INVESTIGATION INTO CORROSION RESISTANCE BEHAVIOUR OF SOME HIGH STAINLESS ALLOYS IN R.O SEAWATER DESALINATION CONDITIONS

-A COMPARATIVE STUDY-

By

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ABSTRACT

Desalination of seawater (SW) by Reverse Osmosis are expected to be the common way for desalination throughout the world on the future due to their simplisity and cost compared with the Multi Stage Flash (M.S.F.) plants . Alot of work was done and in progress to improve there effeceincy and reliability. One of the most problem in such technology is the corrosion of the materials selected on the different parts of the R.O. plants. On this thesis, most of the corrodent factores that may affect the corrosion process were considered and applied on six defferent high stainless alloys available commericially.Flow of the corrodent and Jet effect were also invistigated on this work. Titanium considered to be the best alloy can resist the corrosion, hence the other five alloys were compared with it. It can be seen that Hastelloy-C [15-20%Cr, Bal.Ni, 16-20%Mo] and SMO-245[19.8%Cr, 17.7%Ni, 5.6%Mo] showed good corrosion resistance under RO SW desalination conditions. Alloy 14529[19-21%Cr, 24-26%Ni, 6-7%Mo] manufactured by INCO also showed good corrosion resistance under the above conditions but once the temperature rise to 45^{o}C and more its corrosion behaviour was reduced. 316[16.9%Cr, 11%Ni, 2.5%Mo] and 430[16%Cr] stainless steels were tested and both showed much less in corrosion resistance compared with the other alloys tested specially at elevated temperatures. Finally it should be point out that electrochemical testing of these alloys under the simple laboratory static condition can give an indication about there behaviour at more sever conditions but as a comparative study.

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CHAPTER ONE

INTRODUCTION

The most costly problem facing desalination plants under operation is the corrosion. Multi Stage Flash(MSF) plants and, Reverse Osmosis(RO) plants are the two main types used in desalination. In MSF desalination plants the temperature is the important factor - in addition to the salinity factor- affecting the corrosion process. In RO plants, the pressure and the deoxidation are the two main factors affecting the corrosion process. In RO plants the pumps, energy recovery devices and the pipes under high pressure are the most parts affected by corrosion. Actually there is a lack in informations about which stainless alloys to be the optimum selection for each part mentioned above [1,2]. For example, up to date there have been considerable practical difficulties experienced in specifying suitable alloys fot the buckets of the Pelton Impulse Turbine without sever corrosion within reasonable period. Also most of the pipework under high pressure in RO desalination plants are subjected to crevice corrosion[1]. T. Hodgkiess [2] stated that 316L, 317L and UNS NO8904 grades of stainless steels are unacceptable in aerated seawater in contrast with higher concentration of the critical elements(Cr,Mo and N) alloys. In this thesis the study of the corrosion behaviour under different environment conditions for different types of commercial stainless alloys were carried out. Flow, jet, dissolved oxygen level, temperature and the crevices, all these factors were considered on this study. Their effect on the corrosion behaviour of different stainless alloys was studied. In this chapter a brief explanation about RO desalination plants will be done, also the energy recovery systems used will be discussed, and finally, the impulse turbine will be studied more details as an example of the system in RO plants that subjected to corrosion and no specific alloy can be used safely.

1.1 Reverse Osmosis Plant(RO):

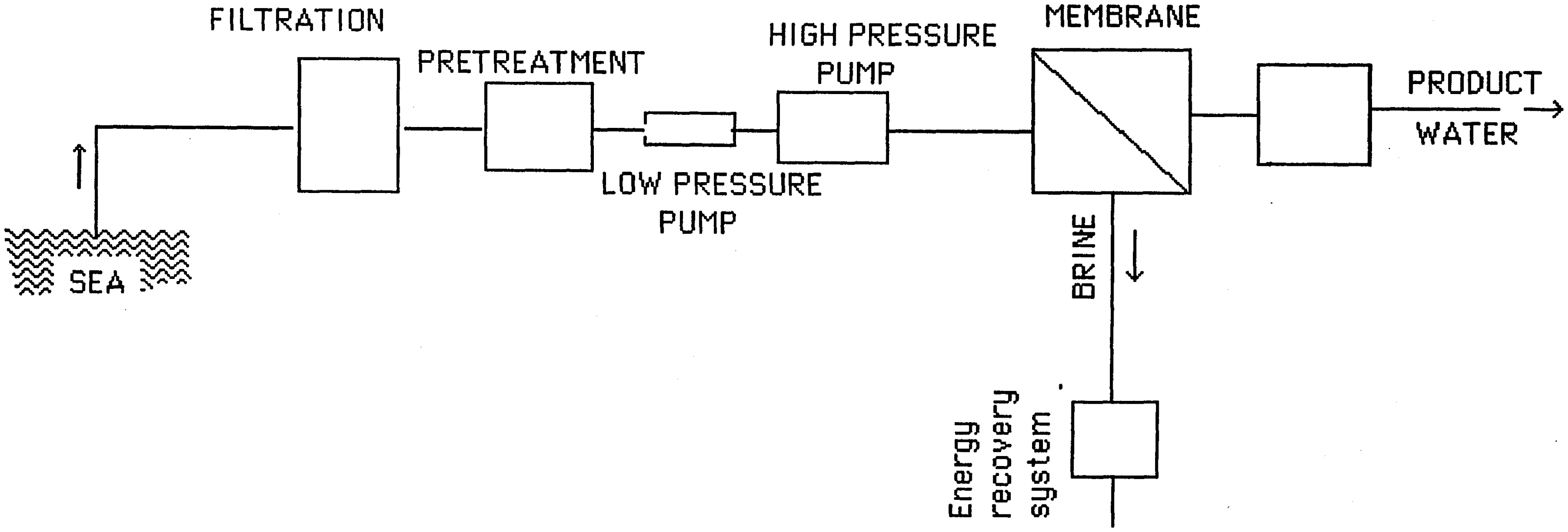
Reverse Osmosis plants are widely used nowadays for the desalination of seawater. Considering the simplicity of their operation, the performance of these plants is very good. The applications of RO plants are increasing rapidly. Many research centres and institutes are conducting research with a view to improve the efficiency, reliability, performance and life-span of RO plants. The basic layout of a RO plant is shown in FIG.(1) . Sea-water must be carefully treated before feeding it to the RO membrane. Gravity filter, Sand filter and Cartridge filter are usually used to eliminate the suspended solids from sea-water. Chlorine or Sodium biosulphate is used as pretreatment to eliminate the bacterial. The membrane and the high pressure pump are the main parts of a RO plant , the remaining parts being auxiliary or supporting parts ,e.g. filters and pretreatment are used to ensure feeding of pure sea-water to the membrane while the low pressure pump is to avoid cavitation or shortage of water to the high pressure pump. A plant designed to produce one million gallon per day of desalinated water consumes 4.00 MW[3] of electric energy (as in the case of Ummluj RO plant) . Major part of this energy ,more than 40%, is consumed by the high pressure pump. In the above example , the pressure needed at the membrane is around 60 bar , the brine (waste) is discharged at 57 bar .If the recovery of the plant is 33% , then the brine discharged as a waste has more than 50% of the energy used [1]. In the past this energy was wasted. At present, numerous devices have been designed to save this energy.

1.2 Energy Recovery Systems.

These systems are designed with the objective of reducing the operating cost . These systems save part of the energy of the brine waste . There are various types of energy recovery systems . Each one of these systems has its advantages under certain operating conditions . Some of these systems are

1-Impulse turbine ,

2-Reaction turbine (Francis,Kaplan,and propeller turbines),



Fig(1 .)

REVERSE OSMOSIS PLANT

3-Integrated Turbo-Pump ,and

4-Work Exchangers [4].

FIG.(2) shows the suitability of the various types of energy recovery systems for different operating conditions [5]. It is clear from FIG.(2) that pelton wheel and multi-stage pump are the recommended devices for the RO system,in view of its high head .Given below is a brief explanation about the devices of ERT and a brief discussion about pelton wheel .

1.2.1 REACTION TURBINES :

This type of hydraulic turbines include Kaplan, Frances and Propeller turbines. Reaction turbines are used for large scale hydroelectric generation where a high flow rate and low head(5-20 m) are available . It is basically a reverse centrifugal pump. The flow through this type of turbines may be radially inward,axial or mixed partially radial and partially axial [4].

1.2.2. INTEGRATED TURBO-PUMP:

Integrated turbo-pump is a pump and turbine connected with one shaft (i.e. back to back).The high head flow passes through the turbine . It is also suitable for the RO system but its efficiency is lower than the pelton wheel turbine [4].

1.2.3. WORK EXCHANGER :

Work exchanger is the most efficient device ,having an efficiency of more than 90%, but its main disadvantage is its low capacity of flow, hence it is suitable for RO systems with an output of 200 to 400 m^3/day . The intention of this device is to use the high pressure waste brine to displace the feedwater through a chamber[4] .

1.2.4. IMPULSE TURBINE:

Impulse turbine is simply a modern design of the Noria (Persian wheel) . As shown in FIG(3) , It converts the head of the water(liquid) into useful energy .

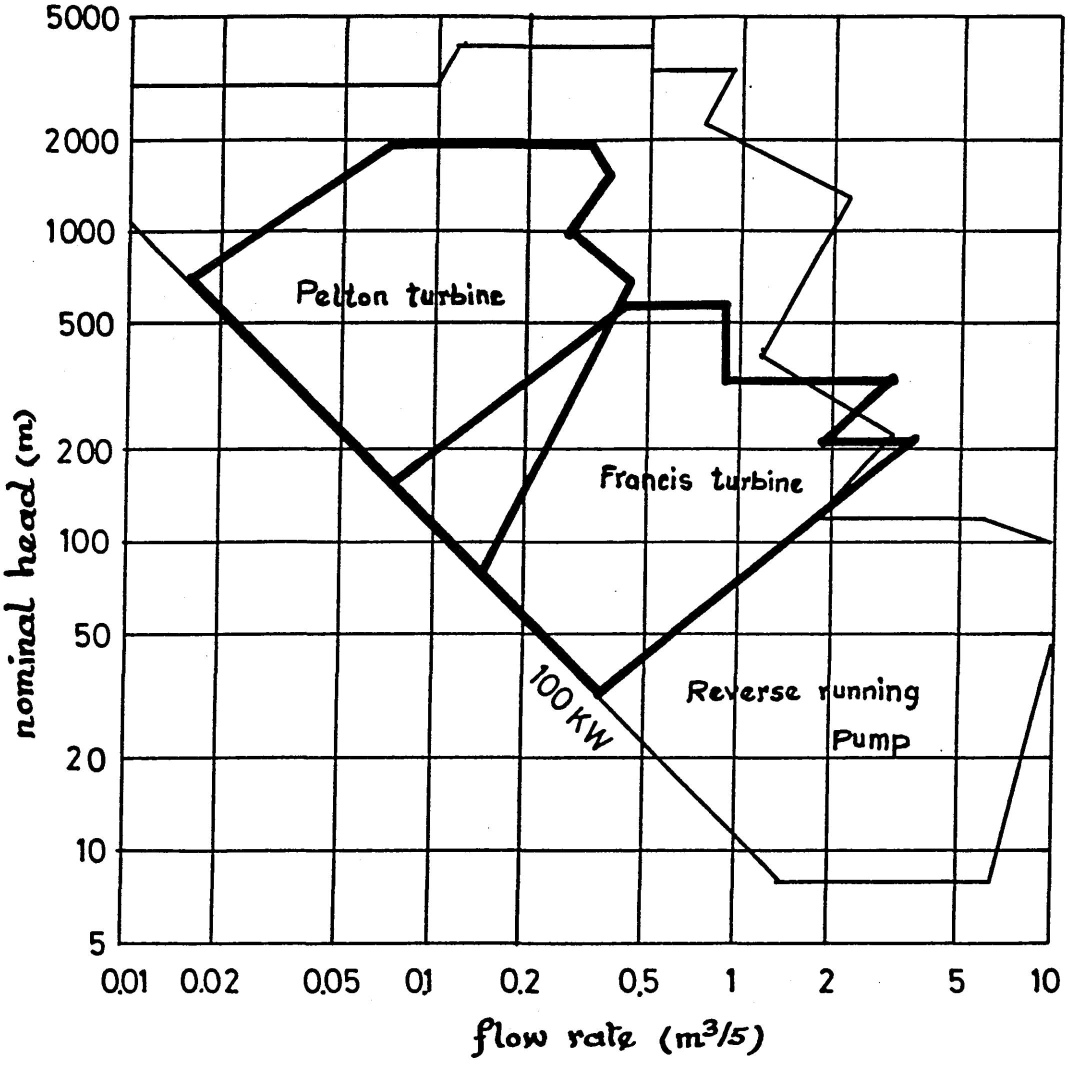
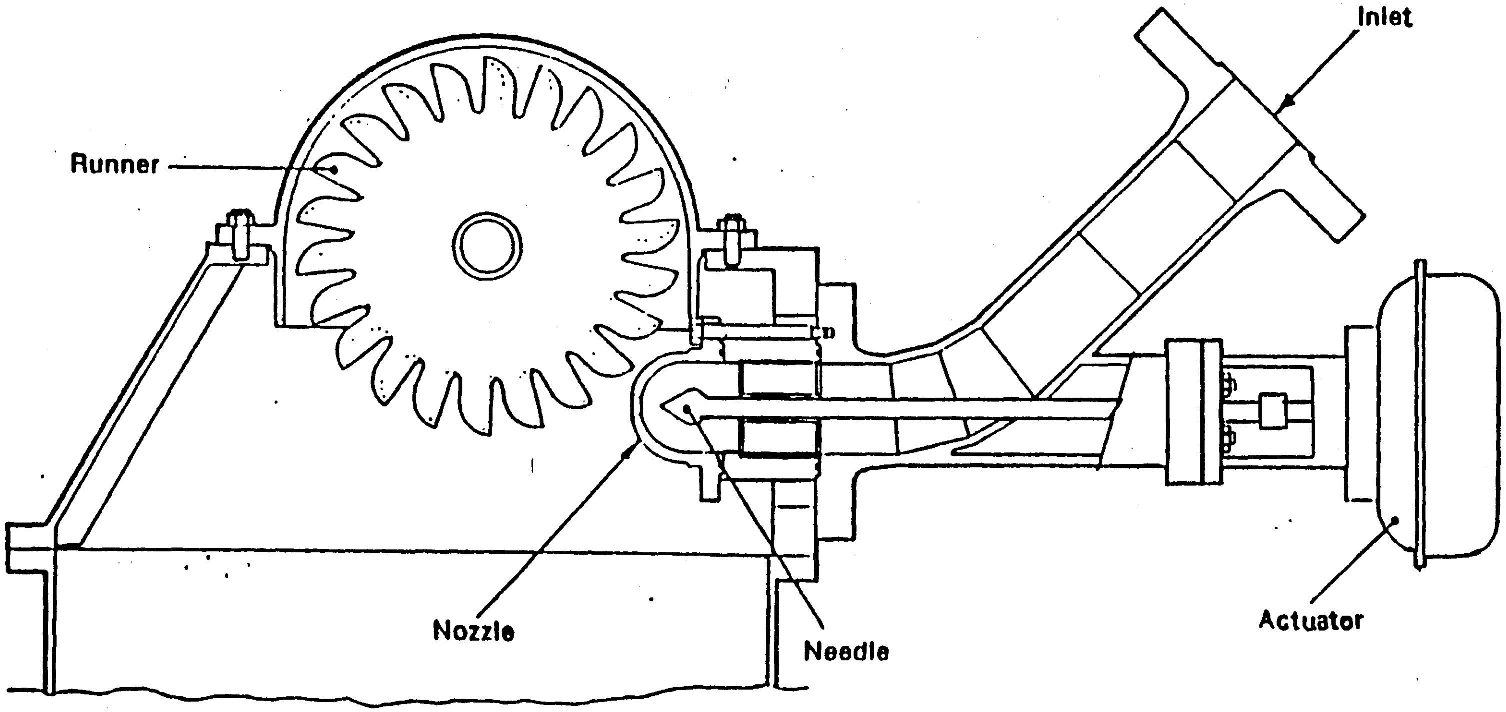


Fig. (2)

Suitability of the various type of energy recovery system.
(reference No. 2)



(reference No. 4)

FIGURE 3 PELTON IMPULSE TURBINE

1.2.4.1. Theory:

Converting the high head of water into a high velocity jet through a nozzle to the atmosphere provides useful energy . This jet is directed at the buckets of the Impulse turbine , which rotates accordingly , thereby giving the energy.

If V_j ,V_r, V_b are jet velocity, relative velocity and the wheel rotating velocity respectively (**m/sec**). $\dot{\theta}$ is the reflecting angle of the flow as shown in FIG.(4) .

$$V_{r1} = V_j - V_b$$

$$V_{r2} = (V_j - V_b) \cos\dot{\theta}$$

$$V_{r1}+V_{r2} = V_j - V_b - V_j \cos\dot{\theta} + V_b \cos\dot{\theta}$$

$$= V_j(1- \cos\dot{\theta}) - V_b (1- \cos\dot{\theta})$$

$$= (V_j - V_b) (1- \cos\dot{\theta})$$

If the bucket shape is a semicircle then $\dot{\theta}$ will be 2π and $\cos\dot{\theta}$ will be **-1** which means ,

$$V_{r1}+V_{r2} = 2 (V_j - V_b)$$

$$= 2 V_{r1}$$

or

$$V_r = V_{r1} = V_{r2}$$

Let $\dot{m}$ be the mass rate of the fluid through the nozzle, then

$$\dot{m} = \rho \dot{Q}$$

where ρ is the fluid density Kg/m^3

and $\dot{Q}$ is the quantity rate of the fluid m^3/sec

$$\dot{Q} = A V_j$$

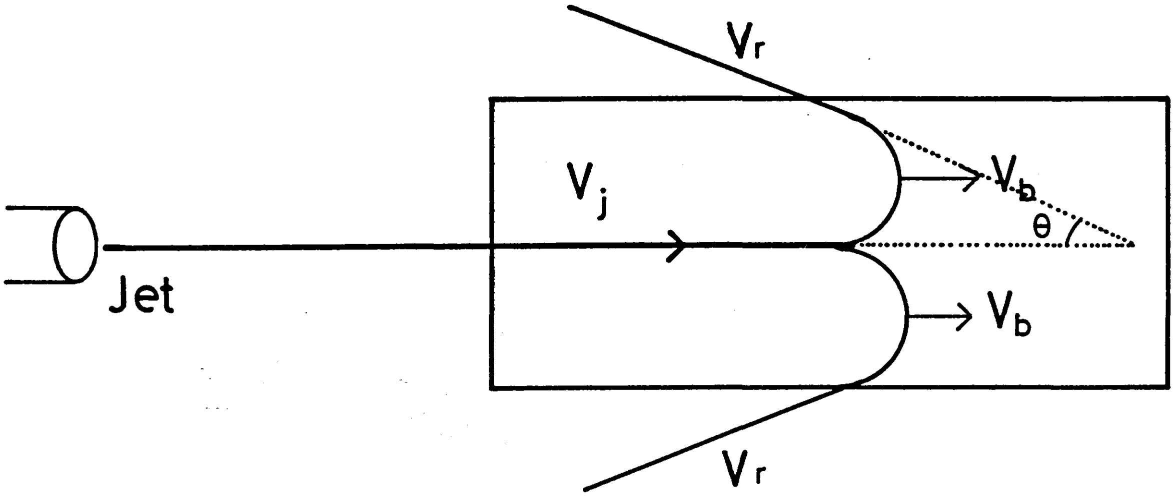


Fig. (4)

FLOW DIAGRAM OF TWIN BUCKET

where A is the cross-section of the nozzle (m^2)

The force applied on the bucket due to this flow rate is

$$F = \rho \dot{Q} \,(V_j - V_b)\,(1 - \cos\dot{\theta})$$

and the power is

$$P = F\, V_b$$

$$= V_b\, \rho \dot{Q} \,(V_j - V_b)\,(1 - \cos\dot{\theta})$$

The speed which gives maximum power is , when dP/dV_b equal to zero.

$$dP/dV_b = 0. = V_j - 2\, V_b$$

or $V_b/V_j = 1/2$

FIG.(5) shows the relations of the speed ratio with the power and force ratio [5-17].

1.2.4.2. Impulse turbine applications in R.O plants

W. Wilson ET AL [18] have discussed the use of pelton wheel turbine in R.O plants to assist the main electric motor in driving the reciprocating pump, they explained the steps of the operation on their study . They also recommend ~~**Duplex**~~ Stainless Steel(5%Ni, 27%Cr, 0.03%C) for the inlet converter and Pelton wheel, **Stellite 6** (26%Cr, 1%C, 5%W)material for the Nozzles , **high polished stainless steels** for the cups and **Duplex** for the shaft. In the Technical discussion held in Riyadh [19] it was agreed that the potential high efficiency and broad operating range of pelton wheel devices makes them an attractive prospect for their use in R.O energy recovery . but the corrosion-erosion resistance of the highly loaded components (nozzles and cups) need further development to with stand the extreme velocities and highly corrosive environment . Possible use of ceramic should be investigated until such development materialise. SASAKURA company have used alloy 20 modified with increase in Molybdenum as material for pelton wheel in Ras Abu-Jarjoor plant in Bahrain. Y.Mimura ET AL [20] introduced a study for optimizing the energy consumption of the

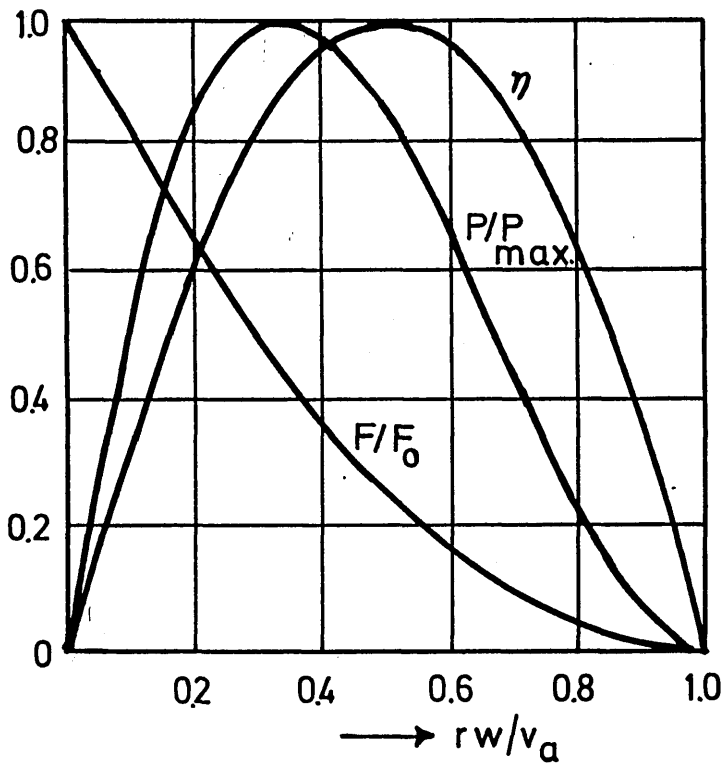


Fig (5)

Theoretical values of power thrust and efficiency in a Pelton wheel.

(reference No. 9)

R.O plant using a micro-processor and their study include the energy saved by Impulse turbine, they collected the data from Umm-Lujj plant in Saudi Arabia. B. Ericsson [21] established some tables for the cost of the R.O plant using the impulse turbines , Salbukh plant in Saudi Arabia and Yuma plant in U.S.A were considered as case study.

Tanjib plant in Arabian Gulf coast for desalination includes energy recovery system . During the first one and half years running, it met the requirements of the owner(ARAMCO) specification [22]. Its capacity is 80 m^3/hr with a head of 67.5 bars .

David&Morgan [23] stated that the impulse turbine can replaces the normal system relief valve and converts the K.E to rotating mechanical energy . Up to 85% of the previously wasted energy can be recovered ,resulting in a significant saving in production cost. The description of the operation method , machine standardised approach to application and economic comparisons of the alternate systems were given in this paper.

Y. Kunisada ET AL[24] saved around 20% of the required energy for the pump by using energy recovery system. From the material of ERT point of view there was galvanic corrosion in the ERT after 3000 hr running , but using the same material of the pump for the ERT ,no corrosion was detected for 10000 hr running [25].

A. Riedenger & C.Hickman [26] stated that the ERT can recover between 50 to 90% of the available energy in the R.O plants , also they made mathematical calculations for studying the pressure required to the membrane . A comparative study, between the MSF and the RO plant was made by C.Sackinger [27] from the energy consumption point of view. In this study it was established that more than 35% of the energy to the RO plant can be saved by using ERT. Mathematical calculations were done by N.Wade & M.Hornsby[28] for the R.O plant with and without ERT. It was concluded that more than 32% of total power can be saved by using ERT. A comparison between the use of Impulse turbine and reversed running pump was made by Al-bawardy consulting engineer[29] . According to Bolinger&Reisser up to 40 % of the pumping power can be saved by using ERT . Design and dimensions of pelton wheel are specified in Sulzer catalogue [30] . A formula for calculating the hydraulic power recovered by the ERT was established by Kerman[31] which is :

$$7.37 * 10^3 * P_b * F_b * E_t$$

where

P_b brine pressure (psi)
F_b brine flow (mgd)
E_t recovery ratio

Calder company [32] have designed different sizes of pelton wheel turbines , starting from 22(m^3**/hr**) to 176(m^3**/hr**) **.** They used the same material as reference [18]. A new design was made with Ceramic mould for the cups.

1.2.4.3. ERT OF UMM-LUJJ RO PLANT:

Umm-Lujj RO plant is a one **mgd** desalination plant . its design includes four identical pelton wheel turbine runners. Two units for each train .The discharged brine water analysis of each train is :

pH	6.3
Conductivity	70000 **moh**
T.D.S	55000 **ppm**
Chloride	30000 **mg/l**
Total hardness	10000 **mg/l**
Brine flow	252 m^3**/hr**
Temperature	33 ^oC

The original material used for these ERT units were Hastelloy-C and CN7M boride coated Appendix A. CN7M boride coated runners failed within a short period and were replaced by Hastelloy-C. Again Hastelloy-C had severe pitting and large cavities after 1400 running hours. Finally it was decided to use alloy Ep-135 . After a short period Ep-135 also failed and showed some corrosion[33-35]. Finally the contractor mentioned that he hadn't more alternatives, because and as stated above there is a lack in the informations available about the proper materials in such devices. Actually this problem represented one of the key aspects of this project. The idea was, what was the main factor that cause such damages in the buckets. The other question, was it necessary to build pelton wheel each time for testing different alloys, or dose the result obtained from corrosion testing of alloy specimen under normal (static) conditions give good indication about the behaviour of this alloy under sever conditions.

CHAPTER TWO

CORROSION RESISTANT MATERIALS

1-Introduction:

Metals and their alloys are the elementary materials of industries. Cost and reliability are the two main factors affecting the selection of the proper material for each product. Each natural metal has its own properties and suitability for application . For example, gold is the best material for corrosion resistance, but it has high cost and low strength. Iron has high strength but low corrosion resistance in certain media, etc.. . Alloys are made to meet the needs of industries in different fields and under different conditions. Some natural metals are mixed together in calculated percentages to form different types of alloys.

2-Alloys

An alloy can be defined as *the combination of a metal with one or more elements* [36]. Usually the alloying is done to increase hardness, improve strength, improve mechanical properties, improve toughness , increase wear resistance, increase corrosion resistance or improve magnetic properties of a metal. There are different types of alloys such as , copper alloys , Aluminium alloys, Magnesium alloys, Nickel alloys ,Lead alloys, Tin alloys, Titanium alloys and Zinc alloys, all these alloys are non-ferrous metal alloys.

2-1 Non Ferrous Alloys:

Not all the above non-ferrous alloy are related to this work because some of them are not suitable for desalination plants and also they are corrosive alloy, such as Magnesium alloys, Lead alloys and Tin alloys.

2-1-1 Copper Alloys:

Pure copper is a good conductor. It is applied in many fields like electric wires , water pipes etc. It is easily cast and shaped. Pure copper is alloyed by adding many other elements such as, Sulphur and Lead to improve its machinability. For strengthening Copper , Chromium may be added. Silver can improve heat resistance of copper. Alloying copper with Nickel gives the famous cupronickels alloys which have the best general resistance to aqueous corrosion of all copper alloys. Copper alloys may be classified into, **brasses,bronzes, cupronickels** and **nickel-silver** alloys .

2-1-1-a) -**Brasses** alloys- are composed of copper and zinc elements. Sometimes other elements are added to certain brass alloys. As the percentages of the two essential elements vary the properties change.

2-1-1-a-1) -**Alpha brasses-** containing up to 36% zinc possess good corrosion resistance. There are two groups from alpha brasses - Yellow and red brasses . **Yellow** brasses have 20-36% zinc . These brasses have good resistance to intergranular corrosion , high ductility and good strength. Yellow brasses are subject to pitting corrosion specially when these brasses in contact with seawater[34]. **Red** brasses contain 5-20% zinc. These brasses have better corrosion resistance than the yellow brasses.

2-1-1-a-2) -**Alpha plus Beta brasses-**. These contain 54-62% copper. **Naval brass** (60Cu-39.25Zn-.75Sn) is the best type from brasses used for seawater corrosion resistance.The most widely used alpha+beta brasses is **munts metal** (60Cu-40Zn).

2-1-1-b) -**Bronzes-** Except the copper-zinc alloys all the alloys with copper are named bronzes. Bronzes are higher-class alloys than brass. Commercial bronzes are primarily alloys of copper and tin, aluminum , silicon or beryllium . **Tin bronzes** or phosphoric bronzes are characterized by high strength and corrosion resistance. **Silicon Bronzes** have mechanical properties comparable to those of mild steel and corrosion resistance comparable to that of copper[40].

2-1-1-c) Common **-cupronickels-** alloys are of 70% Cu, 30% Ni and 90% Cu, 10% Ni. They are widely used for condenser, distiller, evaporator and heat exchanger tubes for naval vessels and coastal power plant[37].It can be improve its corrosion resistance in seawater by adding 0.3% Fe. Other metals, such as manganese and zinc may be present in significant but small amount[43].

2-1-2- **Aluminium alloys:**

The main characteristic of aluminum is its light weight . It is lighter than other engineering metals except magnesium and beryllium. It has good electric and thermal conductivity[36-37]. Small percentages from iron increases the strength and hardness of some alloys and reduce hot cracking. Manganese is used with iron to improve castability , ductility and impact strength. Corrosion resistance can be increased by adding Silicon.Copper and magnesium are added to increase the strength.Aluminum and its alloys have good corrosion resistance in atmosphere. In water aluminum is resistant to the solutions in the pH range of 4.5 to 8.5 without heavy metal ions. Aluminum has poor resistance to pitting corrosion in seawater, so it is not recommended for use it in seawater .

2-1-3- **Nickel alloys.**

Nickel is the essential element in stainless steel alloys. It can be classified as good corrosion resistance metal. It has good workability and good mechanical properties. Nickel makes an ideal coating for parts subjected to corrosion and wear. There are a number of famous nickel alloys systems in commercial use such as :

1- Pure Nickel, A nickel, D nickel, E nickel, Permanickel, and Duranickel. All of these alloys contain at least 93% nickel ; all have a single-phase FCC structure. From corrosion resistance point of view, A nickel is the best and 2% of Si may be added to improve its fluidity and castability. A nickel is used where strength combined with corrosion resistance and oxidation is required. D nickel is similar to A nickel but with the addition of 4.5% manganese . D nickel is also similar to a nickel but with 2% of manganese . Duranickel is a rough, age-hardenable alloy with more than 93% of Ni. It has the excellent corrosion resistance of nickel. It has high strength. Permanickel alloy contains more than 98% of Ni. It has the same corrosion resistance as Duranickel alloy .In addition it has good electrical and thermal conductivity.

2. -Nickel-copper alloys- One of the most commercial alloy used as corrosion resistance alloy is the **Monel** alloy. It is Nickel-copper alloy. Approximately two-third nickel and one-third copper .Table shown in appendix A shows the composition of various types of commercial monel [38]. Copper is completely soluble in nickel. The addition of copper to nickel is made in order to decrease its price while retaining its corrosion resistance. Monel has high corrosion resistance to acids, alkalies, brines, water, and atmosphere. These type of alloys give excellent service in seawater or brackish waters under high-velocity conditions, as in propellers, and condenser tubes, where resistance to cavitation-erosion is important[39]. Monel is benefited by the high degree of nobility of copper and by the ability of nickel to protect itself through the development of passive oxide film [40]. Its mechanical properties are better than those of bronzes and brasses. In addition to its corrosion resistance it has good wear resistance.

3. -**Nickel-Chromium alloys**- There are three alloys based on nickel-chromium alloy which are, nickel-chromium-iron based alloy, nickel-chromium-molybdenum-iron based alloy and nickel-chromium-copper based alloy.

3-a) **-nickel-chromium-iron-** based alloy. **Inconel** alloy is one of this type of alloys. The composition percent of Inconel alloy is 76Ni-16Cr-8Fe. In seawater it may be subject to pitting attack under low velocity conditions. Generally inconel is useful in chemical industries from corrosion resistance point of view[40]. It is applied in furnace and in the heat treating field.

3-b) **-nickel - chromium - molybdenium- iron-** based alloy. The best-known in this group being **Hastelloy-C** alloy. Its composition is 54Ni-17Mo-16Cr-5Fe-4W . Hastelloy-C is outstanding in its corrosion resistance in salt water. Specimens immersed in sea water for 2049 days showed no weight loss and no pitting[40]. Also hastelloy-c has high heat resistance,and it is applied in furnace and heat-treating ,**Hastelloy-A** and **Hastelloy-B** are among the best alloys available (both are free chromium alloy). The composition of hastelloy-A is 57Ni-20Mo-20Fe while hastelloy-B has 62Ni-28Mo-5Fe. These alloys have good corrosion resistance to hydrochloric, phosphoric, and other nonoxidizing acids[37].

3-c) **-nickel-chromium-molybdenum-copper-** based alloys. **Illium B, G** and **R** are the alloys available from this category. They were developed as materials resistant to nitric and sulfric acids.

2-1-5 **Titanium alloys**- Titanium is the fourth most abundant element in the earth. It has excellent corrosion resistance up to approximately 1000 F. Titanium density is $4.45*10^3$ [kg m^{-3}]. therefore, titanium alloy structures have a high strength-weight ratio and are particularly useful for aircraft parts. Commercially pure titanium is more corrosion-resistant ,lower in strength and less expensive than its alloys.

2-1-8 **Zinc alloys**- Zinc is more highly anodic than steel , this is the principal reason for using zinc as coating for steel to prevent corrosion. The major fields for uses for zinc are galvanizing, brass and die casting.

2-2 Ferrous alloys:

2-2-1. Metallurgy.

Stainless steel is Iron-Chromium based alloy. Fig(1) shows the equilibrium diagram for Fe-Cr alloys. Chromium is a member of the group elements known as

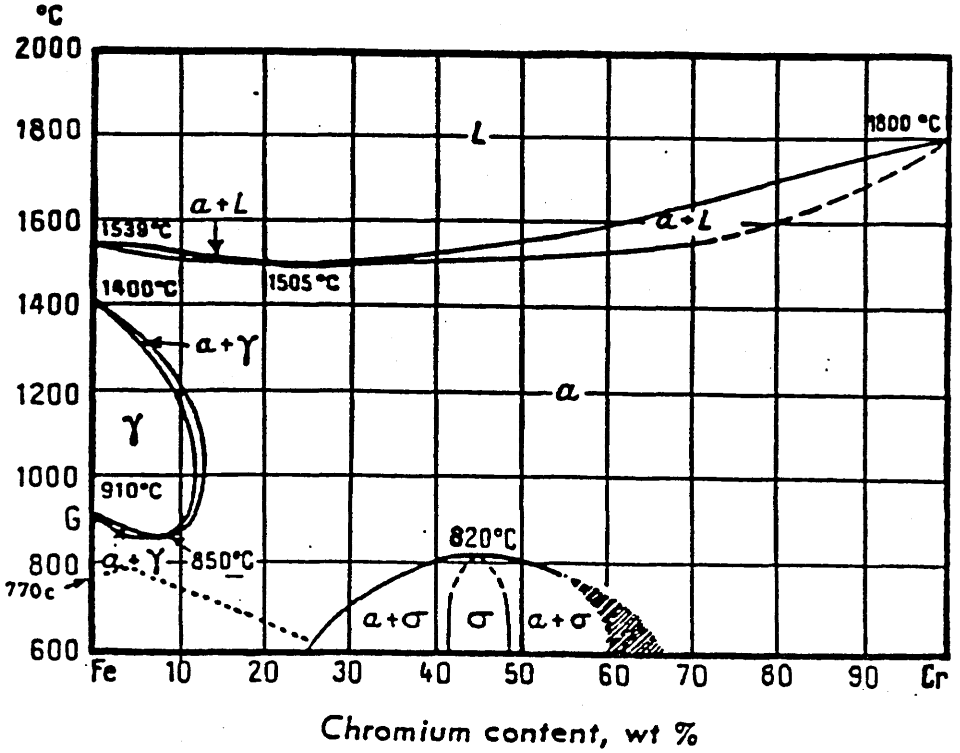


Fig (1)

Equilibrium diagram for Fe-Cr alloys.

Reference No.41

ferritic former. Stainless steel alloys are formed when the content of iron is more than 50% and the chromium is more than 12%. From Fig (1) it is clear that the gamma loop divides the diagram into two main parts, with less than 12% Cr the alloy shows $\alpha \leftrightarrow \gamma$ (where α is Body-centered cubic(b.c.c) and γ is face-centered cubic(f.c.c)). Transformation on heating and the reverse transformation will take place on cooling. With more than 13% Cr ,no transformation will happen by heating. only α (b.c.c.) phase will be existed. With more than 25% Cr there is another phase called sigma (tetragonal structure) will be formed at lower temperature (<800 C). If the γ -loop considered as shown in fig(2), $\alpha + \gamma$ phase can be noticed. It is a narrow region and exists at high temperature. This mixed phase can be stretch to higher Cr percent with present of carbon. Fig (1) shows the Fe-Cr equilibrium diagram without impurities. Fig(3) shows the effect of carbon to this equilibrium diagram. Another important element in stainless steel alloys is **nickel**. It is an austenite stabilizer as shown in fig(4). Nickel increases the austenite stability,but at the same time it increases the hardenability of the alloy. Fig(5) shows the isothermal section at 650°C through Fe-Cr-Ni system. In stainless steel alloys there are other elements may be added for different purposes. For example, **Molybdenum**(Mo) usually added to improve the passivity and chemical resistance of stainless steels in the presence of Cl^- Ions and reducing acids. Mo is a very important additive for corrosion resistance stainless steel alloys. It is ferrite former like Cr. **Silicon** and **Alumenium** are used to improve heat resistance and both are ferrite former. Si improves the resistance of the alloy to attack by oxygen or air. **Copper** which is austenite stabilizer added to improve corrosion resistance in certain reagents. Generally Cr,,Mo,Si,Nb,Al,Ti,V,W are ferrite former, while Ni,C,Mn,Co,Cu,N are austenite stabilizer. The first and second group are called Cr equivalent and Ni equivalent ,respectively. Schaeffler phase diagram fig(6) can explain the results of mixing different type of alloying elements.

