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# Effect of Carbon Overcoat on Corrosion

## of

## Thin Film Magnetic Media

A thesis presented to

The Faculty of the Department

of

Materials Engineering

San Jose State University

In partial fulfillment

of the

Requirements for the

Degree of Master of Science

By

Valérie Vivarès

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**Abstract**

**Effect of Carbon Overcoat on Corrosion of Thin Film Magnetic Media**
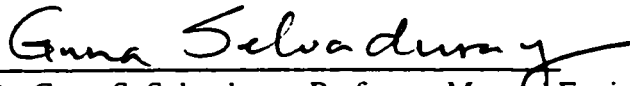
By Valérie Vivarès

Corrosion in thin film magnetic media represents a problem resulting in a potential loss of data for users of hard drives. Typically, the purpose of the carbon overcoat is to reduce wear of the magnetic layer, and possibly to limit corrosion.

The objective of this investigation was to determine the effect the carbon overcoat has on the corrosion behavior of the magnetic layer. Carbon overcoats of different hydrogen and nitrogen content were sputtered on, and the effect of this compositional difference was determined by measuring the corrosion current. Two electrolytes were used: chloride solutions at 0 and 7.5 ppm concentrations. The carbon films were characterized for thickness, k-value, and mechanical wear resistance.

The results indicate that disks with carbon overcoat have better corrosion resistance than disks without overcoat. Disks overcoated with nitrogenated carbon overcoats were found to have better corrosion resistancewhen they were compared to those with hydrogenated carbon overcoats.
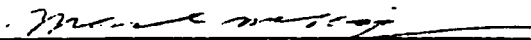
APPROVED FOR THE DEPARTMENT OF MATERIALS ENGINEERING


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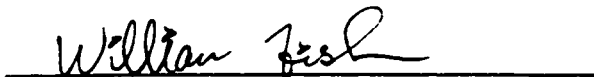San Jose State University


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# Chapter 1. Introduction.

Personal computers are in almost every home. In each of them, there is a hard drive to store data. Based on current technology, magnetic storage offers the best compromise in terms of speed, reliability, capacity and price. Today, it is possible to purchase a 2 Gbit drive for about $0.05/Mbit. In such a drive, the areal density (number of bits per square inch of magnetic media) can be up to 1 Gbit/in$^2$. IBM and Fujistsu have already developed areal densities of up to 5 Gbit/in$^2$, thus confirming the on-going progress of the magnetic disk drive industry. Progress on head characteristics, communication channels and media are responsible for a good part of the impressive increase in areal density of up to 65% per year, as shown in Figure 1.

With such high areal densities, each bit is stored in an increasingly small amount of space; therefore, the magnetic defects on the media have to be extremely small. Corrosion can create a patch of surface where the magnetic surface is damaged and is not able to store magnetic information. Such a patch of surface constitutes a defect that can grow as corrosion progresses. Defects apparent before the drive is shipped to the customer can sometimes be overcome by using an appropriate configuration to arrange the data. Unfortunately, if the defects appear after the drive is in use, or if the defect grows with time, the end user can experience loss of data. Such "growing" defects can result in a major reliability issue. With increasing areal densities the control and minimization of corrosion becomes more important.

In Chapter 2, pertinent background information, including a brief overview of corrosion, and of thin-film magnetic media is presented. Chapter 3 is a review of past research on corrosion of thin film magnetic media. The research hypothesis and objectives are in Chapter 4. In Chapter 5, the research protocol is described, followed by the results and discussion of the results in Chapter 6 and Chapter 7, respectively. Chapter 8 and Chapter 9 contain the conclusions and recommended future research.



*Figure 1: Areal Densities reached per year, based on IBM's Laboratory demonstrations and production product.[1]*

# Chapter 2. Thin film magnetic media and corrosion background

This chapter is a presentation of the background knowledge necessary for full comprehension of the study. The first part is a description of thin film magnetic media, followed by a brief overview of corrosion mechanisms.

## 2.1 Thin film magnetic media

Thin film magnetic disks are composed of a set of layers, each being present for a specific reason. A cross-section of a thin film magnetic disk and head is shown in Figure 2. The substrate is an aluminum alloy or glass. The aluminum substrate is machined to the proper dimensions and then electroplated with a nickel-phosphorous (Ni-P) alloy. The Ni-P layer provides a hardened non magnetic surface as a base for the other layers. The disk is then polished with different grain sizes to form the final substrate.

Texturing is then done on the disk to obtain the desirable surface roughness. The disk is textured for at least two reasons: to enhance stiction characteristics of the head on the finished media and to orient the magnetic layer longitudinally.

After texturing, a chrome-based undercoat is sputtered on to enhance adhesion of the magnetic media, which is sputtered on subsequently. The final sputtered layer is a carbon overcoat which reduces wear of the media in the assembled hard drive. The carbon overcoat can be of at least two types: nitrogenated or hydrogenated. Nitrogenated carbon is used to improve the bonding of the lubricant to the surface of the disk. Hydrogenated carbon usually offers better protection against wear.

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A Lubricant layer is the added, often by a dip and slow pull process, to improve head flight characteristics.



*Figure 2: Head and disk Schematic*

## 2.2    Brief overview of corrosion[2]

This section contains a brief review of the mechanisms and kinetics of corrosion that are relevant to this study.

### 2.2.1    Basis for corrosion

Corrosion is the result of chemical reaction between a metal or a metal alloy and its environment. In thin film magnetic media, the alloy of interest is the magnetic alloy which is composed primarily of cobalt, chromium and tantalum. Other additives are present in the alloy in various concentrations but past research has shown cobalt compounds at the surface of the disk to be a telltale sign of corrosion.[3]

Corrosion is electrochemical in nature. In general, metallic corrosion is the oxidation of the metal in aqueous solution. The oxidation of metallic cobalt in a chloride containing environment can be represented by the following overall reaction:

$$Co + 2HCl \rightarrow CoCl_2 + H_2 \qquad [1]$$

This overall reaction can be separated into an oxidation, or anodic, reaction and a reduction, or cathodic, reaction:

$$Co \rightarrow Co^{2+} + 2e\text{-} \qquad \text{Anodic Reaction} \qquad [2]$$

$$2H^+ + 2e\text{-} \rightarrow H_2 \qquad \text{Cathodic reaction} \qquad [3]$$

Most of the anodic reactions are of the form described above. Cathodic reactions can be of different types, but are often the reduction of oxygen in neutral or acidic solutions, as shown below:

$$\text{In neutral or basic solutions: } O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \qquad [4]$$

$$\text{In acidic solutions: } O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \qquad [5]$$

Oxidation reactions are present at all times; they can be advantageous as in the case of the oxidation of aluminum, which forms a protective layer, or deleterious as in the case of the oxidation of iron under atmospheric conditions, forming rust. The rate at which oxidation occurs determines the corrosion resistance of the material to the environment. In some cases, corrosion can be prevented entirely by stopping one of the three necessary conditions for corrosion, which are illustrated in Figure 3. The driving

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force is thermodynamic in nature. The ion and electron paths are the paths by which the ions reach the reaction surface and the electrons complete the electrochemical cell, respectively.



*Figure 3: Three required elements for corrosion to occur*

In the event when design cannot prevent corrosion entirely, the kinetics of corrosion are the designer's main concern.

### 2.2.2 Electrochemical Kinetics of corrosion

In thin film disks, design is driven by performance in the drive. This design creates several driving forces for corrosion: galvanic corrosion between the magnetic layer and the carbon overcoat, galvanic corrosion between the Ni-P layer and the magnetic layer, and cell corrosion via the pores of the carbon overcoat. Since corrosion cannot be prevented in these cases, the kinetics of the corrosion becomes the main concern. In this section, the kinetics involved in corrosion are discussed. The physical laws governing the reaction rate are presented in Section 2.2.2.1, followed by a brief review of polarization and passivation.

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### 2.2.2.1 Rate of reaction

The rate of production or consumption of electrons can accurately measure the rate at which a reaction occurs. Electron flow can be measured as current ($I$) in amps. Faraday's law gives the proportionality between the mass reacted and the current measured, $I$.

$$m = \frac{a}{n} \cdot \frac{It}{F}$$ [6]

where $F$ is Faraday's constant, $n$ is the number of equivalent weights exchanged, $a$ the atomic weight, and $t$ the time in seconds.

At equilibrium, the forward reaction rate ($r_f$) is equal to the reverse reaction rate ($r_r$).

$$r_f = r_r = \frac{i_0 a}{nF}$$ [7]

where $i_0$ is the exchange current density and has to be measured, $i_0$ is a kinetic constant for the reaction but depends strongly on the surface geometry.

The current density at equilibrium is a measurable quantity that defines the rate of corrosion in a system. Plotting the equilibrium current density as a function of the potential in an active system (a Taffel plot), allows one to gather information regarding the mechanism of corrosion in the system by studying the polarization curves. A discussion of polarization mechanisms follows in Section 2.2.2.2.

### 2.2.2.2  Polarization

The availability of electrons at the surface of a metal determines the rate of the reaction. An excess of electrons at the surface of the metal represents cathodic polarization. Anodic polarization is the deficiency of electrons at the surface of the metal, and a driving force for corrosion.

In aqueous solutions the potential at the surface of the metal reaches a steady state potential, called $E_{corr}$, which depends on the ability and rate at which electrons can be exchanged at the surface by the anodic and cathodic reactions. As the potential at the surface increases above $E_{corr}$ the anodic reaction takes place and corrosion occurs at a finite rate. Anodic polarization then occurs.

Polarization is the difference of potential between the equilibrium electrode potential and the potential resulting from the reaction. Cathodic polarization is present when the electrons are building up at the surface and the surface potential becomes lower than the equilibrium potential. Polarization can be classified into two main categories: activation polarization and concentration polarization.

Activation polarization occurs when the reaction rate (represented by the exchange current) is limited by the reaction itself. Thermodynamics then limits the reaction rate. In that case the overpotential, $\eta$, is related to the reaction rate ($i$) by:

$$\eta = \beta \log \frac{i}{i_0} \qquad [8]$$

The overpotential is related to $E_{corr}$ as shown below:

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$$\eta = E - E_{corr} \qquad [9]$$

were E is the applied potential.

The relationship between the overpotential and the logarithm of the current density (log $i$) is linear. Also, the anodic Taffel constant ($\beta_a$) is positive since the overpotential is positive (E>E_{corr}) and the cathodic Taffel constant ($\beta_c$) is negative since the overpotential is negative (E<E_{corr}).

Concentration polarization occurs when the concentration of the reduced ions limits the reaction rate. In this case, the solution forms a boundary layer in which the ions are depleted and the reaction is driven by the availability of the ions. The overpotential is then related to the current density by:

$$\eta_{conc} = \frac{2.3RT}{nF} \log \left[ 1 - \frac{i_c}{i_L} \right] \qquad [10]$$

where $i_L$ is the minimal current density at which the system shows this behavior.

This limiting current depends on the concentration of the solution, the diffusivity of the species, and the agitation of the solution. For thin film magnetic media, concentration polarization could indicate the lack of availability of reacting ions or electrons at the surface of the magnetic media. This could be due to the presence of the carbon overcoat. The total polarization is the sum of concentration and activation polarization. In many systems, at potentials around $E_{corr}$, the main polarization mechanism is activation polarization; further away from $E_{corr}$ the dominant mechanism is

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concentration polarization. A typical Taffel plot showing these two behaviors is presented in Figure 4.

The Polarization resistance $(R_p)$ is proportional to the inverse of the corrosion current density $(i_{corr})$ according to the Stern-Geary equation

$$i_{corr} = \left[ \frac{\beta_a \beta_c}{2.303(\beta_a + \beta_c)} \right] \frac{1}{R_p} \qquad [11]$$

Polarization resistance is the slope of the polarization curve at the origin $(E_{corr})$ and is independent of the degree of linearity of the curve. The reaction potential $E_{corr}$, current $i_0$, and polarization resistance $R_p$ are constants for a given system.



*Figure 4: Schematic Taffel Plot*

Some metals, such as aluminum and cobalt also exhibit passivation, which is described in the Section 2.2.2.3.

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### 2.2.2.3 Passivation

Some metals form a protective oxide that acts as a barrier for the anodic reaction. In this case, when the potential rises above $E_{corr}$, the corrosion rate first increases. However, when a certain potential is reached, the corrosion current decreases to reach very low rates. Active-passive metals can be active in some environments and passive in others.

The study of Taffel plots for thin film magnetic media would not only allow the determination of expected corrosion rates, but would also provide information on the corrosion mechanisms and the effect of carbon overcoats on the corrosion resistance.

## Chapter 3. Effect of the carbon overcoat on corrosion of magnetic media

Initially magnetic media was composed of metal particulates. As demand for

higher areal density increased thin-film magnetic media, which are easily manufacturable

and customizable, were developed. However, the magnetic film is less chemically stable

than the older metal particulate media. [3] For this reason a number of studies were

dedicated to understanding the mechanism of corrosion of this type of media, with

particular emphasis on the effect of carbon overcoats. Intuitively, the carbon overcoat, if

perfect, should isolate the magnetic media from the environment and protect it from

corrosion. Experimentally, corrosion products composed of cobalt hydroxides have been

found on the surface of disks. [4] These results suggest that water is absorbed by

imperfections in the surface. Water oxidizes the cobalt and the cobalt hydroxides migrate

to the surface. Another hypothesis is the existence of galvanic coupling between cobalt

and the carbon. Both hypotheses were formulated using two main experimental

approaches: exposure to controlled environments, and electrochemical methods. In this

chapter the different experimental approaches, and the results obtained from previous

studies are discussed.

### 3.1    Environmental chamber exposure / Qualitative experimental methods

Environmental chamber exposure and disk testing is often used in industry to

validate disk reliability. Merchant et al. [5] studied the effect of environmental exposure of

annealed and non-annealed, overcoated and non-overcoated, disks to a gaseous corrosive

environment (10ppb $Cl_2$, 120ppb $H_2S$ and 200ppb $NO_2$, at 30°C and 75% relative

humidity (RH)). The magnetic media was either a cobalt-chrome alloy or cobalt-chrome-tantalum alloy. The extent of corrosion was monitored by measuring the change of light scattering with time. The induction time was defined as the time when the reflectivity of the media showed a marked increase of more than 0.1 $\mu W$. This limit was correlated with the time at which the disk would most likely cause a head crash. Scanning Electron Microscope (SEM) observation of non-overcoated disks after environmental exposure showed that, for aluminum substrates, corrosion products gather preferentially along the texture lines. Electron micrographs of the texture lines also indicated an increased porosity of the film. The corrosion products were mainly nickel and chlorine. Annealed disks, with and without overcoat, showed a longer induction time compared to the non-annealed samples, and also showed no nickel in the corrosion products. The overcoated samples showed a shorter induction time compared to non-overcoated samples. A longer induction time, of about 37 hours, was obtained for the annealed non-overcoated samples as opposed to 9 hours for non-annealed overcoated samples and 13 hours for non-annealed non-overcoated samples. On the samples without carbon overcoat Auger depth profiling suggested the presence of an oxide layer passivating the surface.

In two studies [3,4] environmental chamber exposure was used in conjunction with electrochemical measurements in order to correlate the methods, and also to characterize the porosity of the overcoat.

Novotny and Staud [4] experimented on coated and uncoated media. The magnetic layer was a cobalt alloy with various amounts of chromium, nickel, phosphorous,

platinum, etc. Films were sputtered on AlMg/Ni-P substrates or silicon wafers.

Environmental tests were conducted in wet and dry conditions. In dry conditions the

higher temperature was 300°C and in wet conditions the maximum temperature and

relative humidity were 90°C and 90%, respectively. Experiments using corrosive gasses

(2 ppbw $Cl_2$, 300 ppbw $SO_2$, 40 ppbw $H_2S$, and 500 ppbw $NO_2$) were done at 25°C and

70% RH. Other exposure conditions were ambient environment with a temperature of

22°C and relative humidity of 40-50%. The samples were analyzed using X-ray

Photoemission Spectroscopy (XPS), Auger Electron Spectroscopy (AES), and Secondary

Ion Mass Spectroscopy (SIMM). XPS analysis of the non-overcoated samples, after

exposure to ambient environment, showed a mixture of chromium and cobalt oxides and

hydroxides on the surface. The analysis at higher temperature showed preferential

oxidation of cobalt and nickel. Overcoated samples showed no cobalt on the surface

prior to exposure. After exposure cobalt and nickel (when nickel was present in the

magnetic layer) hydroxides were found on the surface. AES depth profiles showed that

cobalt and oxygen levels were high at the surface, minimal in the carbon layer and rose

again when the carbon-magnetic layer interface was reached. Samples exposed to 200°C

in dry air showed no migration of cobalt or nickel to the surface. The amount of cobalt

and nickel present on the surface increases with increased humidity and decreased pH of

the gases. These results indicate that cobalt migrates to the surface not due to thermal

diffusion but probably due to thermodynamic forces. The presence of cobalt at the

surface is in disagreement with the results from Merchant,[5] who did not find any

evidence of cobalt on the surface and concluded that the reacting surface was probably the Ni-P/magnetic interface layer. Novotny and Staud[4] complemented this environmental exposure with electrochemical measurements which are described in Section 3.2.1.1. Also, the concentration of chromium and cobalt oxides on the surface was investigated, using AES depth profiling, and correlated to the electrochemical results.

