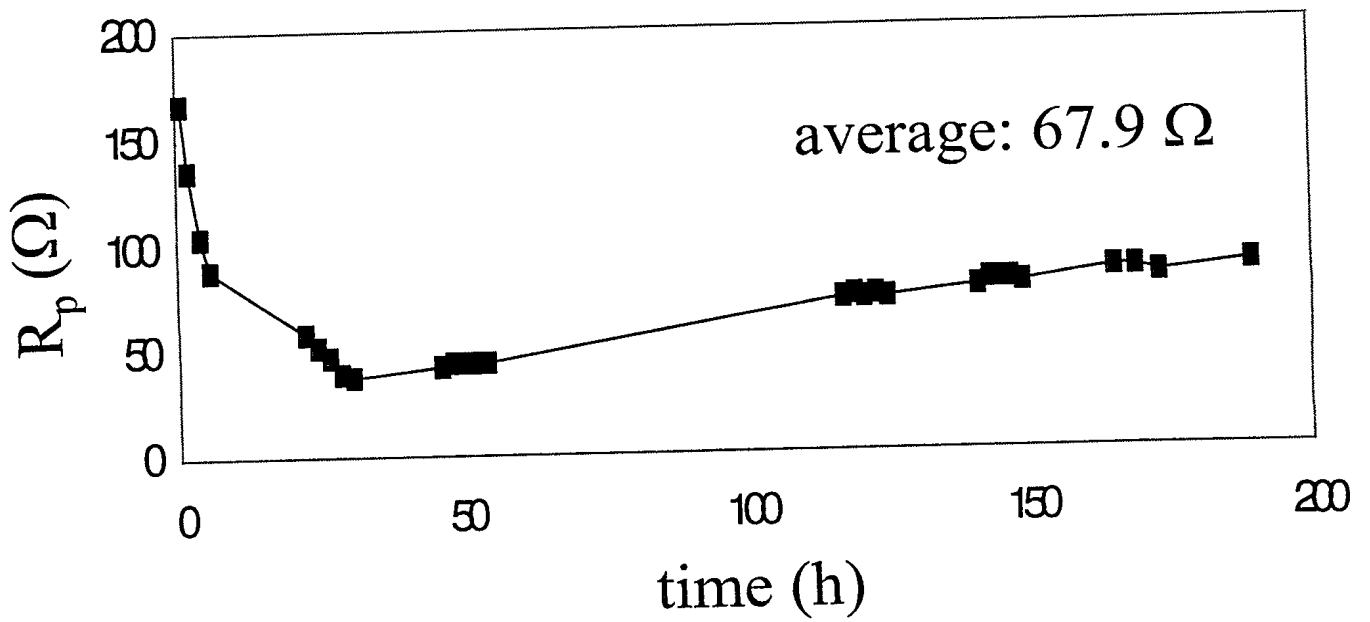


Figure 8: Plot of R_p vs. Time

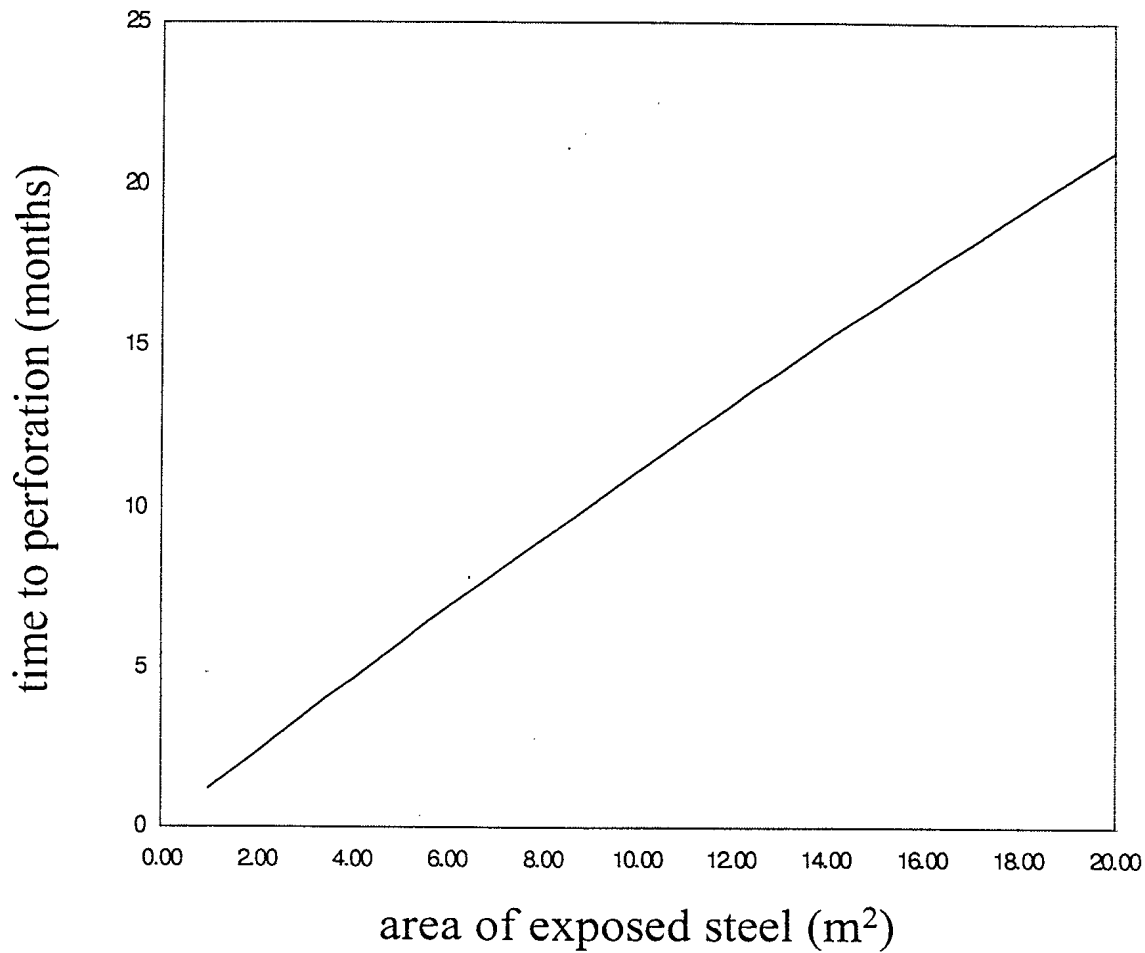


Figure 9: Plot of Time to Perforation vs. Area of Exposed Steel