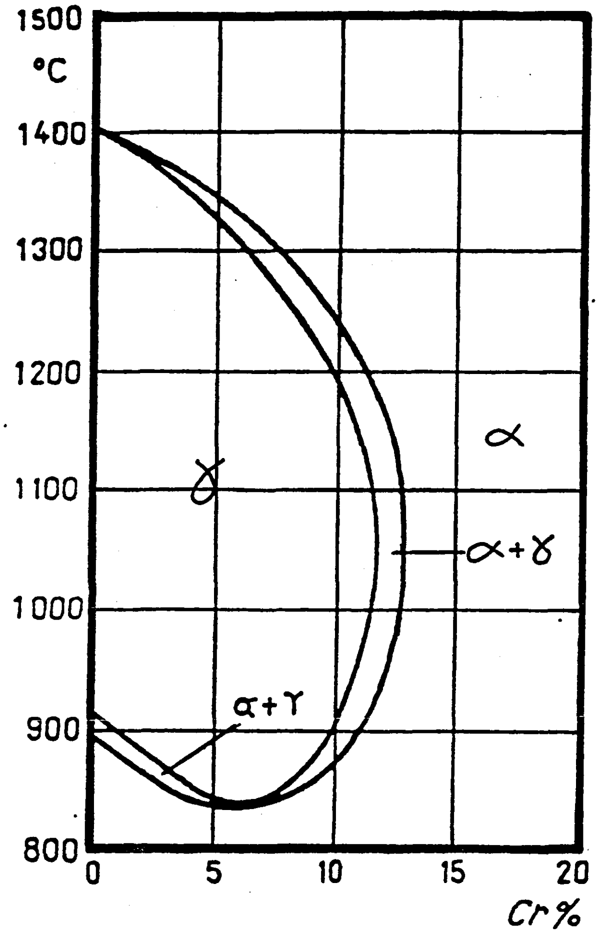


Fig (2)

γ - loop

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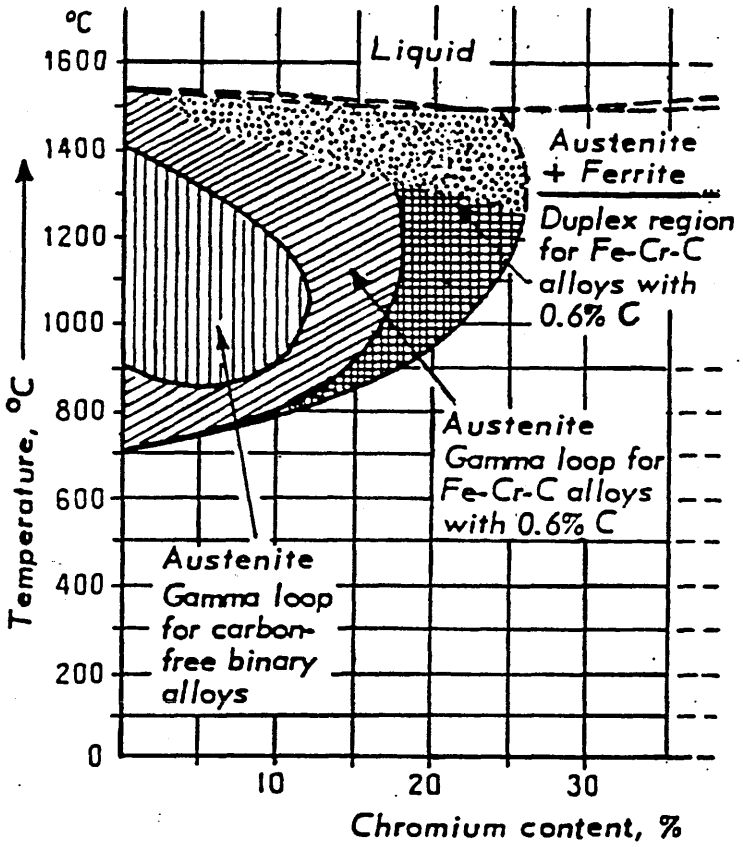

Fig (3)

The influence of carbon in Fe-Cr alloys.

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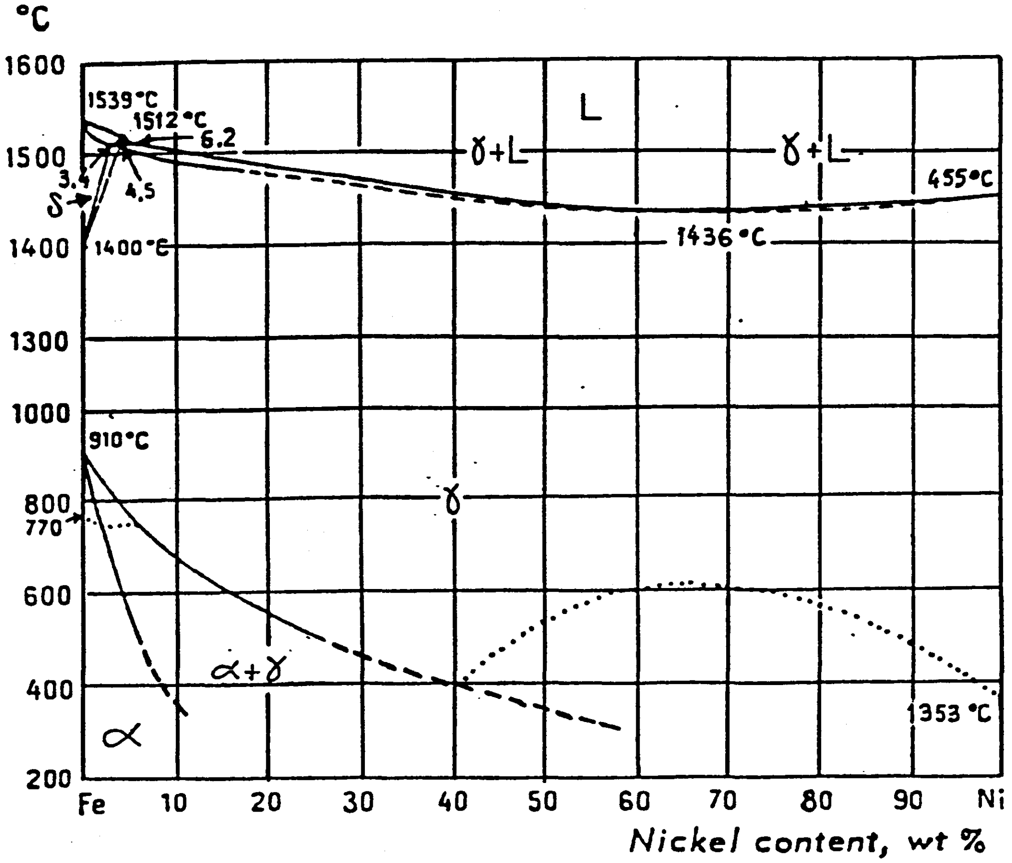

Fig (4)

Equilibrium diagram for Fe - Ni alloys

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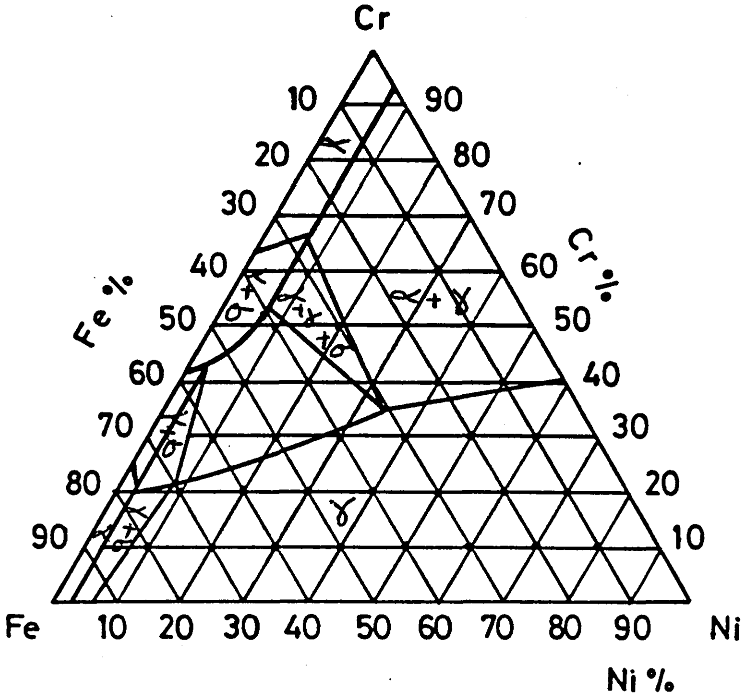

Fig (5)

Fe-Ni-Cr ternary system phase fields on the 650 °C isotherm.

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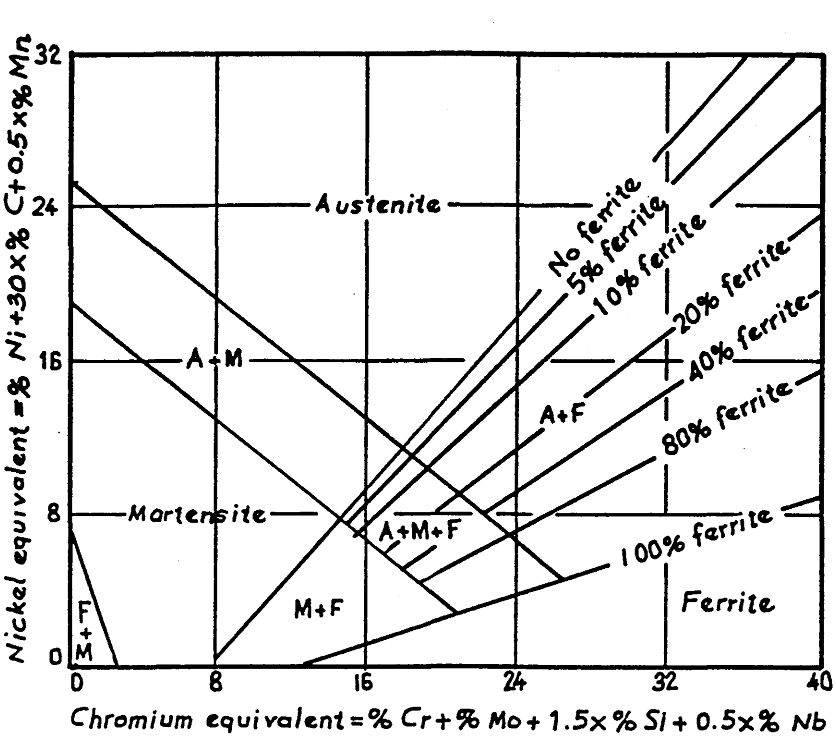


Fig (6)

Phase diagram for stainless steel weld deposits.

Reference No.41

2-2-2. Stainless Steel(S.S.) classification:

From the above it is clear that there is a possibility to produce unlimited number of S.S alloys . All this number of alloys can be classified according to there microstructures. Scaeffler diagram explains that there are four various type of alloys, **Ferrite** , **Austenite** , **Martensite** , and **Duplex** alloys. Of course each of these alloys has its own properties.

2-2-2.1. Ferritic Stainless Steels

Ferritic S.S has b.c.c. crystal structure . It contain approximately 14-27 % Cr with low percentage from Ni (<.5%). Refering to fig(1) it is clear that this alloy occurs where only α phase is available. In other words this alloy cannot be hardened or strengthened by heat treatment but can be moderately hardened by cold working and annealing. Ferritic alloys are subject to grain growth when held for long times at temperature above 1000 C. They develop their maximum corrosion resistance,ductility and softness in the annealed condition. This type of alloy is magnetic. The ferritic steels offer good seawater corrosion resistance provided the water is not stagnant and marine organisms are absent [40-41].

2-2-2.2. Martensitic Stainless Steels.

The main difference between Martinsitic and ferritic S.S. is the ability of martensitic S.S. to the heat treatment, and this feature is gained by adding some carbon to the Fe-Cr system as shown in fig(3). These alloys contains between 11.5 and 18% Cr. The maximum strength and hardness depend on carbon content. Ferritic S.S. is better than martensitic S.S. from corrosion resistance and machinability viewpoint. It can be cold , heat-worked easily.and is magnetic. These steels are normally hardened by heating them above the transformation range to temperature near 1000 C [37-41-42]

2-2-2.3. Austenitic S.S.

Austenitic S.S. are formed by the addition of a f.c.c. elements to the Fe-Cr system.. The main elements usually used are nickel or manganese . Most of the austenitic S.S. available commercially are Fe-Cr-Ni alloys.The total content of chromium and nickel is at least 24%. Chromium can range from 16% to 26% and Nickel range from 8% to 22%. As the percentage of nickel increases the structure of the alloy tends to be more austenitic as shown in fig(7). This type of S.S. is like the ferritic steels in that no transformation will take place by heat treatment. And recrystallization can only be achieved by cold or hot working. It is non-magnetic as compared with the magnetic ferritic and martensitic S.S.. Austenitic S.S. are the most corrosion resistant of the stainless steels group, and this due to their high chromium and nickel content.

2-2-2.4. Duplex Stainless Steels.

Duplex S.S. are formed when the percent of Cr exceed the balance limit in austenitic steels. It is mixed of austenite and ferrite crystals($\alpha + \gamma$). In fact the structure of S.S. can be determined by the balance between those elements that form ferrite(Mo,W,V,Ti,Al,Si, and Cr) and those that stabilize the austenite (C,N, and Ni). Most of the duplex alloys contain very low carbon (< .03%), between 20% and 30% Cr, about 5% Ni, and other ferritizers and austenitizers to abtain the desired structure. There are different grades from duplex steels. Some of the advantages of these steels are:

a) Improvement of corrosion resistence in certain reagents, and this is due to the increase in Cr content.

b) They have higher yield point value from fully austentic S.S. , after treatment at high temperature.

c) These steel can be welded with much less risk of cracking than fully Austenitic steels.

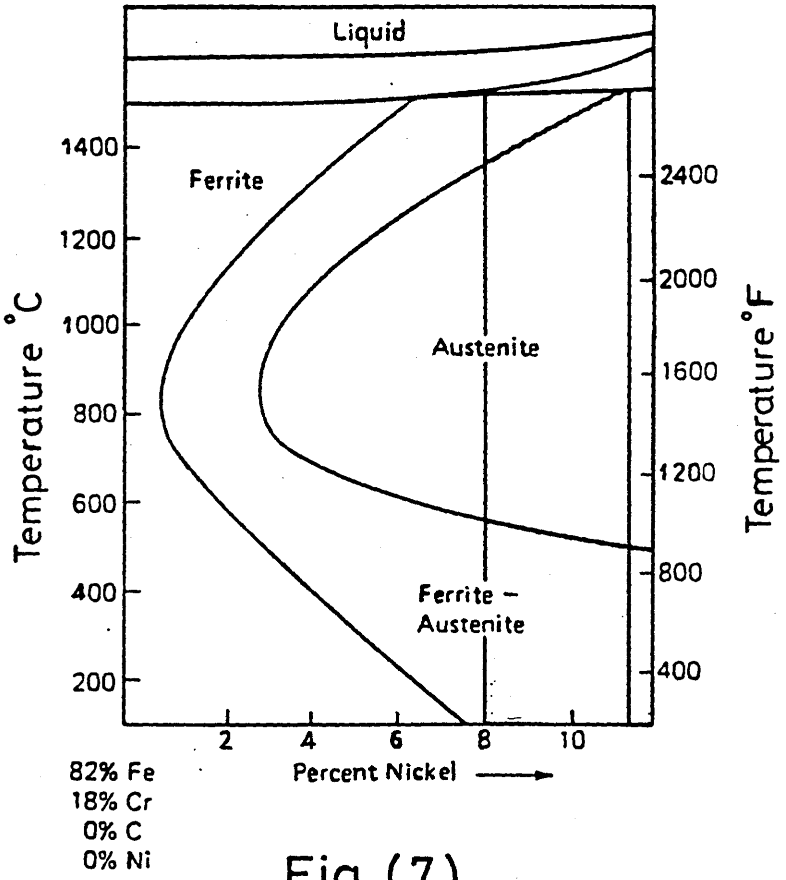


Fig (7)

Effect of Ni percentage.

Reference No.36

2-2-3. Series of Stainless Steels.

There are different commercial naming for S.S. series. In this section only **AISI** standard will be considered [appendix 1] shows the composition of the main standard alloys. According to the above classification, S.S. were classified commercially. **430, 430F, 430Se, 442, 405, and 446** S.S. are ferritic S.S.. 430 type is the basic steel alloy in this group and all the rest types are modified according to the engineering requirement. 430F is the modified alloy to be applicable for free-machining for heavy cuts etc.. 430Se is the Free-machining modification of 430 for light cuts. 405 is the modified alloy to improve the weldability. 442 and 446 are the modified alloys to increase the corrosion resistance.

Some of the commercial martensitic S.S. available are **410 , 403 , 416 , 420 , 431 , 440A , 440B and 440C**. Type 410 is the basic alloy in this group . 416 and 416Se are modified to improve the machinability. 440 steels have high chromium percent to improve the corrosion resistance etc. .

300 series S.S. are from the austenitic steels. The basic alloy is 302. Types 309, 310 and 314 have more Cr and hence greater heat resistance. Types **316** and 317 with additional Mo have the highest corrosion resistance of the standard grades and also have high creep resistance. **316L** alloy is modified from 316 alloy and it has low carbon content for welded constructions . There are another austenitic steel alloys called 200 series and include 201 and 202 , but still these type are modified from 301 and 302 respectively.

The above stainless steels are the standard alloys, and there are some high alloy stainless steels such as AL-6XN, AL-6X, 254 SMO and HR 8N. Some of these alloys designed to resist high temperature media and the other to resist corrosive environments and some of them to resist both. The compositions of some high alloy stainless steels are shown in appendix A.

Finally and as mentioned before that there are unlimited alloys that can be produced, depending on the composition and percent of the elements used. Some of the

S.S. manufacturers are continuing research and developing a new S.S. alloys according to their need and requirement.

2-2-4. Material investigated.

The material and alloys used in the work described in this thesis are **Titanium, SMO, Hastelloy C, 26Ni-18Cr-5Mo , 316 and 430** alloy. The composition of these alloys are shown in appendix A. **Titanium** was selected as the upper reference in this comparative study, due to its significant high corrosion resistance to seawater, while **430** steel was considered as the lower reference due to its fair resistance to seawater corrosion . It is important to note that the above mentioned metal and alloys are ferrous and non-ferrous metals. Titanium and **hastelloy C** are non-ferrous metal and alloy respectively and the rest are ferrous alloys . From the previous study it is clear that Ti and hastelloy C are the best alloys for corrosion resistance in seawater. From the standard classification AISI , **316** was described as the best alloy for corrosion resistance. **SMO** steel alloy is an austenitic stainless steel , with high percentage of Cr , Ni and Mo . The addition of Cr and Mo is to improve its resistance to pitting and crevice corrosion, while the addition of high amounts of Cr , Ni and Mo improves its resistance to stress corrosion cracking. The main reason for producing this alloy is to use it instead of expensive materials such as nickel based alloys or titanium in environments that contain halide ions like chloride [40]. The last sample used is **26Ni-18Cr-5Mo** which is similar to SMO alloy but with additional amount of Ni.

CHAPTER THREE

AQUEOUS CORROSION

1. Definition:

The word corrosion means *the destruction of a material under the chemical or electrochemical action of the surrounding environment*[44]. Some other corrosion definition limit the destruction for the surface of material[45], and some other includes metallurgy reactions[37].

2. Mechanism Of Aqueous Corrosion:

The mechanism of aqueous corrosion is electrochemical in nature. Assuming the metal to be bivalent , the reaction can be written:

$$Me \longrightarrow Me^{2+} +2e \qquad \text{Anodic reaction}$$

$$Me^{2+} +2e \longrightarrow Me \qquad \text{Cathodic reaction}$$

In case of the metallic corrosion there different cathodic reactions may takes place. The most common are:

Hydrogen evolution	$2H^{+}+2e \quad H_2$
Oxygen reduction	$O_2+4H^{+}+4e \quad 2H_2O$
Or	$O_2+2H_2O+ \quad 4(OH)^{-}$

In natural seawater at pH aroun 8 the Oxygen reduction reaction is usually more important in corrosion than Hydrogen evolution.

Before discussing the electrochemical reaction it is preferred to discuss briefly the principles of thermodynamic and kinetics.

2.1. Thermodynamic Principles:

Thermodynamics is the science which study the energy changes of the substances. There are three laws in thermodynamics, but the most important law that related directly to corrosion is the second law. The second law may be expressed as follow; *for any process to occur spontaneously, there must be an increase in entropy of the universe* , and the entropy can be defined with the degree of disorder or randomness of the system[45].

From the definition above it is possible to define the change in free energy as the direct measure of the work capacity or maximum electric energy available from a system. This change in free energy may be a negative or positive value , depending on the change accompanying the transition of the system. If the value is negative, this indicates a loss in free energy of the system.

The above law can be applied to the corrosion processes. During the manufacturing stage of the material from their ore situation, all these materials are subjected to external energy in order to form them . This conduct the materials to reverse their free energy situation as a spontaneous direction .

The free energy change accompanying the electrochemical reaction can be calculated from the following equation

$$\Delta G = -nFE$$

where :-

ΔG = Free energy change

n= the number of electrons involved in the reaction

F= Faraday constant (96, 487)

E= Cell potential

The value of **E** can be calculated from a comparison studies between the potential of different materials . It is the potential difference measured between a certain electrode and a reversible reference electrode. To clarify this potential, the concept of standard half cell should be explained. If an electrochemical cell constructed as shown in Fig(1),

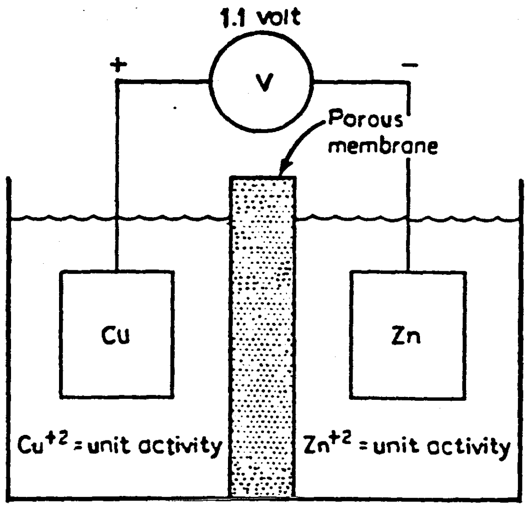


Fig (1)

Reversible cell containing copper and zinc in equilibrium with their ions.

containing two dissimilar materials. The voltmeter will indicate potential difference between these two materials, consequently, there are unlimited potential values between the different materials . To have a unique potential value for each material , the potential of all the materials were measured with hydrogen electrode as the reversible reference electrode. The potential of this reference electrode agreed to be zero. The potential values measured from this cell called the standard oxidation reduction (redox) potentials as listed in table (3-1). To measure the overall potential through electrochemical cell E , **Nernst** formula may be used ,

$$E=E_o+2.3\frac{RT}{nF}\log_{10}\frac{a_{oxid}}{a_{red}}$$

where ,

E_o = Standard half cell potential

R= Gas constant

T= Absolute temperature

n= The number of electrons transferred.

F= Faraday constant

a_{oxid} = Activity of oxidized species.

a_{red} = Activity of reduced species.

From this formula Dr. Pourbaix established graphical methods with the use of diagrams of electrochemical equilibria , drawn as a function of pH (abscissa) and electrode potential (ordinate) as shown in fig(2) . These curves give an indication whether corrosion will take place under certain conditions or not , and gives the immunity of the metals as well as shown in fig (3) .

Fig(2) and (3) shows the diagrams of Fe-H_2O system where the region of stability for Fe^{2+}(aqueous) is bounded by four lines representing the equilibria between the following reactions[45]:

Line (a) $Fe^{2+}(Aq) + 2e(Fe)=Fe(solid)$

Elements	**Potential mv**
$Au=Au^{3+}+3e$	+1.498
$O_2+4H^++4e=H_2O$	+1.229
$Pt=Pt^{2+}+2e$	+1.2
$Pd=Pd^{2+}+2e$	+0.987
$Ag=Ag^++e$	+0.799
$2Hg=Hg_2^{2+}+2e$	+0.788
$Fe^{3+}+e=Fe^{2+}$	+0.771
$O_2+2H_2O+4e=4OH$	+0.401
$Cu=Cu^{2+}+2e$	+0.337
$Sn^{4+}+2e=Sn^{2+}$	+0.15
$2H^++2e=H_2$	0.0000
$Pb=Pb^{2+}+2e$	-0.126
$Sn=Sn^{2+}+2e$	-0.136
$Ni=Ni^{2+}+2e$	-0.250
$Co=Co^{2+}$	-0.277
$Cd=Cd^{2+}$	-0.403
$Fe=Fe^{2+}$	-0.440
$Cr=Cr^{3+}+3e$	-0.744
$Zn=Zn^{2+}$	-0.763
$Al=Al^{3+}+3e$	-1.662
$Mg=Mg^{2+}$	-2.363
$Na=Na^++e$	-2.714
$K=K^++e$	-2.925

Table (3-1)
Standard Redox Potentials(25°C)

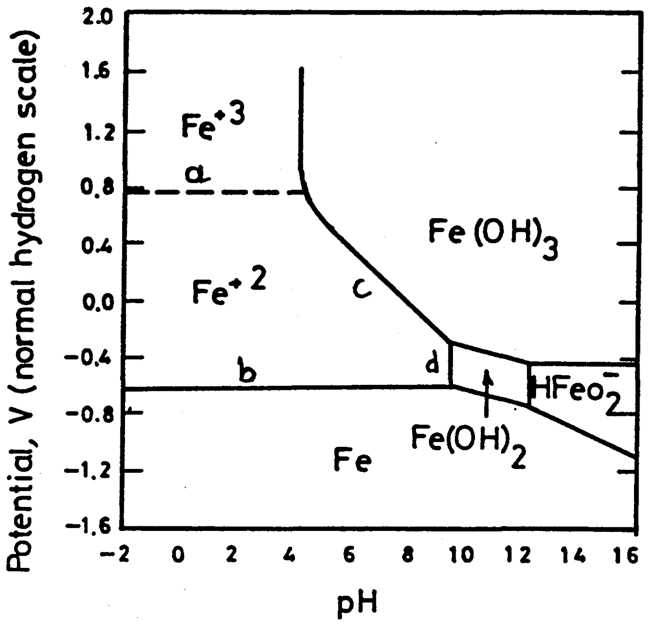


Fig. (2)

Simplified potential-pH diagram for the $Fe-H_2O$ system.

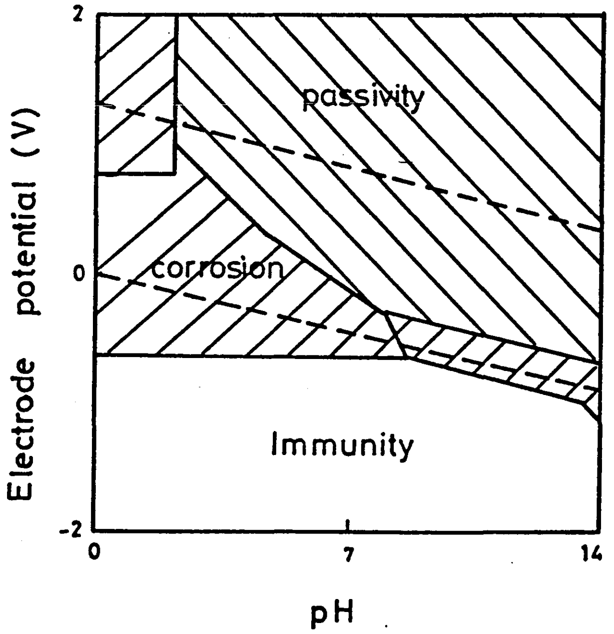


Fig. (3)

$$E=E^o+(RT/2F)\log_{10}(h_{Fe2+}/a_{Fe})$$

$$=-0.61\ V$$

Line (b) $Fe^{3+}(Aq) + e(Fe)=Fe^{2+}(Aq)$

$$E=E^o+(RT/F)\log_{10}(h_{Fe3+}/h_{Fe2+})$$

$$=+0.77\ V$$

Line (c) $Fe_3O_4(solid) + 8H^+(Aq)+2e(Fe)=3Fe^{2+}(Aq)+4H_2O$

$$E=E^o+(RT/F)\log_{10}(h_{H+}/h_{Fe2+})$$

$$=+1.51-0.236pH\ V$$

Line (d)$Fe2O3(solid) + 6H^+(Aq)+2e(Fe)=2Fe^{2+}(Aq)+3H_2O$

$$E=E^o+(RT/F)\log_{10}(h_{H+}/h_{Fe2+})$$

$$=+1.08-0.177pH\ V$$

The left portion of these diagrams represents acid media and the right portion alkaline media ; the top portion represents oxidizing media and the bottom portion reducing media. The region below the dotted line (a) represents the circumstances under which water may be reduced with the evolution of hydrogen ; the region above the dotted line (b) represents the circumstances under which water may be oxidized with evolution of oxygen . The region between the two lines (a) and (b) represents the circumstances in which both this reduction oxidation are impossible [44]. This region represents the region of thermodynamic stability of water .

Finally, these curves predicting the spontaneous direction of reactions and estimating the corrosion products composition.

2.2. Electrode Kinetics.

The above thermodynamic principle gives the indication of the direction of corrosion, but it tells nothing about the rate of corrosion, which is the most important from the corrosion engineering point of view. Electrode kinetics principle can give the behaviour of corrosion rate. Obviously the rate of corrosion may be expressed as a current density (A/m^2) . If the two materials in fig (1) are short circuited as shown in fig(4) , a lot of electrons will transferred from zinc to hydrogen electrode and the zinc

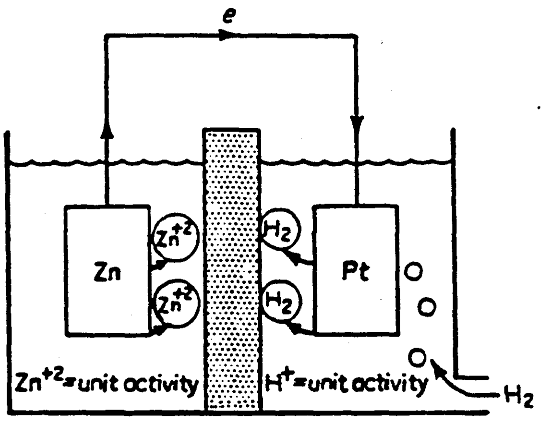


Fig (4)

Short-circuited cell containing zinc and hydrogen electrodes.

will dissolves while hydrogen bubbles will evolve. In this case zinc electrode is oxidized and called **anode** and the hydrogen electrode is reduced and called **cathode**. The electrodes in fig(4) will no longer be at their equilibrium potential. The deviation from the equilibrium potential is called the **polarization** . Of course the cause of this deviation is the net current between the cell electrodes. The magnitude of polarization measured in terms of **overvoltage** μ. To understand the polarization effect , there must be a brief discussion about the exchange current density.

2.2.1. Exchange Current Density i_0.

If a reversible electrode is considered , then the rate of oxidation under equilibrium conditions is equal to the rate of reduction. If for example this reversible electrode was hydrogen established with platinum electrode then the rate of exchange will be constant . If r_{oxid} is denote to the oxidation rate and r_{red} is denote to the rate of reduction , then it is possible to derive the relationship between the rate of reactions and the exchange current density from Faraday's law:

$r_{oxid} = r_{red} = i_0/(nF)$

The exchange current density i_0 can be defined as the rate of oxidation and reduction reactions at an equilibrium electrode expressed in terms of current. It is observed that the exchange current density varies depending on the electrode metal. For example i_0 in case of Hg electrode -under cathodic reaction in HCl solution- is about 2×10^{-12} amp/cm^2, while for Fe electrode under cathodic reaction in H_2SO_4, i_0 is about 10^{-6} amp/cm^2.

2.3. Polarization

If the case of hydrogen reversible electrode is considered again , then the hydrogen evolves from two types of polarization ; activation polarization and concentration polarization. In activation polarization two hydrogen ions are reduced in contact with the metal surface and combined at the metal surface as shown in Fig(5).

while in concentration polarization the evolution of the hydrogen ions reduction is not necessarily take place in contact with metal surface, as shown in Fig(6) . **Tafel** equation can solves the overvoltage of the activation polarization :

$$\mu_{act} = \pm B \log_{10} \frac{i}{i_o}$$

where,

μ_{act} = Overvoltage

B = Tafel constant

i= The rate of oxidation or reduction in terms of current density.

For the concentration polarization the overvoltage can be calculated from the following equation:

$$\mu_{con} = 2.3 \frac{RT}{nF} \log_{10} (1 - \frac{i}{i_L})$$

where,

μ_{con} = Overvoltage .

i_L= Limiting diffusion current.

Or

$$i_L = \frac{D n F C_B}{X}$$

D=Diffusion coefficient of the reacting ions .

C_B= The concentration of the reacting ions.

X= Thickness of the diffusion layer.

Usually both types of polarization occur at electrode . The value of the total overvoltage of electrode is the some of overvoltage of activation and concentration polarization.

$$\mu_t = \mu_{act} + \mu_{con}$$

where,

μ_t = Total overvoltage.

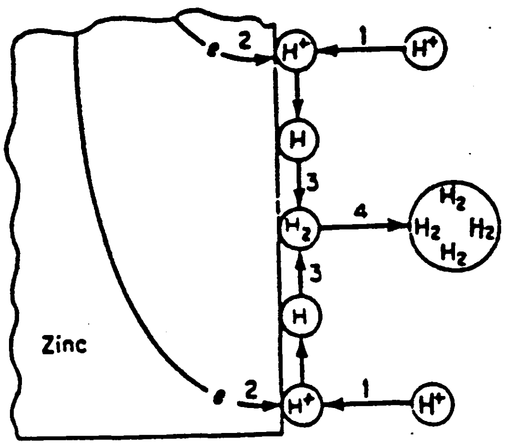


Fig (5)

Hydrogen-reduction reaction under activation control.

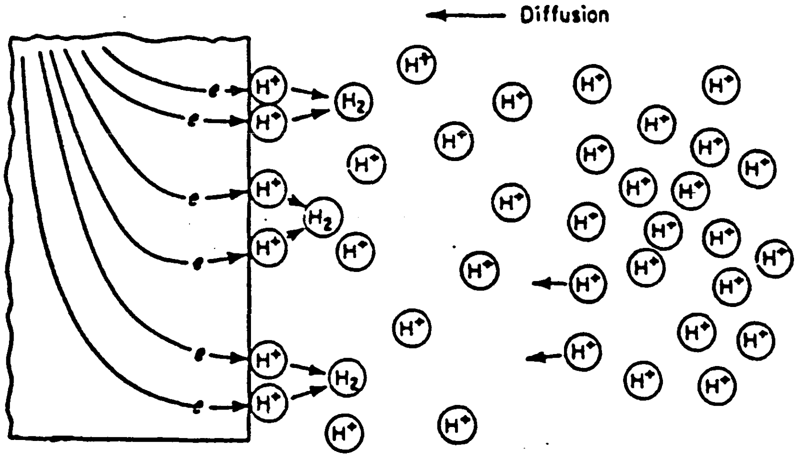


Fig (6)

Concentration polarization during hydrogen reduction.

2.4 Mixed Electrodes.

A mixed electrode is an electrode or metal in contact with two or more oxidation-reduction system . It is based on the mixed-potential theory which state that any electrochemical reaction can be divided into two or more partial oxidation or reduction reactions and the rate of oxidation reaction must equal the rate of reduction rate. Fig (7) shows a typical case of zinc immersed in hydrochloric acid. The reaction will take place at point (A) which is the intersection between the oxidation and reduction lines and at this point the two hypotheses of the mixed-potential theory are satisfied.

2.5. Passivity.

Passivity can be defined as a loss of chemical reactivity of metal or alloy under certain environment conditions [43]. The basic explanation of this phenomena is that there is an oxide film formed on the metal or alloy surface, and this film protect from the chemical or electrochemical reaction. The nature of the oxide film is not identified clearly . The studies on this field do not give sufficient information concerning the nature of this film and its mechanism. Fig (8) shows a typical curve for anodic polarization test. Increasing the potential positively, the current increases and following Tafel slope, and this region is called an active region . Increasing the potential positively a huge reduction in the current flow will take place , and independent to the increase of the potential the current will remains constant and low , the reason of this reduction is the forming of the metal or oxide film, this region being called passive. By increasing the potential , a dramatic increase in the current will happen, which means a breakdown of the oxide film is happened.

In case of mixed electrode principle there will be three possible cases of intersections between the reduction process and the exchange current density as shown in fig (9) . In Case 1, the intersection takes place in the active region which means high corrosion rate will exist. In Case 2 there are two possibilities in the active and hence

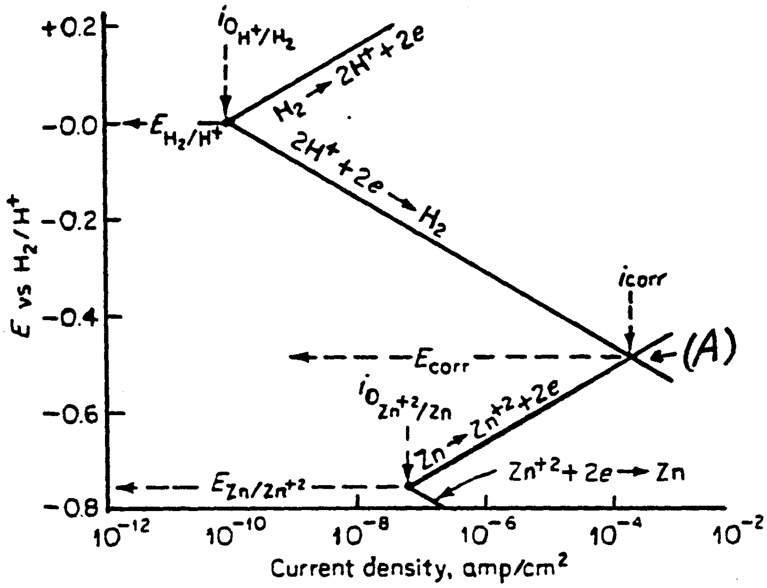


Fig (7)

Electrode kinetic behavior of pure zinc in acid solution-schematic.