Environmental exposure was also used by Brusic et al[3] to characterize the carbon overcoat porosity. Electrochemical methods were used to test samples for corrosion; environmental exposure (10ppb $Cl_2$, 70% RH and 25°C) was used to demonstrate the existence of pores in the carbon overcoat. The samples were composed of electroless Ni-P and magnetic alloy plated on the aluminum substrate; the carbon overcoat was then sputtered on with argon. The magnetic media was pure cobalt or a cobalt-phosphorus alloy. Some samples were not overcoated with carbon. SEM/Electron Discharge Spectroscopy (EDS) analysis was done on the surface corrosion products after exposure. For overcoated samples, the analysis showed that the carbon overcoat was incomplete, with numerous sites where the underlayer was exposed. This "pore decoration" allowed the author to count the number of pores per unit surface area and obtain an approximation of the porosity of the carbon overcoat. Corrosion products were found to be composed of cobalt oxides and chlorine and were located preferentially along surface scratches or other discontinuities. Again, the presence of cobalt is in contradiction with the study by Merchant,[5] but, it is in agreement with the study by Novotny.[4] Brusic also measured the thickness of corrosion products for the coated and uncoated samples. The uncoated

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Merchant,[5] but, it is in agreement with the study by Novotny.[4] Brusic also measured the thickness of corrosion products for the coated and uncoated samples. The uncoated sample showed uniform corrosion of about 3 nm thickness, detected by ellipsometry measurements. The overcoated samples showed localized corrosion products as thick as 1 μm and as large as several μm.

The pore decoration technique would seem useful to characterize the porosity of the overcoat, but it depends on the uniformity of the pore distribution on the surface. Therefore, the results should be used as an indication more than a means of definitive characterization.

The electrochemical measurements done by Brusic et al.[3] are described in Section 3.2.1.1.

## 3.2 Electrochemical methods

Two main types of polarization measurements have been used to study thin film magnetic media: linear polarization and impedance measurements. The studies carried out by Brusic,[3] Novotny [4] and Sides [6] are explained in detail in Section 3.2.1.1 on linear polarization measurements. Section 3.2.1.2 contains the description of impedance measurements by Sides[6] and Walmsley. [7]

### 3.2.1.1 Linear polarization studies

Most polarization studies were done using a standard three-electrode setup, using standard water based electrolytes. Brusic et al.,[3] however, used a water droplet setup to

electrolyte. This setup was intended to replicate atmospheric conditions.

Potentiodynamic curves were plotted after stabilization of the cell for about 15-20 min.

The objective of this study was to define the role of the carbon overcoat in the corrosion

process and evaluate ways to minimize corrosion. The AlMg/Ni-P/magnetic layer/carbon

overcoat samples were described in Section 3.1. The magnetic media was pure cobalt or

a cobalt-phosphorus alloy. The carbon layer was sputtered on using argon. Some other

samples were also made with only the carbon layer on the Si or AlMg substrate. The

reference electrode was mercurous sulfate, and the counter electrode was a platinum

mesh. The setup was designed to mimic atmospheric conditions. The cell was composed

of the working electrode (exposed surface $0.32 cm^2$), covered by a filter paper, followed

by the counter electrode, followed again with another filter paper and finally, the

reference electrode. 20 $\mu$L of solution was used to wet the filter paper. Several solutions

were used, including DI water (pH 7.2) and $NaOH/Na_8B_4O_7$ (pH 11). This setup allowed

the investigators to limit the effect of the ohmic resistance of the electrolyte.

Electrochemical measurements showed that overcoated and non-overcoated magnetic

layers have similar corrosion currents, between 1.1 and 6.9 $nA/cm^2$.

The corrosion potential of an overcoated sample and a sample with only a carbon

layer showed significant differences. This allowed the author to hypothesize that the

corrosion behavior could be explained by galvanic interaction between the magnetic layer

and the carbon overcoat. Galvanic interaction requires that two, active and dissimilar

materials must be in contact with each other, while they are being exposed to the same

environment. The differences in potential between them must also be more than 0.5 V. Since the carbon is conductive and the carbon and the cobalt alloy have a difference in potential of more than 0.5 V, galvanic corrosion can occur, given that both layers are exposed to the same environment. The last condition for galvanic corrosion is fulfilled if the carbon is porous and the magnetic layer is exposed to the environment. That condition has been proved by the environmental exposure study described in Section 3.1. Brusic et al.[3] also evaluated the ratio between the area covered by the carbon and the area where the magnetic layer was "visible" through the overcoat. They evaluated this ratio to be approximately 14:1 for a textured disk. Since the area ratio is so high, the corrosion rate in those galvanic cells has to be several orders of magnitude higher than the average corrosion rate. Brusic et al.[3] then proceeded to isolate the magnetic media from the conductive carbon overcoat using a dielectric. They obtained a lower corrosion current density for relatively thick dielectric layers and relatively smoother surfaces. They concluded that the main driving force for corrosion in thin film disks is galvanic coupling between the magnetic layer and the carbon overcoat.

Novotny and Staud [4] also carried out electrochemical measurements to complement their environmental exposure study. The samples described in Section 3.1 were tested by DC polarization and potentiodynamic scanning techniques. The working electrodes were pie-shaped coupons cut from hard drives or silicon wafers with sputtered films. The area exposed was $1.35 \text{cm}^2$. All potentials were measured using a standard calomel electrode. No detailed description of the cell was given, including the volume of

solution used. The electrolyte, 0.1 N Na$_2$SO$_4$ (pH=7), was deaerated using a nitrogen purge. H$_2$SO$_4$ or NaOH was added to the solution to vary the pH. The potential was varied from $-10$ to $+10$ mV against E$_{corr}$. The cell was allowed to reach equilibrium for 15-20 min before starting the scan at the rate of 0.1 mV/s. Several scans were taken for each condition, and the average taken as the actual corrosion current. Polarization resistance was also measured using a scan from $-200$ to $+800$ mV against corrosion potential, with a scan rate of 1 mV/s.

The corrosion current, for non-overcoated samples, ranged from 0.1 to 0.8 $\mu$A/cm$^2$, depending on the amount of chromium in the magnetic layer. The corrosion potentials ranged from $-400$ to $-600$ mV vs. Standard Calomel Electrode (SCE). The corrosion current was also dependent on the pH; a higher concentration of protons and lower pH, translates to a higher corrosion current which varied from 0.8 to 0.4 $\mu$A/cm$^2$ for pH varying from 1 to 11, respectively.

Overcoated samples showed lower or similar corrosion current when compared to non-overcoated samples, with currents varying from 0.5 to 0.03 $\mu$A/cm$^2$ for samples with overcoats B, C, and D in a solution of pH = 1. Unfortunately, no description of the three different types of carbon overcoats (B, C and D) was given by the author. Sample A was the non-overcoated sample.

The author correlated the chromium oxide concentration at the surface after the environmental exposure with the inverse of the corrosion current. The integrated

chromium oxide concentration over the surface was found to vary according to the inverse of the corrosion current raised to a power 1/x, x being unknown; an increase of corrosion current equates to a decrease in chromium oxide concentration. The author also correlated the surface concentration of cobalt and nickel with the corrosion current density and found a linear relationship. The difference in corrosion current for the various overcoats was said to be dependent on the conductivity of the carbon overcoat film (porosity being assumed to be similar for all films). For a non-conductive carbon, both the anodic reaction and cathodic reaction have to occur at the magnetic layer/electrolyte interface. Therefore, oxygen has to be available at the magnetic layer surface and the pores have to be larger. For a conductive overcoat, only the anodic reaction has to occur at the magnetic layer/solution interface. The cathodic reaction can occur at the carbon layer/solution interface. According to this reasoning, at equal porosity, a non-conductive overcoat would offer better corrosion protection to the magnetic layer. This hypothesis is supported by the measurement of the resistivity of the best carbon overcoat tested and the worst, around 5 $\Omega$cm and $10^5$ $\Omega$cm, respectively. Porosity was not measured and the characterization of the composition of the carbon overcoat was not reported in the article. The two corrosion mechanisms, for a conductive carbon overcoat and a non-conductive carbon overcoat, are illustrated in Figure 5.

a)

Ionic Solution

Carbon Overcoat

Magnetic Layer

Electron Path

b)

Anodic Reaction          Cathodic Reaction

Carbon Overcoat

Magnetic Layer

Electron Path

*Figure 5: Schematic diagram of corrosion mechanism for porous overcoat with a) high electrical conductivity b) low electrical conductivity.[4]*

Sides[6] carried out a dual study of potentiodynamic linear sweep measurement and impedance. The samples were sputtered, using a DC magnetron sputter system, with a magnetic layer of the same composition but under differing conditions which were designed to test the effect on corrosion characteristics. The electrolyte was 30g of KCl dissolved in one liter of DI water (pH 5.5). The reference electrode was Ag/AgCl, but the counter electrode was not identified. The potential was swept from –50 mV to 250 mV against the corrosion potential at a scan rate of 0.5 mV/s. The comparison of the average faradaic resistance was mostly inconclusive since the results were quite scattered. Overcoated samples showed a resistance larger than the resistance for non-overcoated samples by about an order of magnitude (50 k$\Omega$/cm$^2$ to about 350 k$\Omega$/cm$^2$). This result is in agreement with the results from Novotny[4] and Brusic[3] but in disagreement with the

results from Merchant[5] who found carbon overcoats detrimental for corrosion resistance. Sides determined that the carbon overcoat sputtering condition showed no significant effect. Sides[6] also carried out impedance measurements in order to determine the actual corrosion mechanism in this system. These experiments are described in Section 3.2.1.2.

## 3.2.1.2 Impedance studies

Sides[6] measured the impedance and phase shift for frequencies varying from 0.01 Hz to 25,000 Hz. The samples, setup, and solution were the same as described in Section 3.2.1.1. Amplitude and phase were plotted against frequency. The amplitude was directly proportional to frequency in the mid-range of frequency indicating that the system behaved as a capacitor. The phase angle for most samples was between 25°C and 80°C, which indicated that the film was mainly porous and permeable. This was in agreement with previous studies from Brusic[3] and Novotny.[4] However, the phase angle did not change consistently with corrosion susceptibility. The capacitance was lower for higher faradaic resistance, which is characteristic of a relatively non-porous carbon. The author suggests that the impedance study did not produce any results that were not already obtained by linear polarization.

Walmsley et al.[7] studied complete disk structures using AC impedance. The objective of the study was to determine the corrosion mechanism in the complete disk structure. The disk structure consisted of an AlMg substrate, with a nickel-phosphorous underlayer, a 3000 Å chromium layer, a 300-1000 Å cobalt alloy layer, a 100 Å chromium layer, and a 400 Å carbon overcoat. The working electrode had an area of

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1cm$^2$, the counter electrode was platinum, and the reference electrode was a standard calomel electrode. The electrolytes employed were 0.4N NaCl, 0.4N K$_2$SO$_4$, 0.1N KCl/HCl, and 0.1N H$_2$SO$_4$. The electrolytes were de-aerated by nitrogen purging for 10 min prior to exposure. The system was allowed to reach equilibrium for 10 s prior to the experiment. (Note that most other studies allowed the system to reach equilibrium for about 15-20 min before starting the experiment. ) A DC potential, equal to the open circuit potential, was first applied and an AC current of small amplitude was then superimposed. The superimposed frequencies were logarithmically distributed from 50mHz to 100mHz. The experiment was repeated after 10 min, and Nyquist plots were made. The plots corresponded to the graphs obtained for mass transport controlled systems. The corrosion currents were found to be decreasing with an increasing concentration of chromium in the cobalt alloy. The corrosion currents for electrolytes that are more aggressive were higher than for less aggressive electrolytes. This behavior was found to be true for sulfates or chloride containing electrolytes. Magnetic recording tests were also conducted to correlate to the electrochemical results. The results correlated qualitatively, with a higher corrosion current resulting in lower performance in magnetic recording.

In summary, studies on corrosion of thin film magnetic media showed that the active layer is the magnetic alloy, with the presence of cobalt and nickel at the surface (if nickel is present in the magnetic alloy). Only one study[5] showed no presence of cobalt at

the surface. This appears counter intuitive since cobalt is an active metal present in the magnetic media.

The studies involving environmental exposure and electrochemical measurements showed good qualitative and quantitative correlation.

The effect of the carbon overcoat is still poorly understood, but its presence seems to increase corrosion resistance in most cases. This appears to be a reasonable result since the carbon overcoat should limit two of the three main mechanisms of corrosion: ion and electron transport. However, no study was carried out on nitrogenated carbon. In the study by Sides[6] the sputtering conditions of the carbon overcoat were varied, but not the sputtering medium, which was argon. Novotny[4] does not explain the differences in the carbon overcoat he tested, therefore yielding little information to compare amorphous, hydrogenated and nitrogenated carbon in terms of corrosion resistance.

## Chapter 4. Effect of overcoat on corrosion current and research objective

The carbon overcoat plays an important role in protecting the magnetic media. Protection of wear from the head is usually the main concern, but corrosion protection is also a concern. Among the types of overcoats used in industry, two are receiving special interest: hydrogenated and nitrogenated amorphous carbon.

If the carbon overcoat was non-porous and the magnetic layer was not exposed to an aqueous interface, corrosion would not occur. Unfortunately, carbon overcoats are porous and can absorb water. Increasing porosity of the overcoat increases the area of the magnetic layer in contact with the environment. Therefore, a more porous overcoat would be expected to offer lower corrosion resistance to the film.

Hydrogenated and nitrogenated amorphous carbon overcoats have widely different mechanical characteristics and therefore can be expected to have different porosity.

The main objective of this study was to determine the effect of carbon overcoat composition on the corrosion characteristics of the magnetic layer. A secondary objective was to determine the effect of the presence of chloride ions on the corrosion characteristics of the magnetic layer. The corrosion current density and polarization resistance were measured in aerated DI water and 7.5 ppm HCl concentration aerated DI water.

# Chapter 5. Research methodology

The materials, equipment, test matrix and procedure employed in the course of this investigation are described in this chapter.

## 5.1 Disks and Solution Preparation

### 5.1.1 Preparation of disks

Aluminum/Ni-P substrates were sputtered with the chromium, magnetic and carbon layer using an Intervac MDP 250 DCTM system. The magnetic layer was an alloy of cobalt, chrome and tantalum. The sputtering conditions during the deposition of the chrome and magnetic layer were the same for all samples. During carbon overcoat deposition, the gas composition was varied as follows: (a) pure argon, (b) 30% methane balance argon, (c) 20% nitrogen balance argon, and (d) 30% nitrogen balance argon.

Five different disk categories were thus created: no carbon overcoat, argon-carbon overcoat (no intentional hydrogen), hydrogenated-carbon overcoat, nitrogenated-carbon overcoat (nominal 20% nitrogen no intentional hydrogen), and nitrogenated-carbon overcoat (nominal 30% nitrogen, no intentional hydrogen). The samples were then stored in vacuum-sealed cassettes until testing.

Each disk was partitioned, as shown in Figure 6, into six sections using tape or scribe marks. Three alternating sections were used for electrochemical measurements. The other three sections were left untested so that there would be fresh surfaces in case the measurements had to be repeated.

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*Figure 6: Schematic of Disk Partitioning*

### 5.1.2  Solution Preparation

#### 5.1.2.1  Oxygenated DI water

High purity de-ionized water was contained in a glass jar with a narrow opening, and a pump was installed to bubble air through the water for at least 12 hours before testing. In this manner, the solution was saturated with oxygen.

#### 5.1.2.2  7.5 ppmw HCl solution

High purity DI water was mixed with concentrated HCl in order to obtain a concentration of 7.5 ppmw HCl. Air was then bubbled through the solution for an excess of 12 hours to saturate the solution with oxygen.

### 5.2  Equipment

An EG&G flat cell was used to expose the samples to the solutions. The active area was 1cm$^2$ with a solution volume of 500 ml. The working electrode was the disk itself. The counter electrode was a platinum mesh. The reference electrode was silver-silver chloride. A schematic diagram of the flat cell is shown in Figure 7.

Reference electrode site

Sample Disk

Filling opening

Platinum Mesh
counter electrode

Working
electrode contact

Solution level

Capilary tube

Controled
opening (1cm2)

*Figure 7: EG&G Flat cell schematic*

The potential was varied using an EG&G Potentiostat Model 273, which was linked to a standard personal computer. The software used was EG&G Softcorr v 1.0 and v2.1.

The oxygen content, pH and temperature of the solutions were measured using a YSI Model 57 Dissolved $O_2$ Meter.

The wear resistance of the various carbon overcoats was measured using a Selket HD1000A. The Selket test characterizes how much the reflectivity of the surface varies with the time the abrasive tape is in contact with the surface. A lower Selket value indicates a higher wear resistance. The k-value and overcoat thickness were measured using an ellipsometer. The k-value is an optical parameter that correlate with the inverse of the hydrogen content of the film[9].

## 5.3 Test Matrix

Each disk type was tested in aerated DI water and 7.5 ppm HCl solutions. Three

measurements were taken for each condition. Table 1 contains a summary of the

experimental matrix. For each condition, a Taffel plot was created, thus permitting

determination of $E_{corr}$ and $I_{corr}$.

Table 1: Experimental Matrix

| Solution | Carbon overcoat | No Carbon | Argon Carbon | Hydrogenated carbon | Nitrogenated carbon |
|---|---|---|---|---|---|
| $O_2$ saturated DI water | | ✓ | ✓ | ✓ | ✓ |
| $O_2$ saturated 7.5ppmw HCl | | ✓ | ✓ | ✓ | ✓ |

## 5.4 Procedure

The corrosion potential and corrosion current were determined from

potentiodynamic measurements. Taffel plots were plotted and the corrosion potential and

current were inferred by non-linear least square fitting of the Stern-Geary Equation. The

potential was stepped from –250 mV from the open circuit potential to +250 mV at a scan

rate of 0.5mV/s.