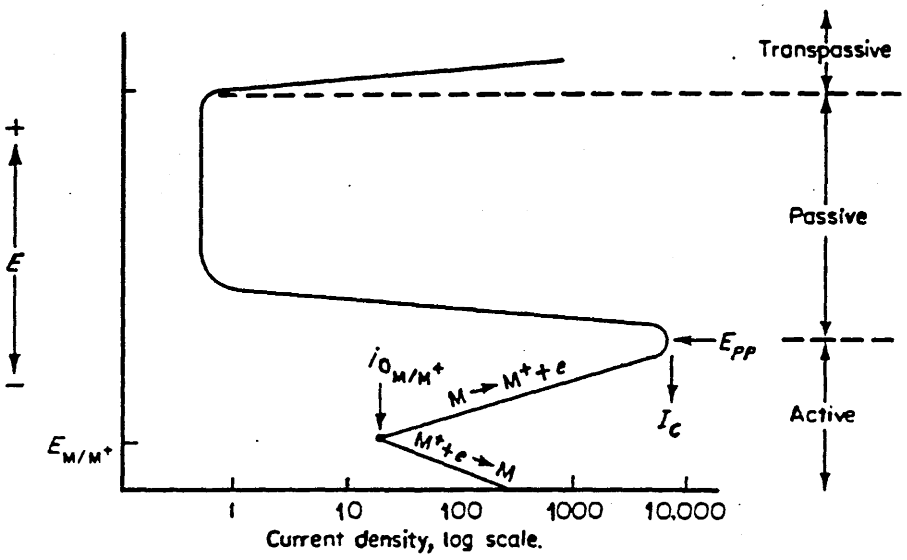
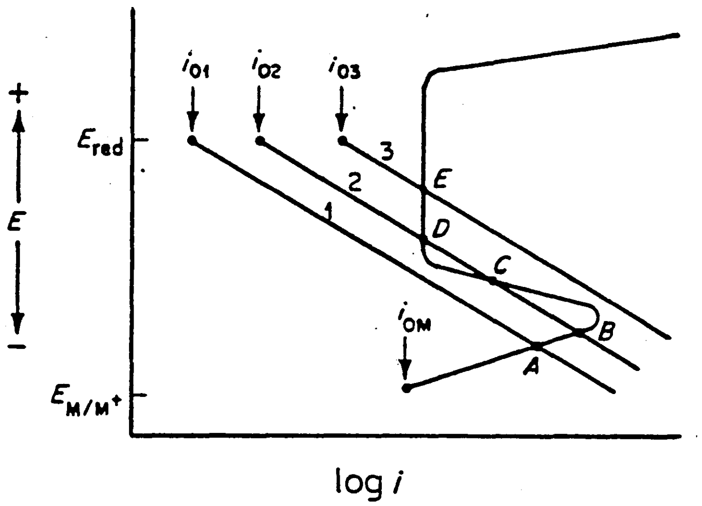


Fig (8)

Typical anodic dissolution behavior of an active-passive metal.



Fig(9)

Behavior of an active-passive metal under corrosive conditions.

high corrosion rate and the other possibility in the passive range with low corrosion rate. Point C was neglected because it is not satisfying the second hypotheses which indicates that the system should be stable electrically and this point is not stable electrically . In Case 3 the intersection takes place in the passive range and low corrosion rate will exist. This point is the most desirable from an engineering point of view .

3. Effect of the Corrodent Conditions

As the corrosion is an electrochemical reaction between the metal and its environment, it is necessary to study the effect of the environmental conditions to the corrosion process. The conditions of the corrodent or the environments may be considered as the temperature , velocity , oxygen , chloride concentration and pH .

3.1 Temperature

Increases of temperature has two effects. First it increases the critical current density as shown in fig (10.a) , second it reduces the concentration of dissolved gases , such as oxygen which leads to a greater degree of polarization of the oxygen reduction reaction as shown in fig (10.b)[47], Hence these two effects act in opposite. The combination of these two effects makes the corrodent more aggressive by increasing its temperature. Of course this conclusion is in general , otherwise there are some metals and alloys slightly affected by the temperature .

3.2 Velocity

Corrodent velocity affects the corrosion rate of systems rate controlled by concentration polarization and does not affect the activation polarization. As the velocity of the solution increase , the rate of corrosion increases , but this increasing corrosion rate is limited by certain levels of velocity. Fig (11) shows this fact , corrosion rate is independent of solution velocity at curves 4 and 5. This is from electrochemical reaction

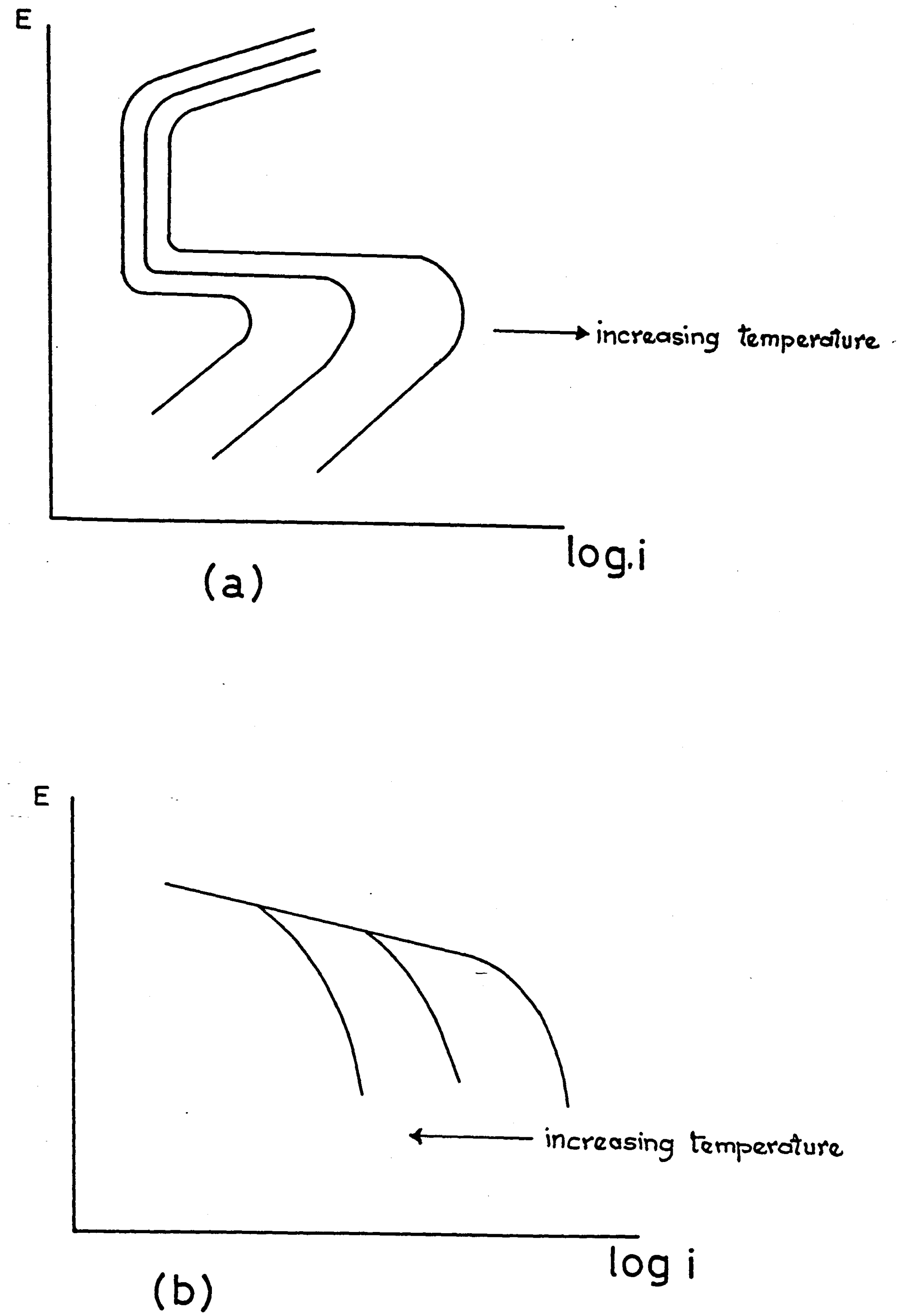


Fig (10)

Effect of temperature.

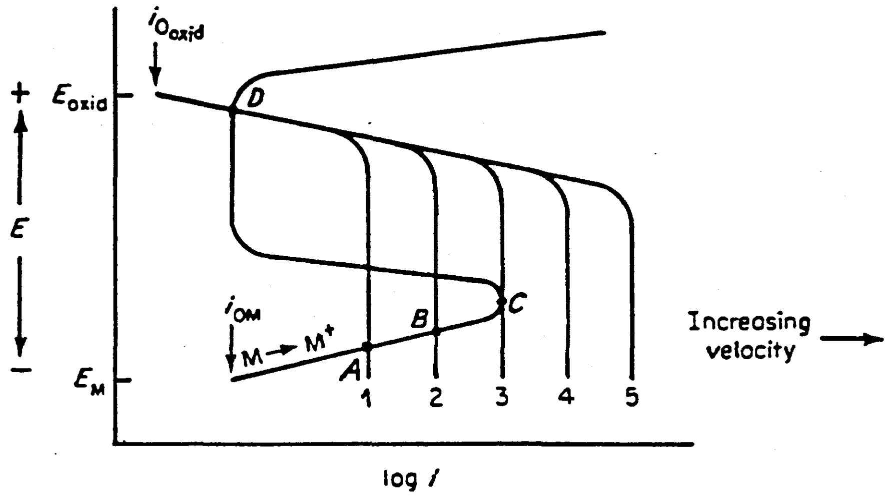


Fig (11)

Effect of velocity.

point of view . Practically there is a possibility for erosion corrosion reaction at high velocity specially if the solution contains suspended particles.

3.3 Effect Of Oxidizer

In case of active-passive metal, as the oxidizing agents increase the rate of corrosion increases as shown in fig (12.a) points A, B and C . But with a little increasing of oxidizing agents the metal becomes passive and intersect with the anodic curve at point F . By adding more oxidizing agent , the metal tends to be active as it intersect the anodic curve at point J as shown in Fig (12.b) .

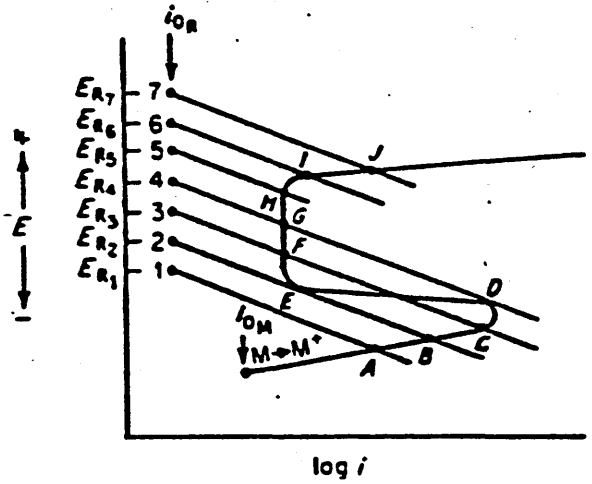
3.4 Chloride Concentration

Chloride ions are responsible for attacking and damaging the oxide film which protect the active-passive metals from corrosion. Fig(13) shows who the concentration of chloride reducing the passivity of the metal and increasing the critical current density

.

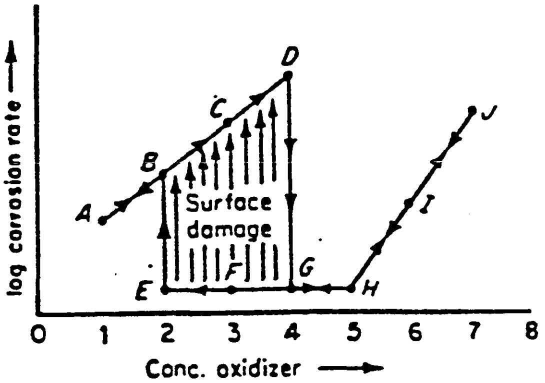
3.5 pH Effect

As pH increases the hydrogen ions (H^+) decreases, as the concentration of the H^+ increase the corrosion rate usually increases . In other word as the pH increase the rate of corrosion will decrease. The shape of the effect of H^+ is shown in fig (14).



(a)

Effect of oxidizer concentration on the electrochemical behavior of an active-passive metal.



(b)

Fig. (12)

Effect of oxidizer concentration on the corrosion rate of an active-passive metal.

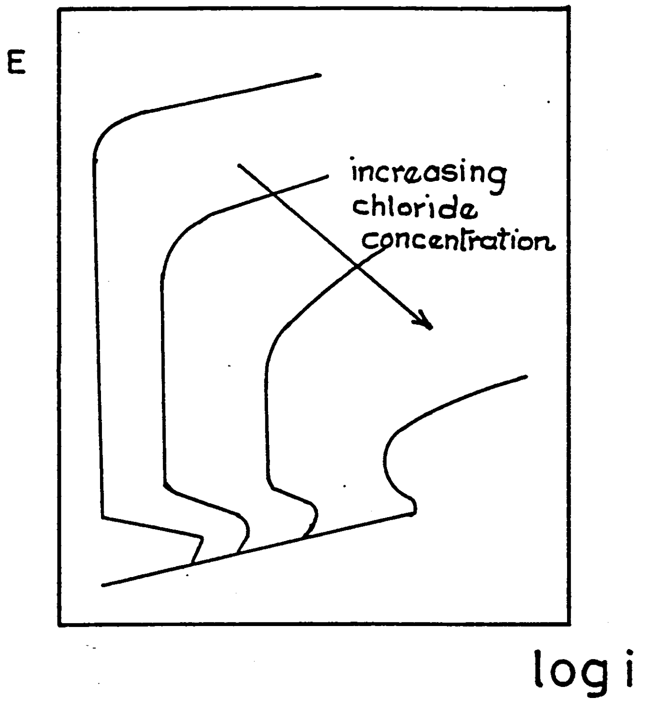


Fig (13)

Effect of chloride-concentration on active passive metal.

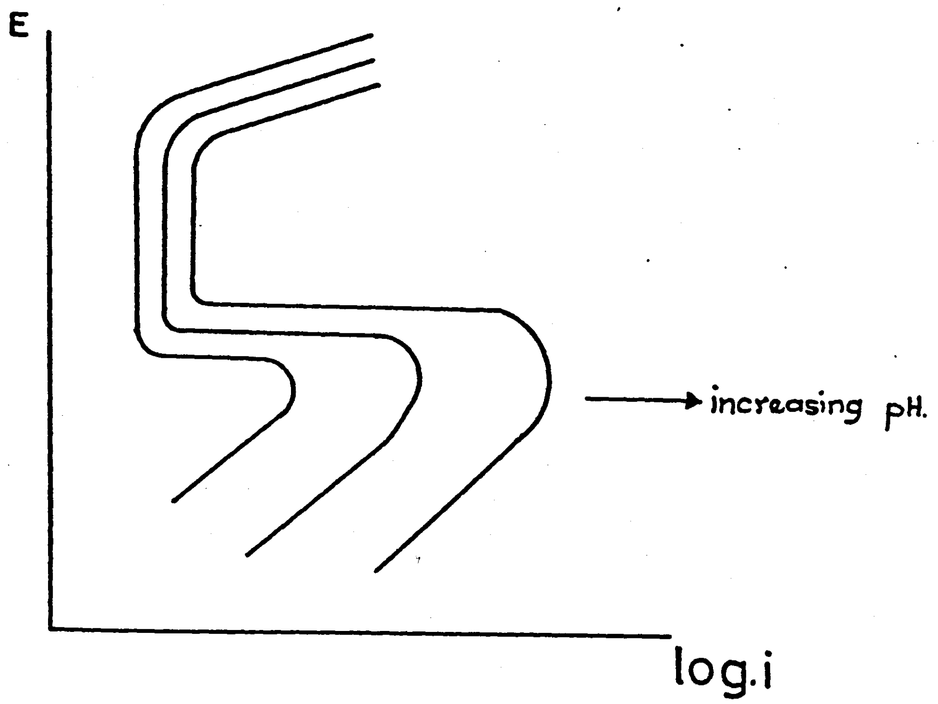


Fig (14)

Effect of pH value.

CHAPTER FOUR

CORROSION TESTING

1-Introduction

It is very important to study the corrosion effects on the materials in the laboratory . The economic benefits gained from the results of laboratory testing are considerable . These results can reduce the cost of production, installation and maintenance of metal products . In so many cases the life time of metal products can be improved due to the results of testing . But the corrosion testing in the laboratory has some difficulties , such as the limitation of the size of metal to be tested and the corrodents used . As well as the limitation on the laboratory , the simulation of the actual environment in the laboratory is another difficulty . In so many cases the corrosion takes place after a long period of exposing the metals to the environment , while in the laboratory it is difficult to wait for a long time to study the effect of corrosion on a sample .

2-Reasons For Corrosion Testing :

There are different reasons for corrosion testing . Sometimes corrosion testing is carried out to check the standardization of material, or to find the time required to start the corrosion of the material . Testing is also carried out to study the mechanism of corrosion . Tests are also made to select the proper material for a certain environment .

3- Testing Classification:

Corrosion testing may be classified in the following way:

1- Laboratory tests.

2- Pilot plant tests.

3- Field tests.

3-1 Laboratory Tests:

Laboratory tests use small specimens and a small quantity of the corrodent compared to the actual corrodent . It is very important to simulate the test environment with the actual as possible. The results obtained give a good indication of the application of the material tested .

3-2 Pilot Plant Tests :

The idea of this type of test is to build a small scale product or prototype of the actual products , then to expose this prototype to a typical environment where the actual products will be exposed to . The results from this type of test are more accurate and reliable . This type of test is used usually when commercial quantity of products will be produced .

3-3 Field Tests:

Field tests are carried out on the site of any plant or equipment. The results from these tests are very useful for the equipment and site . The disadvantages of this test are the limitation on the samples number, lack of control cost and irreversibly .

4- Factors In Laboratory Testing:

From the basic definition of the corrosion , it is clear that the two main factors are the specimen and the corrodents.

4-1 Specimen

The main factor in the corrosion testing is the specimen or sample. The specimen should pass through three stages during corrosion testing . The first stage is the specimen preparation , which takes place before commencing the test . The second stage is the exposure of the samples to the corrodent. Finally, the analysis of the sample after exposure to the corrodent.

4-1-1 Specimen Preparation

Selection of the specimens should be carried out carefully . The chemical composition , fabrication history and metallurgical history are all required and should be reported well before starting the testing. The shape of the specimen should be designed according to the requirements of the test. The size of the specimen used must be selected carefully , because the results of corrosion tests cannot be expected to be independent of the size of the test specimen used [48], but if the dimensions of the specimens used are kept the same when comparing different material , it will be possible to make reliable estimates of the behaviour of the materials tested , but as comparison results. A square shape with one half square inches is the common shape used [49] . Rectangular or circular shapes may also be used .

The specimens should be cut from the suitable material. For example , if the application requires a casted metal , then the samples should be cut from casted sheet . It is not recommended to use specimens cut from bar , in order to minimize the exposed cut grain . It is preferable to duplicate the specimens .Corrosion rates of duplicate specimens are usually within 10% under the same conditions . If the mechanical properties test will analyse the damage on the specimens , then some specimens should be stored and protected to compare it with the exposed specimens.

Finally all damages or cold working during specimen preparation should be reported.

4-1-2 Specimens During Exposure

All the specimens should be subjected to identical conditions (i.e corrodent temperature , salinity , oxygen and velocity etc..) .

4-1-3 Specimen After Exposure

This stage is after the specimen exposed to the corrodent and before analysing it . At this stage only the cleaning of the specimens is required . There are two main methods for cleaning the specimens , mechanical method such as scraping , brushing , scrubbing with abrasives or sandblasting . The chemical method , where some chemical materials are used for cleaning such as Clark solution which is consist of 1. liter HCl, 20gm antimony trioxide and 50gm stannous chloride..

4-2 Corrodents

The corrodents used in the laboratory should be prepared carefully. The characteristics of the corrodents should remain as constant as possible , such as temperature , viscosity , conductivity, purity and pH value.

5- Measurement Of The Damage On The Specimens

There are different methods and techniques for measuring the damage on the specimens caused by corrosion . Each method depends on the type of corrosion to be measured.

5-1 Visual examination

Corrosion may be detected visually . This method is used on sites like tanks , pipes equipments or industries . Cracks , pitting or change in the surface colour of the metal can be guided to recover the corrosion . It should be noticed that change in surface colour may be due to scaling and not corrosion .

5-2 Weight Loss Method

The common method used for measuring the damage of the corrosion is the weight loss method. This method describes the amount of the metal lost due to the corrosion reaction. Practically this method has disadvantages, e.g, the corrosion which takes place is not usually uniform. Another disadvantage is that the corroding metal has a film of corrosion products and to weight the remaining metal accurately it is necessary to remove the corrosion products without removing parts from the metal. In this method the corrosion rates are expressed in weigh loss per unit area per unit time . In S.I units , the corrosion rate measured by g/(m2)(sec).

5-3 Pit Depth

A pit is an area of localised attack on the metal . There are different methods to determine this type of corrosion . If the pitting are broad and shallow , the measurement can be done by a rounded spindle micrometer . If the pitting are deep , then it is possible to use a micrometer with a sharply pointed spindle . Another method may be used to measure the depth of pittings by a microscope . A microscope fitted with a calibrated focusing knob can be used by focusing first on the lip of the pit then on the bottom of the pit and then the pit depth can be calculated from the difference between the two readings. Finally, in some cases it is easy to section the specimen through an axis passing through the pittings and measure the depth with a normal micrometer.

5-4 Change In Mechanical Properties.

This type of measurement depend on the comparison between the metal exposed to the corrodents and the same metal not exposed . The comparisons will be from the mechanical properties point of view (i.e Ultimat, tensile strength , fatigue etc..) . The comparison shows the effect of corrosion on the mechanical properties.

6. Electrochemical Tests.

Electrochemical tests have been attractive to many investigators because they operate on the mechanism of the corrosion process . Electrochemical techniques offer a clean way to accelerate the corrosion process . For example , they can be used to increase or control the oxidizing potential of an environment and thereby reveal specific characteristics of a material , such as passivity , without adding chemical oxidizing agents . Similarly for measuring corrosion rates without removing the sample from the environment [50] .

It is possible to estimate the corrosion current using polarization techniques . There are three different techniques used in this regard. All these techniques are based on the Tafel behaviour , where the anodic contribution to the net current density can be ignored if the specimen potential is 50 mV more negative than the open circuit value and the same for the cathodic but the neglecting will be at potential 50 mV more positive as shown dramatically in fig (1) .

The first technique is to polarize the specimen to potential at least 50 mV more negative than the open circuit corrosion potential, and sufficient data points taken to obtain a reliable Tafel line . The current density data can be extrapolated back to corrosion potential using semilogarithmic plot to obtain the corrosion current density value .

The second technique is the same as the first but the specimen polarized anodically to a potential greater than 50 mV more positive than the corrosion current potential and the process repeated as the first.

The third technique requires that both anodic and cathodic polarization be carried out as described above, and the intersection of the anodic and cathodic gives the corrosion current.

Anodic polarization techniques have been used to characterize the corrosion characteristics of metal alloys in specific environments . The approach is to immerse the specimen in an environment which does not have oxidizing agents present . The specimen is then polarized anodically to determine its corrosion current as a function of oxidation potential . This technique is desirable for metals showing passivity such as stainless steels . Also this technique can be used to evaluate different alloys over a range of oxidizing conditions if the conditions are held constant. This technique requires potentiostat , scan generator , calomel electrode ,

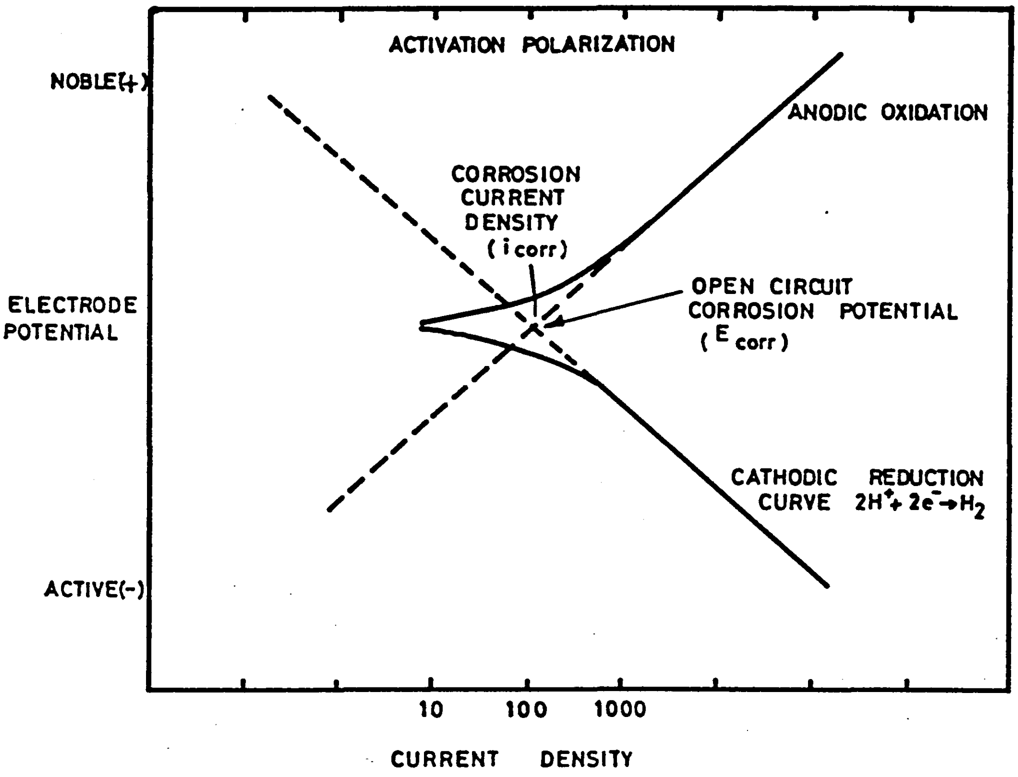


Fig. (1)

Schematic cathodic and anodic polarization curve.

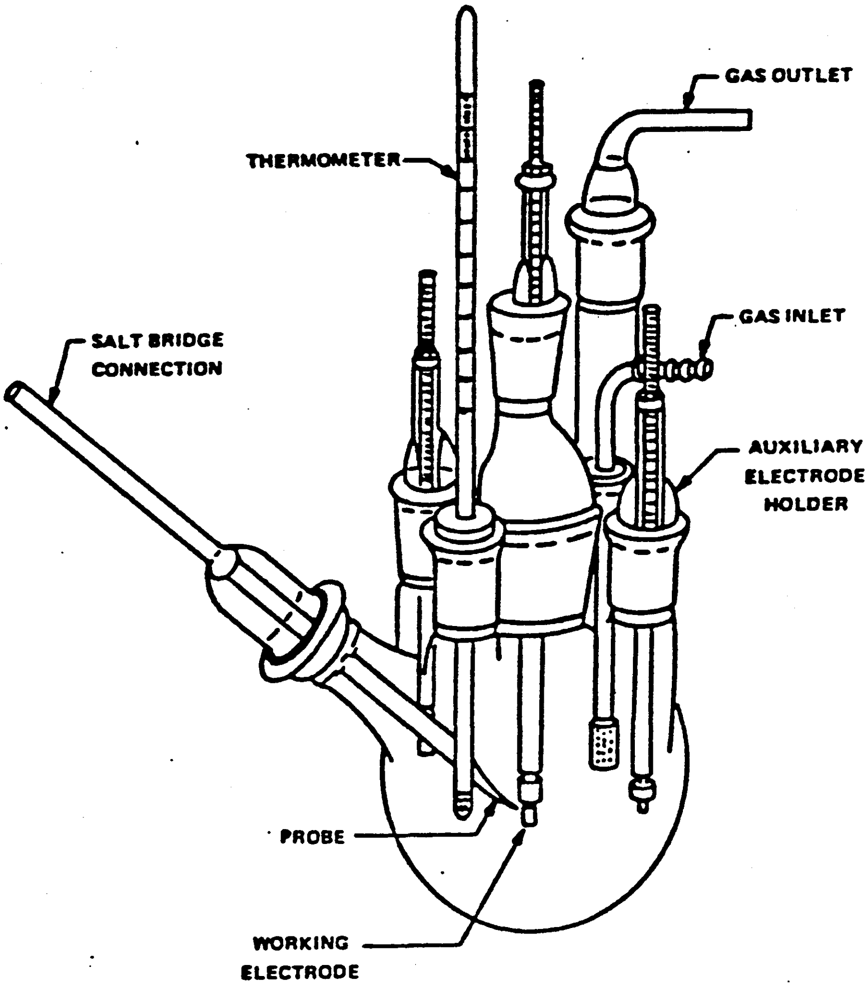


Fig. (2)

Standard multineck polarization cell.

CHAPTER FIVE

SCOPE OF WORK

1. Introduction.

Corrosion is still one of the most industrial disease not fully controlled. From previous chapters, it is clear that corrosion investigation is still based on the laboratory experiments and field experiences. In general, no specific equations or models can deal with corrosion behaviour . Each material or alloy has its corrosion behaviour under certain conditions . In Ummlaj RO plant there was a problem, on which alloy is the best to use as mentioned in chapter one , and to investigate this problem , is it necessary to built a pelton wheel turbine from a wide range of high grade alloys in the laboratory and test them under the same conditions?. Of course this will be the ideal, but it will be costly . In other word , is it possible to take the ordinary polarization test results under the static and normal conditions as a guide to compare the different alloys corrosion behaviour under severe conditions , and what is the effect of the environmental conditions on the corrosion process, specially for the high grade alloys .

2. Literature review.

A lot of work made to study the corrosion resistance behaviour of stainless alloys. Different media were considered , such as, acids, potable water , seawater, oxidizing environments[51], Chloride environments[52,53,54], bromine-containing environments[69], bleach-plant environments[55] and paper industry environments[57]. Effect of of environmental variables and alloy contents on the crevice corrosion was made by R.Kain[56]. Much of this work has used electrochemical techniques to assess corrosion behaviour, and much valuable information can be gained from such measurements.

2.1 Summary of electrochemical study of localised corrosion:

As described in chapter four, there are numbers of electrochemical techniques which have been used to study localised corrosion of stainless alloys. The most frequently used one is to carry out an anodic polarization scan from corrosion potential(Ecor). A typical result from this techniques is shown in fig(1). X-axis shows the current measured from the specimen, while Y-axis shows the scan potential. Ecor is the free corrosion potential. Ec is the potential at which breakdown of the passive film occurs and hence is a measure of the resistance of the material under test to the initiation of localised corrosion. By reversing the scan of the potential from Ec negatively, the oxide film try to reform again, Ep explain the potential where the oxide film is reformed and is often called the repassivation potential. Ec and Ep values can give an indication about the behaviour of corrosion of diffrerent alloys, for example, when the value of Ec potential very high (1000 mv) this means that the oxide film of this alloy is strong enough and can resist the corrosion on this environment. when the scan of the potential is reversed after localised corrosion took place, and the oxide film reformed immediately, again this means that the oxide film is strong. Generally Ec's may be considered as a unique property[58] and its measurement does provide very useful comparative information on behaviour of different materials in a given environment or of the behaviour of one material in varying environment.

2.2 Corrosion Resistance of Stainless Alloys in Seawater:

A lot of work made at ambient temperature and oxygen saturated seawater conditions, and the previous work in other conditions relevant to desalination plant have been rather limited, specially in respect of RO-plant conditions. Hence this work was aimed at providing some more precise information under these conditions.

T.Lee[60] reported the results for types 304 and 316 stainless steel exposed in natural seawater. Crevices were made on the specimens . Times to initiation and

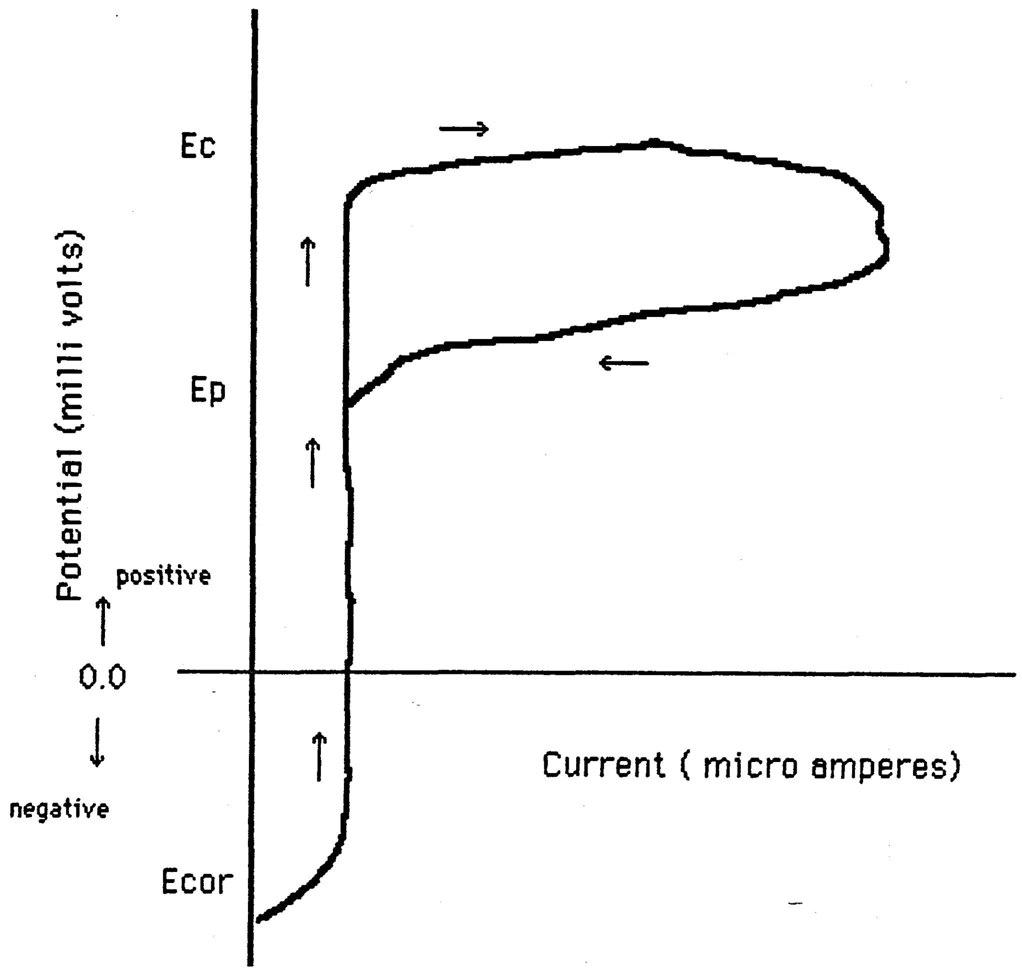


Fig. (1)

Typical anodic polarization test curves

propagation rates as determined from current measurements were compared with visual observations of times to initiation and gravimetrically determined propagation rates. He conclude excellent correlation exists between corrosion rates determined from conventional weight loss and current measurements between creviced anodes and a bold cathode. The tests done at 10,25 and 50°C. T. Hodgkiess & Asimakopoulos[61] demonstrated that Titanium has excellent corrosion resistance in a range of seawater conditions up to 60° C. Also they stated that, alloys with higher (Cr + Mo) contents have been shown to have superior corrosion resistance to type 316L stainless steel at low temperatures but not under highly-oxygenated conditions at elevated temperatures. A comparison of the corrosion resistance of some high-alloy stainless steels in seawater at 20-100° C was made by T. Hodgkiess and S.Rigas[62]. Six alloys were used in this study, 316L was one of them. Crevice corrosion was considered. They concluded that in aerated seawater at higher temperatures , even the higher-grade stainless steels become more susceptible to crevice corrosion initiation, also they stated that under lower oxygen conditions at 25° C and 60° C the susceptibility to crevice corrosion is much reduced in all materials. T .Hodgkiess ET Al[63] made a study of the corrosion behaviour in MSF plants of a number of materials, including welded joints. The results shows that stainless steel welds showed better corrosion resistance but corrosion of types 304 and 316L steels occurred at crevices. Titanium exhibited very good corrosion resistance. Potzschke & Rockel[64] stated that the pitting resistance generally drops strongly in the temperature of 60° C. Only few alloys namely with the highest Cr an Mo contents are pitting resistant even at temperature up to around 100° C. Different grade from stainless steels were tested in Arab Gulf by S. Nordin[65]. Crevice corrosion was considered. Type 321 Stainless steel showed extensive crevice and pitting corrosion after 2000 hours exposure , where type 316 showed the crevice corrosion after 5000 hours. High grades stainless NU 44LN and 904L showed only shallow crevice attack. A high-alloy ferritic stainless steel , was completely free from corrosion.T. Hodgkiess Et AL[70] studied the localised corrosion behaviour of some high alloy stainless steels in seawater at 20-100°C, some austenitic and ferritic stainless steels and titanium were tested, also they used aerated and deaerated seawater, their conclusion was that all stainless steel alloys included in their study exhibited at least slight crevice attack after extended exposures to seawater at 100°C. Olsson & Wallen[66] made field test at ambient temperatures and aerated conditions and they mentioned that the corrosion resistance of the 6% Mo stainless steel in seawater is superior to that of other stainless steels and excellent alternative to copper-base and nickel-base alloys. Laboratory and field tests were done. 316, 254 SMO and hastelloyC were some of the materials tested. A beneficial aspect of galvanic-corrosion of carbon steel is that it can confer a degree of sacrificial protection which reduces the susceptibility of adjacent regions of coupled stainless steels to pitting or crevice corrosion, this was stated by T.Hodgkiess ET AL[67] after testing different alloys such as cupro-nickel, Titanium and stainless steels in saewater. A. Mollica ET AL[68] evaluated the crevice corrosion resistance of series of SSs in natural seawater in the temperature range of 25 to 40°C.

The above literature gave the idea of the plan of this work, that most of the work above were done for the effect of the temperature on corrosion of the materials, while in RO-desalination plants there are other important factors that affecting corrosion processes, such as the flow of the corrosive media, the pressure, varying oxygen concentrations, jet impingement effect and the level of salinity. In this work all these factors were considered in addition to the effect of the temperature, crevices and time factors.

3. Experiments Plan

The environment factors considered in this thesis were as follows:-

a- Temperature.
b- Salinity.
c- Dissolved Oxygen .
d- Time .
e- Flow.

f- Jet impingement effect.

Another factor considered and not related to the environment which is the effect of the crevice on the specimens .

The techniques used are the anodic polarization and weight loss methods. The tests on this project may be classified into four main tests as follow :

Ordinary polarization tests.

Long term immersion tests.

Weight loss method tests.

Flow effect tests.

Jet impingement effect tests.

The alloys used are as mentioned in Chapter Two and listed in table (2-1) .

3.1 Ordinary Polarization tests

In these tests, all the six alloys are tested under the following conditions:-

1) Fixing the salinity of the solution at 35000 ppm with aeration to keep dissolved oxygen high (i.e 7 ppm), and testing the specimens under temperatures 25 , 35 , 45 , 65 and 85° C . In each test the solution is changed by a fresh one .
2) Deaerating the solution to keep the dissolved oxygen below 0.5 ppm, and again testing the specimens at the above temperatures .
3) The same procedure above is done but for solution salinity of 55000 ppm.

In this case each specimen is tested 20 times. The number of tests required for this group is 120 tests.

3.1.1. Apparatus Required:

The apparatus required to carry out these tests are potentiostat , scan generator , calomel electrodes , auxiliary or counter electrodes thermometer , voltmeters , resistance , plotter , electric wires for the specimens , solders , on-off hot plate , resin set , moulds for the resin , silver adhesive , instant ocean(mixed chemicals used for preparing artificial seawater and its composition is shown below) , nitrogen bubbling source , distilled water and polishing set .

	wt% of salt
Nacl	78.0
$Mgcl_2$	10.5
$MgSO_4$	5.0
$CaSO_4$	3.9
$K2SO_4$	2.3
KBr	0.3

3.1.2 Specimens Preparation:

Pieces from different alloys were cut down to a size of $1cm^2$. Then a wire enabling electrical connections to be made was attached to the base of the metal . This way was done by heating the specimen over a hot plate and the back surface cleaned chemically then the wire connected by solder. Only Titanium was connected to the wire by adhesive containing silver to ensure good electrical contact. This was then cast in an epoxy resin as shown in fig (2). When the resin had hardened , the surface was ground down, exposing the metal face. All specimens were ground down to a 600 grit finish .

3.1.3. Instrumentation:

The instrumentation of the rig is shown in fig (3) . Potentiostat gives the potentiatial to the specimen where the scan generator increases this potential 15mv/min gradually, Y-axis of the plotter will plot this sweep in potential. The auxiliary electrode (counter) will count the current from the specimen where it will be plotted as X- axis on the plotter . Solariton voltmeter will show the potential as digits. The resistence connected to the voltmeter in series will gives a current reading on the voltmeter digitally . The scan generator is reversed manually .

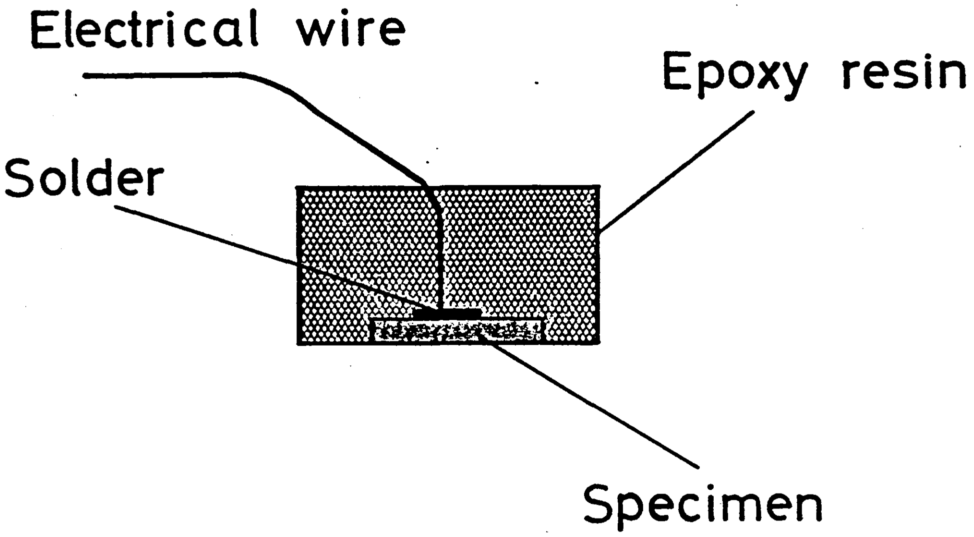


Fig. (2)

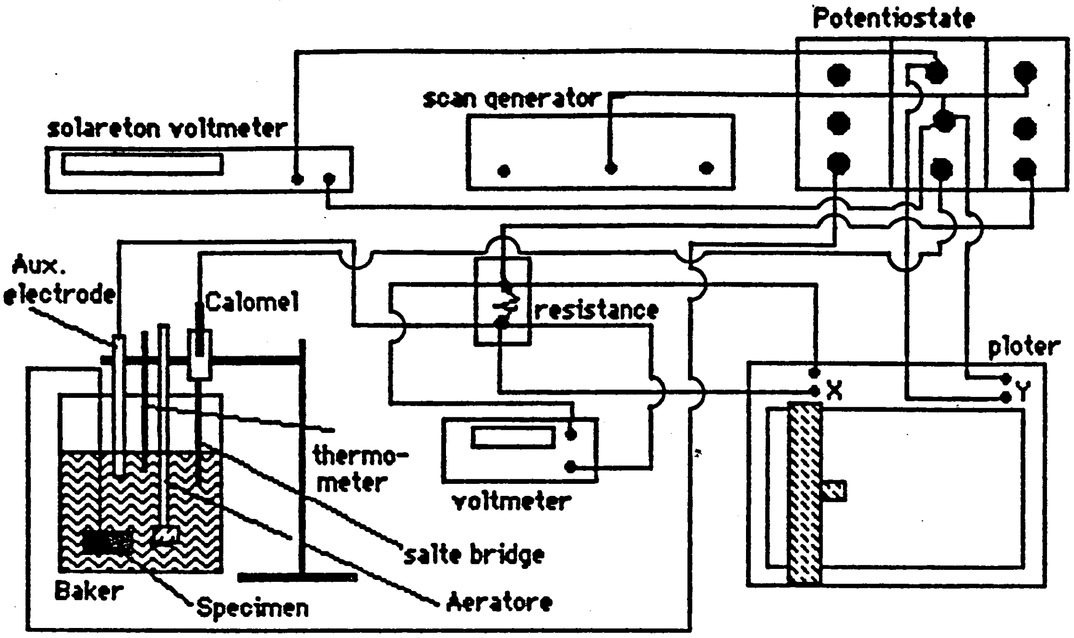


Fig (3)

Anodic polarization test-rig.

3.1.4 Environments Preparation:

The environment suggested is to be seawater and brine water. Instant Ocean and distilled water were used in laboratory to produce artificial seawater and brine water. The temperature of the solution was controlled through an on-off hot plate. In case of aeration there was a small air pump with air bubbles in the solution. Nitrogen was bubbled from a nitrogen cylinder in the case of deaeration. Oxygen level was about .5 mg/lit and measred by color solution kitt, while pH was about 8 and measured by pH- meter.

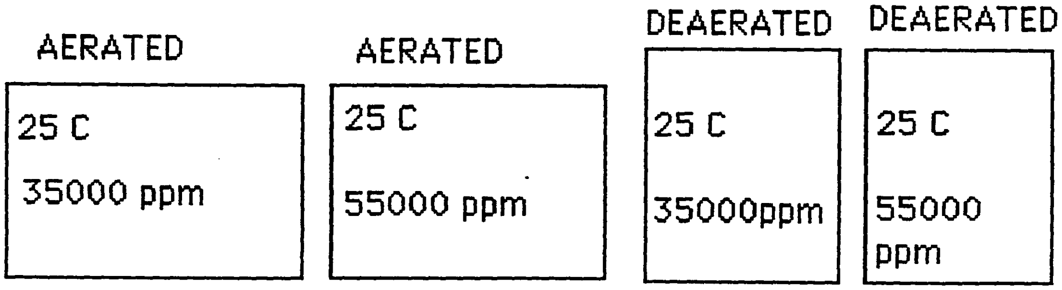
3.2. Long Term Immersion Tests:

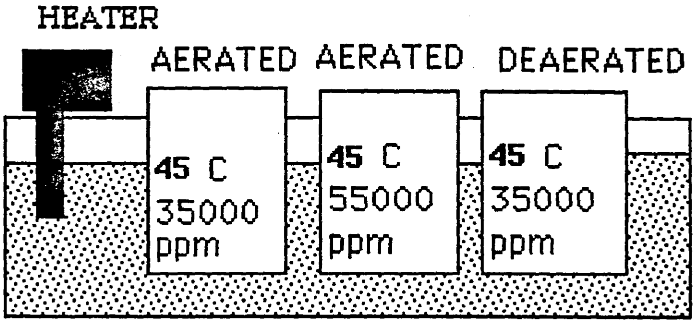
Time factor is the main object of this category . The idea of these tests is to study the time effect on the specimens . And to study the behaviour of Ecor over a long period immersion as well. Also the effect of the crevice on the corrosion process was considered. It should be noticed that the solution preparation and instrumentation are the same as the ordinary polarization tests. For measuring Ecor only voltmeter and calomel electrode were required . The period for this test is 60 to 70 days.

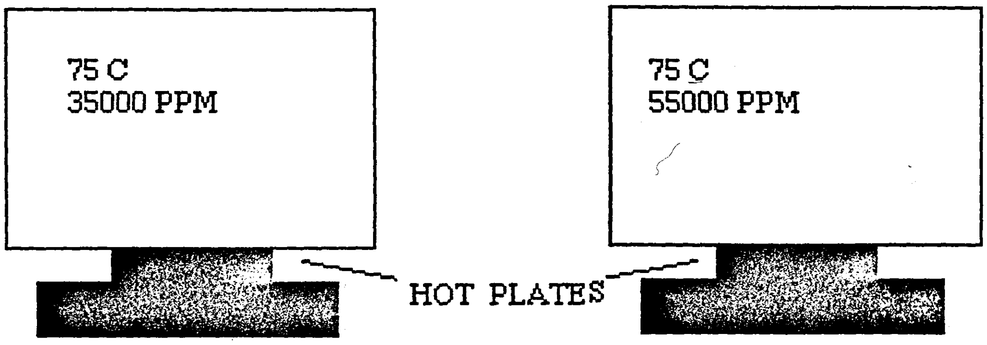
3.2.1 Environment Preparation :

Seven tanks was prepared with different environment conditions(See Fig. 3.1). At ambient temperature there were four tanks two of them were aerated with solution salinity 35000 ppm and 55000ppm, and the other two tanks were deaerated with again 35000ppm and 55000 ppm . At 45^{o}C there were three tanks, two of them aerated with solution salinity 35000ppm and 55000ppm and the other tank was deaerated with 35000ppm . All the three tanks were immersed in a large tank who's temperature was fixed at 45^{o}C by using a stirrer. For the deaerated tanks, a tanks with lids were used . Two holes made on these lids. one for the specimen wires and the other for the calomel electrodes . After preparing these

LONG TERM IMMERSION TEST AND WEIGHT LOSS TESTS







tanks they sealed with epoxy and deaerated using nitrogen bubbles. Every week they deaerated to keep the dissolved oxygen at low level.

3.2.2 Specimen Preparation :

There were two types of specimens , one is as described in 3.1.2 (see fig.2) and the other included an intentional crevice produced as follows, the size is 1.5 cm by 1.5 cm, a small hole was made on this specimen and its epoxy, a plastic thread was fixed on this hall with a plastic nut as shown in fig (4). It should be pointed out that duplicate specimens were used.

3.3 Weight Loss Tests :

Two types of specimens were used on this test. One is plane specimen with 2mm in diameter hole for holding it. The other type is with a hole in the centre of the specimen to fix plastic threads with a nut to study the weight loss in presence of artificial crevises. The size of both types were 1.5cm by 2.cm.

The specimens were immersed in the same seven tanks . Another two tanks used especially for this test. Each tank was with 85°C but one with 35000 ppm solution salinity and the other with 55000 ppm. Both of these tanks were heated by on-off hot plate. External thermostats were used for safety.

3.4 Effect of Flow :

This test is to investigate the effects of corrosion in the flowing rig . The technique used for measuring the corrosion effects is the anodic polarization technique. The rig used is shown in fig (5) and Phtogoraph 5-1. It is a closed system and consist from a propylene 2" pipe . The working fluid was driven round the system by a 2.2 kw pump . The fluid was pumped from a large tank, capable of holding 180 litres. A 3 kw heater and cooler were situated in the tank for controlling the temperature. The fluid, started in the tank , was driven round the pipe network and returned once again to the tank . Flowmeter was used to measure

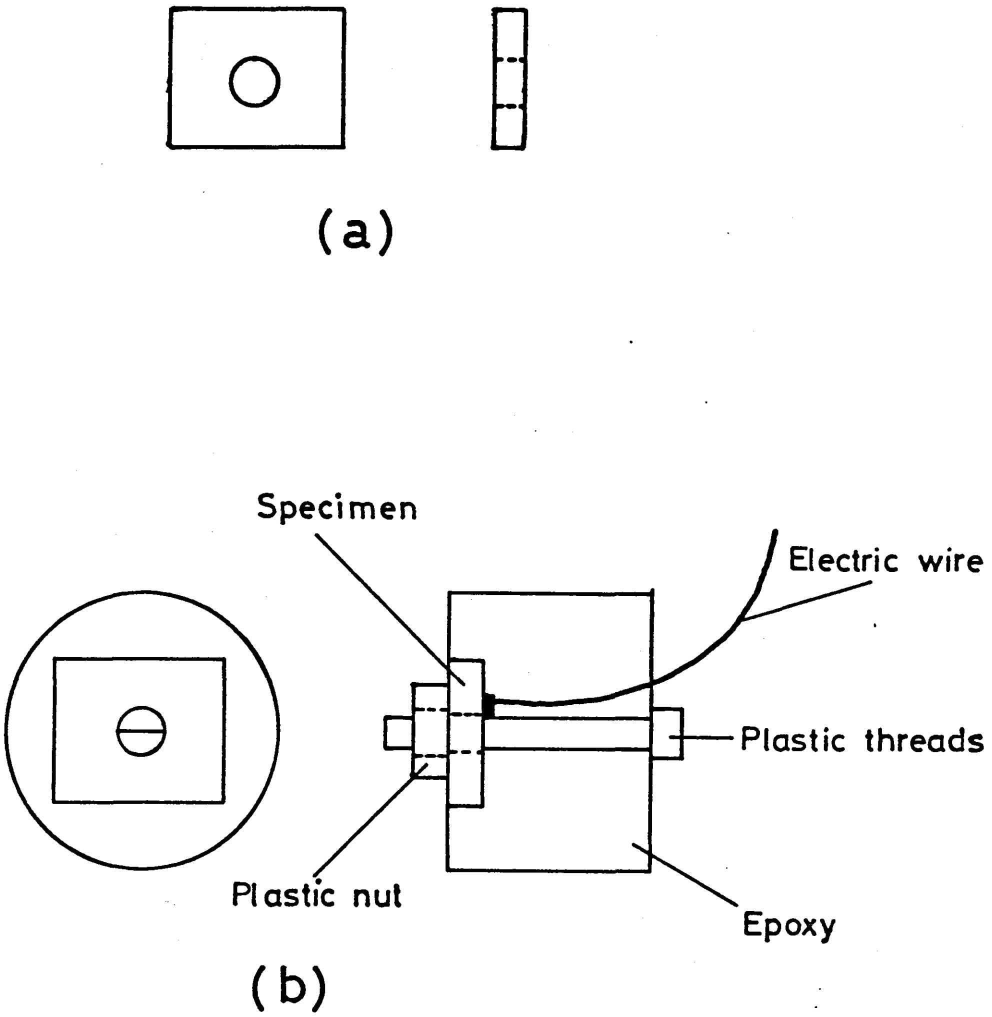


Fig (4)

Creviced specimen

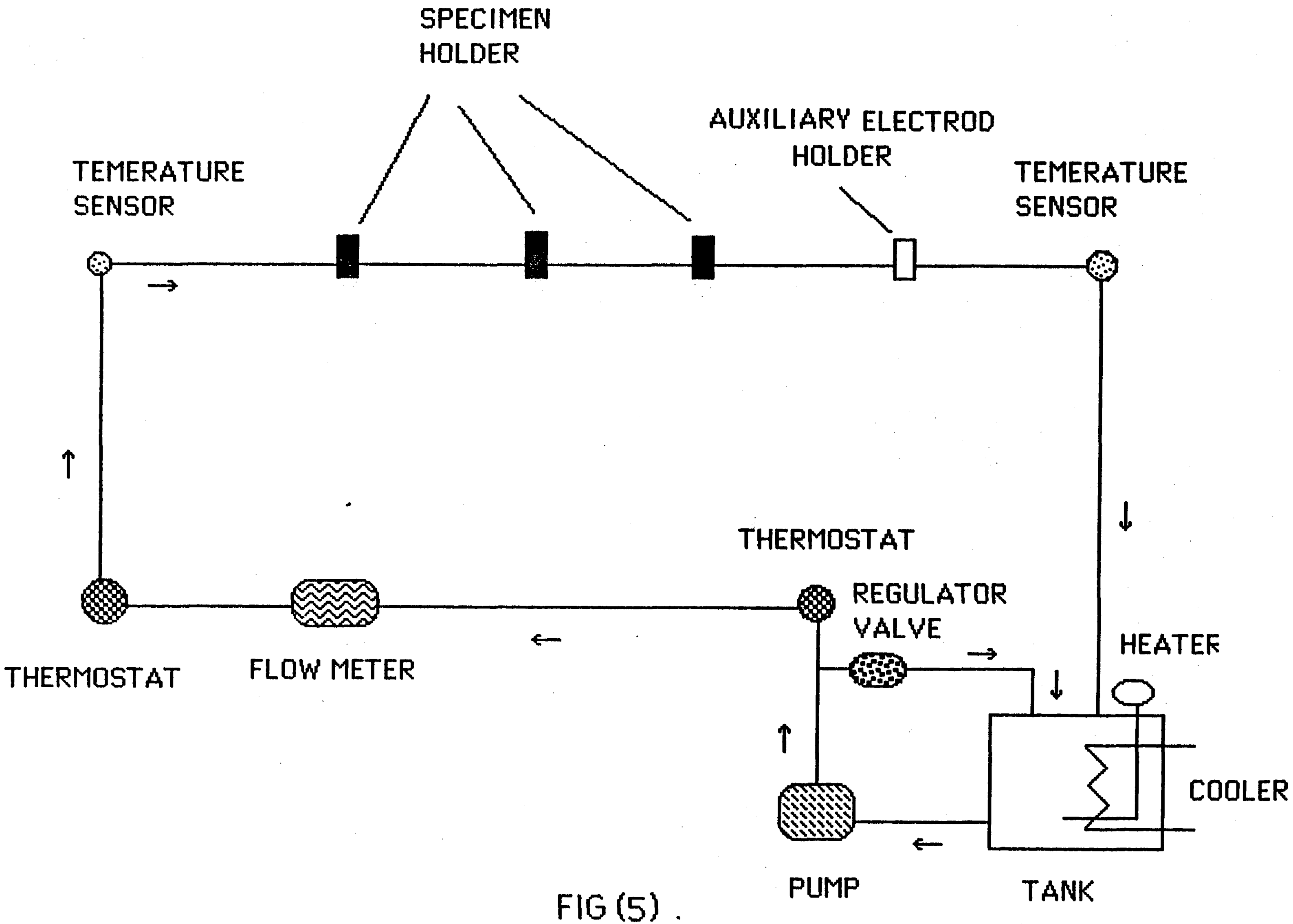
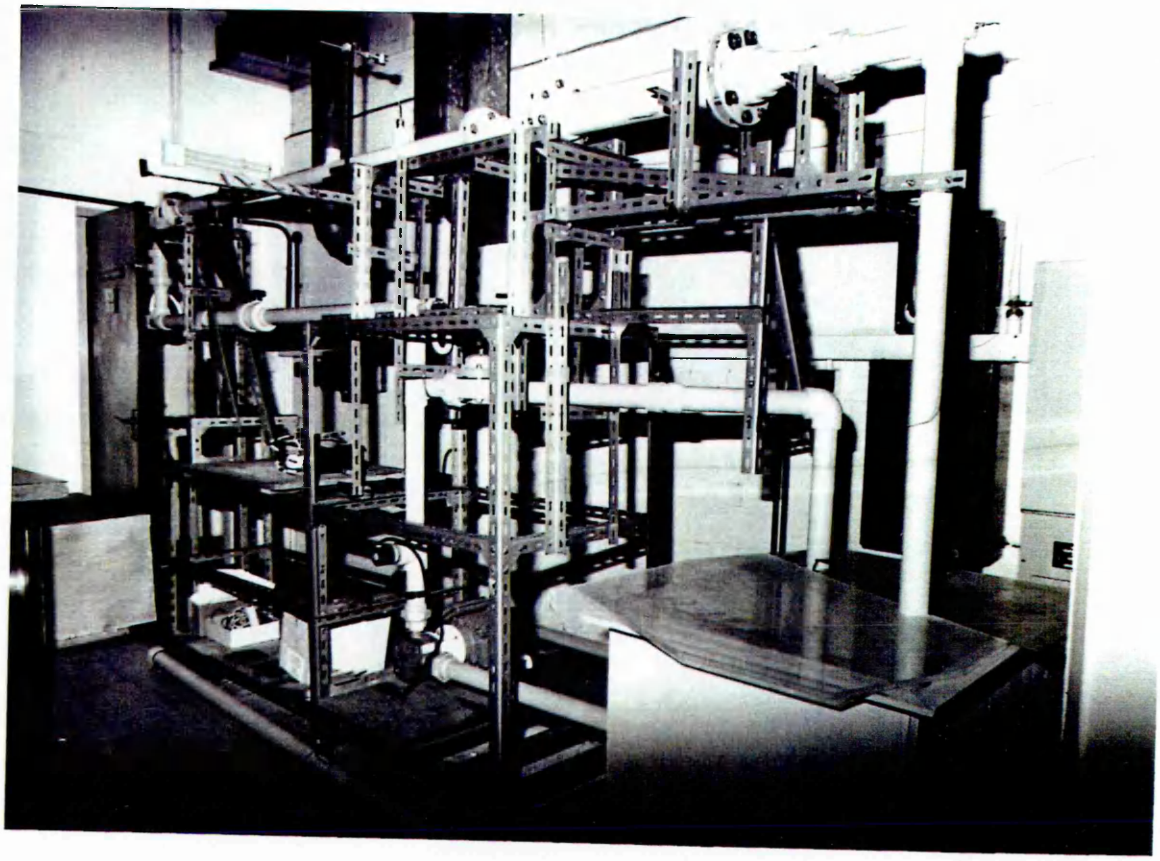


FIG (5) .

FLOW DIAGRAM OF THE FLOW RIG



Photograph 5-1
Flow effect Test-Rig

the quantity of fluid . Through the piping there were two thermostats for controlling the heater in the tank. The pump used was capable of providing flow-rate up to 375 lit/min and controlled primarily by a 2" PVC ball valve, while a diaphragm valve was situated in a bypass pipe returning to the tank . A dryrun safety switch was also present to act as a safety cut out . The instrumentation used was the same as previous tests .

3.4.1 Specimen Preparation:

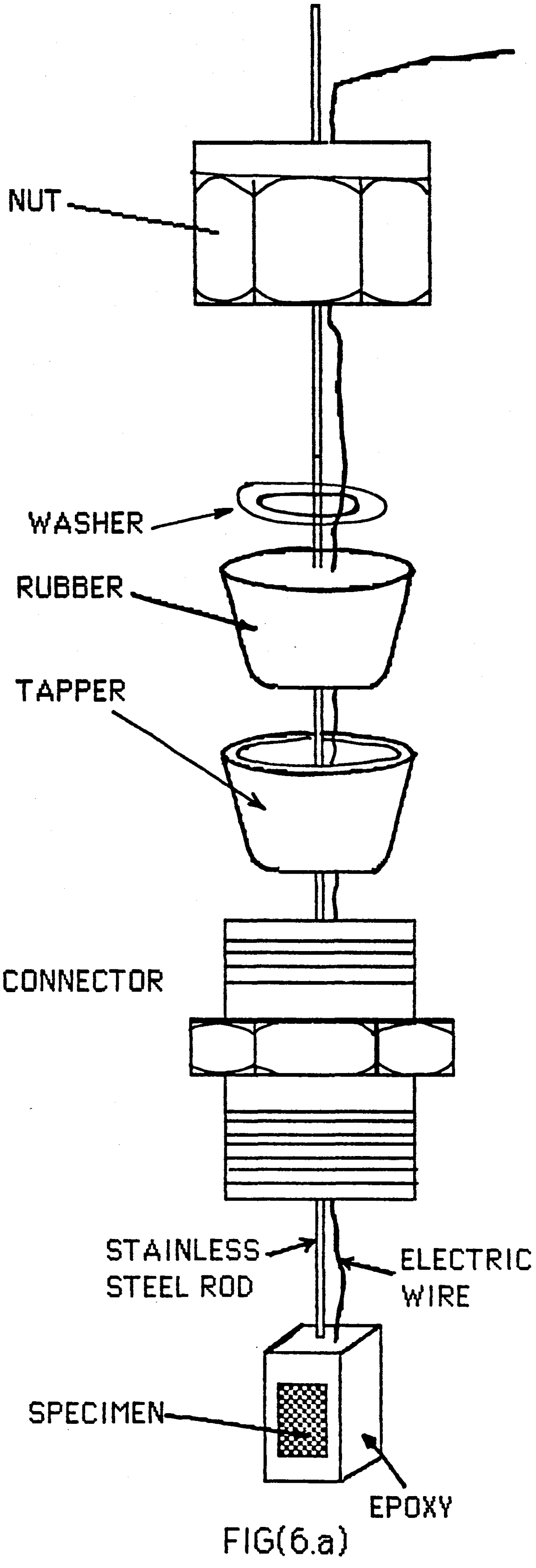
The specimens in this test were prepared to fit with the device shown in fig (6.a) and photograph 5-2. The epoxy should be square shaped and should mount a stainless steel rod and elctrical wire, the function of the rod is to keep the specimen in tangential to the direction of the fluid inside the tube. Tapped rubber is used to avoid any water leakage fromt the tube. Photogrphs 5-2 shows the specimen holder and 5-3 shows the specimen fitted in the rig.

3.4.2 Fluid Preparation:

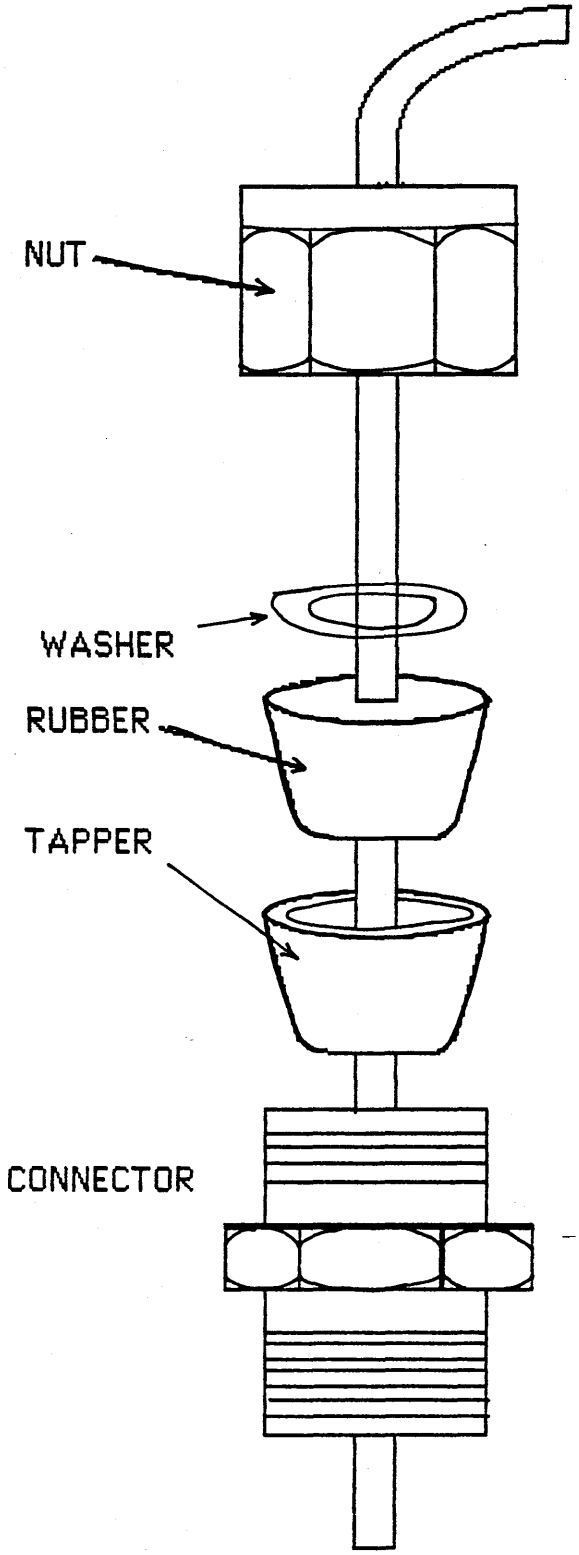
From the salinity point of view the fluid was prepared by the same method indicated above. The test was run at ambiant temperature with fluid salinity 35000 ppm and 55000 ppm. Again it was run at 45^{o} C with fluid salinity 35000 ppm and 55000 ppm .

3.5 Jet Impingement Effect:

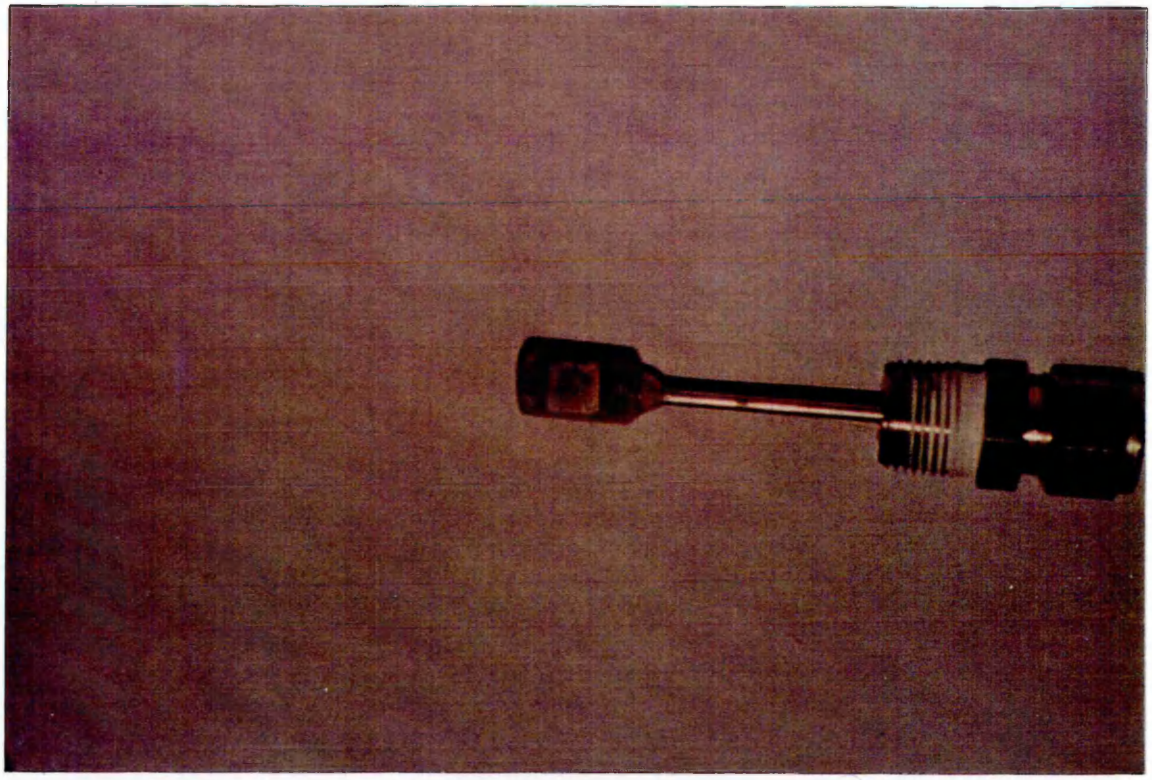
In this test a jet of seawater and brine water were subjected over the specimens, while anodic polarization measure was done . The design of the rig is shown in fig (7) and photograph 5-4. It consists of a high pressure reciprocating pump driven by a 2.2 kw single phase motor . A flexible high pressure Stainless Steel hose was handling the fluid to a 0.5" stainless steel pipe . At the terminal of this tube a beam jet nozzle was fixed with a diameter of 1/16 inch . A fine filter was used to avoid any foreign particle blocking the nozzle . To avoid high pressure pump cavitation



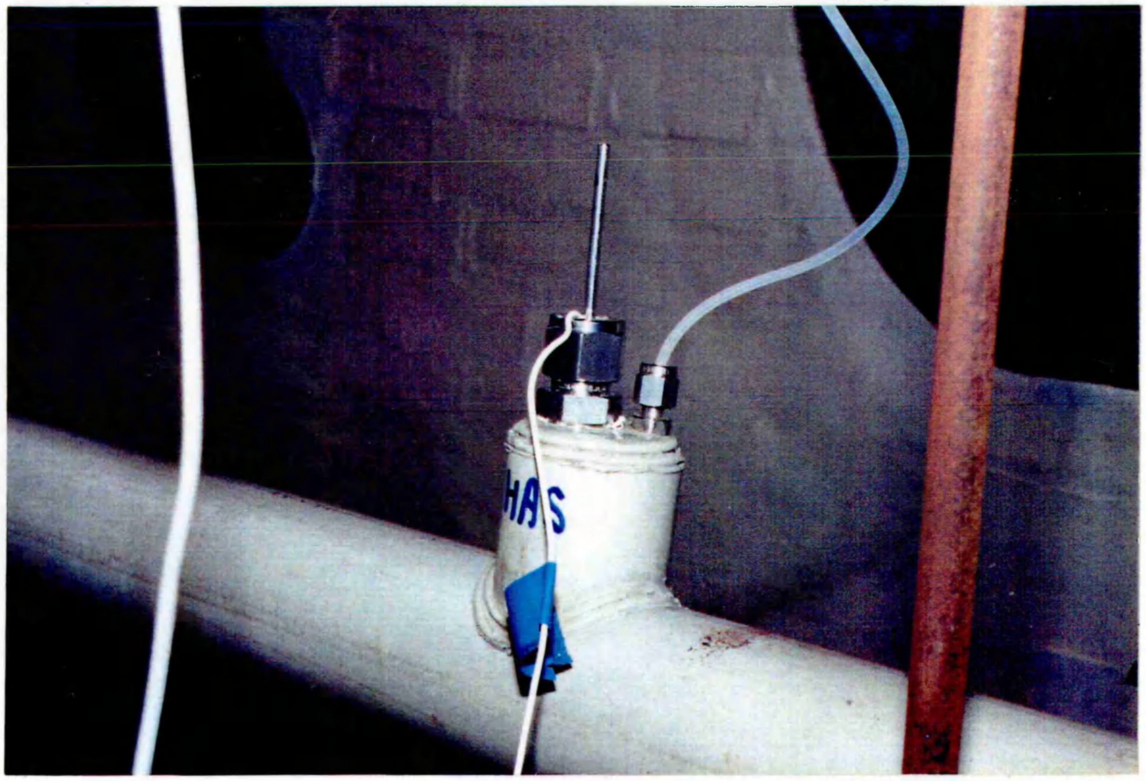
FIG(6.a)
SPECIMEN HOLDER FOR FLOW TEST



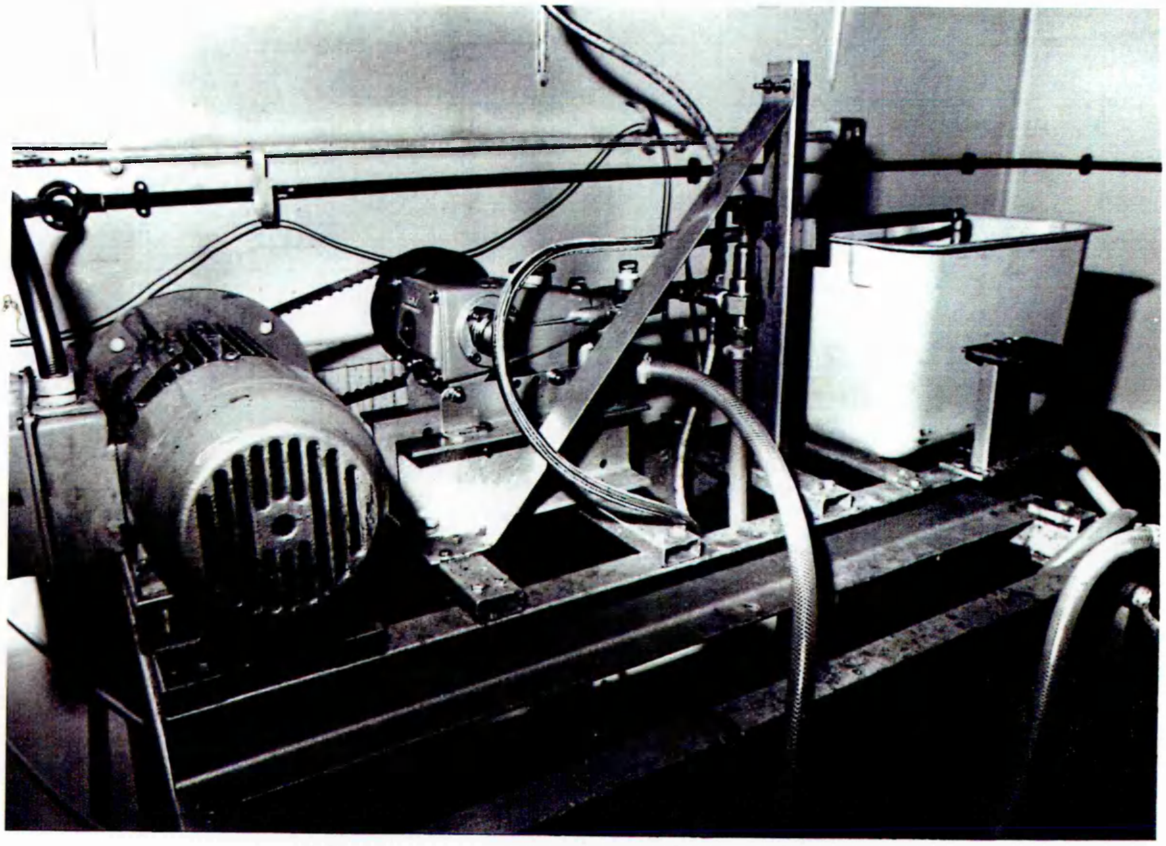
FIG(6.b)
AUXILIARY ELECTRODE HOLDER



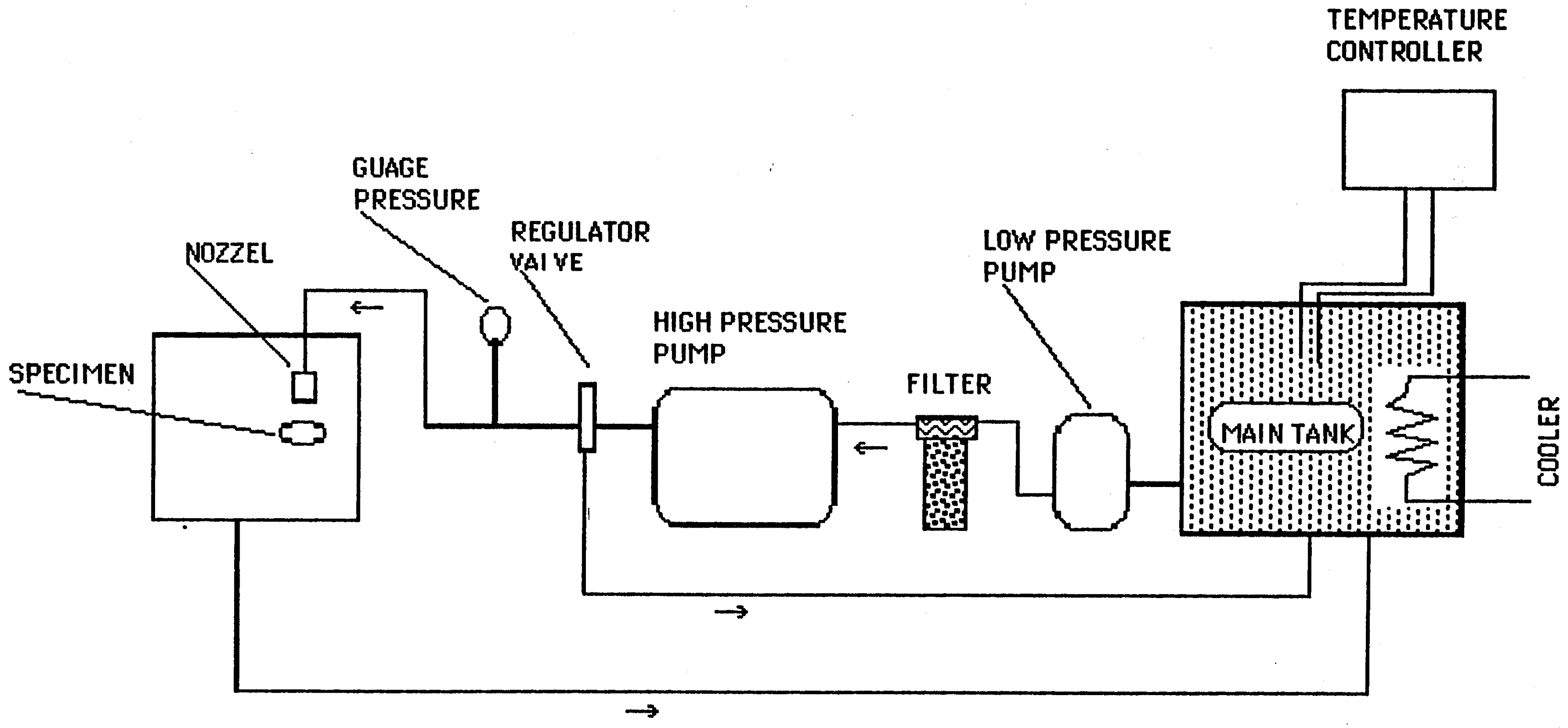
Photograph 5-2
specimen and its holder (Flow effect)



Photograph 5-3
Specimen holder and the salt agar used for the calomel



Photograph 5-4
Jet imingement effect Test-Rig



FIG(7)

FLOW DIAGRAM OF THE JET TEST-RIG

there was a low pressure pump , which handled the fluid from the tank to the filter. A regulator valve was used to control the pressure through the nozzle and to avoid any build up pressure through the system. A pressure gauge was fixed to measure the pressure . To control the temperature of the fluid through the system, there was a cooler and heater both in the fluid tank . The cooler was a solenoid stainless steel pipe with a diameter of about 1/8", tap water was used as the coolant of this cooler . The heater used consisted of two electric heaters controlled through a digital panel , the heater allowing for upper and lower temperature limits. The specimens holder was designed as shown in fig (8) . Two acrylic sheets of 1/4" thick were used , one for holding the specimen while the other sheet fixed by the nozzle directly . The two sheets were arranged opposite by four stainless steel bars, the distance between the sheets can be adjusted through nuts .