The sample was positioned and clamped in the sample holder of the flat cell, after

which the solution was poured through the top opening. The reference electrode was then

positioned in the reference electrode holder. The cell was left for 15 min in order to

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## Chapter 6. Material characterization and electrochemical results

The results of the sample and sample characterization are presented first, followed by the results of the electrochemical measurements.

### 6.1  Materials characterization

The disk characterization measurements are presented Table 2. The Selket values are consistent with the general knowledge that nitrogenated carbon is more graphitic, and therefore less wear resistant, than hydrogenated carbon, which is more diamond like. Argon carbon was similar to hydrogenated carbon in terms of these measurements. The k-values were expected to be approximately 0.6 for argon carbon and 0.8 for nitrogenated overcoats[8]. However, the measured k values are somewhat different than the expected values. In particular, the k-value for argon carbon is significantly lower than expected, and it is thought that this is due to the presence of residual hydrogen in the sputtering chamber since the same chamber had been previously used for sputtering hydrogenated carbon. While the k-values for nitrogenated carbon are also lower than expected, the drop in values isn't as dramatic. Nevertheless, the nitrogenated carbon overcoat still has k-values higher than those for hydrogenated carbon overcoats. The solution characterization measurements are presented Table 3. As expected, the conductivity of the 7.5 ppmw HCl $O_2$ saturated solution was higher, by about 10 times, than $O_2$ saturated DI water. The pH of the HCl solution was one point lower that the pH of the DI water, which accounts for part of the conductivity difference. The dissolved oxygen content was the same for both solutions.

Table 2 : Carbon overcoat characteristics

| Carbon type | No | Argon Carbon | Hydrogenated Carbon | Nitrogenated carbon (20%) | Nitrogenated Carbon (30%) |
|---|---|---|---|---|---|
| Sputtering gas | None | Argon 100% | 20% Methane balance Argon | 20% Nitrogen balance Argon | 30% Nitrogen balance Argon |
| Thickness | 0 | ~110Å | ~120Å | ~130Å | ~120Å |
| K value | N/A | ~0.240 | ~0.200 | ~0.500 | ~0.600 |
| Selket value | N/A | 13 | 14 | 21 | 24 |

Table 3: Solution characteristics

| Solution | DI water | 7.5ppmw HCl |
|---|---|---|
| Conductivity | $6.1\mu\Omega^{-1}$ | $63\mu\Omega^{-1}$ |
| $O_2$ Content | 8.1mg/l | 8.3mg/l |
| pH | 4.3 | 3.2 |
| Temperature | 22°C | 22°C |

## 6.2   Taffel plots

The Taffel plots generated during this study are contained in Appendix A.  The three typical plots types found during this study are presented in Figure 8.  All Taffel plots for non-overcoated samples, in DI water or 7.5 ppm HCl, were similar in terms of the shape of the plot.  For overcoated samples, the plots were similar in shape for all samples in DI water, and for samples in 7.5ppm HCl.

a) No Carbon Overcoat



b) Carbon Overcoat, DI Water



c) Carbon Overcoat, 7.5 ppm HCl

*Figure 8: Typical results for: a) No carbon overcoat; b) Carbon overcoated samples in DI*

*water, c) Carbon overcoated Samples in 7.5ppm HCl*

The shapes of the anodic reaction are slightly different for each of these three cases. In the samples without carbon overcoats the anodic current density increased continuously and never stabilized at a given value. This is indicative that not only was passivation not attained but also that no steady state was reached.

For the samples with carbon overcoats, in DI water, the anodic current density tended to stabilize at higher voltages, suggesting that a steady state current was reached. This is an indication that the dominant process at higher voltages was concentration polarization. For overcoated samples, in HCl, the anodic current does not reach a steady state and there was no apparent concentration polarization.

## 6.3 Corrosion current

The corrosion currents reported in this section represent the average value of three measurements. The average corrosion currents for the different conditions are plotted in Figure 9 and Figure 10.

The samples with no carbon overcoat showed the highest corrosion current density, with about 450 nA/cm$^2$ in DI water and 4300 nA/cm$^2$ in 7.5 ppm HCl. The overcoated samples had a much lower corrosion current density, with the values being less than 50 nA/cm$^2$ for both DI water and HCl solution.

The lowest corrosion current was obtained for the two nitrogenated carbon overcoats, with average values of 5 and 9 nA/cm$^2$ in DI water (20% nitrogen and 30% nitrogen respectively) and 23 nA/cm$^2$ in HCl solution. The highest average corrosion

current, for overcoated samples, was found for argon carbon with 36 nA/cm$^2$ in DI water and 13 nA/cm$^2$ in HCl solution. The corrosion current density average for hydrogenated carbon was 17 nA/cm$^2$ in DI water and 32 nA/cm$^2$ in HCl.

All samples, with the exception of argon-carbon, had a lower corrosion current density in DI water than in diluted HCl.



*Figure 9: Corrosion Current density for all samples; error bars represent data scattering*

*Figure 10: Corrosion Current density for Overcoated samples*

First of all, the results indicate that the presence of a carbon overcoat reduces the corrosion current. The effect is quite dramatic, with corrosion current for the samples with overcoats being less than 1/10 of that of the samples without overcoats. This trend was found for both aerated DI water and aerated HCl solution.

When the hydrogenated and nitrogenated carbon overcoats are compared, the latter were found to have lower corrosion currents than the former. While this trend is significant for DI water, the trend for the HCl solution is less significant.

The data for argon-carbon overcoats is somewhat anomalous. While the trend for DI water is the same as that stated above, the trend for the HCl solution is not the same. Possible reasons for this anomalous behavior are discussed in Chapter 7.

## 6.4 Polarization resistance

The polarization resistances around $E_{corr}$ results are presented in Figure 11. The samples without carbon overcoat had an average polarization resistance of about 22 k$\Omega$ for the HCl solution and about 330 k$\Omega$ for DI water.

For overcoated samples, the polarization resistance goes up to several M$\Omega$. The highest polarization resistance was found for 30% nitrogenated carbon in DI water with an average value of 8.2 M$\Omega$. In diluted HCl, the polarization resistance drops to 2.6 M$\Omega$. 20% carbon showed a polarization resistance of 6.5 M$\Omega$ and 2.6 M$\Omega$ for DI water and diluted HCl, respectively. The lowest polarization resistance, for overcoated samples, was found for argon carbon with 3.1 M$\Omega$ in DI water, and 3.7 M$\Omega$ in diluted HCl.

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Hydrogenated carbon had a polarization resistance of 5.1 M$\Omega$ in DI water and 1.5 M$\Omega$ in diluted HCl. Most samples had higher polarization resistance in DI water that in diluted HCl, with the exception of argon carbon.

The polarization resistance measurements are consistent with the corrosion current measurements, with the argon-carbon overcoated samples showing anomalous behavior.

*Figure 11: Polarization resistance for all samples; error bars represent data scattering*

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## Chapter 7. Corrosion mechanisms in thin film magnetic media: Interpretation of results

In this chapter, the results obtained in this study are discussed, starting with a brief explanation of the Taffel plots and then followed by an explanation of the electrochemical results.

### 7.1   Taffel plots

As seen in Figure 8, the Taffel plots for non-overcoated samples show no concentration polarization and no passivation. This means that the cobalt alloy does not passivate and that the ion and electron paths are not the controlling factors.

For samples with carbon overcoats in DI water, the Taffel plots show anodic concentration polarization. This was valid for any of the carbon overcoats and it means that the controlling factor for the reaction rate was either the electron path or the ion path. In this case, it was probably due to the restriction in ion path due to the build-up of corrosion products on the surface. This hypothesis is supported by the fact that the Taffel plots of overcoated samples in dilute HCl solution shows no concentration polarization. The corrosion products were probably soluble in the HCl solution but not in DI water since cations generally have much higher solubilities in chloride-containing solutions. This theory is consistent with the fact that in most cases the corrosion current was lower in DI water than that in 7.5 ppm HCl.

## 7.2 Current density and polarization resistance

The main parameter extractable from the Taffel plot is the corrosion current density which indicates the relative corrosion resistance of the system.

For samples without overcoats, the corrosion currents were higher than for overcoated samples. This result is consistent with intuition: since less surface area is in contact with the solution we can expect to obtain a lower current density for the samples with carbon overcoat. These results are in accordance with the results of Sides,[6] Novotny[4] and Brusic[3] but in disagreement with the study by Merchant. [5]

The polarization resistance measurements are consistent with the corrosion current measurement. This is compatible with the Stern-Geary Equation. Since the two measurements use different computational methods, good correlation is an indication of the validity of the mathematical model. Polarization resistance results are in fair agreement with Sides[6] who reports a polarization resistance increase by about an order of magnitude between non-overcoated and overcoated samples. Sides[6] measured a polarization resistance of about 50 k$\Omega$ for non-overcoated samples and 350 k$\Omega$ for overcoated samples. The polarization resistance measured during this research was on the order of several hundred k$\Omega$ for non-overcoated samples and several M$\Omega$ for overcoated samples. The differences in the actual values of the resistance between the two studies can be attributed to differences in the cobalt alloy composition, texture roughness, carbon overcoat composition and sputtering conditions.

Both, polarization resistance and corrosion current for the argon carbon sample, show confusing results. The corrosion current density was actually higher in DI water than in dilute HCl. This result is counter-intuitive since corrosion rates are usually higher in chlorinated solutions than in DI water, as has also been demonstrated by the results obtained for the hydrogenated and nitrogenated carbon overcoat disks. This is due to the higher solubility of corrosion products in chlorinated solutions than in DI water and the higher concentration of protons in lower pH solutions. If the argon-carbon samples had followed the trend of the other samples, the corrosion current density would have been in the range of 100 nA/cm$^2$. This would be a large corrosion current density since most of the surface was covered by the argon-carbon overcoat. It is possible that during the time the system was allowed to equilibrate the magnetic layer was completely consumed by corrosion and that the results plotted were actually the corrosion current density of the chromium undercoat.

The corrosion current results for overcoated samples show nitrogenated samples to have better corrosion resistance than hydrogenated samples. According to the abrasion test hydrogenated carbon was the overcoat with the highest wear resistance, as was shown in Table 2. Intuitively, this overcoat should be the less porous and the corrosion current lower than argon carbon and nitrogenated carbon. The results for these specific carbon overcoats appear counter intuitive. Also, hydrogenated carbon is relatively more insulating than nitrogenated carbon,[9] and therefore, according to Novotny's[4] theory illustrated in Figure 5, hydrogenated carbon should have better corrosion resistance.

However, hydrogenated carbon is also more hydrophilic than nitrogenated carbon.[9] Since the carbon layer is hydrophilic, the solution can penetrate deeper into pores and form an interface with the magnetic layer. In hydrophobic overcoats the pore needs to be larger in order for the solution to enter and be in contact with the magnetic layer. If the magnetic layer is not in contact with the solution, no ions can migrate from the magnetic layer to the solution and little to no corrosion occurs in that pore. This mechanism is illustrated in Figure 12.



Figure 12: Hydrophilic (a), and hydrophobic (b) carbon overcoat-solution contact comparison

## Chapter 8. Conclusions

The presence of carbon overcoats was found to enhance the corrosion resistance of the magnetic media by reducing the area exposed to the solution.

For the overcoated samples, nitrogenated carbon has better corrosion resistance than all other films tested in terms of corrosion current. This could be due to the relatively low affinity of this carbon film for water.

## Chapter 9. Recommendations for future research

The following studies are recommended to improve the understanding of the effect of the carbon overcoat on corrosion of thin film magnetic media.

### 9.1 Wetting angle of water and carbon overcoat

Measure contact angle and corrosion current for various carbon and correlate the results. A lower contact angle, between the solution and the carbon overcoat, should lead to a lower corrosion resistance of the overcoated magnetic media. A higher contact angle should lead to a higher corrosion resistance.

### 9.2 Carbon overcoat porosity measurements

Measure carbon overcoat porosity in terms of pore size and number of pores and correlate to corrosion current or polarization resistance.

# Chapter 10. References

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**Appendix A**

```
Model 352/252 Corrosion Analysis Software. v.  8.88
Filename:  c:\m352\data\8C1.T
TA TAFEL                                        File Status:  NORMAL
Date Run:  UNKNOWN                              Time Run:  UNKNOWN

Cond. Time       CT   pass         s     Initial Pot.    IP  -58.88E-3    V oc
Cond. Pot.       CP   pass         V     Final Pot.      FP   258.8E-3    V oc
Initial Delay    ID   pass         s

Scan Rate        SR   288.8E-3     mV/s  Curr. Range     CR  Auto
Scan Incr.       SI   1.888        mV    Step Time       ST  5.888        s
No. of Points    NP   388

                                         GI Time Const.  TC  Off
Line Sync.       LS   no                 IR Mode         IR  none
Rise Time        RT   high stability     Filter          FL  ± 5.3Hz
Working Elec.    WE   Solid              Ref. Elec.      RE  AgCl  197.8E-3V
Sample Area      AR   1.888        cm^2  Equiv. Wt.      EW  8.8888        g
Density          DE   8.8888       g/ml  AUX A/D         AU  no
Open Circuit     OC   278.8E-3     V

Comment:  No Carbon Overcoat. DI water 02 saturated


Rp CALCULATIONS:
Corrosion Rate =     N.A.             Correlation = -1888.8E-3
Rp = 527.8 KOhms
E(I=8) = 299.8 mV                     Icorr(R) = 449.4 nA/cm^2
Beta Anodic = 1.188                   Beta Cathodic = 1.816 V/decade
Begin = 221.8 mV                      End = 517.8 mV


TAFEL CALCULATIONS:
Corrosion Rate =     N.A.             Chi^2 =  6.86E-882
E(I=8) = 299.3 mV                     Icorr = 458.8 nA/cm^2
Beta Anodic = 1.188                   Beta Cathodic = 1.816 V/decade
Begin = 221.8 mV                      End = 519.8 mV
```

――――― 8C1.T


```
560.0 ─
520.0 ─
480.0 ─
440.0 ─
E vs. AgCl (mV)
400.0 ─
360.0 ─
320.0 ─
280.0 ─
240.0 ─
200.0 ─
      -10        -9        -8        -7        -6
                I/area (A/cm^2)                10^n
```

Model J52/252 Corrosion Analysis Software. v.  0.00
Filename:  c:\m352\data\NoCO2
TA TAFEL                                    File Status:  NORMAL
Date Run:  UNKNOWN                          Time Run:  UNKNOWN

Cond. Time        CT    pass        s       Initial Pot.    IP   -250.0E-3    V oc
Cond. Pot.        CP    pass        V       Final Pot.      FP    250.0E-3    V oc
Initial Delay     ID    pass        s

Scan Rate         SR    200.0E-3    mV/s    Curr. Range     CR    Auto
Scan Incr.        SI    2.000       mV      Step Time       ST    10.00          s
No. of Points     NP    250
                                            GI Time Const.  TC    Off
Line Sync.        LS    no                  IR Mode         IR    none
Rise Time         RT    high stability      Filter          FL    I 5.3Hz
Working Elec.     WE    Solid               Ref. Elec.      RE    AgCl  197.0E-3V
Sample Area       AR    1.000       cm^2    Equiv. Wt.      EW    0.0000         s
Density           DE    0.0000      g/ml    AUX A/D         AU    no
Open Circuit      OC    424.0E-3    V

Comment:  No Carbon Overcoat. DI water O2 Saturated. Sample#2

Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -993.0E-3
Rp = 216.2 KOhms
E(I=0) = 433.2 mV                   Icorr(R) = 327.7 nA/cm^2
Beta Anodic = 288.4E-3              Beta Cathodic = 375.5E-3 V/decade
Begin = 412.0 mV                    End = 452.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 = 4.71E+001
E(I=0) = 432.9 mV                   Icorr = 414.6 nA/cm^2
Beta Anodic = 288.4E-3              Beta Cathodic = 375.5E-3 V/decade
Begin = 184.0 mV                    End = 672.0 mV

——————  NoCO2

```
Model 352/252 Corrosion Analysis Software. v.   2.10
Filename:  c:\m352\data\NocDI3.t
TA TAFEL                                     File Status:  NORMAL
Date Run:  UNKNOWN                           Time Run:  UNKNOWN

Cond. Time       CT   pass        s      Initial Pot.   IP  -250.0E-3    V oc
Cond. Pot.       CP   pass        V      Final Pot.     FP   250.0E-3    V oc
Initial Delay    ID   pass        s

Scan Rate        SR   500.0E-3    mV/s   Curr. Range    CR   Auto
Scan Incr.       SI   2.000       mV     Step Time      ST   4.000        s
No. of Points    NP   250
                                         GI Time Const. TC   Off
Line Sync.       LS   no                 IR Mode        IR   none
Rise Time        RT   high stability     Filter         FL   I 5.3Hz
Working Elec.    WE   Solid              Ref. Elec.     RE   AgCl   197.0E-3V
Sample Area      AR   1.000       cm^2   Equiv. Wt.     EW   0.0000       g
Density          DE   0.3000      g/ml   AUX A/D        AU   no
Open Circuit     OC   287.0E-3    V

Comment:  No Carbon Overcoat. DI water. O2 Saturated. Sample #3

Rp CALCULATIONS:
Corrosion Rate =   N.A.                Correlation = -998.4E-3
Rp = 262.4 kOhms
E(I=0) = 321.0 mV                      Icorr(R) = 82.76 nA/cm^2
Beta Anodic = 100.0E-3                 Beta Cathodic = 100.0E-3 V/decade
Begin = 297.0 mV                       End = 335.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                Chi^2 = 4.08E+000
E(I=0) = 321.7 mV                      Icorr = 468.5 nA/cm^2
Beta Anodic = 1.469                    Beta Cathodic = 379.7E-3 V/decade
Begin = 119.3 mV                       End = 531.0 mV

          ———— NocDI3.t
```