Salt agar bridge -for calomel- and the counter were immersed as shown in fig.(9) .

For calibration, a measure of Ecor was measured without jet . The sytem run at low pressure (less than .5 bar) and Ecor was measured again . There was not a big difference between the two readings. Changing the positions of the counter and the salt agar, show almost the same reading of Ecor. Another calibration was made at 2 bar to study the position effect of the counter or the agar bridge shows that , any position inside the large baker will measure the right reading .

The tests were started according to the following conditions :

- 2bar pressure and 35000 ppm salinity
- 30 bar pressure with fluid condition of a) 25^oC and 35000 ppm

b) 45^oC and 35000 ppm

c) 25^oC and 55000 ppm

d) 45^oC and 55000 ppm

It should be noticed that the sizes of the specimens on this test were larger than the previous tests, the size of each specimen was 2cm by 2cm. The speed of the jet measured experimentally from the following formula:

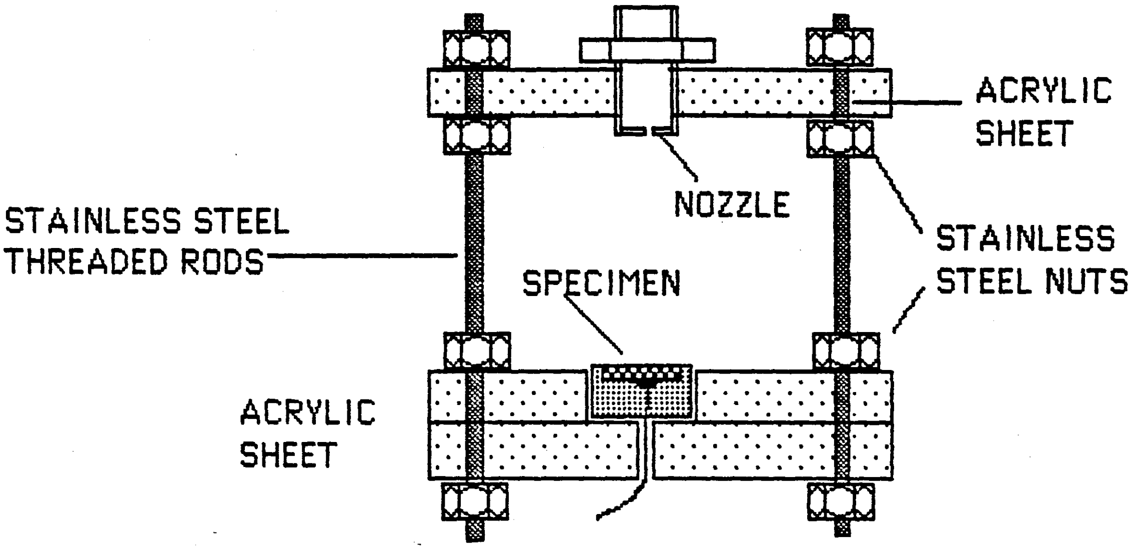


FIG. (8)

SPECIMEN AND NOZZLE HOLDER

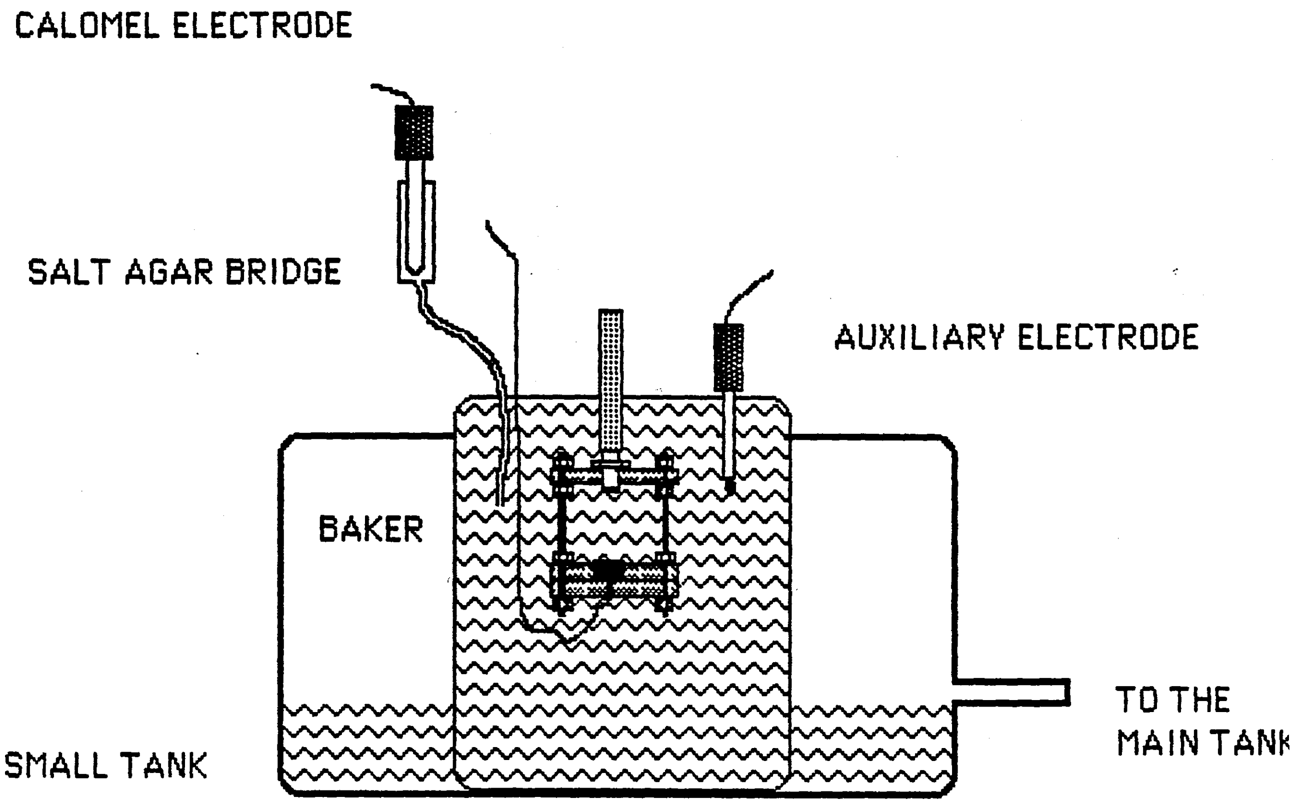


FIG.(9)
SPECIMEN, NOZZLE, CALOMEL AND COUNTER
ELECTRODE ARRANGEMENT

$$V=Q/A$$

where V= Jet velocity m/sec

Q= Flow rate from the jet m^3/sec

A= Jet cross section m^2

$= \pi r^2$

r= raduis of the jet

$=0.75$ mm

$A= \pi (.75)^2$

$= 1.767\ mm^2$

$= 1.767\ \ 10^{-6}\ m^2$

	q (lit.)	t (sec)	Q=q/t
1	.790	4.48	.1763
2	.730	4.43	.1647
3	.910	5.26	.1730
4	.950	5.91	.1607
5	.860	5.13	.1676

Average Q= .16846 $10^{-3}\ m^3$/sec

The velocity of the jet (V) is

$$V= \frac{.16846 \times 10^{-3}}{1.767 \times 10^{-6}}$$

=95 m/sec

The value of the velocity is changing according to the density of the fluid, but in our case there was'nt big change between seawater and brine seawater.

CHAPTER SIX
RESULTS

1-Introduction:

The usual aim in anodic curves is to identify the potential at which breakdown of the passive film commences. This is often fairly clearly signalled by a rapid increase in current at a certain potential. In this thesis, this potential will be referred to as the " breakdown potential,"Ec without distinction as to whether the passive film breakdown is on the free surface or within crevices. The rational of this is that the basic aim of this investigation has been to study and compare the resistance of a number of materials to localised corrosion of whatever type. Note, however, that the distinctions between the tow types of passiv filmbreakdown are discussed in some of the following sections.

In many of the experiments in this work the value of Ec was clearly identifiable from the polarization curve (see for example figures 1 and 2); a rapid increase in current from a very low value (<10 micro amps.) maintained over a range of potential between Ecor and Ec. This will be reffered as a type I curve.

However in other experiments (see for example figs. 3 and 4), the currents recorded immediately positive to Ecor were very small but subsequently increased to relatively higher (e.g. 40-80 micro amps.) values prior to a potential being attained at which the **rapid** increase in current occurred. This behaviour is designated as type II.

And in a few tests, limited to the behaviour of the lower grade materials in the most severe conditions(e.g. jet impingement) the current was found to increase continuously at potentials immediately more positive than Ecor (see for example figs. 5 and 6). This will be referred as type III.

The detailed evidence of these three types of curves are found in the results but as a rough indication of this point the general pattern was as follows:

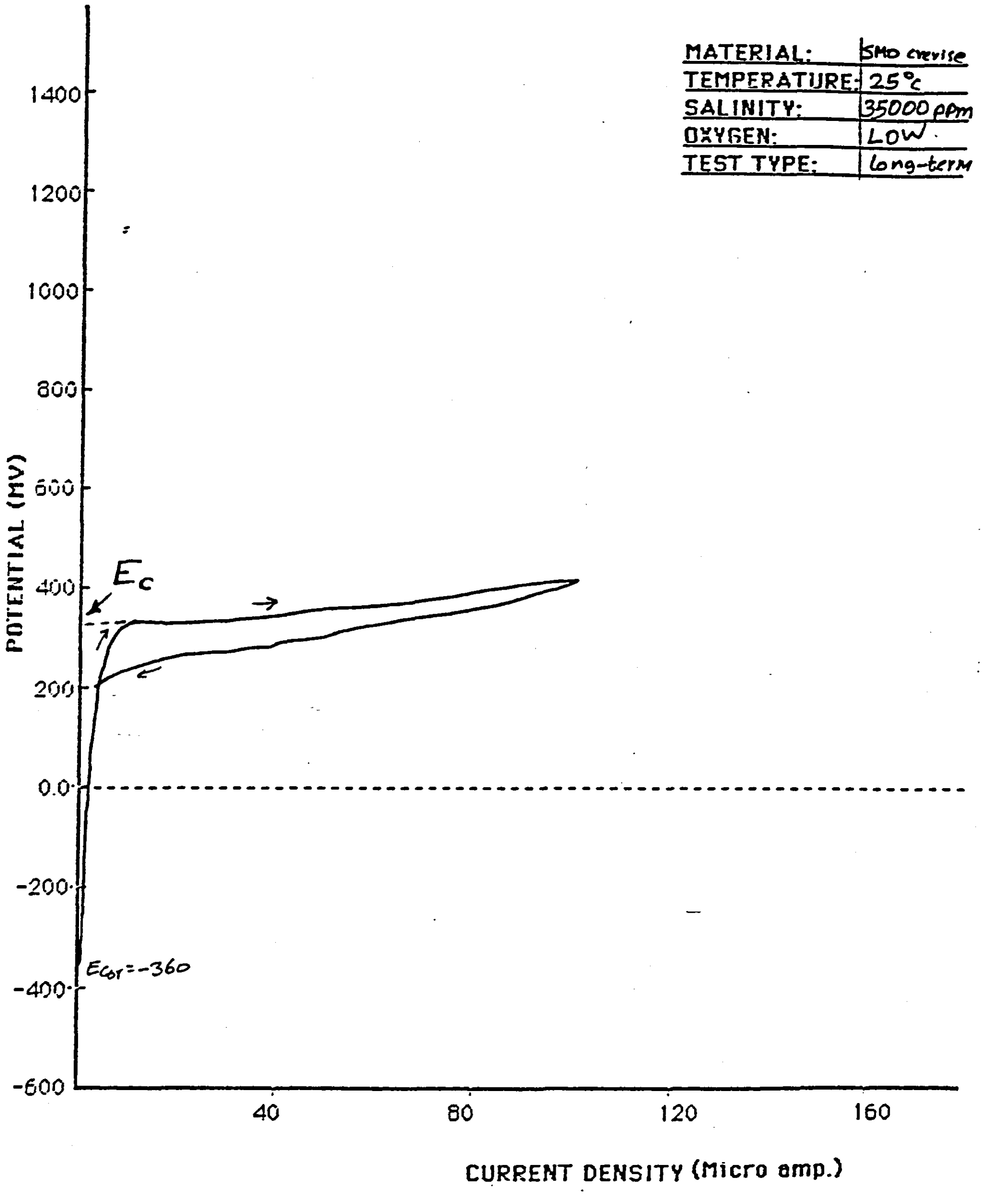

MATERIAL: 5MO crevise
TEMPERATURE: 25°c
SALINITY: 35000 ppm
OXYGEN: LOW
TEST TYPE: long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
E_c
E_{cor}=-360
40
80
120
160
CURRENT DENSITY (Micro amp.)

Figure 1

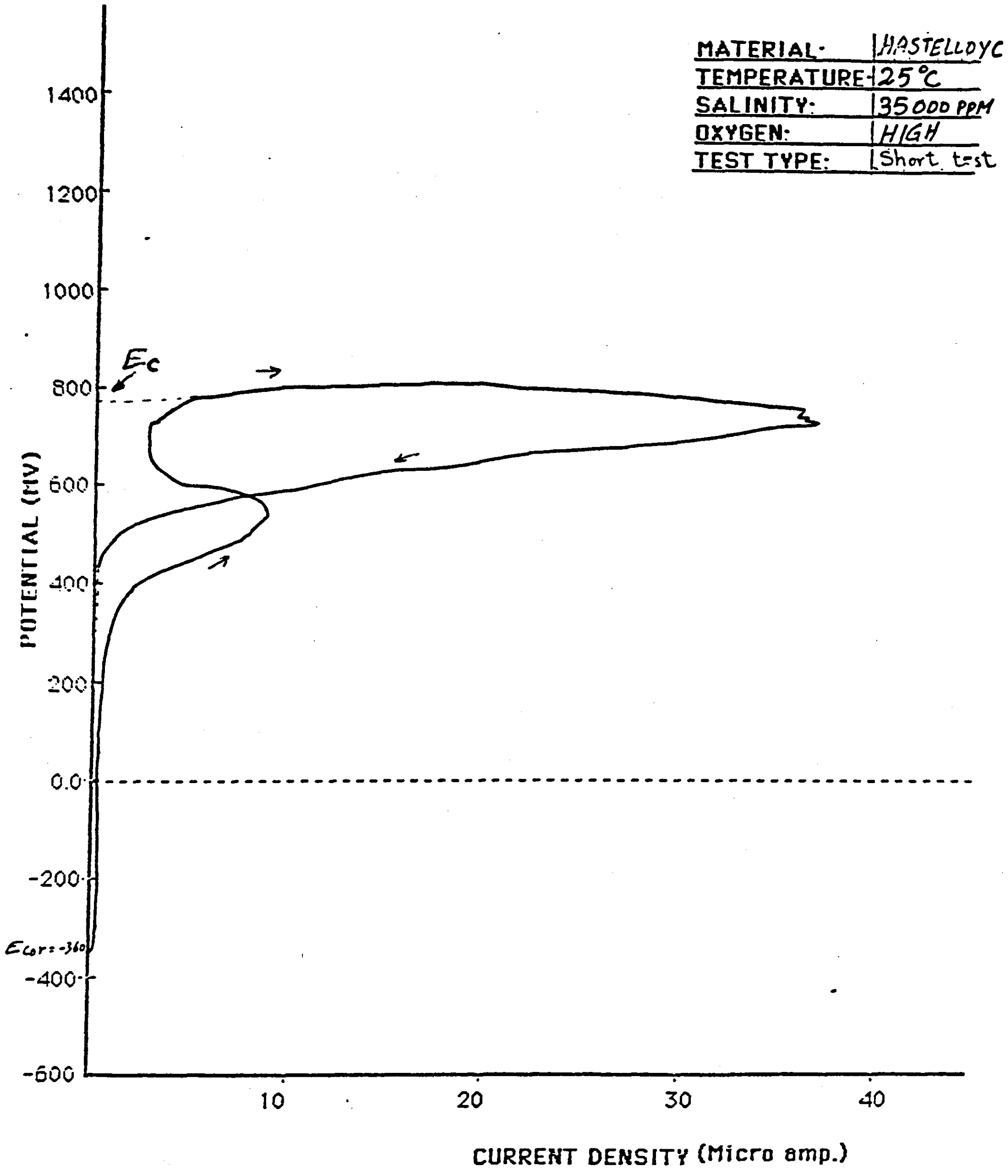
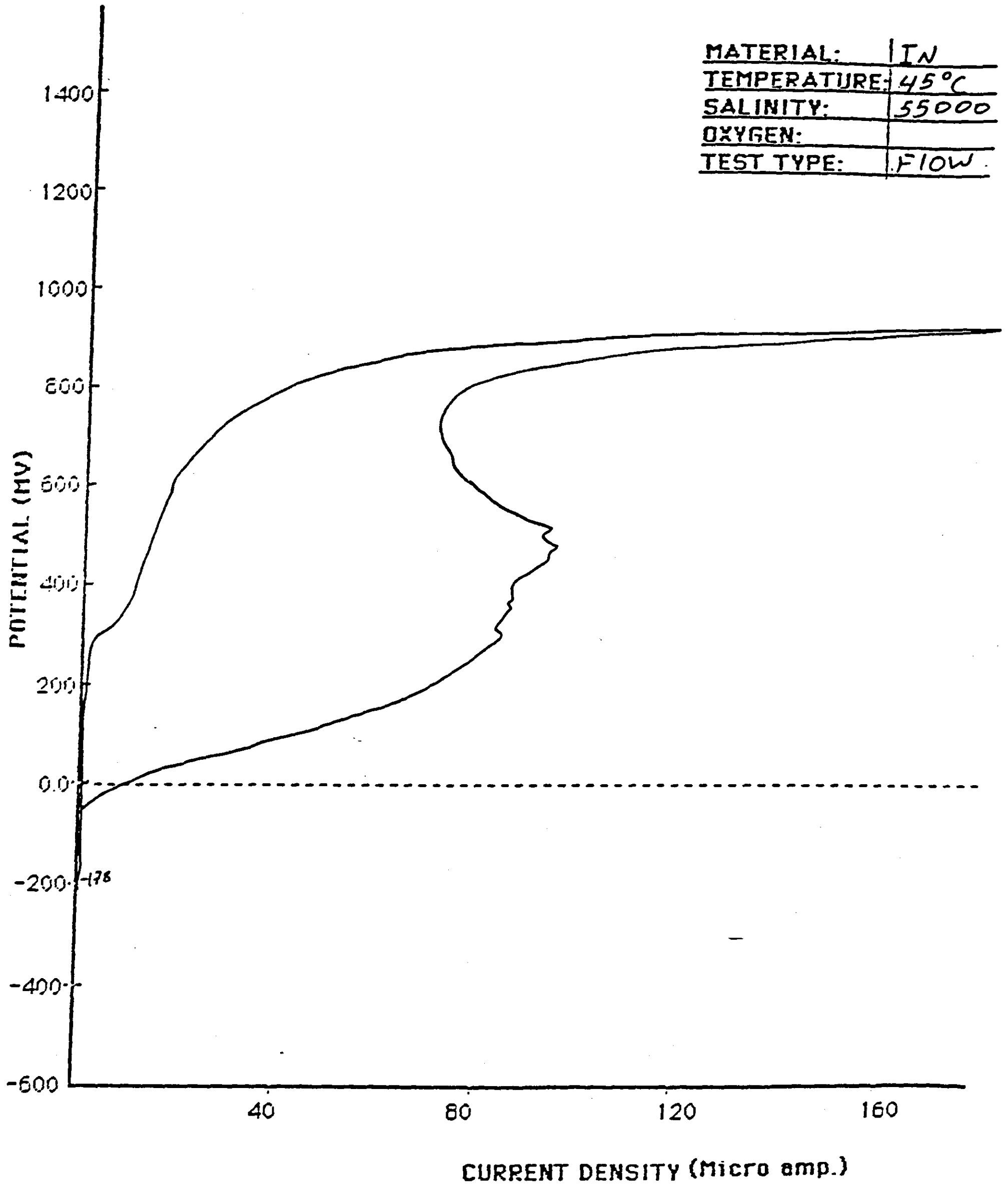

MATERIAL: HASTELLOYC
TEMPERATURE: 25°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: Short test
Ec
Ecorr=-360
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
10
20
30
40
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)

Figure 2



MATERIAL:	IN
TEMPERATURE:	45°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	FlOW

Figure 3

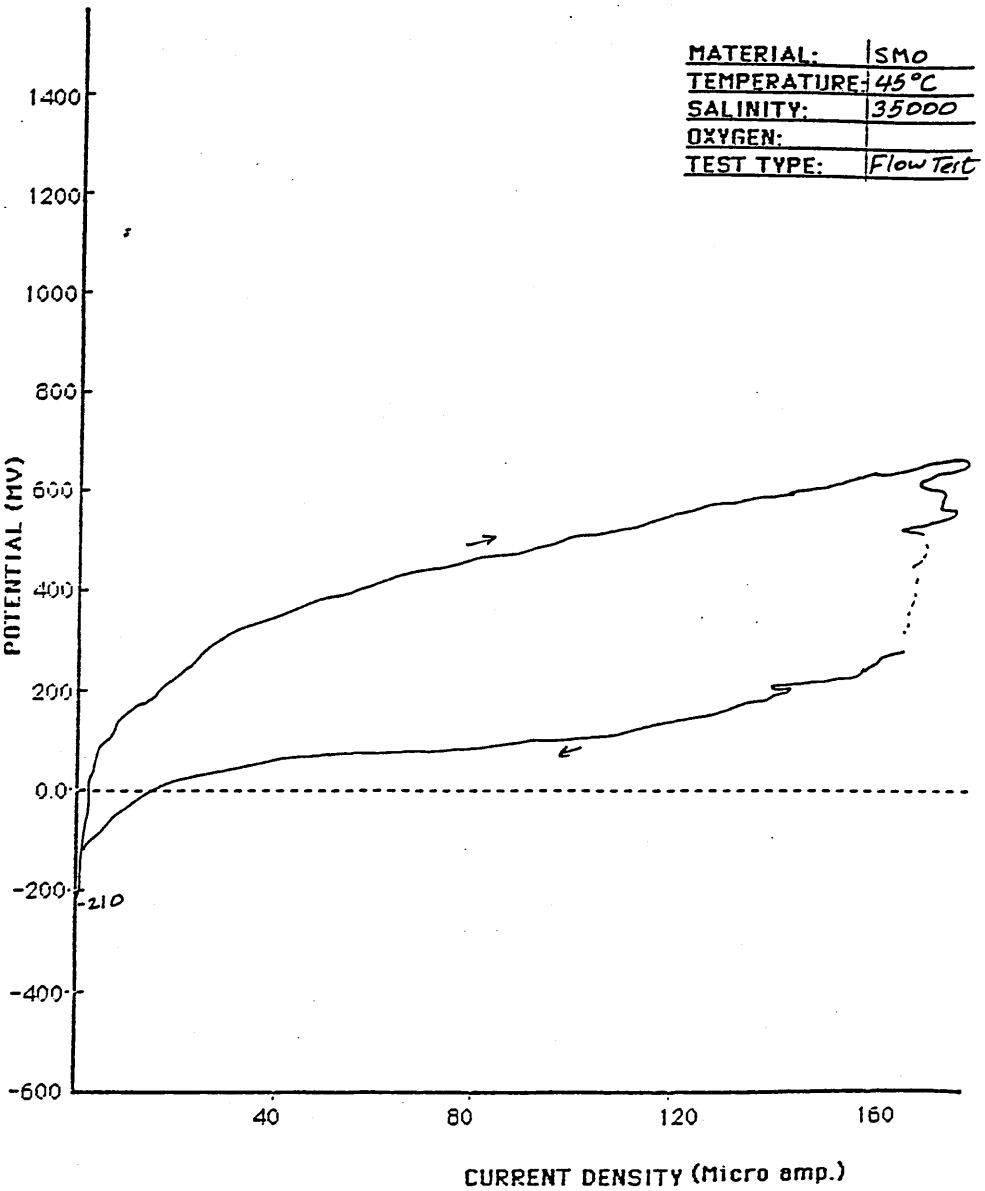
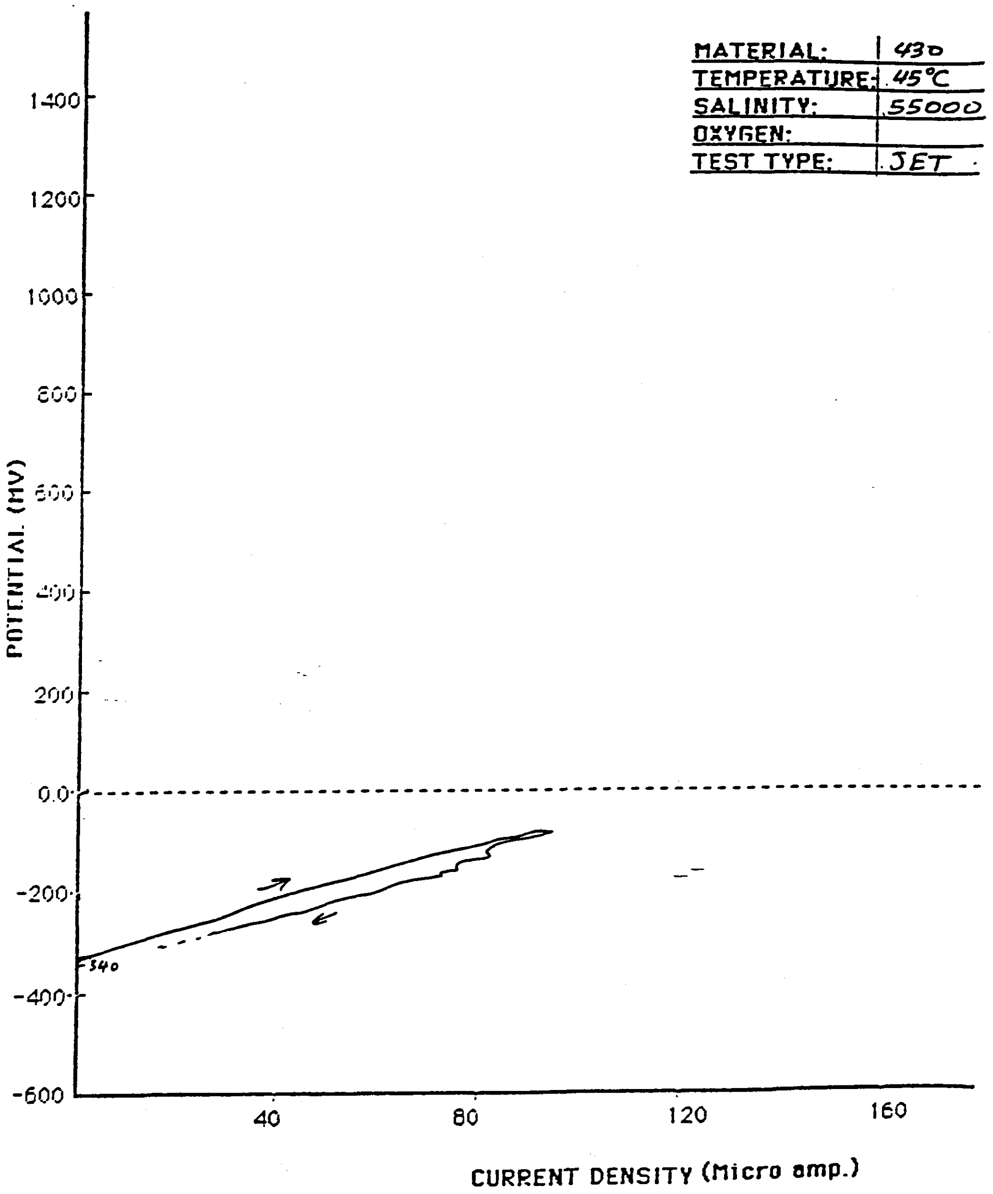

MATERIAL: SMO
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-210
-400
-600
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)

Figure 4



MATERIAL: 430
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET

Fig 5

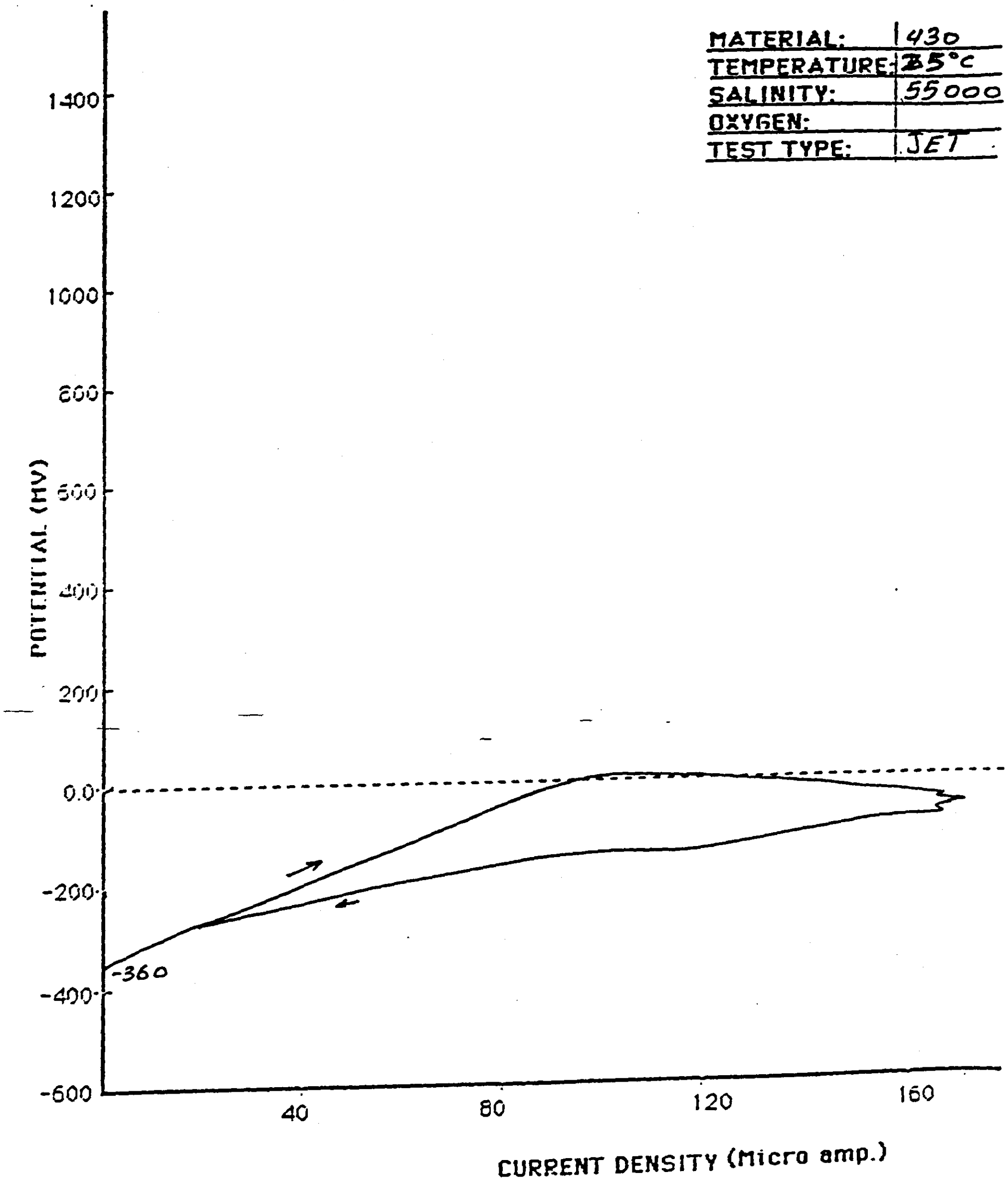

MATERIAL: 430
TEMPERATURE: 35°c
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-360
40
80
120
160
CURRENT DENSITY (Micro amp.)

Fig 6

In the short-term static tests, all the material exhibited a simple type I curve except for hastelloy C and SMO under some deaerated conditions.

In long term tests, most of Ti plane specimens shows a simple type-I curve, while most of the creviced specimens exhibit type-II curve, and most of the hastelloy C exhibit type-II curve. SMO exhibit a simple type-I curve under ambient temperature and 35000ppm salinity conditions, while under the remaining conditions the behaviour was irreproducible in this respect.

All the IN alloy results shows type-II curve, only three plane specimens exhibit simple type-I curve. Most of the 316 specimens exhibit a simple type-I curve, only five specimens shows type-II curve. For 430 alloy specimens all the specimens exhibit simple type-I curve and only two specimens under deaerated conditions shows type-II curve.

In flow condition tests, Ti exhibit simple curve, only one specimen shows type-II curve which was under 45°C and 35000ppm. Hastelloy C shows a simple curve at higher temperature (45°C) conditions and type-II curve under the ambient temperature conditions. SMO and IN alloys exhibit a simple curve under the ambient temperature and type-II curve under higher conditions. 316 stainless steel exhibit type-I curve under 35000ppm conditions and type-II curve under 55000ppm conditions. All 430 alloy specimens exhibit type-II curve.

Under jet impingement conditions Ti specimens exhibit a simple curve, Hastelloy C and SMO alloys exhibit type-II curve under 45°C and 55000ppm and under the remaining conditions they exhibit a simple type-I curve. IN alloy results shows type-II curve. 316 and 430 stainless steel alloys exhibit type-III curve throuout all the tests under the jet impingement tests.

In order to be able to compare the materials behaviour in these fairly complex circumstances, the following potentials have been recorded for the results:

1) The clearly identifiable potential (Ec) at which the current starts to increase rapidly from low value(Type-I).

2) For the other experiments (Type-II and Type-III) the potential recorded at:

10 micro amps.(Ec10)

30 micro amps.(Ec30)

50 micro amps.(Ec50)

and when the current starts to increased rapidly, and called Ec(r).

It should be emphasised that the rate of current increase with potential at and more positive to Ec(r) was considerably greater than that at potentials more negative than Ec(r) (see fig 3 and many curves in Appendix B).

For the purposes of presenting the results in the graphs and histograms, all the above recorded potentials were termed "Ec". It is quite clear from the results histograms etc., which type of polarization curve were obtained because, for instsnce, a type-I curve would give the same "Ec" value for 1),2) and 3) potential recorded.

Before classifying the results it should be pointed out that the oxygen level in the aerated conditions was about 7 mg/l, and in the deaerated conditions it was less than 0.5 mg/l. Colour kit set were used to measure the oxygen level. For the pH value it was about (7.8- 8.3) and measured by pH-meter available in the laboratory.

2- Results Classification:

The results recorded can be classified into five groups. as follows:

- Anodic polarization test results under static condition.
- Anodic polarization test results after long term immersion condition.
- Anodic polarization test results under flow condition.
- Anodic polarization test results under jet impingement condition.
- weight loss test results.

Some of the curves obtained from the plotter of these tests are presented in appendix[B,C,D and E]. All the anodic polarization test results were summarized and presented through curves and histograms.

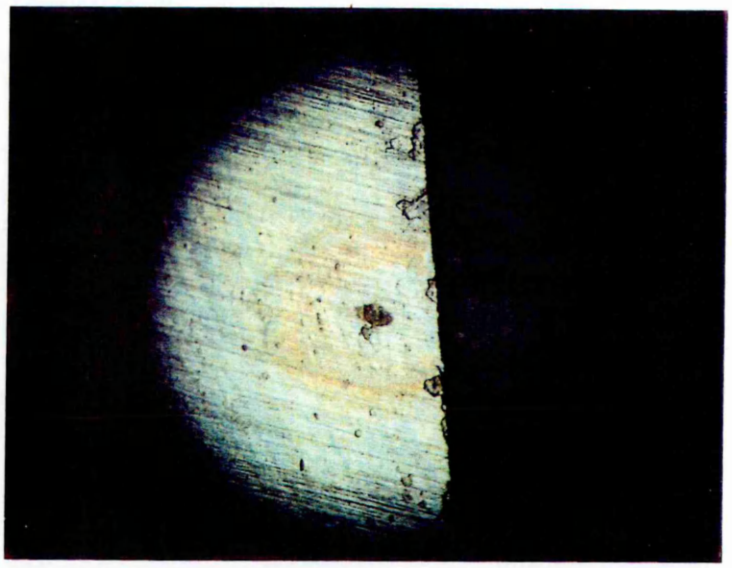
2-1. Anodic polarization test results under static conditions:

The results of this group are presented on pages (106 to 132). Free corrosion potential(Ecor), breakdown potential(Ec) and the repassivation potential(Ep) of each alloy under the same condition are shown at first, then the values of Ec of each alloy under different conditions are shown on pages(111 to117). Ecor, Ec and Ep of the alloys under the same condition were compared through histograms shown on pages (118-125). Finally a comparisons between the value of Ec-Ecor for each alloy under diffrerent conditions were made on the remaining pages of this group.