Model 352/252 Corrosion Analysis Software. v. 2.10
Filename: c:\m352\data\acoil.t
TA TAFEL
Date Run: UNKNOWNN                          File Status: NORMAL
                                            Time Run: UNKNOWNN

Cond. Time        CT    pass        s       Initial Pot.   IP   -250.0E-3    V oc
Cond. Pot.        CP    pass        V       Final Pot.     FP    250.0E-3    V oc
Initial Delay     ID    pass        s

Scan Rate         SR    500.0E-3    mV/s    Curr. Range    CR   Auto
Scan Incr.        SI    2.000       mV      Step Time      ST   4.000        s
No. of Points     NP    250

Line Sync.        LS    no                  GI Time Const. TC   off
Rise Time         RT    high stability      IR Mode        IR   none
Working Elec.     WE    Solid               Filter         FL   I 5.3Hz
Sample Area       AR    1.000       cm^2    Ref. Elec.     RE   AgCl  197.0E-3V
Density           DE    0.0000      g/ml    Equiv. Wt.     EW   0.0000       g
Open Circuit      OC    512.0E-3    V       AUX A/O        AU   no

Comment:  Argon Carbon. DI water. O2 saturated. Sample#1

Rp CALCULATIONS:
Corrosion Rate =   N.A.
Rp = 2.835 MOhms                    Correlation = -999.0E-3
E(I=0) = 509.5 mV
Beta Anodic = 100.0E-3              Icorr(R) = 7.660 nA/cm^2
Begin = 438.0 mV                    Beta Cathodic = 100.0E-3 V/decade
                                    End = 592.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =   N.A.
E(I=0) = 506.4 mV                   Chi^2 = 4.42E-001
Beta Anodic = 728.4E-3             Icorr = 38.53 nA/cm^2
Begin = 294.0 mV                    Beta Cathodic = 390.3E-3 V/decade
                                    End = 700.0 mV

Model 352/252 Corrosion Analysis Software, v. 2.10
Filename: c:\m352\data\ACD2Z.t
TA TAFEL                                    File Status: NORMAL
Date Run: UNKNOWN                           Time Run: UNKNOWN

Cond. Time        CT   pass      s     Initial Pot.    IP  -250.0E-3   V oc
Cond. Pot.        CP   pass      V     Final Pot.      FP   250.0E-3   V oc
Initial Delay     ID   pass      s

Scan Rate         SR   500.0E-3  mV/s  Curr. Range     CR   Auto
Scan Incr.        SI   2.000     mV    Step Time       ST   4.000      s
No. of Points     NP   250

                                       GI Time Const.  TC   Off
Line Sync.        LS   no              IR Mode         IR   none
Rise Time         RT   high stability  Filter          FL   I 5.3Hz
Working Elec.     WE   Solid           Ref. Elec.      RE   AgCl  197.0E-3V
Sample Area       AR   1.000     cm^2  Equiv. Wt.      EW   0.0000     g
Density           DE   0.0000    g/ml  AUX A/D         AU   no
Open Circuit      OC   418.0E-3   V

Comment:  Argon Carbon, DI water, O2 saturated, Sample2

Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -993.4E-3
Rp = 3.885 MOhms
E(I=0) = 417.9 mV                   Icorr(R) = 5.589 nA/cm^2
Beta Anodic = 100.0E-3              Beta Cathodic = 100.0E-3 V/decade
Begin = 394.0 mV                    End = 516.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 = 2.80E-001
E(I=0) = 416.8 mV                   Icorr = 31.63 nA/cm^2
Beta Anodic = 1.890                 Beta Cathodic = 261.5E-3 V/decade
Begin = 276.0 mV                    End = 566.0 mV

——————  ACD2Z.t



700.0

600.0

500.0

E vs. AgCl (mV)

400.0

300.0

200.0

100.0
     -14    -13    -12    -11    -10    -9     -8     -7     -6     -5
                        I/area (A/cm^2)                           $10^n$

Model 352/252 Corrosion Analysis Software. v.  2.10
Filename:  c:\m352\data\acd:3.t
TA TAFEL
Date Run:  UNKNOWNN

File Status:  NORMAL
Time Run:  UNKNOWNN

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cond. Time | CT | pass | s | Initial Pot. | IP | -250.0E-3 | V oc |
| Cond. Pot. | CP | pass | V | Final Pot. | FP | 250.0E-3 | V oc |
| Initial Delay | ID | pass | s | | | | |
| Scan Rate | SR | 500.0E-3 | mV/s | Curr. Range | CR | Auto | |
| Scan Incr. | SI | 2.000 | mV | Step Time | ST | 4.000 | s |
| No. of Points | NP | 250 | | | | | |
| | | | | GI Time Const. | TC | Off | |
| | | | | IR Mode | IR | none | |
| Line Sync. | LS | no | | Filter | FL | ≤ 5.3Hz | |
| Rise Time | RT | high stability | | Ref. Elec. | RE | AgCl  197.0E-3V | |
| Working Elec. | WE | Solid | | Equiv. Wt. | EW | 0.0000 | g |
| Sample Area | AR | 1.000 | cm^2 | AUX A/D | AU | no | |
| Density | DE | 0.0000 | g/ml | | | | |
| Open Circuit | OC | 250.0E-3 | V | | | | |

Comment:  Argon Carbon. DI water. O2 saturated. Sample=3

Rp CALCULATIONS:
Corrosion Rate =  N.A.
Rp = 2.829 MOhms
E(I=0) = 359.6 mV
Beta Anodic = 100.0E-3
Begin = 306.0 mV

Correlation = -987.4E-3

Icorr(R) = 7.676 nA/cm^2
Beta Cathodic = 100.0E-3 V/decade
End = 398.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.
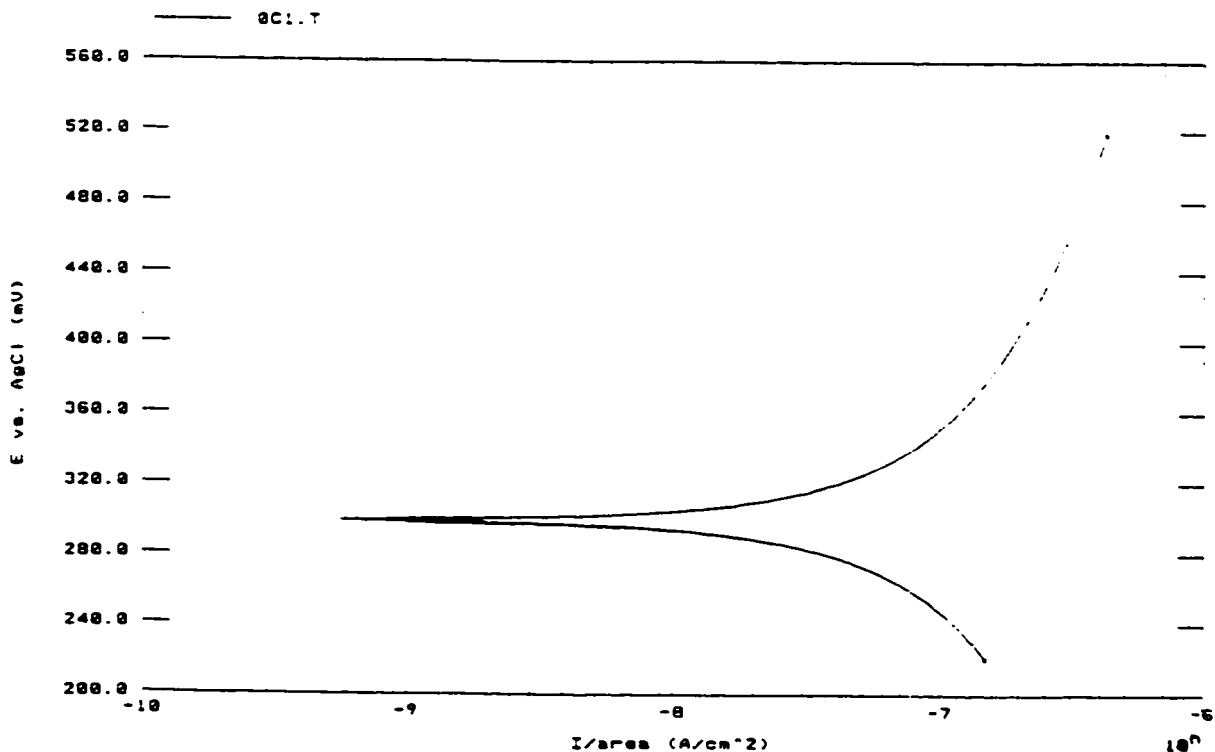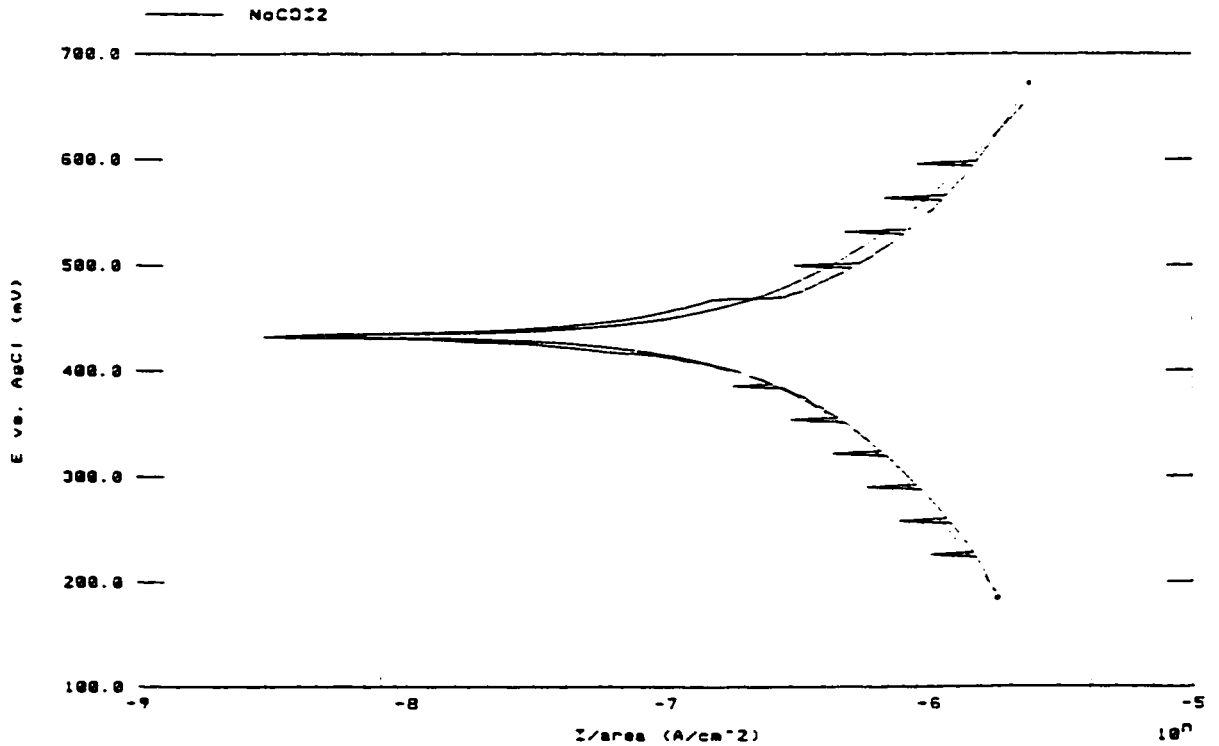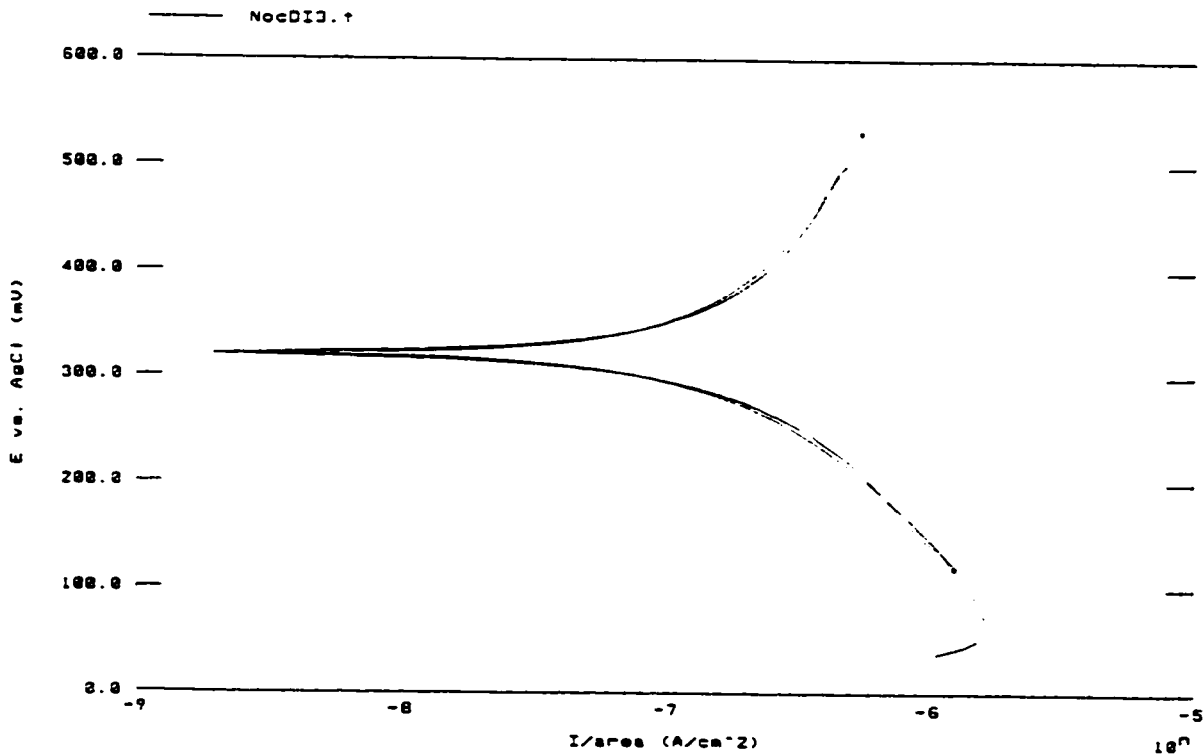E(I=0) = 356.8 mV
Beta Anodic = 2.064
Begin = 192.3 mV

Chi^2 =  4.18E-001
Icorr = 37.25 nA/cm^2
Beta Cathodic = 280.9E-3 V/decade
End = 482.0 mV

———— acd:3.t

Model 352/252 Corrosion Analysis Software, v.  2.10
Filename:  c:\m352\data\hcdil.t
TA TAFEL
Date Run:  UNKNOWN

File Status:  NORMAL
Time Run:  UNKNOWN

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Cond. Time | CT | pass | s | Initial Pot. | IP | -250.0E-3 | V oc |
| Cond. Pot. | CP | pass | V | Final Pot. | FP | 250.0E-3 | V oc |
| Initial Delay | ID | pass | s | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Scan Rate | SR | 500.0E-3 | mV/s | Curr. Range | CR | Auto | |
| Scan Incr. | SI | 2.000 | mV | Step Time | ST | 4.000 | s |
| No. of Points | NP | 250 | | | | | |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | GI Time Const. | TC | off | |
| Line Sync. | LS | no | | IR Mode | IR | none | |
| Rise Time | RT | high stability | | Filter | FL | I 5.3Hz | |
| Working Elec. | WE | Solid | | Ref. Elec. | RE | AgCl  197.0E-3V | |
| Sample Area | AR | 1.000 | cm^2 | Equiv. Wt. | EW | 0.0000 | s |
| Density | DE | 0.0000 | g/ml | AUX A/D | AU | no | |
| Open Circuit | OC | 372.0E-3 | V | | | | |

Comment:  Hydrogenated Carbon. DI water. O2 saturated. Sample #1

Rp CALCULATIONS:
Corrosion Rate =  N.A.                    Correlation = -995.4E-3
Rp = 5.785 MOhms
E(I=0) = 380.0 mV                         Icorr(R) = 3.754 nA/cm^2
Beta Anodic = 100.0E-3                    Beta Cathodic = 100.0E-3 V/decade
Begin = 350.0 mV                          End = 450.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                    Chi^2 =  1.87E-001
E(I=0) = 379.3 mV                         Icorr = 18.40 nA/cm^2
Beta Anodic = 1.365                       Beta Cathodic = 251.4E-3 V/decade
Begin = 150.0 mV                          End = 594.0 mV

———— hcdil.t



E vs. AgCl (mV)

I/area (A/cm^2)

TA TAFEL                                    File Status:  NORMAL
Date Run:  UNKNOWNN                          Time Run:  UNKNOWNN

Cond. Time      CT    pass        s      Initial Pot.    IP   -250.0E-3      V oc
Cond. Pot.      CP    pass        V      Final Pot.      FP    250.0E-3      V oc
Initial Delay   ID    pass        s

Scan Rate       SR    500.0E-3    mV/s   Curr. Range     CR   Auto
Scan Incr.      SI    2.000       mV     Step Time       ST   4.000          s
No. of Points   NP    250
                                         GI Time Const.  TC   Off
Line Sync.      LS    no                 IR Mode         IR   none
Rise Time       RT    high stability     Filter          FL   I 5.3Hz
Working Elec.   WE    Solid              Ref. Elec.      RE   AgCl   197.0E-3V
Sample Area     AR    1.000       cm^2   Equiv. Wt.      EW   0.0000         g
Density         DE    0.0000      g/ml   AUX A/D         AU   no
Open Circuit    OC    404.0E-3    V