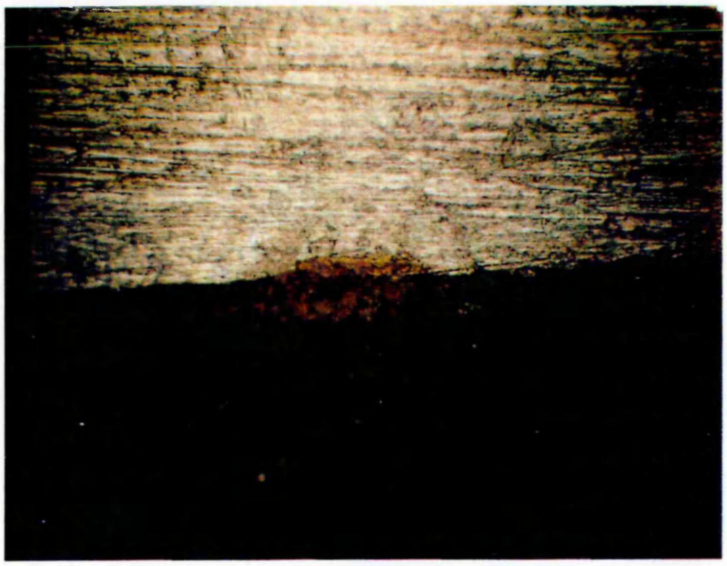
It should be pointed out that the specimens were examined visually after the polarization tests for evidence of corrosion including type of attack. However, on account of the fact that the period experianced at the high currents was small (due to the action of the reversing the scan to determine Ep), it was usually difficult to make these visual assessments. There were some exceptions to this- usually in the higher temperatures specimens. Photographs 6-1,6-2 and 6-3 reveal evedince of clear free-surface pitting on a SMO specimen (65°C), crevice corrosion at specimen edge on a IN specimen (65°C) and some slight pitting plus evidence of some more-general corrosion on a Hastelloy C specimen (85°C).

2-2. Anodic polarization results after long term immersion:

In this category of tests the effect of the time on Ecor was considered. consiquently curves shown on pages (134-151) described the effect of the time (60-70 days).factor. The anodic polarization tests were carried out only at the end of the experiments and these results are shown on pages (152-178). The values of Ec at different current densities were considered and presented for each alloy under different conditions on pages (152-157). a comparisons between the values of Ecor and Ep of the alloys under the same condition are shown on pages (158-164). Also a comparisons between the value of Ec of the alloys under the same condition were made and shown on pages (165-171) Finally another comparisons between the



Photograph 6-1
SMO, 65^{o}C, 55000 ppm, short static test, Aerated



Photograph 6-2
IN, 65^{o}C, 55000 ppm, short static test, Aerated

value of (Ec-Ecor) were made and shown on pages (172-178). It should be pointed out that the creviced specimens are specified by a small "c" beside the symbol of the alloys. Many of these specimens showed clear evidence of crevice corrosion, either under the crevice deliberately induced by the central washer or at specimen edges. Typical examples are shown in photographs 6-4, 6-5 and 6-6.

2-3. Anodic polarization test results under flowing condition:

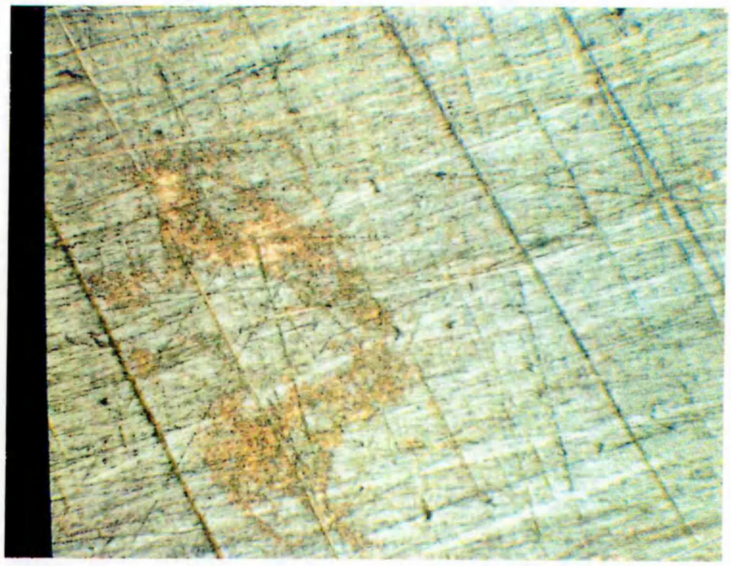
The effect of the environment flowing was studied and the results are shown through histograms form as above tests. Ecor of the alloys under different conditions are shown on page (180). The values of Ec of each alloy under different conditions are shown through pages (181-183). Pages (184-187) are showing Ec values under different conditions in comparison form between the alloys. Pages (188-189) are presented (Ec-Ecor) values. It should be pointed out that the anodic polarization tests were started after 10 minuets from pumping the fluid through the system. This time was found to be sufficient to have stable Ecor reading.

2-4. Anodic polarization results under jet impingement condition:

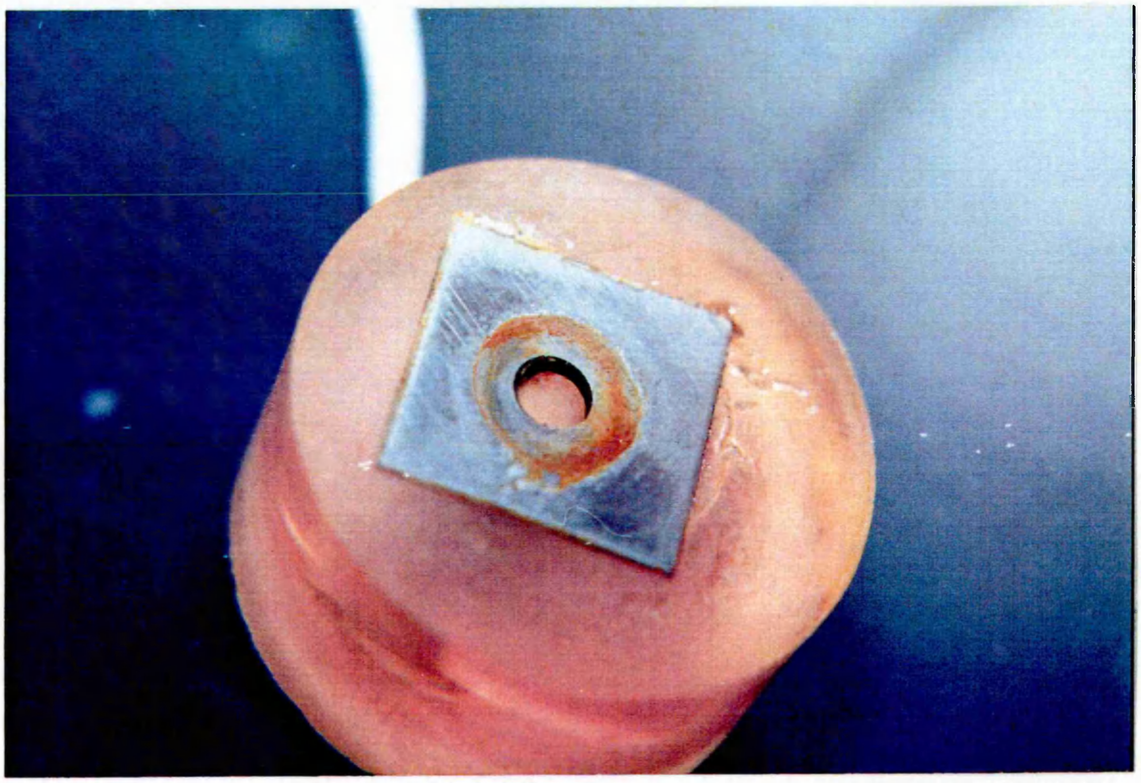
As above, histogram on page(191) indicates the value of Ecor of the alloys under the tests conditions, followed by histograms of Ec of each alloy under different conditions. again the value of Ec but for all the alloys under the same condition are shown on pages (198-199). Finally the value of (Ec-Ecor) of each alloy are mentioned on the rest pages of this group. As in flow tests it was found that about 10 minuets are sufficient to have stable reading foe Ecor.

2-5. Weight loss test results.

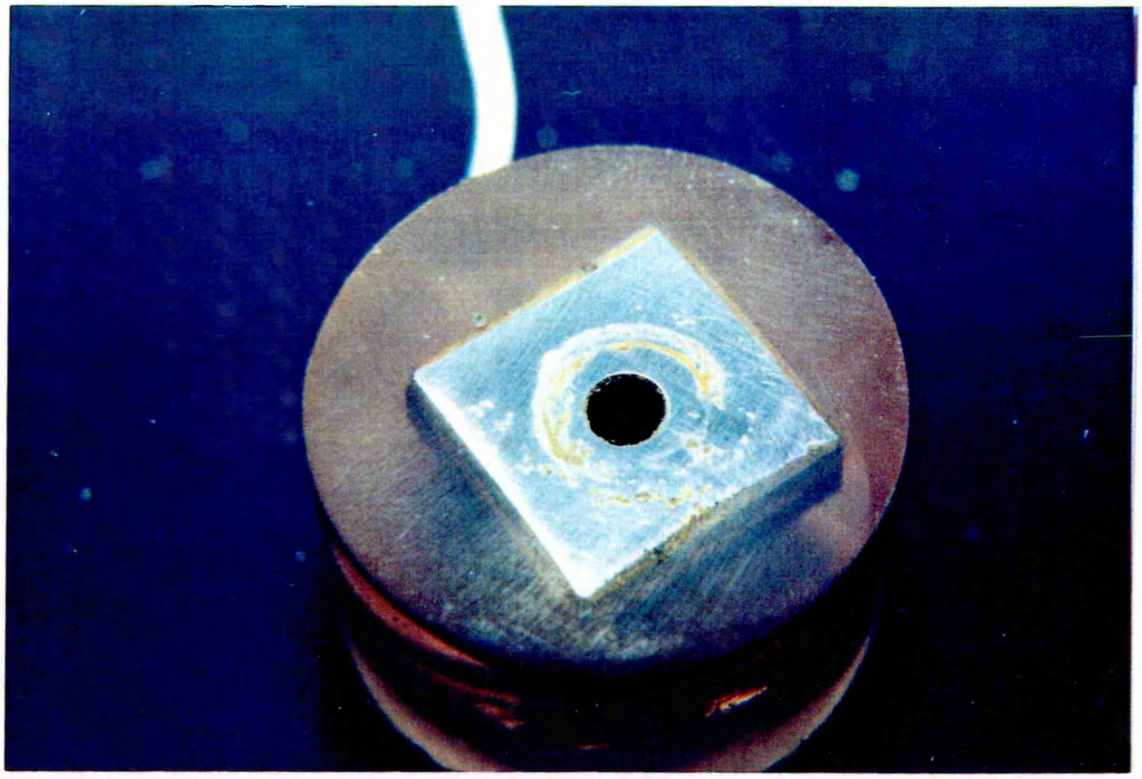
The results of this test are shown on table 6-1. The weight of the specimens before immersion, after immersion and the loss are shown on this table. The period of immersion was 60 days. From table 6-1 it can be noted that most of the losses were very small (less than 2mg) only 6 specimens shows a slightly higher losses. There was only one specimen showed 0.6305 gm, it was 430 alloy under 25^{o}C and



Photograph 6-3
Hastelloy C, 85^{0}C, 35000 ppm, short static test, Aerated

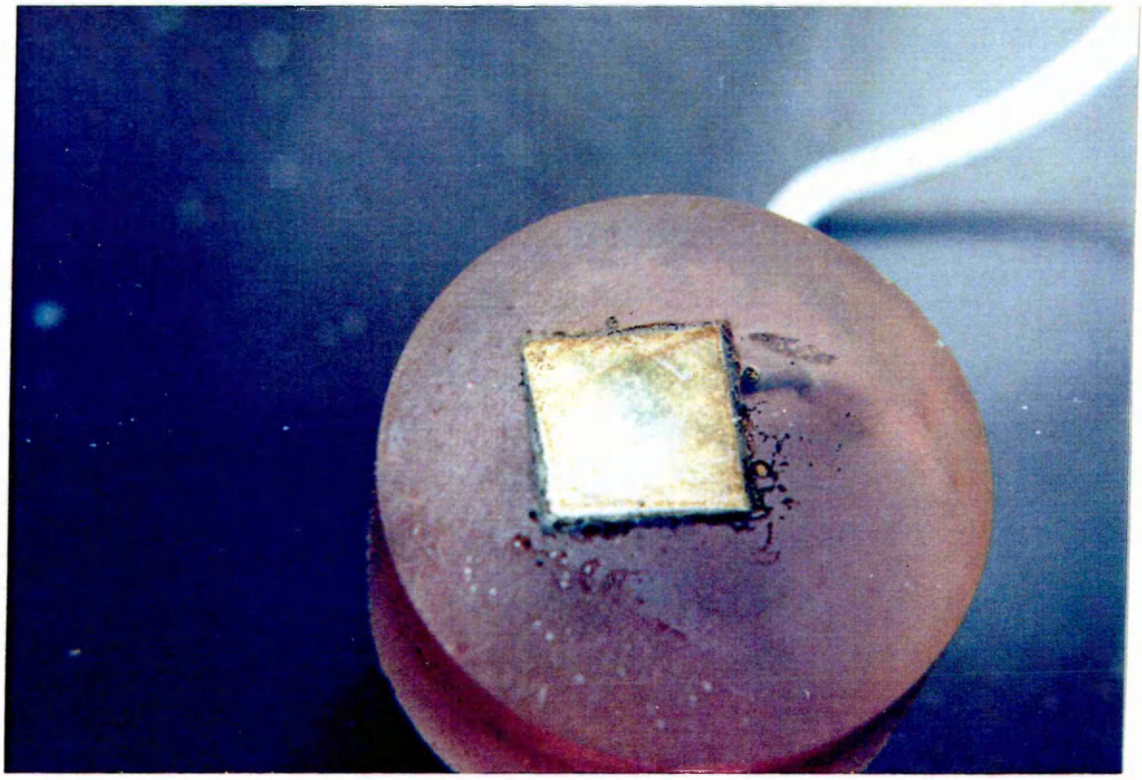


Photograph 6-4
430, 45^{0}C, 35000 ppm, long term test, Aerated



Photograph 6-5

430, $25^{o}C$, 55000 ppm, Long term test, Aerated



Photograph 6-6

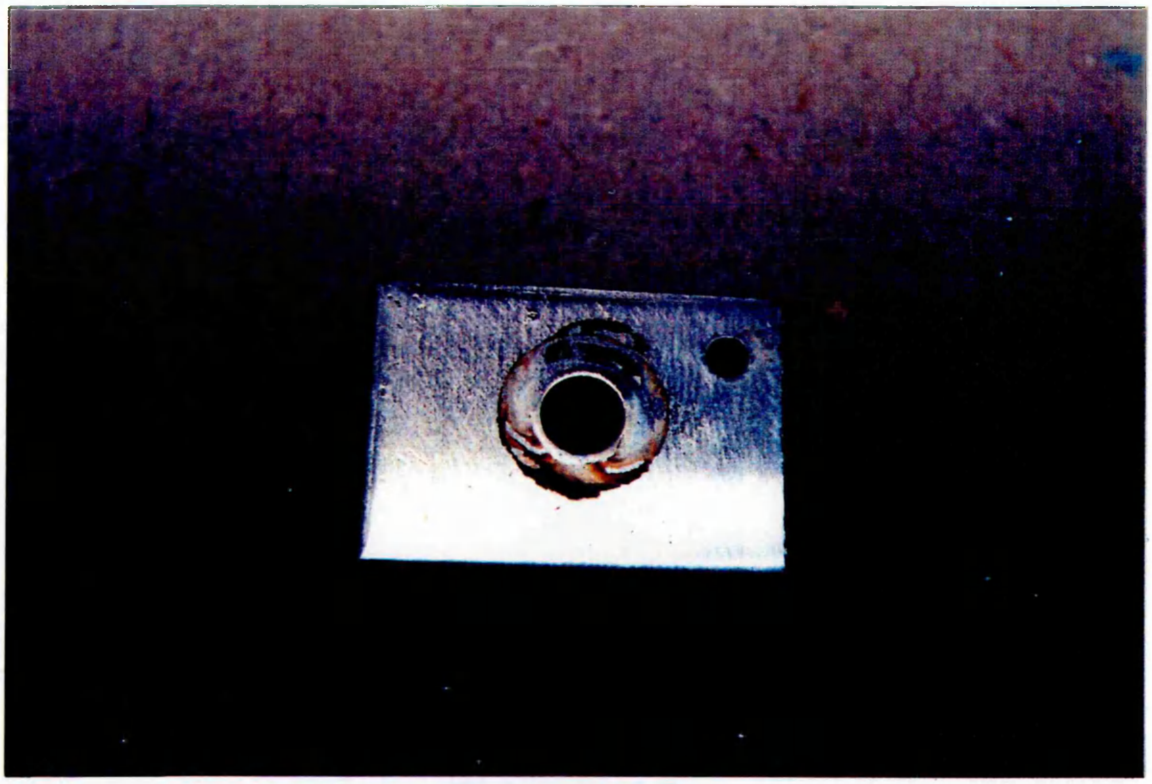
316, $45^{o}C$, 55000 ppm, long term test, Aerated

35000ppm condition, the reason for this high loss may be due to mistake on the weight measured before immersion. The photos presented on the appendix F shows some of the specimens after the immersion. Since the specimens have different degree of corrosion attack, four symbolise were used on table 6-2 to explain the condition of each specimen after immersion. Blanks mains no corrosion observed visually, white triangle means slight surface discolouration was observed, half darked triangle means moderate corrosion with slight corrosion product. and the black triangle means severe corrosion with abundant corrosion product.

Photographs 6-7 and 6-8 show the clear visual appearence of the severe crevice corrosion on the 430 alloy over the entire temperatures range of these long tests.

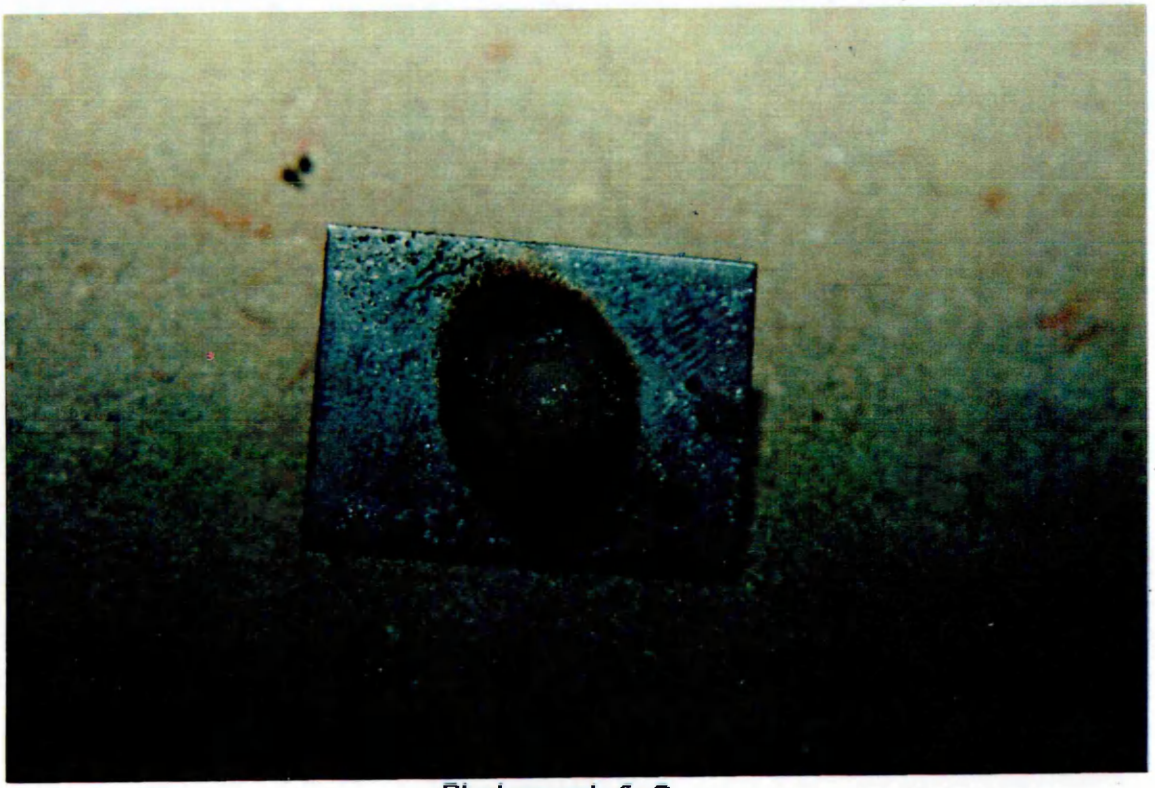
The visual examination clearly revealed much less severe corrosion on all the other materials tested. An example of slight pitting attack on 316 after exposure at the highest temperature (75°C) is shown in photograph 6-9. As indicated in table 6-2 only one each of the hastelloy C and IN weight loss specimens showed any evidence of corrosion after exposure to the highest temperature, there was evidence of pitting over an extensive area of the surface (photograph 6-10) but this did not appear to be of significant penetration - as was indicated by weight loss of only 1.4 mg (table 6-2) for this specimen. The sole IN specimen exhibit any corrosion in fact only did so on the cut edge (photograph 6-11) and not on the prepared main surfaces.

The unexpected results from the visual examination are for SMO alloy but the great majority of these specimens showing corrosion had in fact only small area of light surface dscolouration (e.g. phtograph 6-12) with no significant corrosion product and no evidence of significant penetration of the corrosion. This conclusion is clearly supported by the actual weight loss measurement (table 6-1) which show that, at 25°C , the maximum weight loss recorded was only o.8 mg (even though, table 6-2, six of these specimens showed visual signs of slight corrosion). Interestingly, for the higher temperatures, the weight loss of the SMO specimens were higher (but still usually < 2 mg) indicating more attack (also shown visually in photograph 6-13)



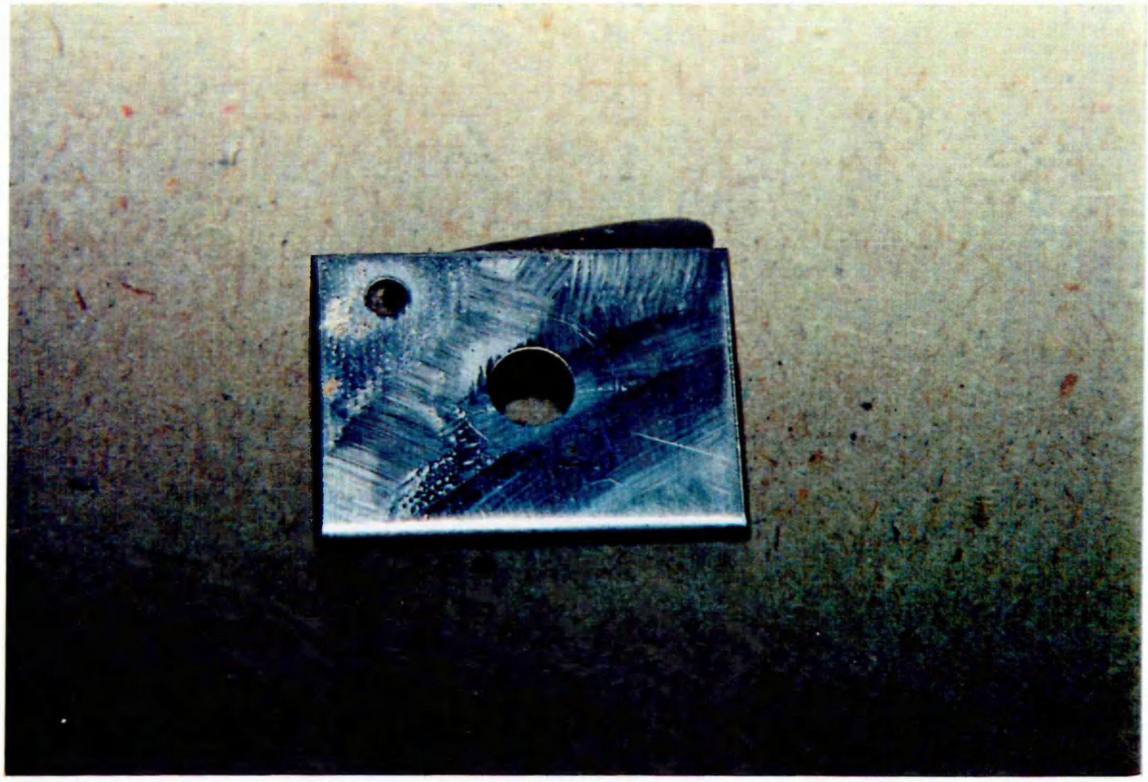
Photograph 6-7

430, 25^{0}C, 55000 ppm, Weight loss test, Aerated



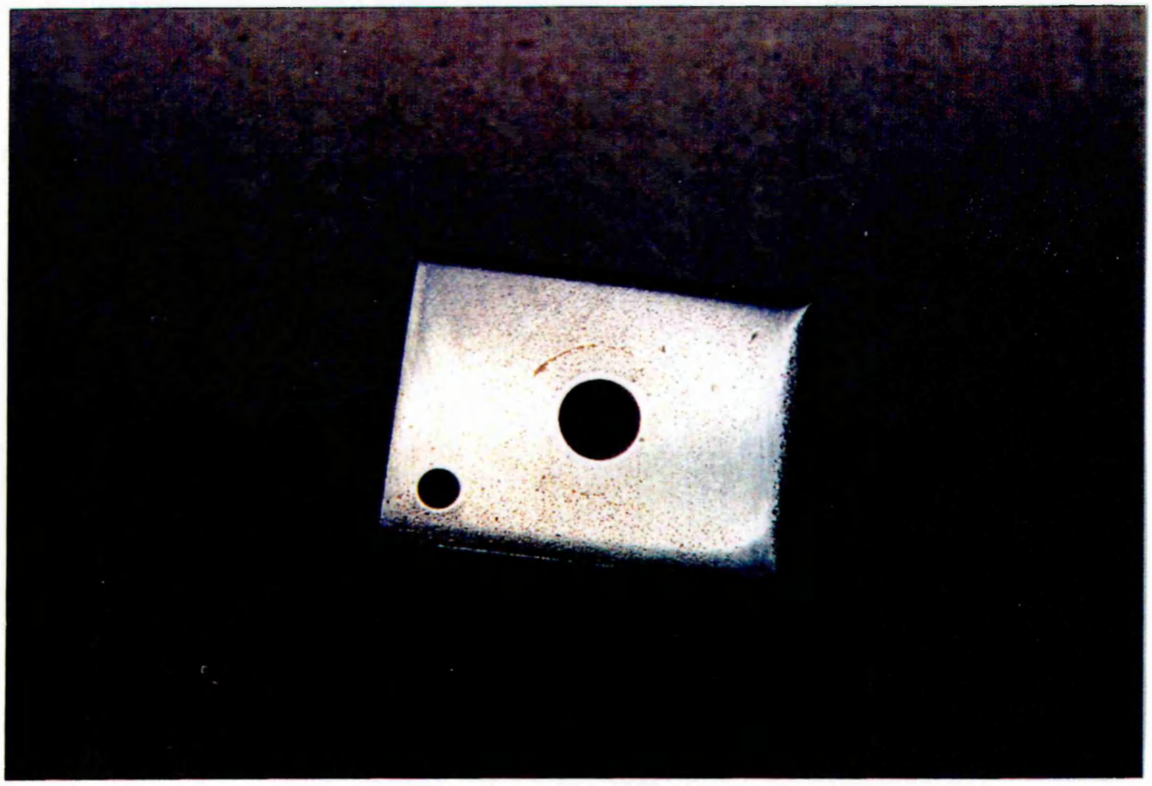
Photograph 6-8

430, 75^{0}C, 55000 ppm, Weight loss test, Aerated



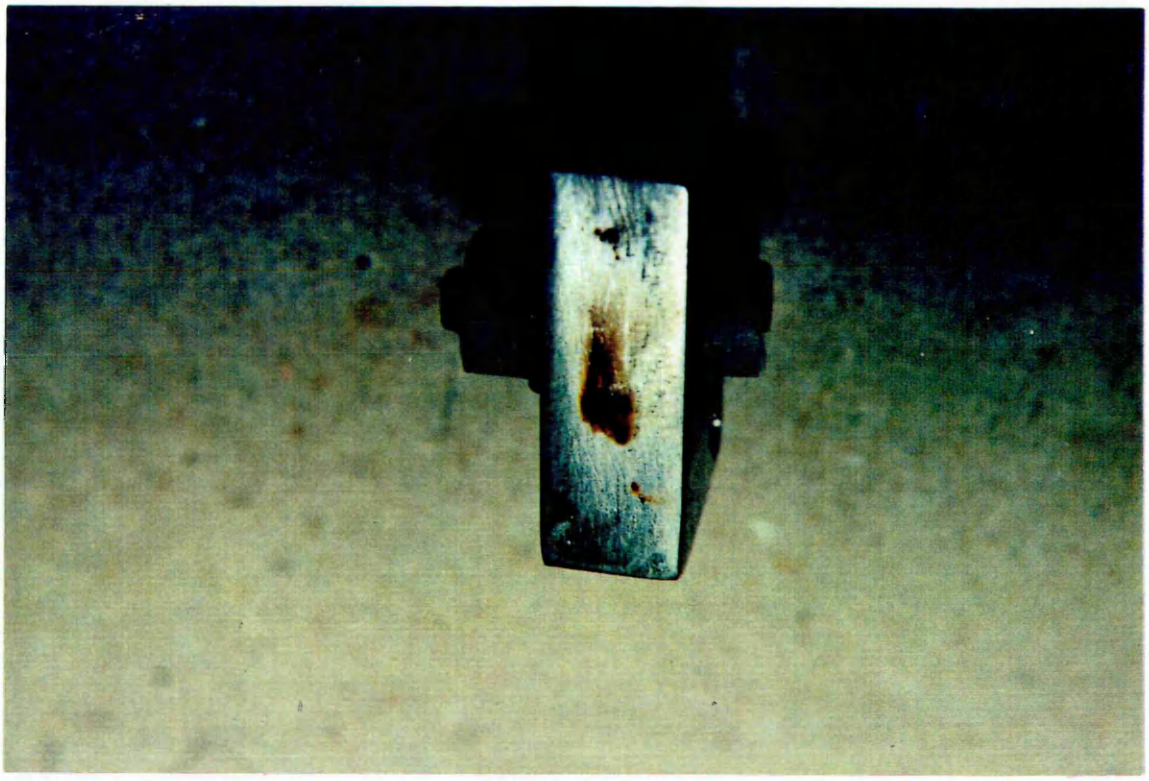
Photograph 6-9

316, 75^{o}C, 55000 ppm, Weight loss test, Aerated

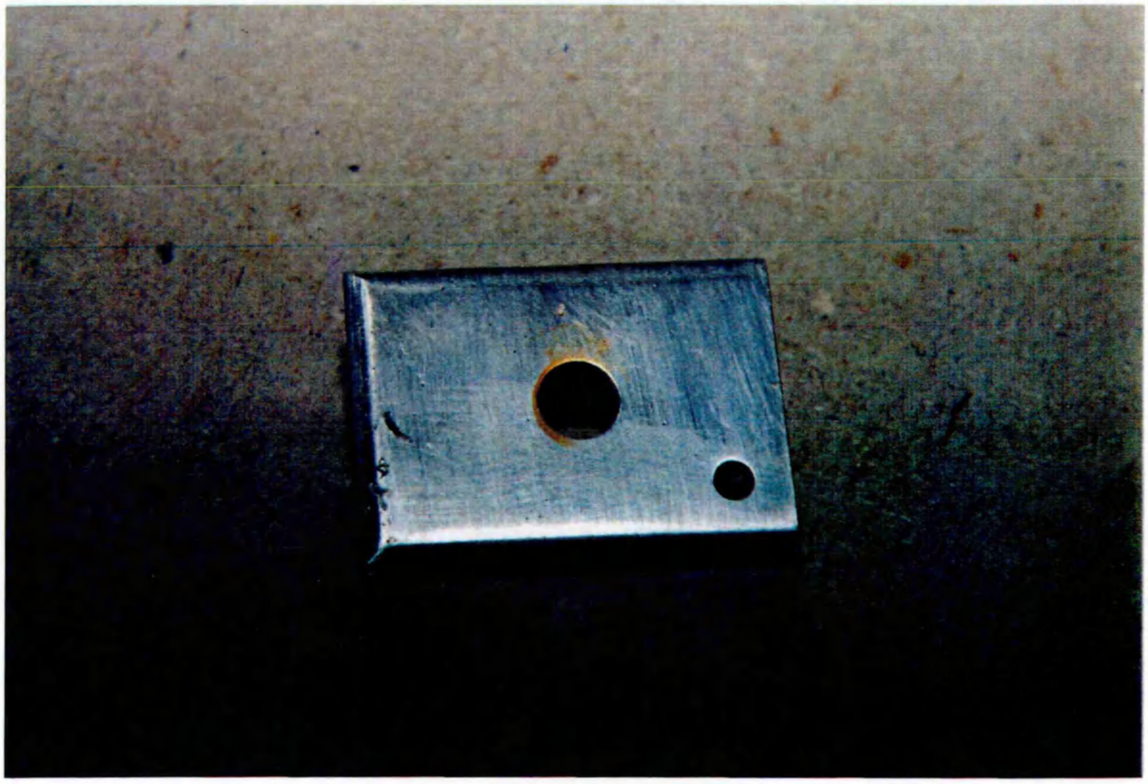


Photograph 6-10

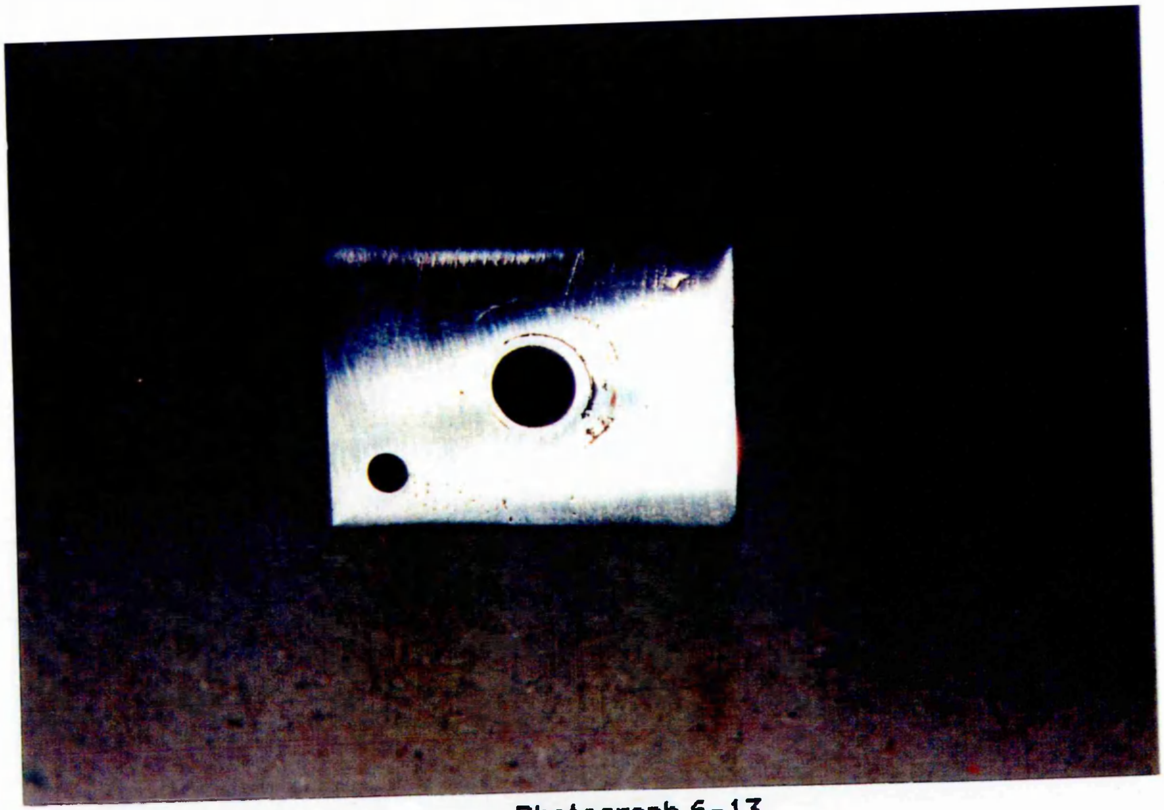
Hastelloy C, 75^{o}C, 35000 ppm, Weight loss test, Aerated



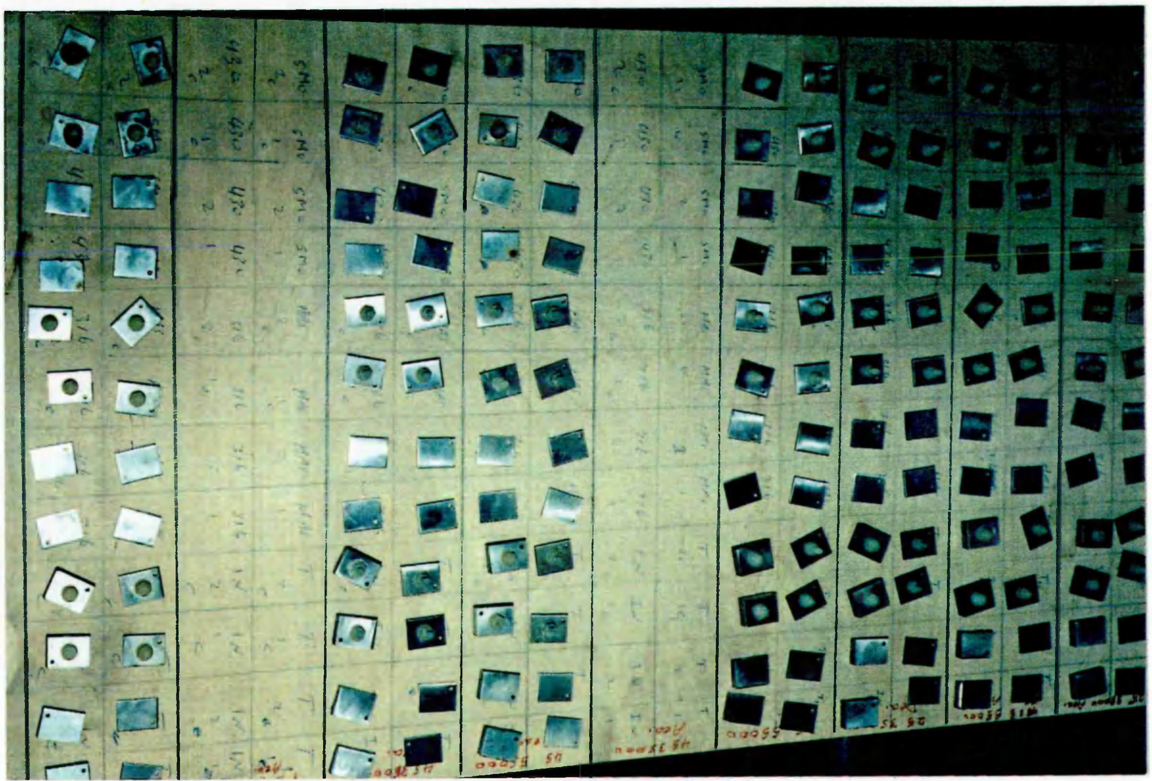
Photograph 6-11
IN, 25^{0}C, 55000 ppm, Weight loss test, Aerated