Comment:  Hydrogenated Carbon. DI water. O2 saturated. Sample #2


Rp CALCULATIONS:
Corrosion Rate =  N.A.                   Correlation = -993.5E-3
Rp = 4.221 MOhms
E(I=0) = 439.0 mV                        Icorr(R) = 5.144 nA/cm^2
Beta Anodic = 100.0E-3                   Beta Cathodic = 100.0E-3 V/decade
Begin = 358.0 mV                         End = 474.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                   Chi^2 = 1.61E+000
E(I=0) = 405.0 mV                        Icorr = 23.98 nA/cm^2
Beta Anodic = 1.359                      Beta Cathodic = 274.0E-3 V/decade
Begin = 154.0 mV                         End = 652.0 mV



——— hcdi2.t

```
Model 352/252 Corrosion Analysis Software. v.   2.10
Filename:  c:\m352\data\hcdi3.t
TA TAFEL                                      File Status:   NORMAL
Date Run:   UNKNOWNN                          Time Run:  UNKNOWNN

Cond. Time        CT    pass         s        Initial Pot.    IP   -250.0E-3    V oc
Cond. Pot.        CP    pass         V        Final Pot.      FP    250.0E-3    V oc
Initial Delay     ID    pass         s

Scan Rate         SR    500.0E-3     mV/s     Curr. Range     CR   Auto
Scan Incr.        SI    2.000        mV       Step Time       ST   4.000         s
No. of Points     NP    250

                                              GI Time Const.  TC   off
Line Sync.        LS    no                    IR Mode         IR   none
Rise Time         RT    high stability        Filter          FL   I 5.3Hz
Working Elec.     WE    Solid                  Ref. Elec.      RE   AgCl   197.0E-3V
Sample Area       AR    1.000        cm^2     Equiv. Wt.      EW   0.0000         g
Density           DE    0.0000       g/ml     AUX A/D         AU   no
Open Circuit      OC    396.0E-3     V

Comment:  Hydrogenated Carbon. DI water. O2 Saturated. Sample #3

Rp CALCULATIONS:
Corrosion Rate =  N.A.                   Correlation = -998.4E-3
Rp = 5.281 MOhms
E(I=0) = 411.6 mV                        Icorr(R) = 13.72 nA/cm^2
Beta Anodic = 501.3E-3                   Beta Cathodic = 250.1E-3 V/decade
Begin = 298.0 mV                         End = 430.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                   Chi^2 =  1.48E-001
E(I=0) = 415.6 mV                        Icorr = 9.987 nA/cm^2
Beta Anodic = 501.3E-3                   Beta Cathodic = 250.1E-3 V/decade
Begin = 230.0 mV                         End = 636.0 mV

          ———— hcdi3.t
```

Model 352/252 Corrosion Analysis Software. v. 2.10
Filename: c:\m352\data\nicdil.t
TA TAFEL                              File Status: NORMAL
Date Run: UNKNOWN                     Time Run: UNKNOWN

Cond. Time      CT  pass      s      Initial Pot.  IP  -250.0E-3    V oc
Cond. Pot.      CP  pass      V      Final Pot.    FP   250.0E-3    V oc
Initial Delay   ID  pass      s

Scan Rate       SR  500.0E-3  mV/s   Curr. Range   CR  Auto
Scan Incr.      SI  2.000     mV     Step Time     ST  4.000        s
No. of Points   NP  250
                                     GI Time Const. TC  Off
Line Sync.      LS  no                IR Mode       IR  none
Rise Time       RT  high stability    Filter        FL  I 5.0Hz
Working Elec.   WE  Solid             Ref. Elec.    RE  AgCl  197.0E-3V
Sample Area     AR  1.000     cm^2   Equiv. Wt.    EW  0.0000       s
Density         DE  0.0000    g/ml   AUX A/D       AU  no
Open Circuit    OC  450.0E-3  V

Comment: 20% Nitrogenated Carbon. DI water. O2 saturated. Sample #1


Rp CALCULATIONS:
Corrosion Rate =   N.A.              Correlation = -989.7E-3
Rp = 6.044 MOhms
E(I=0) = 560.0 mV                    Icorr(R) = 6.762 nA/cm^2
Beta Anodic = 211.4E-3               Beta Cathodic = 169.6E-3 V/decade
Begin = 520.0 mV                     End = 600.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =   N.A.              Chi^2 = 5.50E+000
E(I=0) = 560.4 mV                    Icorr = 7.435 nA/cm^2
Beta Anodic = 211.4E-3               Beta Cathodic = 169.6E-3 V/decade
Begin = 314.0 mV                     End = 642.0 mV

———— nicdil.t



$E$ vs. AgCl (mV) versus I/area (A/cm^2)

Model 352/252 Corrosion Analysis Software, v. 2.10
Filename: c:\m352\data\nicdi2.t
TA TAFEL
Date Run: UNKNOWN

File Status: NORMAL
Time Run: UNKNOWN

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cond. Time | CT | pass | s | Initial Pot. | IP | -250.0E-3 | V oc |
| Cond. Pot. | CP | pass | V | Final Pot. | FP | 250.0E-3 | V oc |
| Initial Delay | ID | pass | s | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Scan Rate | SR | 500.0E-3 | mV/s | Curr. Range | CR | Auto | |
| Scan Incr. | SI | 2.000 | mV | Step Time | ST | 4.000 | s |
| No. of Points | NP | 250 | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | GI Time Const. | TC | Off | |
| Line Sync. | LS | no | | IR Mode | IR | none | |
| Rise Time | RT | high stability | | Filter | FL | I 5.3Hz | |
| Working Elec. | WE | Solid | | Ref. Elec. | RE | AgCl 197.0E-3V | |
| Sample Area | AR | 1.000 | cm^2 | Equiv. Wt. | EW | 0.0000 | g |
| Density | DE | 0.0000 | g/ml | AUX A/D | AU | no | |
| Open Circuit | OC | 206.0E-3 | V | | | | |

Comment: 20x Nitrogenated Carbon. DI water. O2 saturated. Sample #2

Rp CALCULATIONS:
Corrosion Rate = N.A.
Rp = 6.403 MOhms
E(I=0) = 272.1 mV
Beta Anodic = 100.0E-3
Begin = 212.0 mV

Correlation = -981.8E-3

Icorr(R) = 3.391 nA/cm^2
Beta Cathodic = 100.0E-3 V/decade
End = 316.0 mV

TAFEL CALCULATIONS:
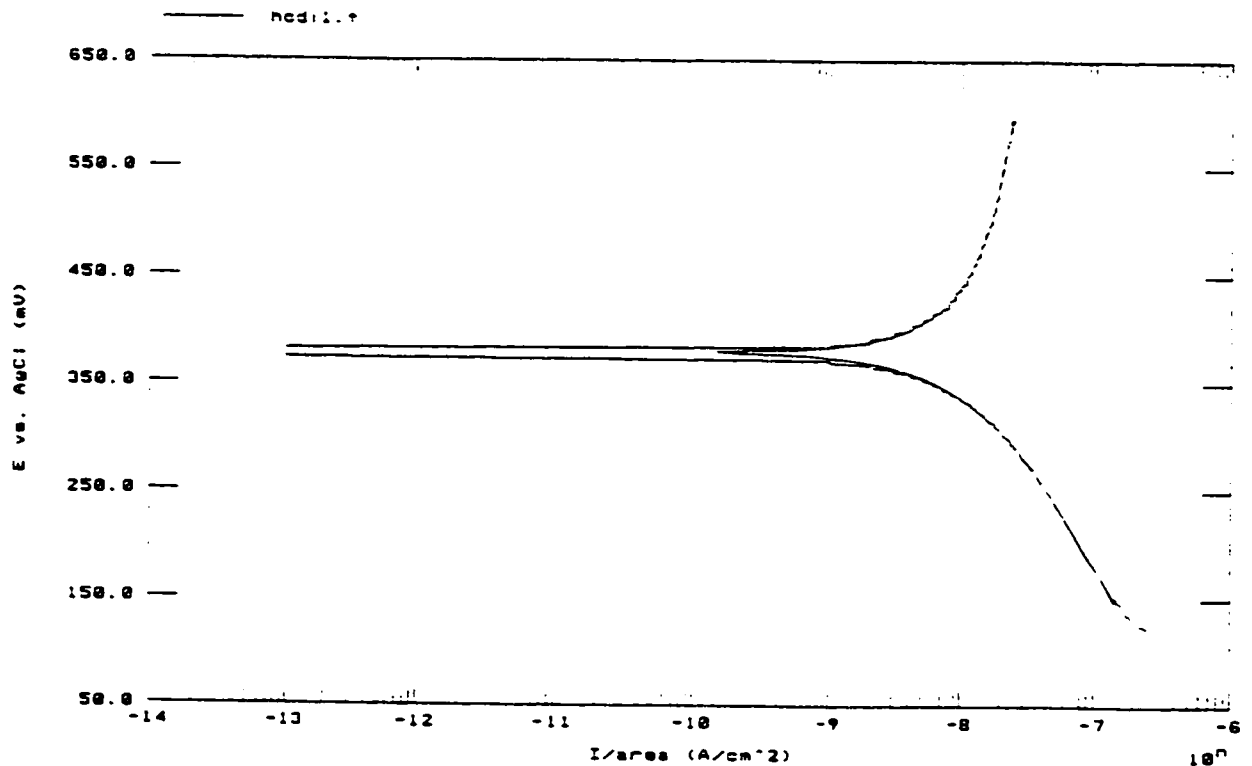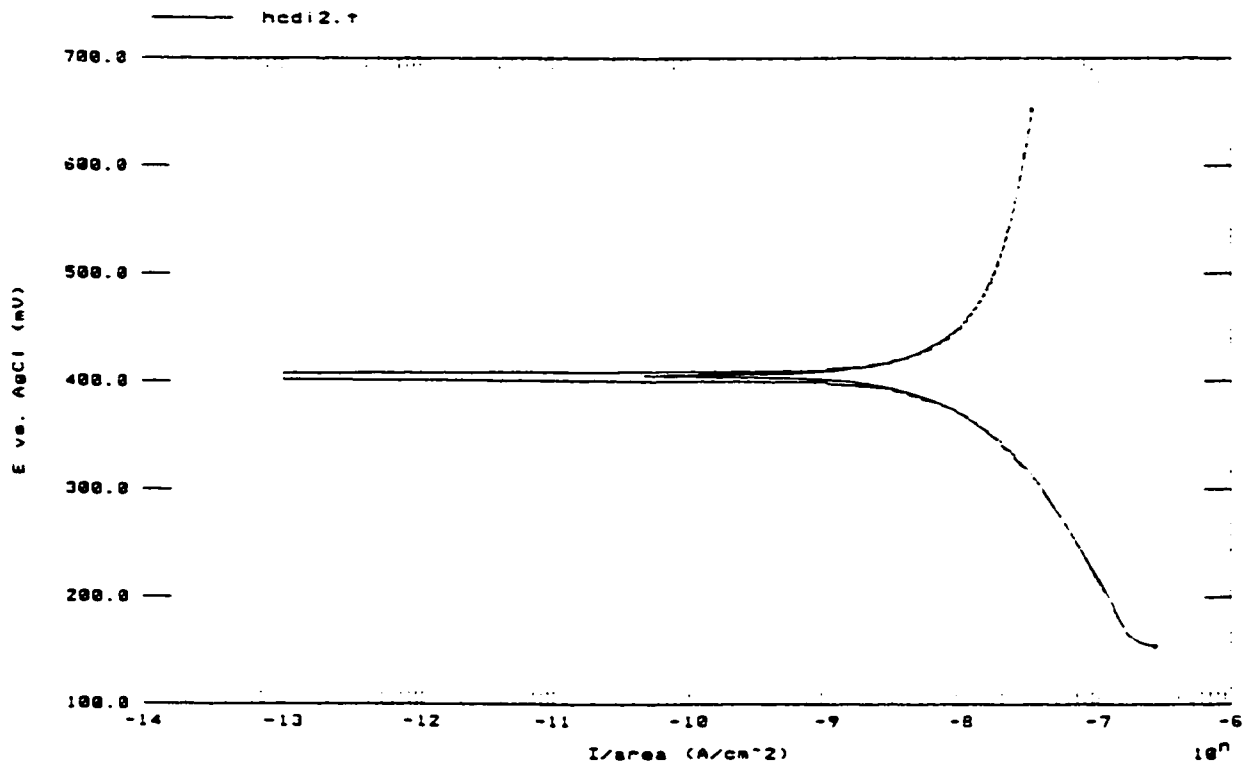Corrosion Rate = N.A.
E(I=0) = 269.2 mV
Beta Anodic = 307.4E-3
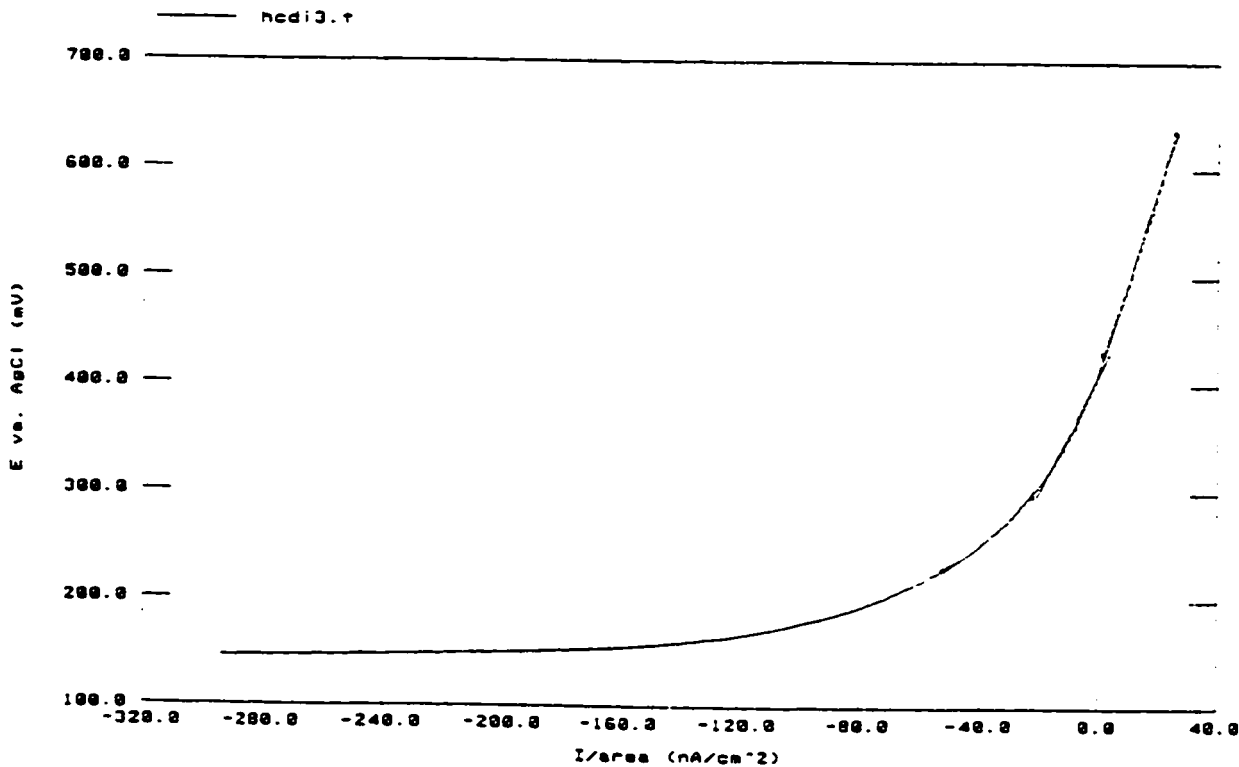Begin = 22.00 mV

Chi^2 = 5.35E+000
Icorr = 5.095 nA/cm^2
Beta Cathodic = 132.3E-3 V/decade
End = 482.0 mV

——— nicdi2.t



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Model 352/252 Corrosion Analysis Software. v. 2.10
Filename: c:\m352\data\nicdi3.t
TA TAFEL                                          File Status:  NORMAL
Date Run:  UNKNOWNN                               Time Run:  UNKNOWNN

Cond. Time        CT    pass          s       Initial Pot.    IP   -250.0E-3    V oc
Cond. Pot.        CP    pass          V       Final Pot.      FP    250.0E-3    V oc
Initial Delay     ID    pass          s

Scan Rate         SR    500.0E-3      mV/s    Curr. Range     CR    Auto
Scan Incr.        SI    2.000         mV      Step Time       ST    4.000        s
No. of Points     NP    250
                                              GI Time Const.  TC    Off
Line Sync.        LS    no                    IR Mode         IR    none
Rise Time         RT    high stability        Filter          FL    I 5.3Hz
Working Elec.     WE    Solid                 Ref. Elec.      RE    AgCl :97.0E-3V
Sample Area       AR    1.000         cm^2    Equiv. Wt.      EW    0.3000        g
Density           DE    0.0000        g/ml    AUX A/D         AU    no
Open Circuit      OC    166.0E-3      V

Comment:   20% Nitrogenated Carbon. DI water. O2 saturated. Sample3

Rp CALCULATIONS:
Corrosion Rate =   N.A.                Correlation = -942.0E-3
Rp = 7.311 MOhms
E(I=0) = 294.3 mV                      Icorr(R) = 2.970 nA/cm^2
Beta Anodic = 100.0E-3                 Beta Cathodic = 100.0E-3 V/decade
Begin = 154.0 mV                       End = 346.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                Chi^2 =  1.14E-001
E(I=0) = 298.3 mV                      Icorr = 3.214 nA/cm^2
Beta Anodic = 991.0E-3                 Beta Cathodic = 157.8E-3 V/decade
Begin = 48.00 mV                       End = 362.0 mV