Photograph 6-12
SMO, 25^{0}C, 55000 ppm, Weight loss test, Aerated



Photograph 6-13
SMO, 75^{0}C, 55000 ppm, Weight loss test, Aerated



Photograph 6-14
Some of the weight loss test specimens

STATIC TEST RESULTS ANALYSIS

NOTATION:

35 >>>> 35000 PPM

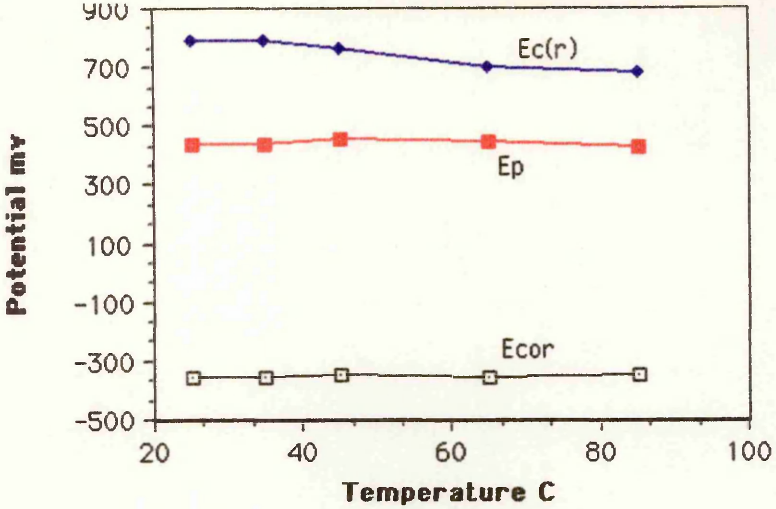
55 >>>> 55000 PPM

D , De. >>>> Deaerated

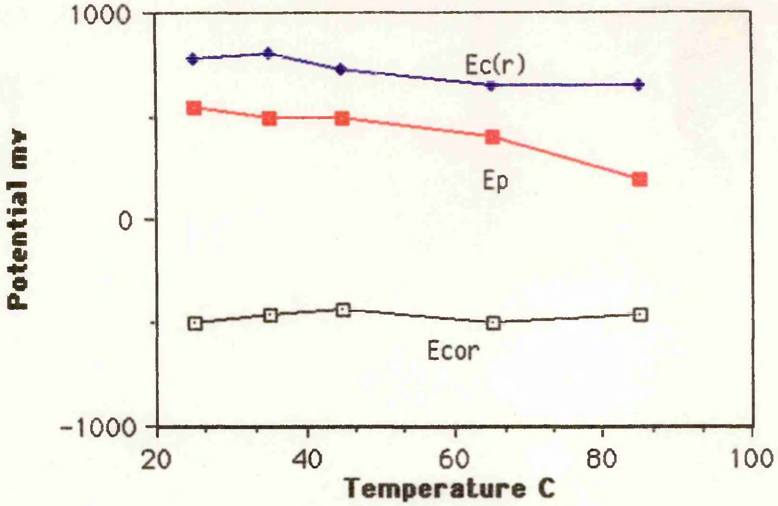
A, Aer. >>>> Aerated

25 >>>> 25°C

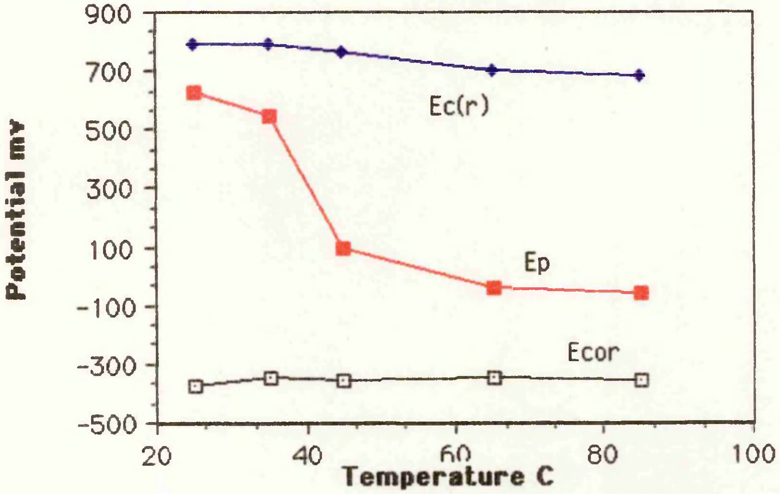
45 >>>> 45°C



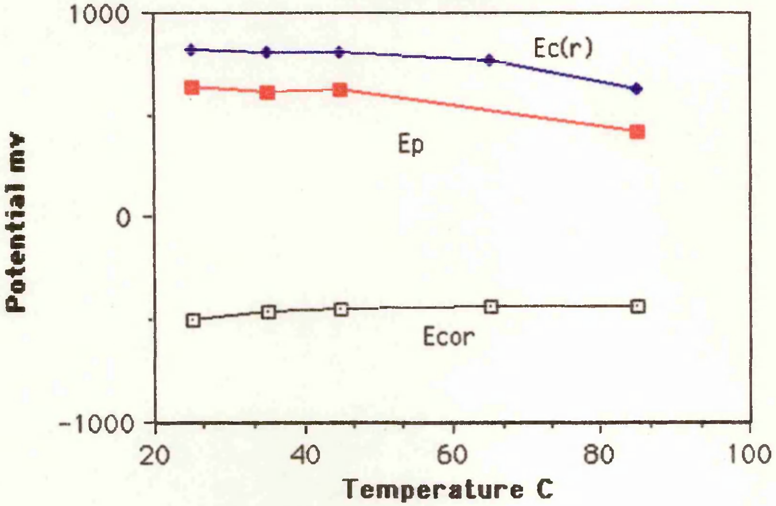
Hastelloy C , STATIC TEST , 35000 PPM, AERATED



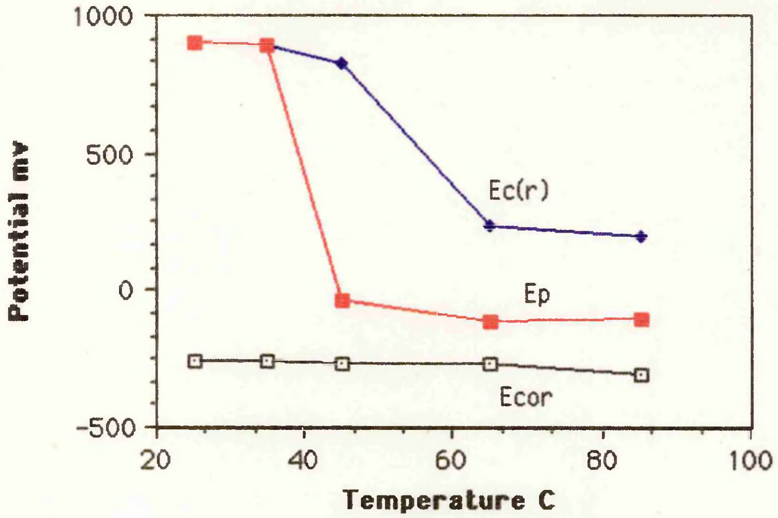
Hastelloy C , STATIC TEST, 35000 PPM DEAERATED

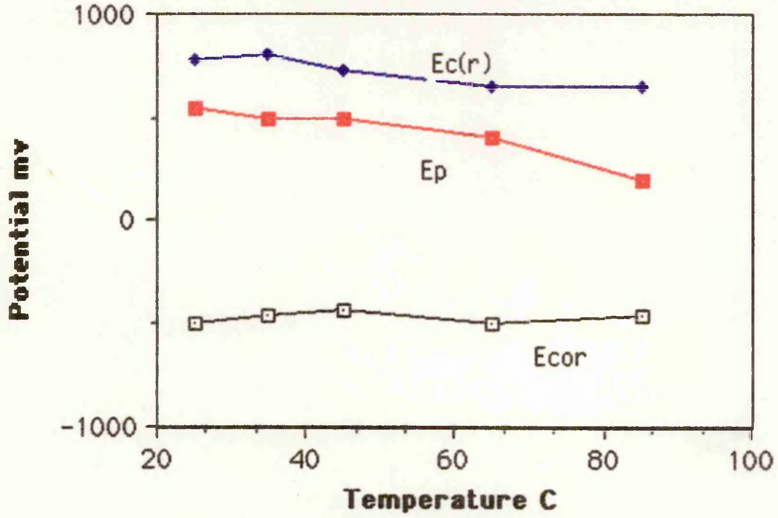


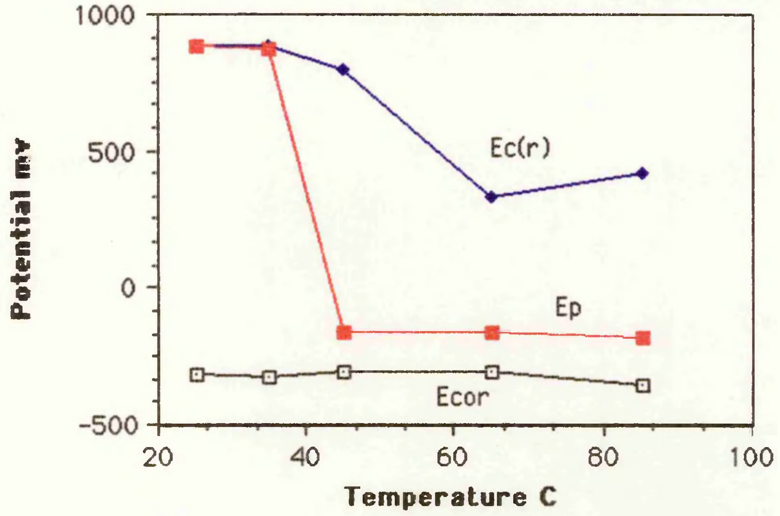
Hastelloy C , STATIC TEST , 55000 PPM AERATED

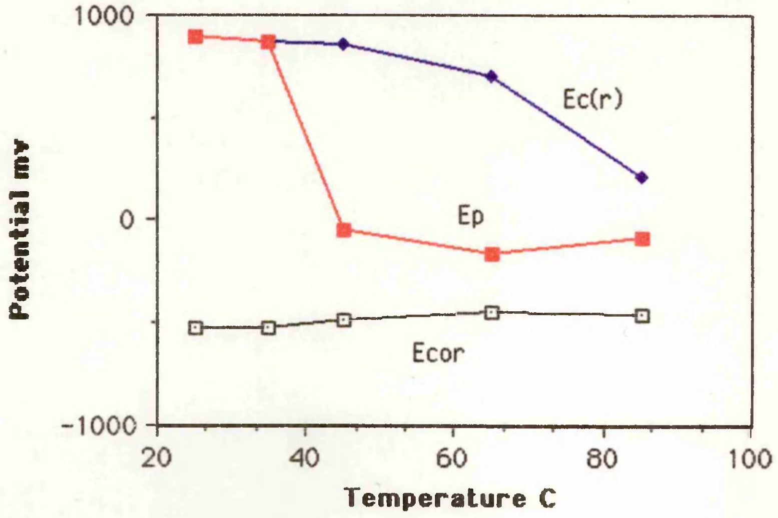


Hastelloy C , STATIC TEST , 55000 PPM DEAERATED

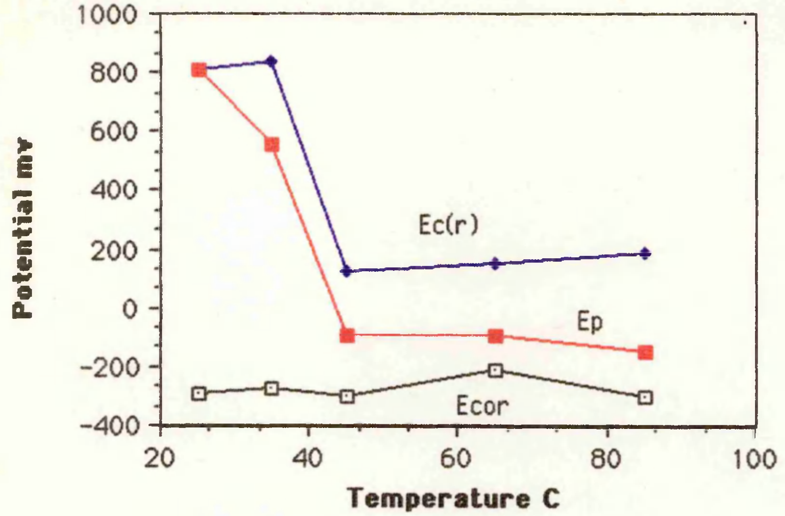

SMO,STATIC TEST, 35000 PPM, AERATED


SMO,STATIC TEST,35000 PPM , DEAERATED

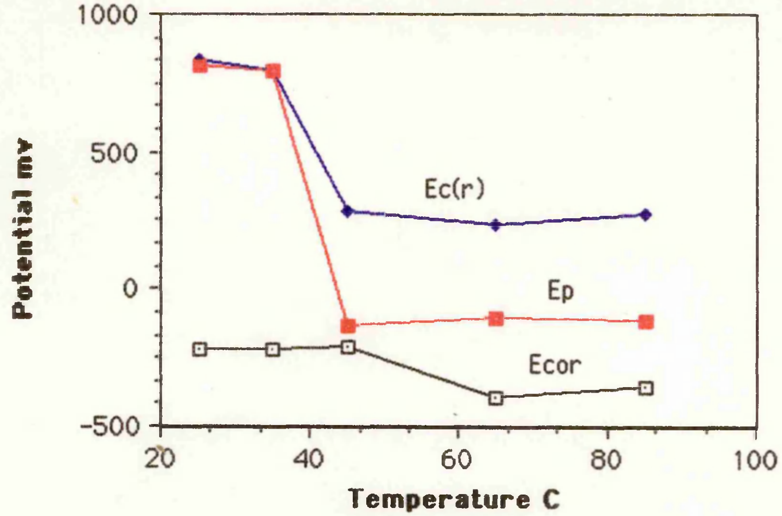

SMO,STATIC TEST,55000 PPM, AERATED


SMO,STATIC TEST,55000 PPM, DEAERATED

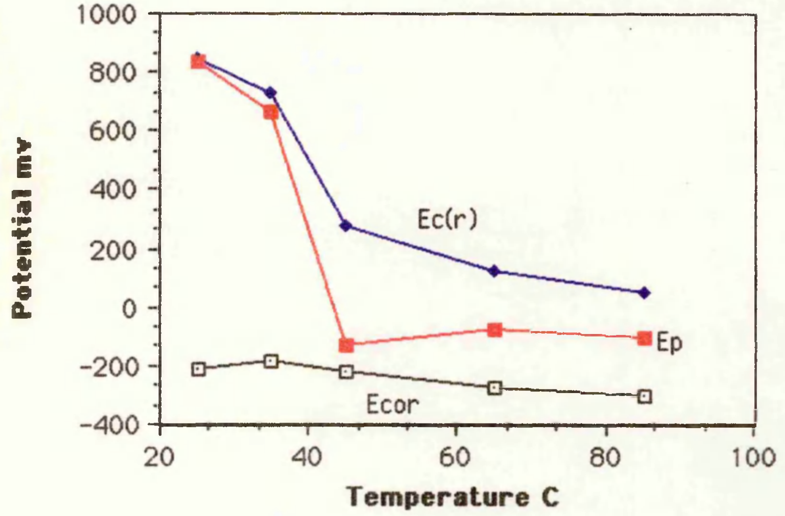
IN, STATIC TEST , 35000 PPM , AERATED



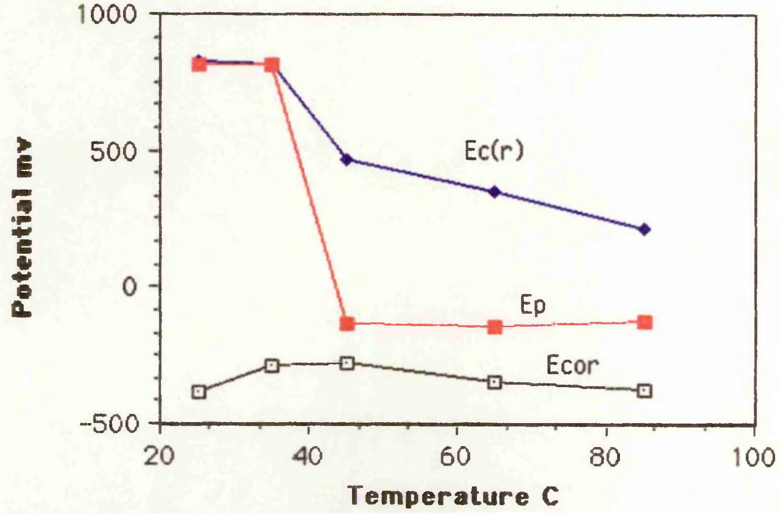
IN,STATIC TEST, 35000 PPM, DEAERATED



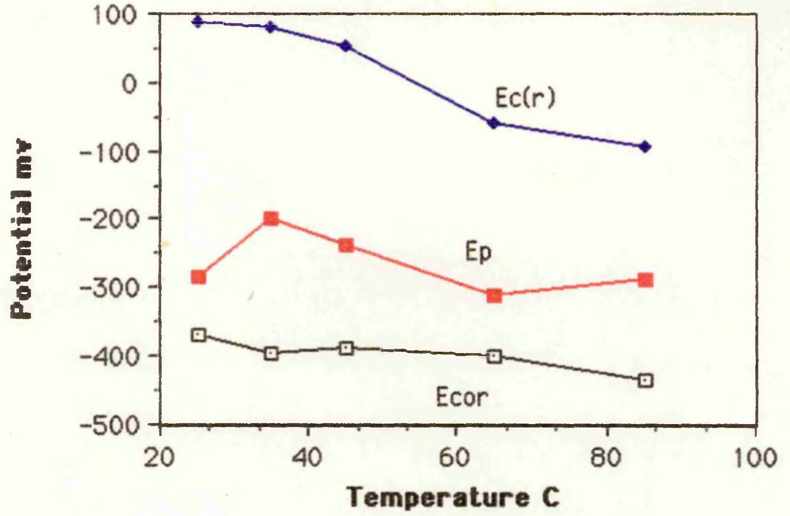
IN, STATIC TEST , 55000 PPM, AERATED



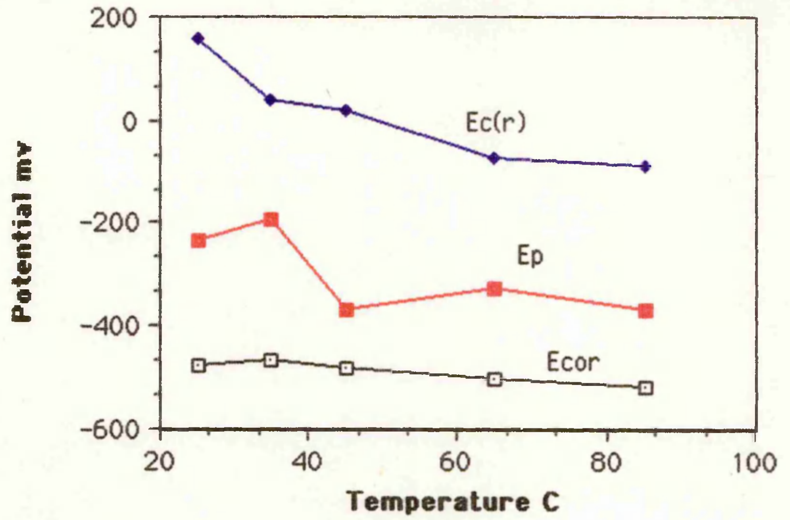
IN , STATIC TEST, 55000 PPM, DEAERATED



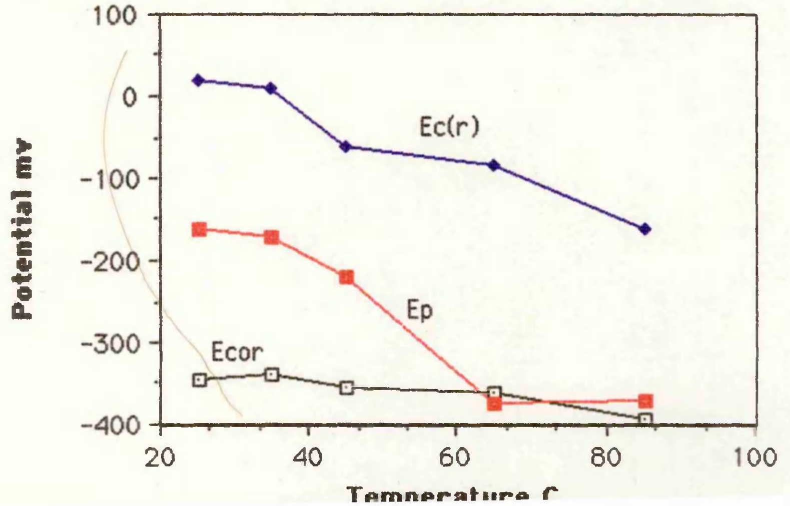
316 Static test ,35000 ppm , Aerated



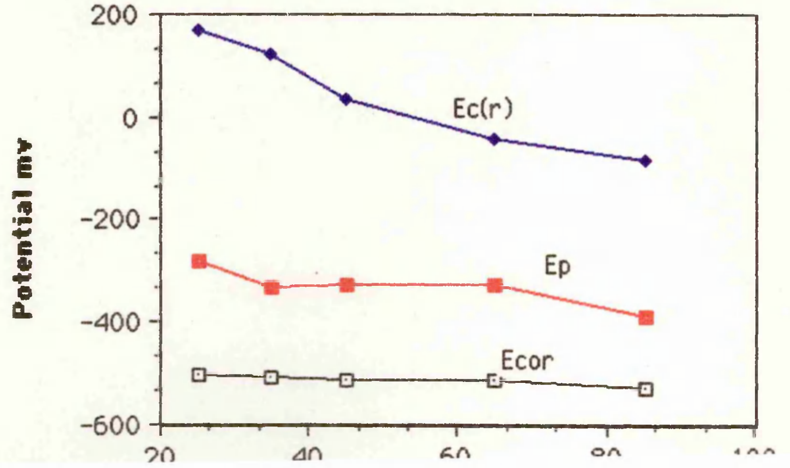
316 STATIC TEST , 35000 PPM DEAERATED



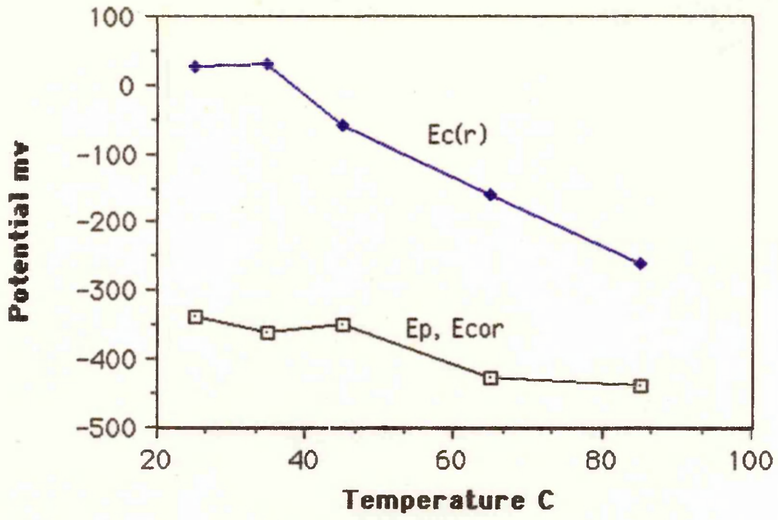
316 STATIC TEST, 55000 PPM , AERATED



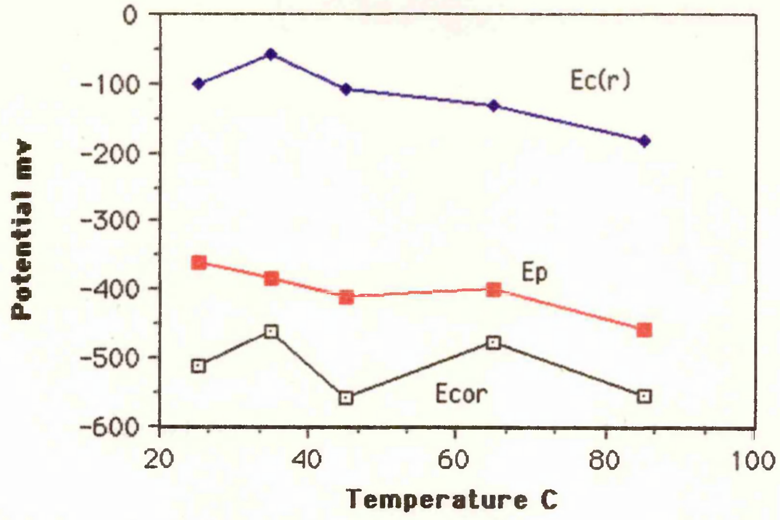
316 STATIC TEST, 55000 PPM , DEAERATED



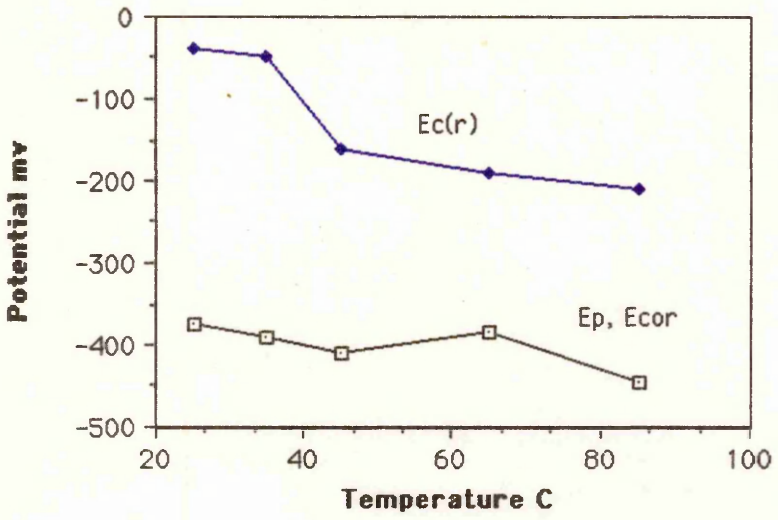
430 , Static test, 35000 ppm, Aerated



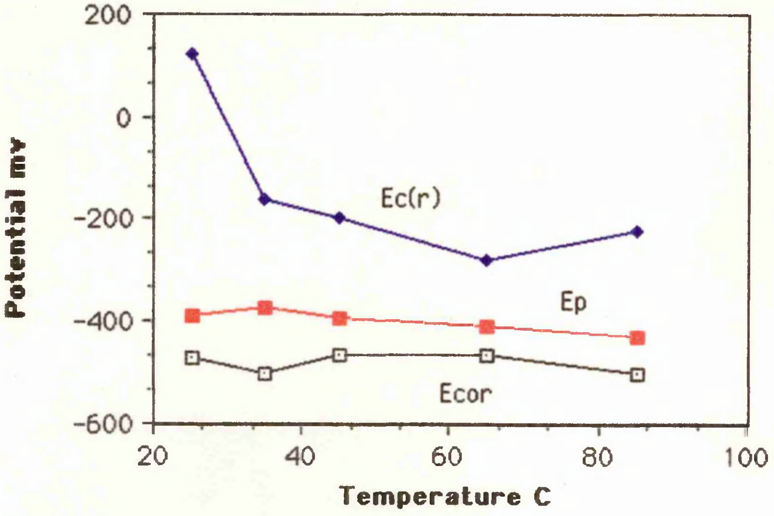
430 , STATIC TEST , 35000 PPM , DEAERATED



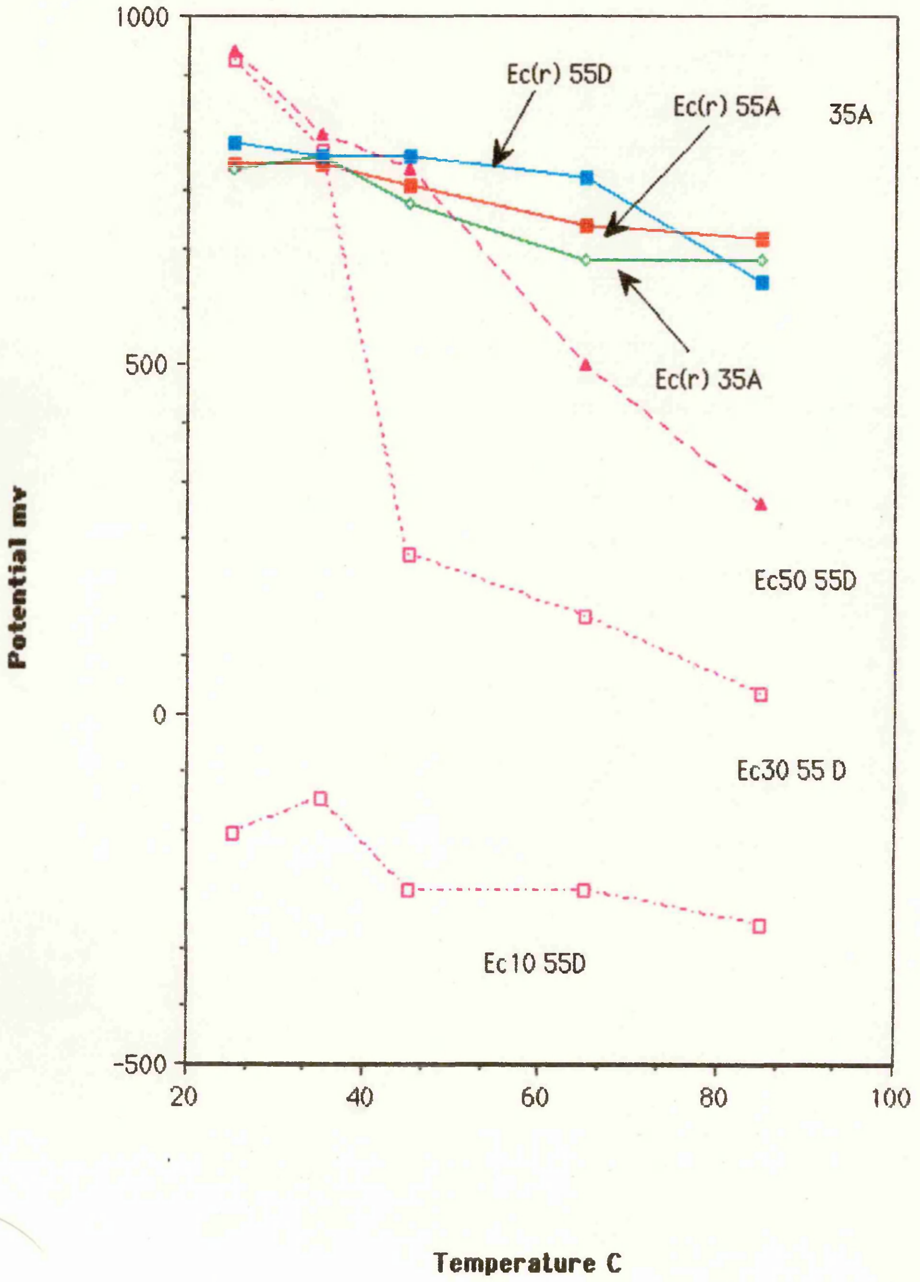
430 , static test, 55000 ppm aerated



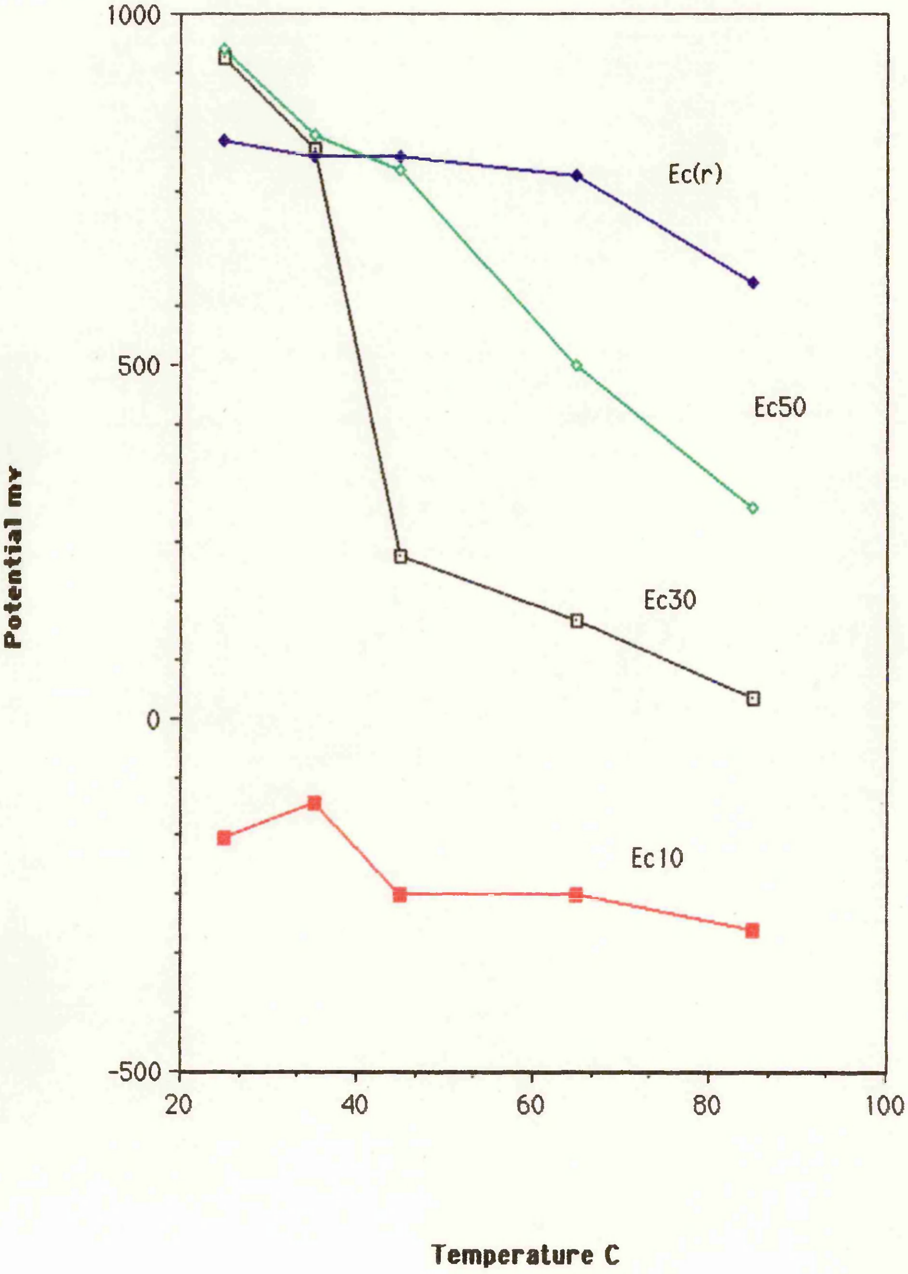
430, STATIC TEST , 55000 PPM , DEAERATED



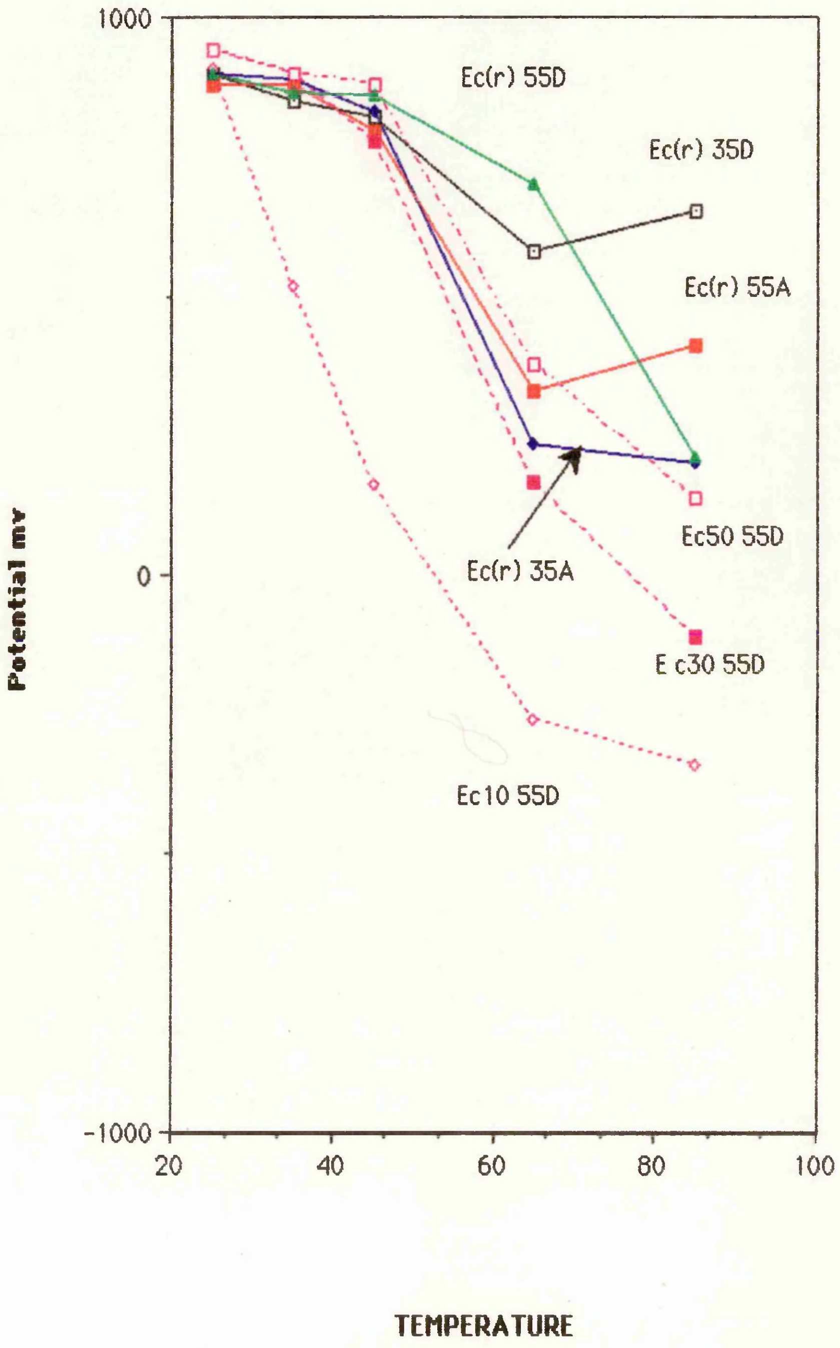
Ec of Hastelloy C under different conditions