——— nicdi3.t



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Model 352/252 Corrosion Analysis Software, v.  2.10
Filename:  c:\m352\data\n2dil.t
TA TAFEL                                     File Status:  NORMAL
Date Run:  UNKNOWNN                          Time Run:  UNKNOWNN

Cond. Time        CT    pass        s       Initial Pot.    IP   -250.0E-3    V oc
Cond. Pot.        CP    pass        V       Final Pot.      FP    250.0E-3    V oc
Initial Delay     IC    pass        s

Scan Rate         SR    500.0E-3    mV/s    Curr. Range     CR   Auto
Scan Incr.        SI    2.000       mV      Step Time       ST   4.000        s
No. of Points     NP    250
                                            GI Time Const.  TC   Off
Line Sync.        LS    no                  IR Mode         IR   none
Rise Time         RT    high stability      Filter          FL   I 5.3Hz
Working Elec.     WE    Solid               Ref. Elec.      RE   AgCl  197.0E-3V
Sample Area       AR    1.000       cm^2    Equiv. Wt.      EW   0.0000       g
Density           DE    0.0000      g/ml    AUX A/D         AU   no
Open Circuit      OC    485.0E-3    V

Comment:  30 x Nitrogen, DI water, O2 Saturated, Sample#1

Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -989.7E-3
Rp = 8.315 MOhms
E(I=0) = 586.3 mV                   Icorr(R) = 2.611 nA/cm^2
Beta Anodic = 100.0E-3              Beta Cathodic = 100.0E-3 V/decade
Begin = 529.0 mV                    End = 627.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 = 1.46E-001
E(I=0) = 586.0 mV                   Icorr = 7.274 nA/cm^2
Beta Anodic = 343.9E-3              Beta Cathodic = 227.1E-3 V/decade
Begin = 337.0 mV                    End = 733.0 mV

——— n2dil.t



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Model 352/252 Corrosion Analysis Software. v.   2.18
Filename:   c:\m352\data\N2CI2.T
TA TAFEL                                    File Status:   NORMAL
Date Run:   UNKNOWN                         Time Run:   UNKNOWN

Cond. Time      CT    pass       s      Initial Pot.    IP    -250.0E-3    V oc
Cond. Pot.      CP    pass       V      Final Pot.      FP     250.0E-3    V oc
Initial Delay   ID    pass       s

Scan Rate       SR    500.0E-3   mV/s   Curr. Range     CR    Auto
Scan Incr.      SI    2.000      mV     Step Time       ST    4.000          s
No. of Points   NP    250
                                        GI Time Const.  TC    Off
Line Sync.      LS    no                IR Mode         IR    none
Rise Time       RT    high stability    Filter          FL    I 5.3Hz
Working Elec.   WE    Solid             Ref. Elec.      RE    AgCl  197.0E-3V
Sample Area     AR    1.000      cm^2   Equiv. Wt.      EW    0.0000         g
Density         DE    0.0000     g/ml   AUX A/D         AU    no
Open Circuit    OC    499.0E-3   V

Comment:   30x Nitrogenated Carbon, DI water, O2 Saturated, Sample#2


Rp CALCULATIONS:
Corrosion Rate =   N.A.                 Correlation = -994.4E-3
Rp = 8.421 MOhms
E(I=0) = 562.0 mV                       Icorr(R) = 2.579 nA/cm^2
Beta Anodic = 100.0E-3                  Beta Cathodic = 100.0E-3 V/decade
Begin = 545.0 mV                        End = 639.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                 Chi^2 =  7.86E-002
E(I=0) = 563.3 mV                       Icorr = 9.983 nA/cm^2
Beta Anodic = 556.0E-3                  Beta Cathodic = 225.3E-3 V/decade
Begin = 319.0 mV                        End = 713.0 mV

————— N2CI2.T

Model 352/252 Corrosion Analysis Software. v.  2.10
Filename:  c:\m352\data\N2C0I3.T
TA TAFEL
Date Run:  UNKNOWN

File Status:  NORMAL
Time Run:  UNKNOWN

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Cond. Time | CT | pass | s | Initial Pot. | IP | -250.0E-3 | V oc |
| Cond. Pot. | CP | pass | V | Final Pot. | FP | 250.0E-3 | V oc |
| Initial Delay | ID | pass | s | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Scan Rate | SR | 500.0E-3 | mV/s | Curr. Range | CR | Auto | |
| Scan Incr. | SI | 2.000 | mV | Step Time | ST | 4.000 | s |
| No. of Points | NP | 250 | | | | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | GI Time Const. | TC | off | |
| Line Sync. | LS | no | | IR Mode | IR | none | |
| Rise Time | RT | high stability | | Filter | FL | I 5.3Hz | |
| Working Elec. | WE | Solid | | Ref. Elec. | RE | AgCl  197.0E-3V | |
| Sample Area | AR | 1.000 | cm^2 | Equiv. Wt. | EW | 0.0000 | g |
| Density | DE | 0.0000 | g/ml | AUX A/D | AU | no | |
| Open Circuit | OC | 499.0E-3 | V | | | | |

Comment:  30% Nitrogenated Carbon, DI water, O2 saturated, Sample#3

Rp CALCULATIONS:
Corrosion Rate =  N.A.
Rp = 7.881 MOhms
E(I=0) = 563.7 mV
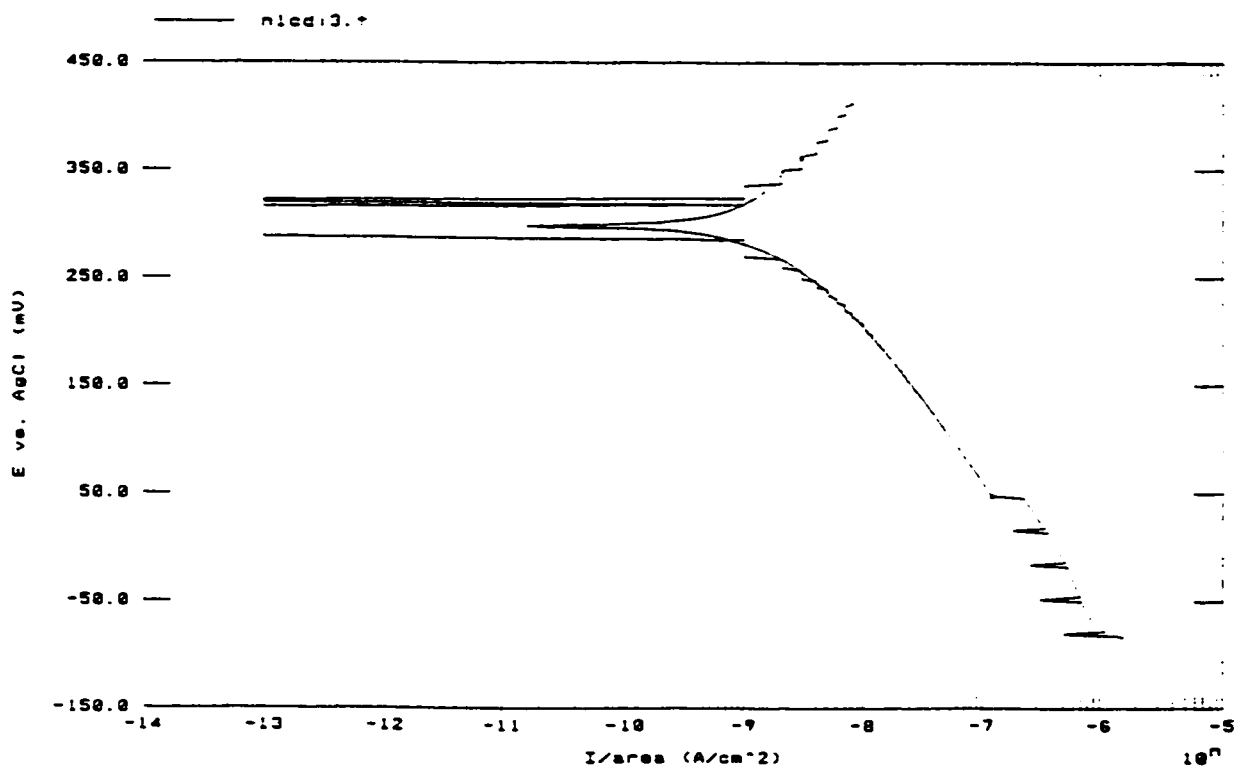Beta Anodic = 100.0E-3
Begin = 533.0 mV

Correlation = -992.9E-3

Icorr(R) = 2.755 nA/cm^2
Beta Cathodic = 100.0E-3 V/decade
End = 627.0 mV

TAFEL CALCULATIONS:
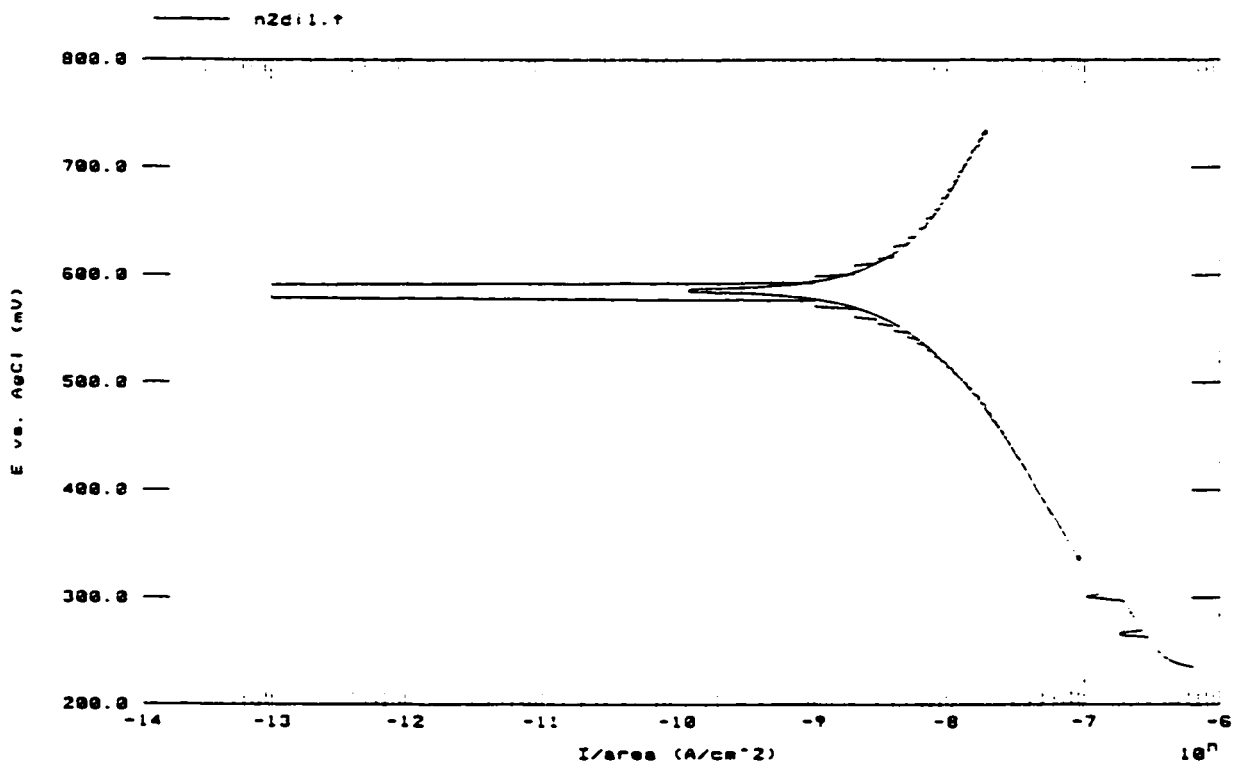Corrosion Rate =  N.A.
E(I=0) = 564.0 mV
Beta Anodic = 489.6E-3
Begin = 333.0 mV

Chi^2 =  9.68E-002
Icorr = 9.390 nA/cm^2
Beta Cathodic = 220.3E-3 V/decade
End = 747.0 mV

———— N2C0I3.T



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Model 352/252 Corrosion Analysis Software. v.   2.10
Filename:  c:\m352\data\@CHCL1.t
TA TAFEL                                    File Status:  NORMAL
Date Run:   UNKNOWNN                        Time Run:   UNKNOWNN

Cond. Time       CT    pass        s       Initial Pot.    IP   -250.0E-3    V oc
Cond. Pot.       CP    pass        V       Final Pot.      FP    250.0E-3    V oc
Initial Delay    IO    pass        s

Scan Rate        SR    500.0E-3    mV/s    Curr. Range     CR   Auto
Scan Incr.       SI    2.000       mV      Step Time       ST   4.000        s
No. of Points    NP    250
                                           GI Time Const.  TC   off
Line Sync.       LS    no                  IR Mode         IR   none
Rise Time        RT    high stability      Filter          FL   : 5.3Hz
Working Elec.    WE    Solid               Ref. Elec.      RE   AgCl  197.0E-3V
Sample Area      AR    1.000       cm^2    Equiv. Wt.      EW   0.0000       g
Density          DE    0.0000      g/ml    AUX A/D         AU   no
Open Circuit     OC    253.0E-3    V

Comment:  No Carbon, 7.5 ppmw HCl, O2 Saturated. Sample #1


Rp CALCULATIONS:
Corrosion Rate =   N.A.                    Correlation = -998.1E-3
Rp = 15.84 KOhms
E(I=0) = 294.6 mV                          Icorr(R) = 1.371 uA/cm^2
Beta Anodic = 100.0E-3                     Beta Cathodic = 100.0E-3 V/decade
Begin = 285.0 mV                           End = 389.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                    Chi^2 =  1.50E+003
E(I=0) = 294.6 mV                          Icorr = 4.132 uA/cm^2
Beta Anodic = 369.7E-3                     Beta Cathodic = 434.6E-3 V/decade
Begin = 45.00 mV                           End = 439.0 mV

───────  @CHCL1.t

Model 352/252 Corrosion Analysis Software. v.  2.10
Filename:  c:\m352\data\nochcl2.t
TA TAFEL                                    File Status:  NORMAL
Date Run:  UNKNOWNN                         Time Run:  UNKNOWNN

Cond. Time        CT    pass        s       Initial Pot.   IP   -250.0E-3      V oc
Cond. Pot.        CP    pass        V       Final Pot.     FP    250.0E-3      V oc
Initial Delay     ID    pass        s

Scan Rate         SR    500.0E-3    mV/s    Curr. Range    CR    Auto
Scan Incr.        SI    2.000       mV      Step Time      ST    4.000          s
No. of Points     NP    250
                                            GI Time Const. TC    Off
Line Sync.        LS    no                  IR Mode        IR    none
Rise Time         RT    high stability      Filter         FL    I 5.3Hz
Working Elec.     WE    Solid               Ref. Elec.     RE    AgCl   197.0E-3V
Sample Area       AR    1.000       cm^2    Equiv. Wt.     EW    0.0000         g
Density           DE    0.0000      g/ml    AUX A/D        AU    no
Open Circuit      OC    482.0E-3    V

Comment:  No Carbon. 7.5 ppmu HCl. O2 saturated. Sample#2


Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -885.0E-3
Rp = 28.54 KOhms
E(I=0) = 503.6 mV                   Icorr(R) = 3.592 uA/cm^2
Beta Anodic = 307.8E-3              Beta Cathodic = 1.013 V/decade
Begin = 476.0 mV                    End = 518.3 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 = 7.96E+002
E(I=0) = 503.8 mV                   Icorr = 3.721 uA/cm^2
Beta Anodic = 307.8E-3              Beta Cathodic = 1.013 V/decade
Begin = 254.0 mV                    End = 730.0 mV


            ———— nochcl2.t

Model 352/252 Corrosion Analysis Software, v.  2.10
Filename:  c:\m352\data\NoCHCL3.t
TA TAFEL                                      File Status:  NORMAL
Date Run:  UNKNOWN                            Time Run:  UNKNOWN

Cond. Time        CT    pass          s      Initial Pot.    IP   -250.0E-3      V oc
Cond. Pot.        CP    pass          V      Final Pot.      FP    250.0E-3      V oc
Initial Delay     ID    pass          s

Scan Rate         SR    500.0E-3      mV/s   Curr. Range     CR   Auto
Scan Incr.        SI    2.000         mV     Step Time       ST   4.000          s
No. of Points     NP    250
                                             GI Time Const.  TC   off
Line Sync.        LS    no                   IR Mode         IR   none
Rise Time         RT    high stability       Filter          FL   I 5.3Hz
Working Elec.     WE    Solid                Ref. Elec.      RE   AgCl  197.0E-3V
Sample Area       AR    1.000         cm^2   Equiv. Wt.      EW   0.3000         g
Density           DE    0.0000        g/ml   AUX A/D         AU   no
Open Circuit      OC    254.0E-3      V

Comment:  No Carbon, 7.5 ppmw HCl, O2 saturated, Sample #3

Rp CALCULATIONS:
Corrosion Rate =  N.A.               Correlation = -909.8E-3
Rp = 22.36 KOhms
E(I=0) = 278.6 mV                    Icorr(R) = 971.3 nA/cm^2
Beta Anodic = 100.0E-3               Beta Cathodic = 100.0E-3 V/decade
Begin = 254.0 mV                     End = 294.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.               Chi^2 =  1.20E+003
E(I=0) = 273.3 mV                    Icorr = 4.934 uA/cm^2
Beta Anodic = 1.320E27               Beta Cathodic = 292.4E-3 V/decade
Begin = 78.00 mV                     End = 294.0 mV

─────────  NoCHCL3.t



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Model 352/252 Corrosion Analysis Software. v.    2.10
Filename:   c:\m352\data\ACHCL1.t
TA TAFEL                                          File Status:   NORMAL
Date Run:   UNKNOWN                               Time Run:   UNKNOWN

Cond. Time        CT    pass        s     Initial Pot.     IP    300.0E-3    V
Cond. Pot.        CP    pass        V     Final Pot.       FP    900.0E-3    V
Initial Delay     ID    pass        s

Scan Rate         SR    500.0E-3    mV/s  Curr. Range      CR    Auto
Scan Incr.        SI    2.000       mV    Step Time        ST    4.000       s
No. of Points     NP    300
                                          GI Time Const.   TC    off
Line Sync.        LS    no                IR Mode          IR    none
Rise Time         RT    high stability    Filter           FL    I 5.3Hz
Working Elec.     WE    Solid             Ref. Elec.       RE    AgCl  197.0E-3V
Sample Area       AR    1.000       cm^2  Equiv. Wt.       EW    3.0000      g
Density           DE    0.0000      g/ml  AUX A/D          AU    no
Open Circuit      OC    476.0E-3    V

Comment:   Argon Carbon. 7.5 ppmw HCl. O2 Saturated. Sample 1

Rp CALCULATIONS:
Corrosion Rate =  N.A.                Correlation = -974.2E-3
Rp = 2.928 MOhms
E(I=0) = 718.0 mV                     Icorr(R) = 7.417 nA/cm^2
Beta Anodic = 100.0E-3                Beta Cathodic = 100.0E-3 V/decade
Begin = 658.0 mV                      End = 754.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                Chi^2 =  5.76E+000
E(I=0) = 723.6 mV                     Icorr = 18.73 nA/cm^2
Beta Anodic = 121.4E-3                Beta Cathodic = 901.3E-3 V/decade
Begin = 522.0 mV                      End = 844.0 mV

——————  ACHCL1.t



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Model 352/252 Corrosion Analysis Software. v. 2.18
Filename: c:\m352\data\ACHCL2.t
TA TAFEL                                    File Status: NORMAL
Date Run: UNKNOWN                           Time Run: UNKNOWN

Cond. Time       CT   pass        s      Initial Pot.   IP   300.0E-3    V
Cond. Pot.       CP   pass        V      Final Pot.     FP   850.0E-3    V
Initial Delay    ID   pass        s

Scan Rate        SR   500.0E-3   mV/s    Curr. Range    CR   Auto
Scan Incr.       SI   2.000      mV      Step Time      ST   4.000       s
No. of Points    NP   275
                                         GI Time Const. TC   Off
Line Sync.       LS   no                 IR Mode        IR   none
Rise Time        RT   high stability     Filter         FL   I 5.3Hz
Working Elec.    WE   Solid              Ref. Elec.     RE   AgCl   197.0E-3V
Sample Area      AR   1.000      cm^2    Equiv. Wt.     EW   0.0000      g
Density          DE   0.3000     g/ml    AUX A/D        AU   no
Open Circuit     OC   495.0E-3   V

Comment:  Argon Carbon. 7.5 ppmw HCl. O2 Saturated. Sample #2

Rp CALCULATIONS:
Corrosion Rate = N.A.              Correlation = -951.3E-3
Rp = 2.803 MOhms
E(I=0) = 709.4 mV                  Icorr(R) = 7.748 nA/cm^2
Beta Anodic = 100.0E-3             Beta Cathodic = 100.0E-3 V/decade
Begin = 674.0 mV                   End = 748.0 mV


TAFEL CALCULATIONS:
Corrosion Rate = N.A.              Chi^2 = 5.83E+000
E(I=0) = 712.7 mV                  Icorr = 12.80 nA/cm^2
Beta Anodic = 110.6E-3             Beta Cathodic = 188.2E-3 V/decade
Begin = 592.0 mV                   End = 796.0 mV

———— ACHCL2.t

Model 352/252 Corrosion Analysis Software, v. 2.10
Filename: c:\m352\data\achcl3.t
TA TAFEL
Date Run: UNKNOWN

File Status: NORMAL
Time Run: UNKNOWN

| Cond. Time | CT | pass | s | Initial Pot. | IP | -150.0E-3 | V oc |
| Cond. Pot. | CP | pass | V | Final Pot. | FP | 300.0E-3 | V oc |
| Initial Delay | ID | pass | s | | | | |

| Scan Rate | SR | 500.0E-3 | mV/s | Curr. Range | CR | Auto | |
| Scan Incr. | SI | 2.000 | mV | Step Time | ST | 4.000 | s |
| No. of Points | NP | 225 | | | | | |

| | | | | GI Time Const. | TC | Off | |
| Line Sync. | LS | no | | IR Mode | IR | none | |
| Rise Time | RT | high stability | | Filter | FL | I 5.3Hz | |
| Working Elec. | WE | Solid | | Ref. Elec. | RE | AgCl 197.0E-3V | |
| Sample Area | AR | 1.000 | cm^2 | Equiv. Wt. | EW | 0.0000 | s |
| Density | DE | 0.0000 | g/ml | AUX A/D | AU | no | |
| Open Circuit | OC | 507.0E-3 | V | | | | |

Rp CALCULATIONS:
Corrosion Rate = N.A.
Rp = 5.474 MOhms
E(I=0) = 716.0 mV
Beta Anodic = 130.1E-3
Begin = 675.0 mV

Correlation = -989.6E-3

Icorr(R) = 7.960 nA/cm^2
Beta Cathodic = 438.4E-3 V/decade
End = 749.0 mV

TAFEL CALCULATIONS:
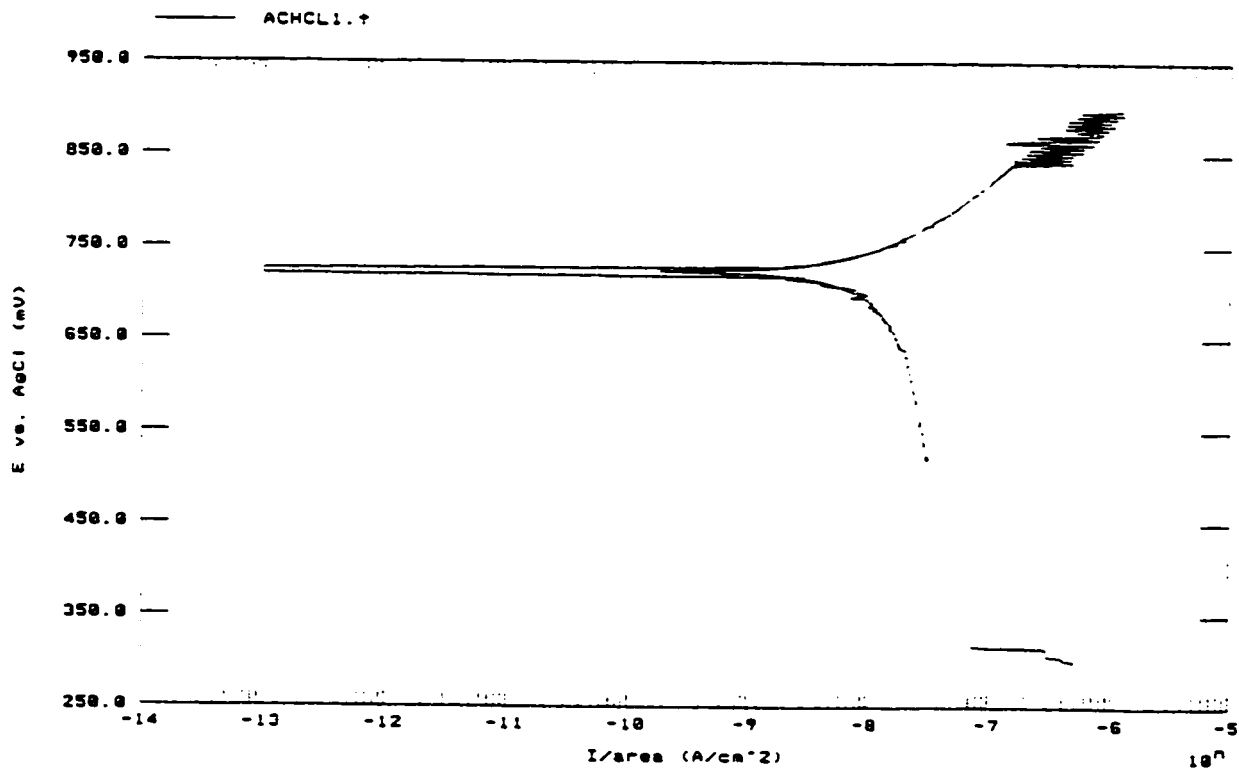Corrosion Rate = N.A.
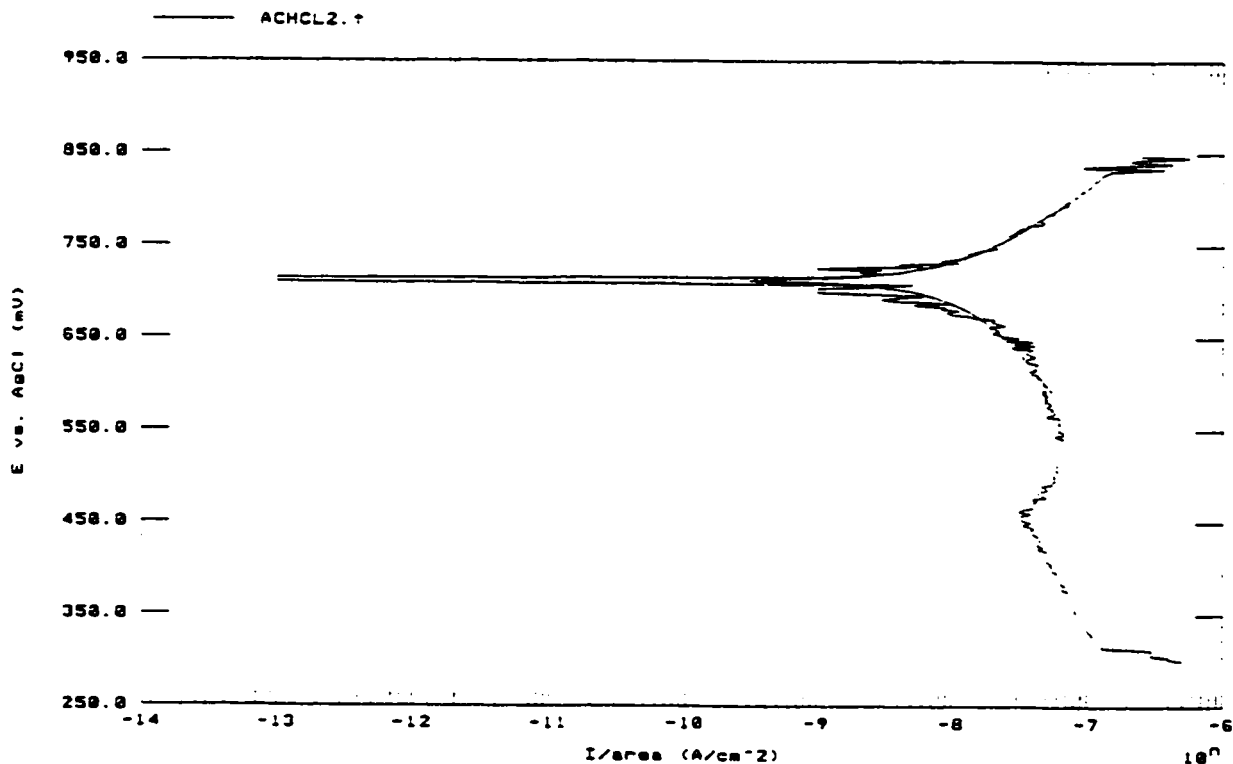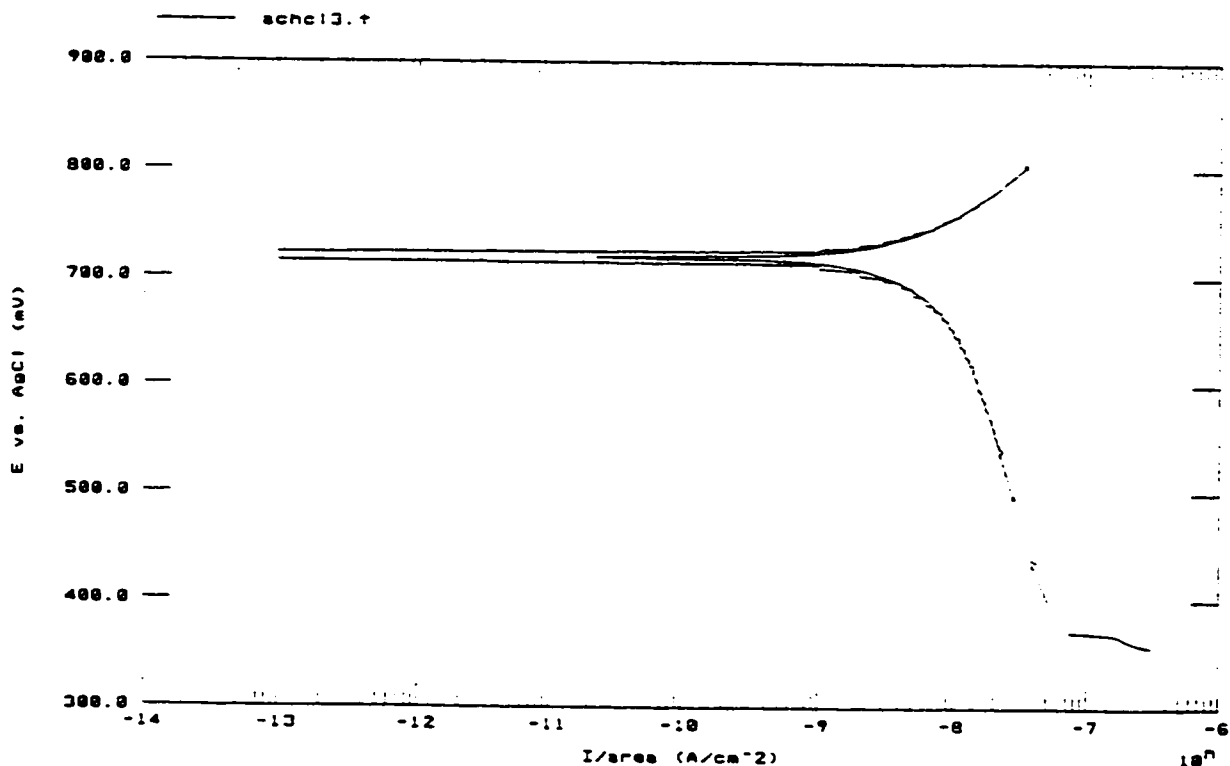E(I=0) = 718.9 mV
Beta Anodic = 130.1E-3
Begin = 497.0 mV

Chi^2 = 1.05E-001
Icorr = 8.700 nA/cm^2
Beta Cathodic = 438.4E-3 V/decade
End = 805.0 mV

———— achcl3.t

Model 352/252 Corrosion Analysis Software. v.   2.10
Filename:  c:\m352\data\HCHCL1.t
TA TAFEL                                    File Status:  NORMAL
Date Run:  UNKNOWN                          Time Run:  UNKNOWN

Cond. Time       CT    pass        s      Initial Pot.   IP    500.0E-3      V
Cond. Pot.       CP    pass        V      Final Pot.     FP    1.000         V
Initial Delay    ID    pass        s

Scan Rate        SR    500.0E-3    mV/s   Curr. Range    CR    Auto
Scan Incr.       SI    2.000       mV     Step Time      ST    4.000         s
No. of Points    NP    250
                                          GI Time Const. TC    Off
Line Sync.       LS    no                 IR Mode        IR    none
Rise Time        RT    high stability     Filter         FL    ± 5.3Hz
Working Elec.    WE    Solid              Ref. Elec.     RE    AgCl   197.0E-3V
Sample Area      AR    1.000       cm^2   Equiv. Wt.     EW    0.0000        g
Density          DE    0.0000      g/ml   AUX A/D        AU    no
Open Circuit     OC    469.0E-3    V

Comment:  Hydrogenated Carbon. 7.5 ppmw HCl. O2 saturated. Sample#1


Rp CALCULATIONS:
Corrosion Rate =  N.A.                Correlation = -982.0E-3
Rp = 1.679 MOhms
E(I=0) = 833.9 mV                     Icorr(R) = 12.94 nA/cm^2
Beta Anodic = 100.0E-3                Beta Cathodic = 100.0E-3 V/decade
Begin = 794.0 mV                      End = 882.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                Chi^2 =  1.34E-001
E(I=0) = 839.3 mV                     Icorr = 34.32 nA/cm^2
Beta Anodic = 140.5E-3                Beta Cathodic = 98.62E6 V/decade
Begin = 694.0 mV                      End = 928.0 mV


———————  HCHCL1.t



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Model 352/252 Corrosion Analysis Software, v.   2.10
Filename:  c:\m352\data\HCHCL2.t
TA TAFEL                                    File Status:  NORMAL
Date Run:  UNKNOWN                          Time Run:  UNKNOWN

Cond. Time        CT    pass       s      Initial Pot.    IP    400.0E-3    V
Cond. Pot.        CP    pass       V      Final Pot.      FP    950.0E-3    V
Initial Delay     ID    pass       s

Scan Rate         SR    500.0E-3   mV/s   Curr. Range     CR    Auto
Scan Incr.        SI    2.000      mV     Step Time       ST    4.000       s
No. of Points     NP    275
                                          GI Time Const.  TC    off
Line Sync.        LS    no                IR Mode         IR    none
Rise Time         RT    high stability    Filter          FL    I 5.3Hz
Working Elec.     WE    Solid             Ref. Elec.      RE    AgCl  197.0E-3V
Sample Area       AR    1.000      cm^2   Equiv. Wt.      EW    0.0000      g
Density           DE    0.0000     g/ml   AUX A/D         AU    no
Open Circuit      OC    421.0E-3   V

Comment:  Hydrogenated Carbon, 7.5 ppmw HCl, O2 Saturated, Sample #2

Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -970.0E-3
Rp = 1.368 MOhms
E(I=0) = 756.9 mV                   Icorr(R) = 15.88 nA/cm^2
Beta Anodic = 100.0E-3              Beta Cathodic = 100.0E-3 V/decade
Begin = 714.0 mV                    End = 814.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 =  6.99E-002
E(I=0) = 764.3 mV                   Icorr = 30.68 nA/cm^2
Beta Anodic = 116.5E-3              Beta Cathodic = 4.995 V/decade
Begin = 586.0 mV                    End = 844.3 mV

——————  HCHCL2.t



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Model 352/252 Corrosion Analysis Software. v.   2.10
Filename:   c:\m352\data\HCHCL3.t
TA TAFEL                                    File Status:  NORMAL
Date Run:   UNKNOWN                         Time Run:   UNKNOWN

Cond. Time      CT    pass        s     Initial Pot.    IP   400.0E-3    V
Cond. Pot.      CP    pass        V     Final Pot.      FP   950.0E-3    V
Initial Delay   ID    pass        s

Scan Rate       SR    500.0E-3    mV/s  Curr. Range     CR   Auto
Scan Incr.      SI    2.300       mV    Step Time       ST   4.000        s
No. of Points   NP    275
                                        GI Time Const.  TC   Off
Line Sync.      LS    no               IR Mode         IR   none
Rise Time       RT    high stability   Filter          FL   I 5.3Hz
Working Elec.   WE    Solid            Ref. Elec.      RE   AgCl   197.0E-3V
Sample Area     AR    1.000       cm^2  Equiv. Wt.      EW   0.0000       g
Density         DE    0.0000      g/ml  AUX A/D         AU   no
Open Circuit    OC    437.0E-3    V

Comment:  Hydrogenated Carbon. 7.5 ppmw HCl. O2 saturated. Sample#3

Rp CALCULATIONS:
Corrosion Rate =  N.A.                  Correlation = -976.7E-3
Rp = 1.519 MOhms
E(I=0) = 819.2 mV                       Icorr(R) = 14.29 nA/cm^2
Beta Anodic = 100.0E-3                  Beta Cathodic = 100.0E-3 V/decade
Begin = 774.0 mV                        End = 866.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                  Chi^2 =  1.09E-001
E(I=0) = 826.2 mV                       Icorr = 31.68 nA/cm^2
Beta Anodic = 113.4E-3                  Beta Cathodic = 5.335 V/decade
Begin = 570.0 mV                        End = 896.0 mV
```

——————— HCHCL3.t



E vs. AgCl (mV)

I/area (A/cm^2)

Model 352/252 Corrosion Analysis Software, v. 2.10
Filename: c:\m352\data\nihcl1.t
TA TAFEL                                    File Status: NORMAL
Date Run: UNKNOWNN                          Time Run: UNKNOWNN

Cond. Time        CT   pass         s      Initial Pot.    IP   500.0E-3    V
Cond. Pot.        CP   pass         V      Final Pot.      FP   1.000       V
Initial Delay     ID   pass         s

Scan Rate         SR   500.0E-3     mV/s   Curr. Range     CR   Auto
Scan Incr.        SI   2.000        mV     Step Time       ST   4.000       s
No. of Points     NP   250
                                           GI Time Const.  TC   Off
Line Sync.        LS   no                  IR Mode         IR   none
Rise Time         RT   high stability      Filter          FL   I 5.3Hz
Working Elec.     WE   Solid              Ref. Elec.      RE   AgCl  197.0E-3V
Sample Area       AR   1.000        cm^2   Equiv. Wt.      EW   0.0000      s
Density           DE   0.0000       g/ml   AUX A/D         AU   no
Open Circuit      OC   447.0E-3     V

Comment: 20x Nitrogenated Carbon, 7.5 ppmu HCl, O2 Saturated, Sample#1

Rp CALCULATIONS:
Corrosion Rate = N.A.                      Correlation = -940.3E-3
Rp = 3.628 MOhms
E(I=0) = 701.9 mV                          Icorr(R) = 13.66 nA/cm^2
Beta Anodic = 123.7E-3                     Beta Cathodic = 1.465 V/decade
Begin = 548.0 mV                           End = 748.0 mV

TAFEL CALCULATIONS:
Corrosion Rate = N.A.                      Chi^2 = 1.45E-001
E(I=0) = 711.8 mV                          Icorr = 25.83 nA/cm^2
Beta Anodic = 123.7E-3                     Beta Cathodic = 1.465 V/decade
Begin = 532.0 mV                           End = 798.0 mV

———————— nihcl1.t



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Model 352/252 Corrosion Analysis Software, v.   2.18
Filename:   c:\m352\data\N1HCL2.t
TA TAFEL                                    File Status:   NORMAL
Date Run:   UNKNOWN                         Time Run:   UNKNOWN

Cond. Time        CT    pass        s       Initial Pot.    IP    400.0E-3    V
Cond. Pot.        CP    pass        V       Final Pot.      FP    950.0E-3    V
Initial Delay     ID    pass        s

Scan Rate         SR    500.0E-3    mV/s    Curr. Range     CR    Auto
Scan Incr.        SI    2.000       mV      Step Time       ST    4.000       s
No. of Points     NP    275
                                            GI Time Const.  TC    Off
Line Sync.        LS    no                  IR Mode         IR    none
Rise Time         RT    high stability      Filter          FL    I 5.3Hz
Working Elec.     WE    Solid               Ref. Elec.      RE    AgCl    197.0E-3V
Sample Area       AR    1.000       cm^2    Equiv. Wt.      EW    0.0000      g
Density           DE    0.0000      g/ml    AUX A/D         AU    no
Open Circuit      OC    468.0E-3    V

Comment:   20 x Nitrogenated Carbon. 7.5ppmw HCl. O2 saturated. Sample #2

Rp CALCULATIONS:
Corrosion Rate =   N.A.                     Correlation = -970.2E-3
Rp = 1.864 MOhms
E(I=0) = 777.8 mV                           Icorr(R) = 11.65 nA/cm^2
Beta Anodic = 100.0E-3                      Beta Cathodic = 100.0E-3 V/decade
Begin = 726.0 mV                            End = 830.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                     Chi^2 = 1.33E-001
E(I=0) = 785.9 mV                           Icorr = 25.47 nA/cm^2
Beta Anodic = 118.9E-3                      Beta Cathodic = 2.128 V/decade
Begin = 528.0 mV                            End = 862.0 mV

———— N1HCL2.t



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Model 352/252 Corrosion Analysis Software, v.   2.10
Filename:   c:\a352\data\NIHCL3.t
TA TAFEL                                          File Status:   NORMAL
Date Run:   UNKNOWN                               Time Run:   UNKNOWN

Cond. Time        CT    pass        s      Initial Pot.    IP    400.0E-3      V
Cond. Pot.        CP    pass        V      Final Pot.      FP    950.0E-3      V
Initial Delay     ID    pass        s

Scan Rate         SR    500.0E-3    mV/s   Curr. Range     CR    Auto
Scan Incr.        SI    2.000       mV     Step Time       ST    4.000         s
No. of Points     NP    275

                                           GI Time Const.  TC    Off
Line Sync.        LS    no                 IR Mode         IR    none
Rise Time         RT    high stability     Filter          FL    I 5.3Hz
Working Elec.     WE    Solid              Ref. Elec.      RE    AgCl   197.0E-3V
Sample Area       AR    1.000       cm^2   Equiv. Wt.      EW    0.3000        g
Density           DE    0.0000      g/ml   AUX A/D         AU    no
Open Circuit      OC    468.0E-3    V

Comment:  20x Nitrogenated Carbon, 7.5ppmw HCl, O2 saturated, Sample#3

Rp CALCULATIONS:
Corrosion Rate =   N.A.                    Correlation = -980.7E-3
Rp = 2.420 MOhms
E(I=0) = 767.3 mV                          Icorr(R) = 19.80 nA/cm^2
Beta Anodic = 122.7E-3                     Beta Cathodic = 1.093 V/decade
Begin = 724.0 mV                           End = 810.3 mV

TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                    Chi^2 =   2.03E-001
E(I=0) = 772.3 mV                          Icorr = 19.26 nA/cm^2
Beta Anodic = 122.7E-3                     Beta Cathodic = 1.093 V/decade
Begin = 448.0 mV                           End = 884.0 mV

———— NIHCL3.t



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Model 352/252 Corrosion Analysis Software. v.  2.10
Filename:  c:\m352\data\N2HCL1.t
TA TAFEL                                          File Status:  NORMAL
Date Run:  UNKNOWN                                Time Run:  UNKNOWN

Cond. Time        CT    pass       s      Initial Pot.    IP    450.0E-3      V
Cond. Pot.        CP    pass       V      Final Pot.      FP    1.000         V
Initial Delay     ID    pass       s

Scan Rate         SR    500.0E-3   mV/s   Curr. Range     CR    Auto
Scan Incr.        SI    2.000      mV     Step Time       ST    4.000         s
No. of Points     NP    275

                                          GI Time Const.  TC    off
Line Sync.        LS    no                IR Mode         IR    none
Rise Time         RT    high stability    Filter          FL    I 5.3Hz
Working Elec.     WE    Solid             Ref. Elec.      RE    AgCl   197.0E-3V
Sample Area       AR    1.000      cm^2   Equiv. Wt.      EW    0.0000        g
Density           DE    0.0000     g/ml   AUX A/D         AU    no
Open Circuit      OC    543.0E-3   V

Comment:  30% Nitrogenated Carbon. 7.5 ppmw HCl, O2 saturated. Sample#1


Rp CALCULATIONS:
Corrosion Rate =   N.A.                   Correlation = -975.1E-3
Rp = 2.560 MOhms
E(I=0) = 892.9 mV                         Icorr(R) = 17.51 nA/cm^2
Beta Anodic = 187.0E-3                    Beta Cathodic = 2.853 V/decade
Begin = 822.0 mV                          End = 916.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =   N.A.                   Chi^2 =  8.65E-002
E(I=0) = 895.8 mV                         Icorr = 26.31 nA/cm^2
Beta Anodic = 187.0E-3                    Beta Cathodic = 2.853 V/decade
Begin = 644.3 mV                          End = 930.3 mV


————————  N2HCL1.t



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Model 352/252 Corrosion Analysis Software, v.  2.10
Filename:  c:\m352\data\N2HCL2.t
TA TAFEL                                        File Status:  NORMAL
Date Run:  UNKNOWN                              Time Run:  UNKNOWN

Cond. Time        CT    pass         s      Initial Pot.    IP    400.0E-3     V
Cond. Pot.        CP    pass         V      Final Pot.      FP    950.0E-3     V
Initial Delay     ID    pass         s

Scan Rate         SR    500.0E-3     mV/s   Curr. Range     CR    Auto
Scan Incr.        SI    2.000        mV     Step Time       ST    4.000        s
No. of Points     NP    275
                                            GI Time Const.  TC    Off
Line Sync.        LS    no                  IR Mode         IR    none
Rise Time         RT    high stability      Filter          FL    : 5.3Hz
Working Elec.     WE    Solid               Ref. Elec.      RE    AgCl  197.0E-3V
Sample Area       AR    1.000        cm^2   Equiv. Wt.      EW    0.0000       g
Density           DE    0.0000       g/ml   AUX A/D         AU    no
Open Circuit      OC    585.0E-3     V

Comment:  30x Nitrogenated Carbon, 7.5 ppmw HCl, O2 saturated, Sample#2


Rp CALCULATIONS:
Corrosion Rate =  N.A.                   Correlation = -986.7E-3
Rp = 2.447 MOhms
E(I=0) = 865.3 mV                        Icorr(R) = 18.30 nA/cm^2
Beta Anodic = 108.4E-3                   Beta Cathodic = 2.133 V/decade
Begin = 822.0 mV                         End = 888.0 mV


TAFEL CALCULATIONS:
Corrosion Rate =  N.A.                   Chi^2 = 6.99E-002
E(I=0) = 867.9 mV                        Icorr = 22.63 nA/cm^2
Beta Anodic = 108.4E-3                   Beta Cathodic = 2.133 V/decade
Begin = 616.0 mV                         End = 948.0 mV

———— N2HCL2.t



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Model 352/252 Corrosion Analysis Software. v. 2.10
Filename: c:\m352\data\N2HCL3.t
TA TAFEL                                File Status: NORMAL
Date Run:  UNKNOWN                       Time Run:  UNKNOWN

Cond. Time      CT   pass        s      Initial Pot.   IP   400.0E-3    V
Cond. Pot.      CP   pass        V      Final Pot.     FP   950.0E-3    V
Initial Delay   ID   pass        s

Scan Rate       SR   500.0E-3    mV/s   Curr. Range    CR   Auto
Scan Incr.      SI   2.000       mV     Step Time      ST   4.000       s
No. of Points   NP   275
                                        GI Time Const. TC   Off
Line Sync.      LS   no                 IR Mode        IR   none
Rise Time       RT   high stability     Filter         FL   I 5.3Hz
Working Elec.   WE   Solid              Ref. Elec.     RE   AgCl   197.0E-3V
Sample Area     AR   1.000       cm^2   Equiv. Wt.     EW   0.0000      s
Density         DE   0.0000      g/ml   AUX A/D        AU   no
Open Circuit    OC   560.0E-3    V

Comment:  30x Nitrogenated Carbon, 7.5ppmu HCl, O2 saturated. Sample#3

Rp CALCULATIONS:
Corrosion Rate =  N.A.              Correlation = -989.5E-3
Rp = 2.955 MOhms
E(I=0) = 873.3 mV                   Icorr(R) = 14.79 nA/cm^2
Beta Anodic = 100.8E-3             Beta Cathodic = 1.338 V/decade
Begin = 830.0 mV                    End = 888.0 mV

TAFEL CALCULATIONS:
Corrosion Rate =  N.A.              Chi^2 = 8.50E-002
E(I=0) = 874.2 mV                   Icorr = 19.38 nA/cm^2
Beta Anodic = 100.9E-3             Beta Cathodic = 1.338 V/decade
Begin = 622.0 mV                    End = 948.0 mV

———————  N2HCL3.t



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**From:** Vivares, Valerie
**Sent:** Monday, June 29, 1998 8:31 AM
**To:** 'grchwski@almaden.ibm.com'
**Subject:** Authorization to use Figure in thesis

Sir,

I called you the first week of April to solicit the authorization to use one of your figures in my thesis. You did authorize me on the phone and I would appreciate if you could confirm your authorization by replying favorably to this email.

I attached the page of my thesis where I used the illustration in order for you to be able to judge of the context in which it is used.

The thesis this page belong to is my Master's thesis from San Jose State University's Material Engineering program.

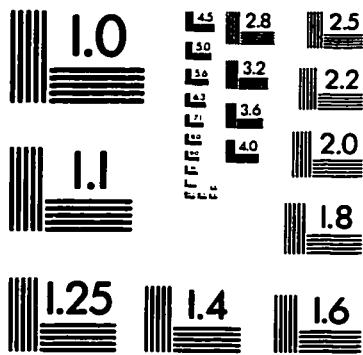Thanks you for your help

Page1thesis.doc

Regards


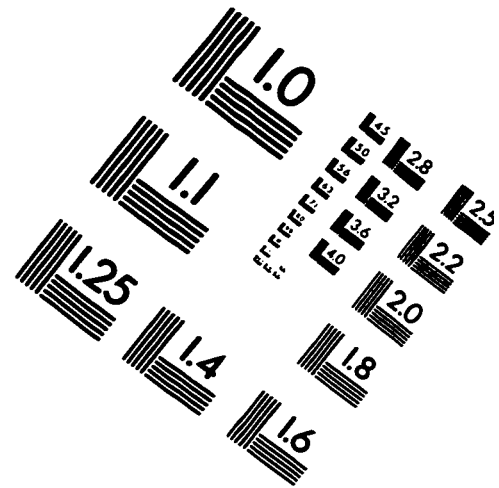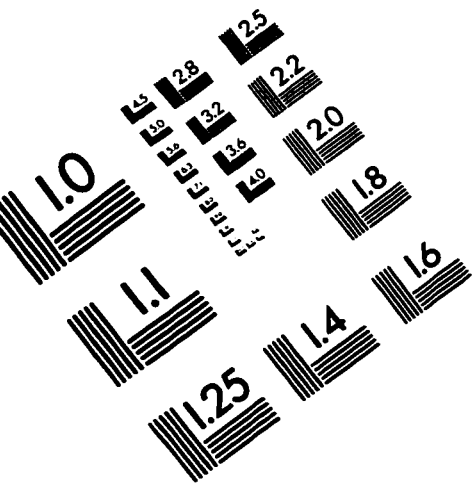Valerie Vivares
Package engineer
AMD Inc.
(408) 982-6027

**From:**                  .        grchwski@almaden.ibm.com
**Sent:**                Monday, June 29, 1998 8:41 AM
**To:**                     Vivares, Valerie
**Subject:**           Re: Authorization to use Figure in thesis

Val: You are authorized to use the figure we discussed. Good luck. Ed

# IMAGE EVALUATION
# TEST TARGET (QA-3)

150mm

6"