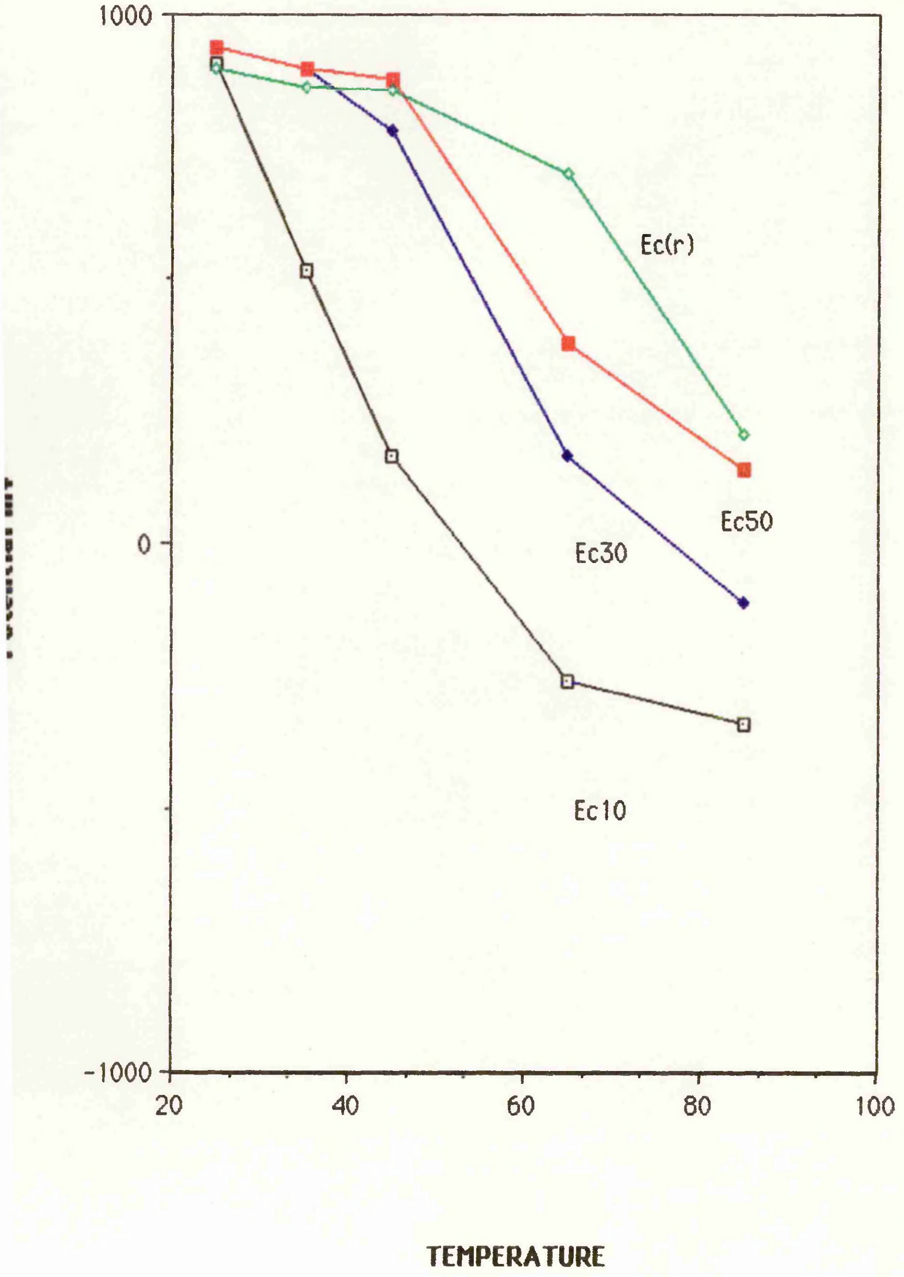
Ec of Hastelloy C at different current density.
55000 ppm, Deaerated

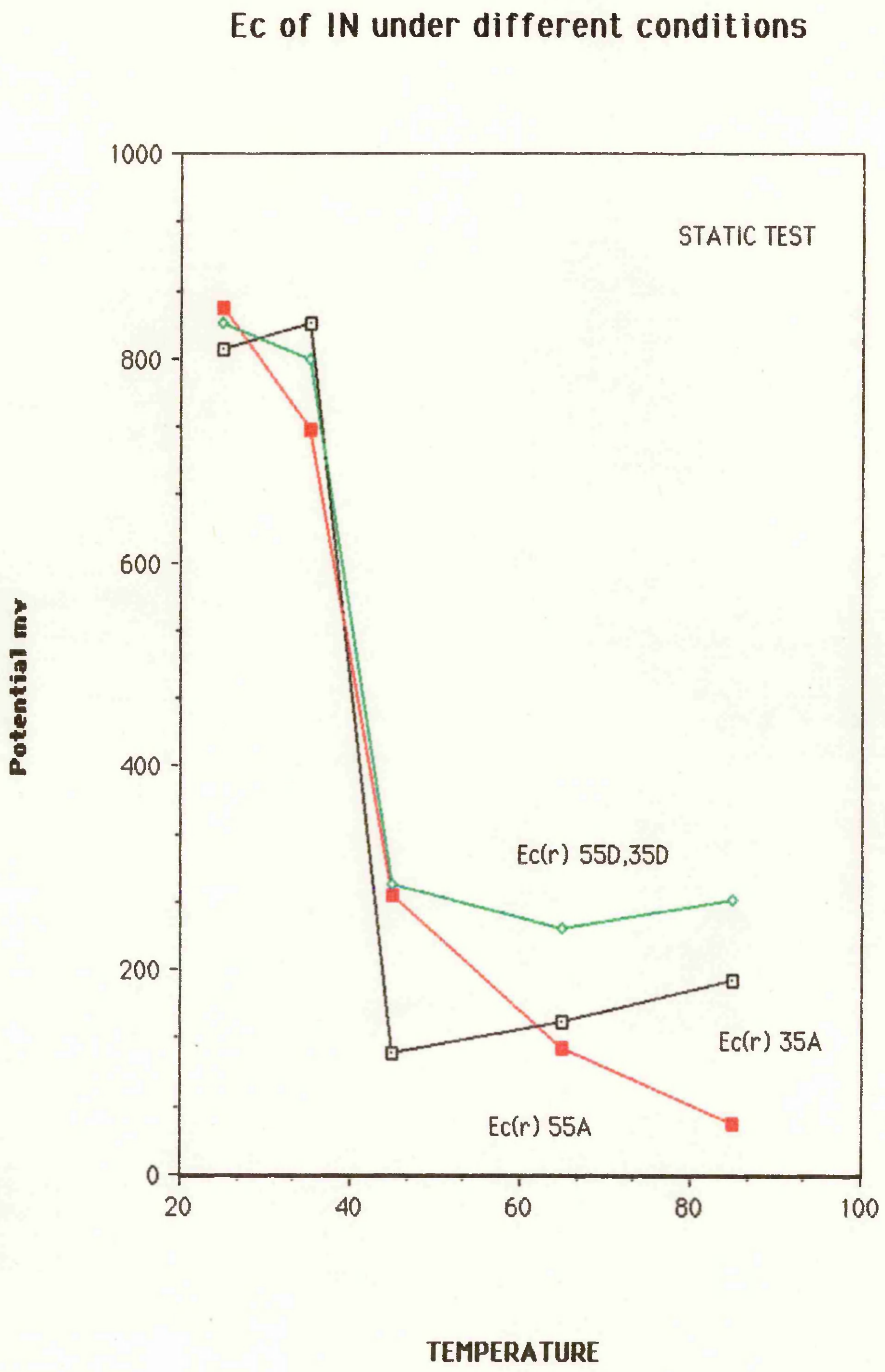


Ec of SMO under different conditions



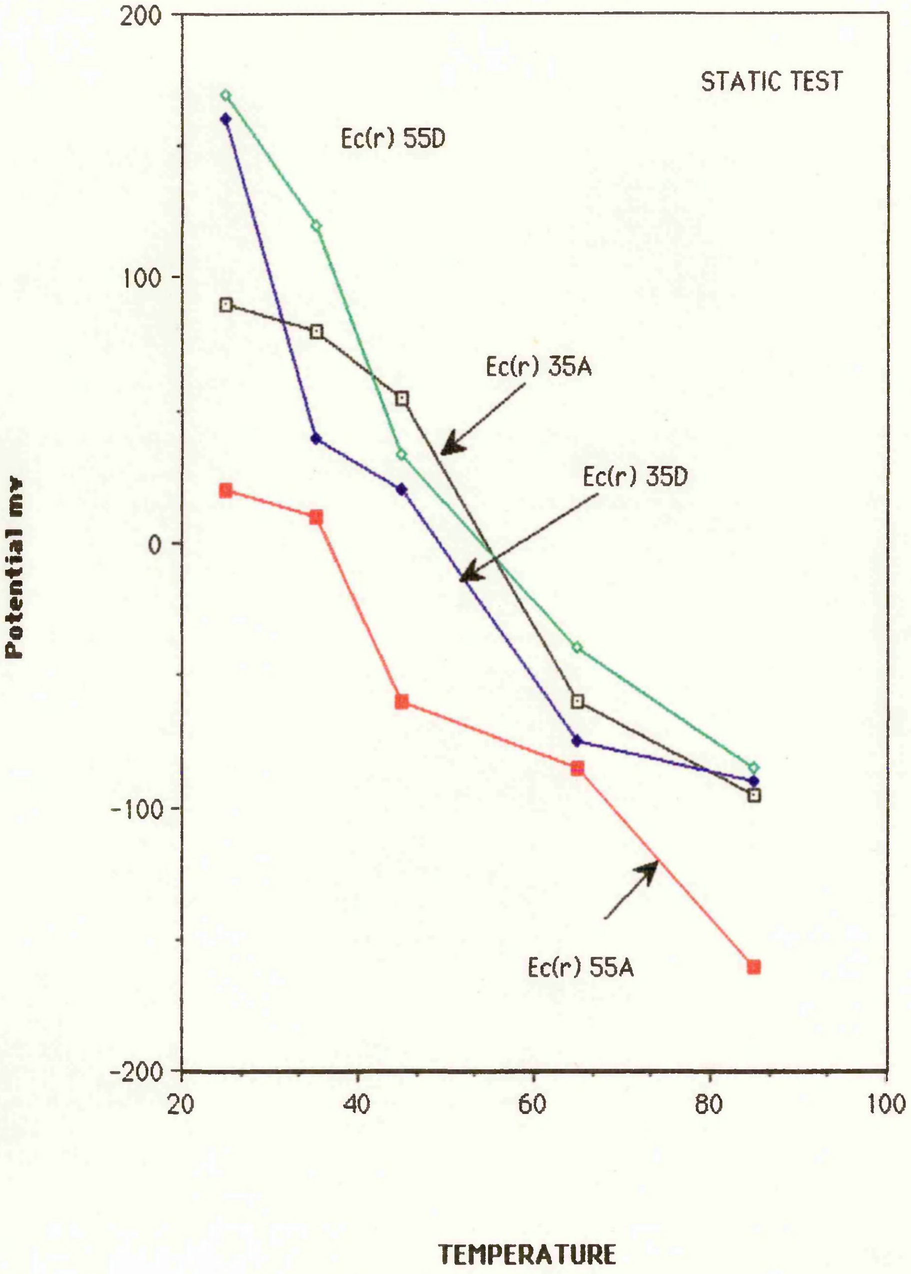
Ec of SMO at different current density.
55000 ppm. Deaerated



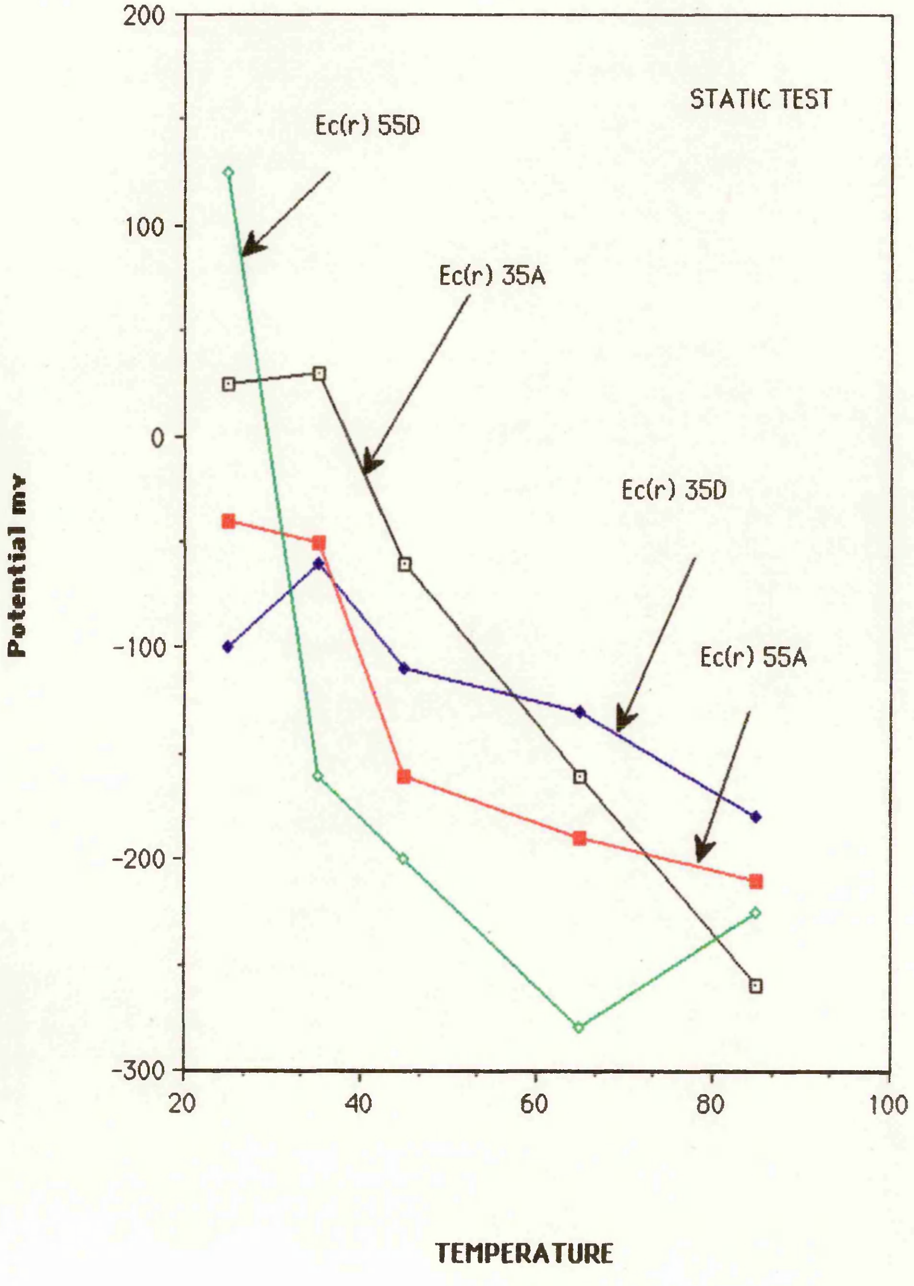


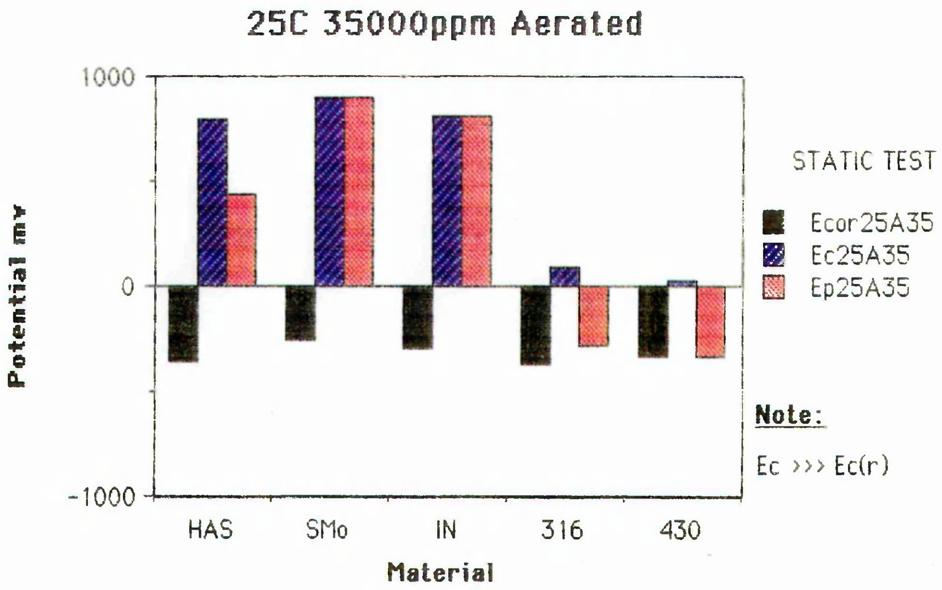
Ec of IN under different conditions

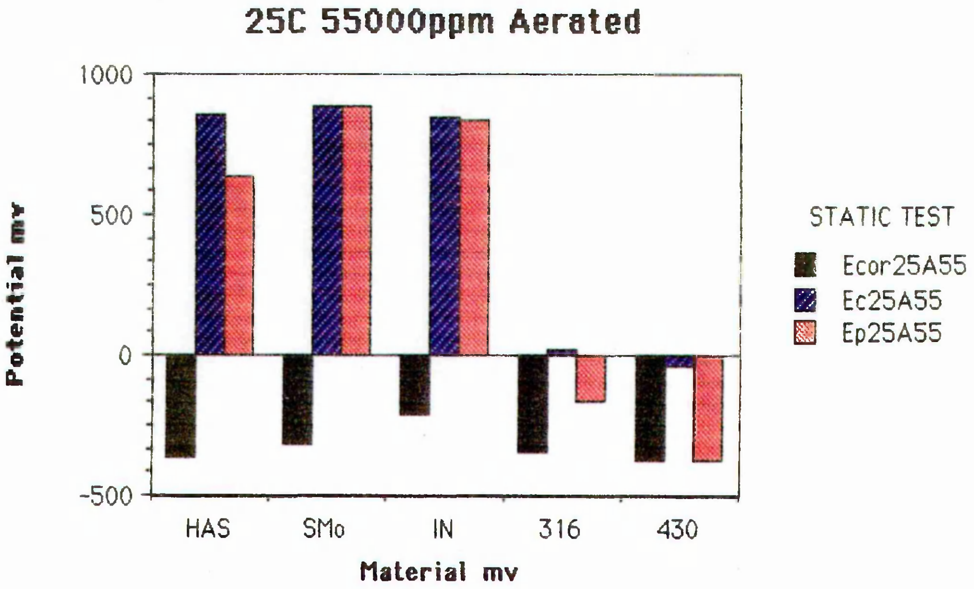
Ec of 316 under different conditions

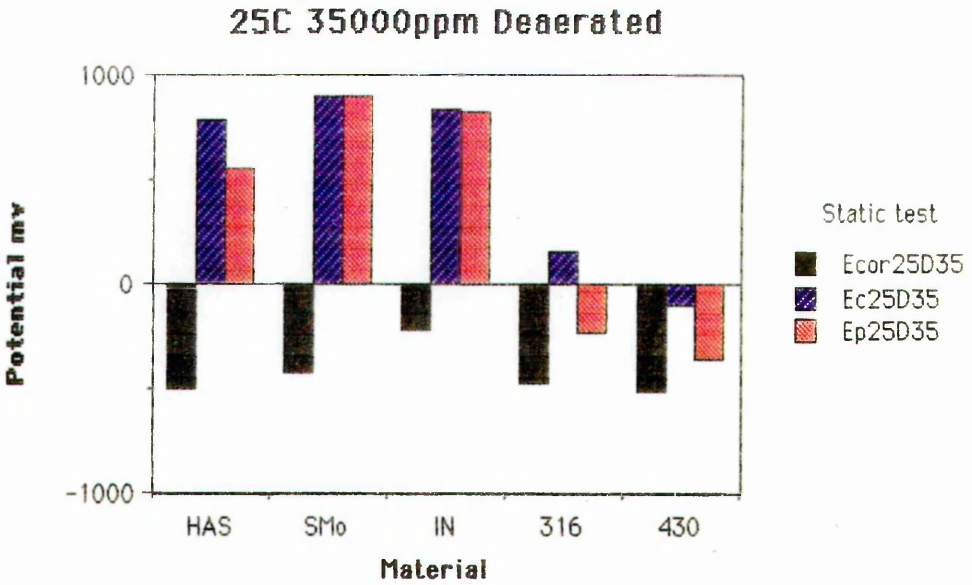


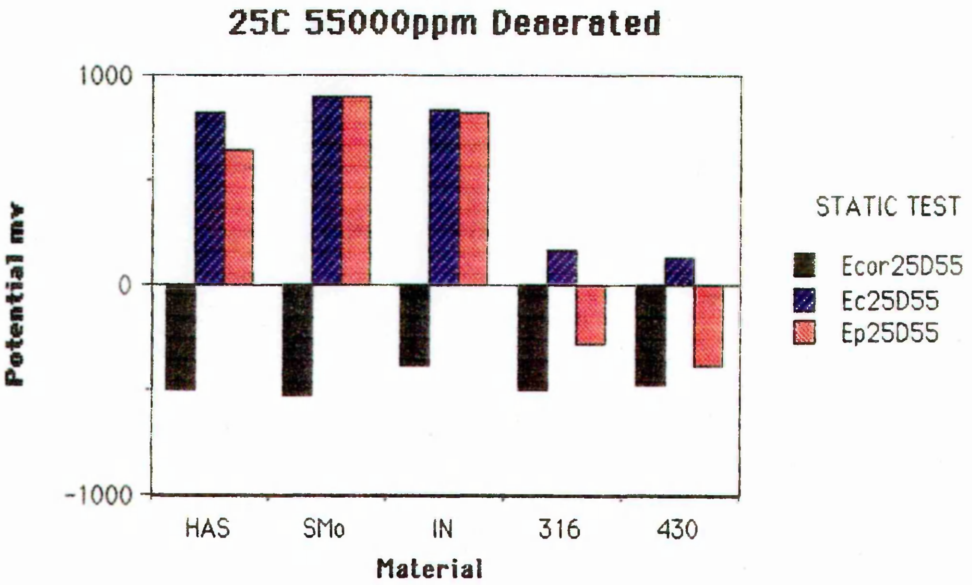
Ec of 430 under different conditions

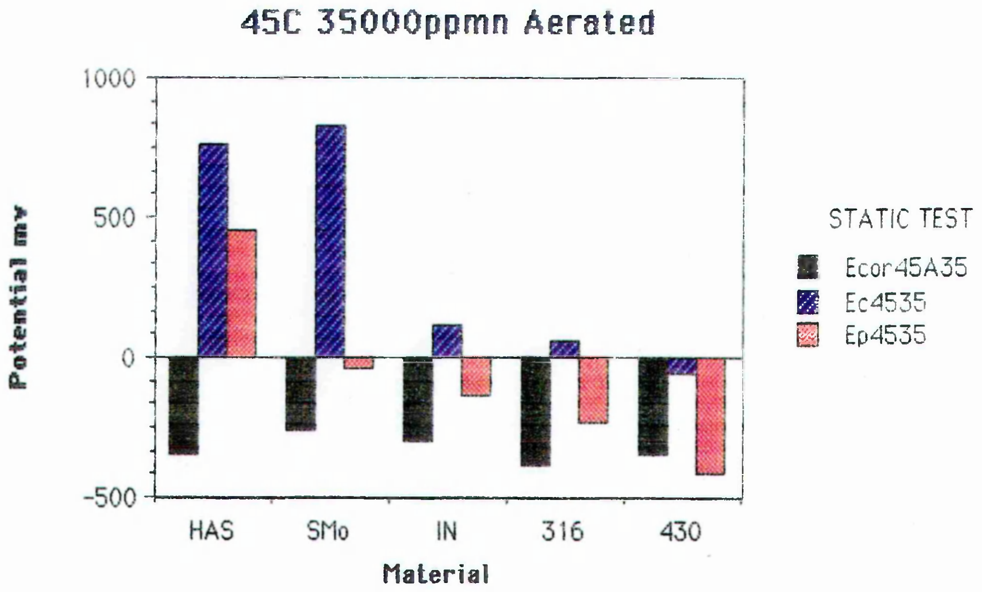


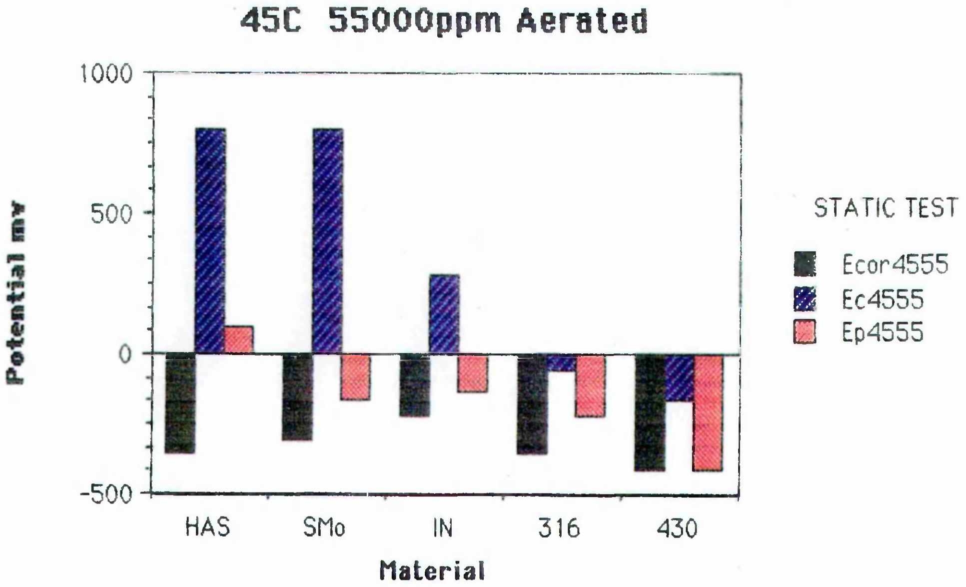

25C 35000ppm Aerated
1000
0
-1000
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor25A35
Ec25A35
Ep25A35
Note:
Ec >>> Ec(r)

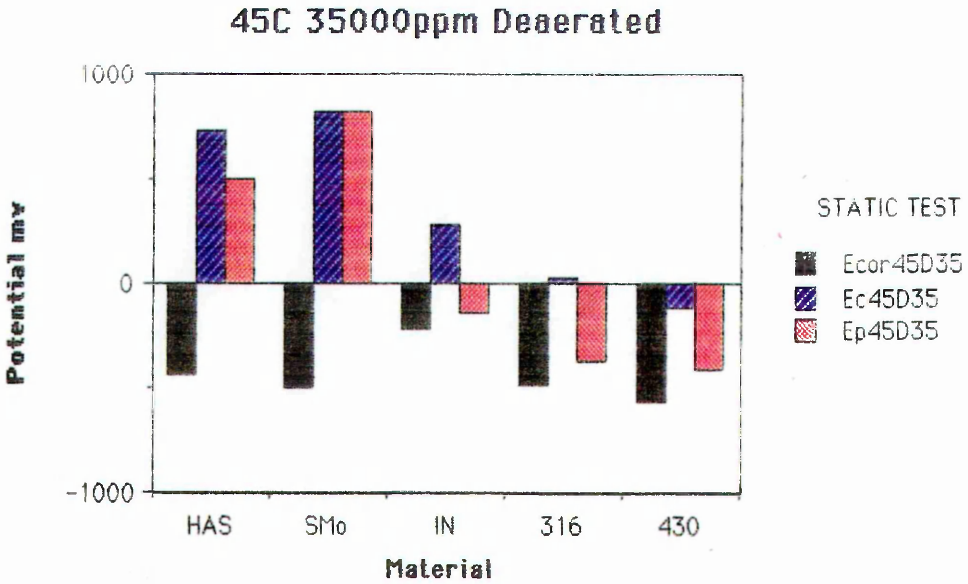

25C 55000ppm Aerated
1000
500
0
-500
Potential mv
HAS
SMo
IN
316
430
Material mv
STATIC TEST
Ecor25A55
Ec25A55
Ep25A55

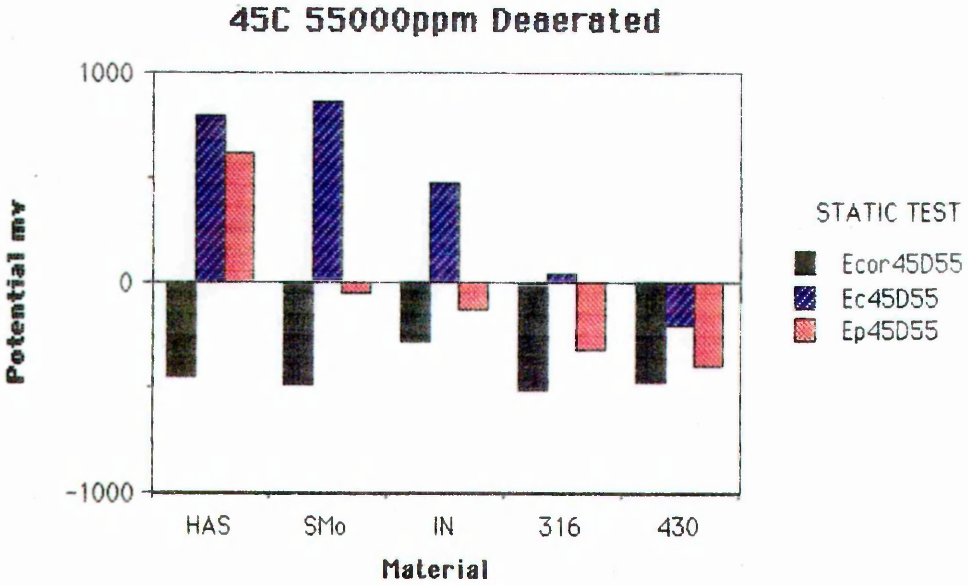

25C 35000ppm Deaerated
1000
0
-1000
Potential mv
HAS
SMo
IN
316
430
Material
Static test
Ecor25D35
Ec25D35
Ep25D35

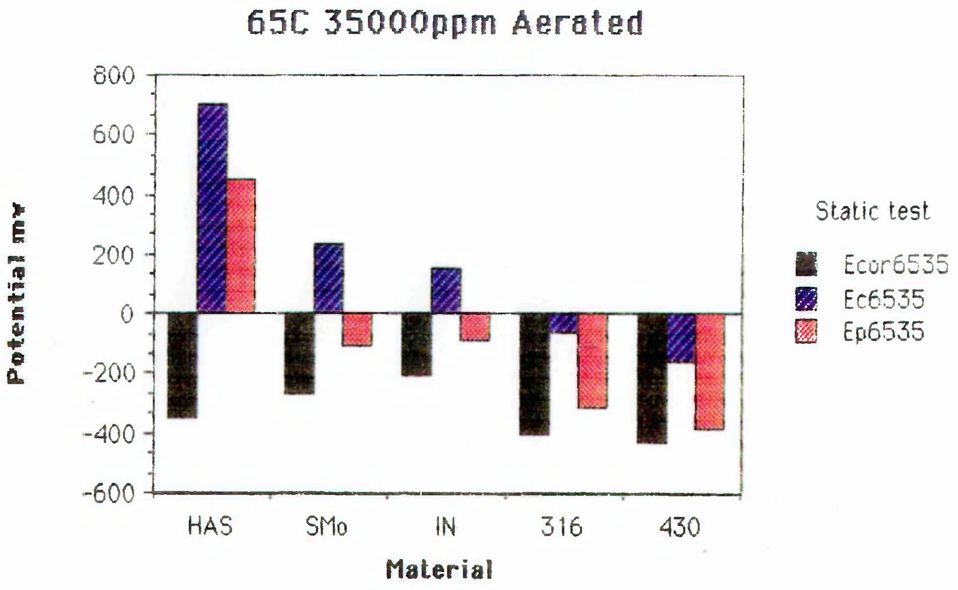

25C 55000ppm Deaerated
1000
0
-1000
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor25D55
Ec25D55
Ep25D55

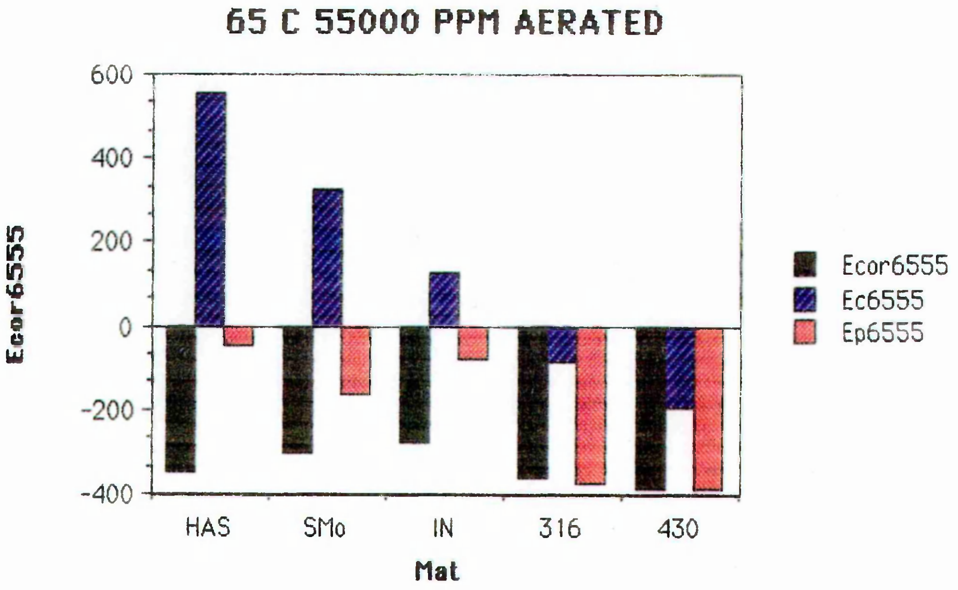

45C 35000ppmn Aerated
Potential mv
1000
500
0
-500
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor45A35
Ec4535
Ep4535

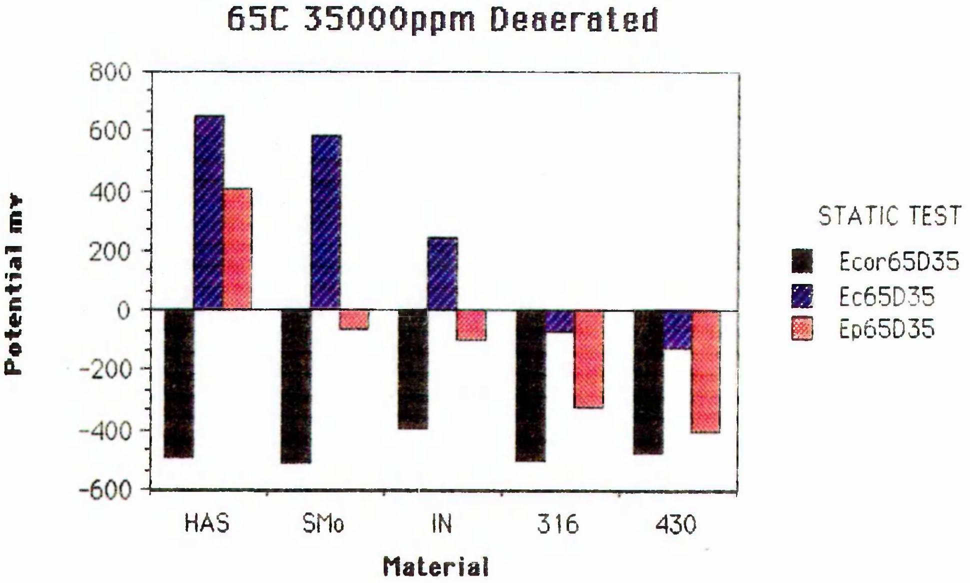

45C 55000ppm Aerated
Potential mv
1000
500
0
-500
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor4555
Ec4555
Ep4555

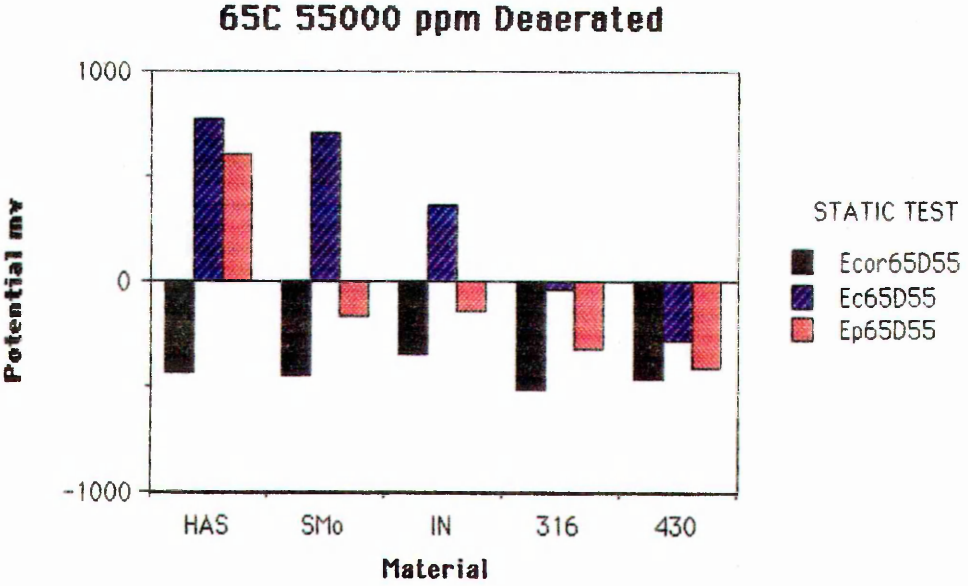

45C 35000ppm Deaerated
1000
0
-1000
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor45D35
Ec45D35
Ep45D35

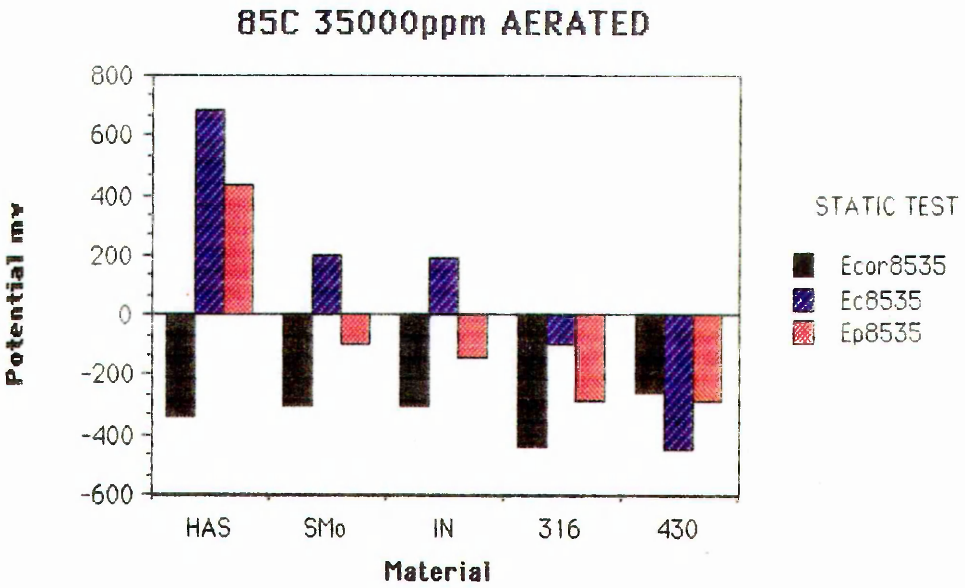

45C 55000ppm Deaerated
1000
0
-1000
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor45D55
Ec45D55
Ep45D55

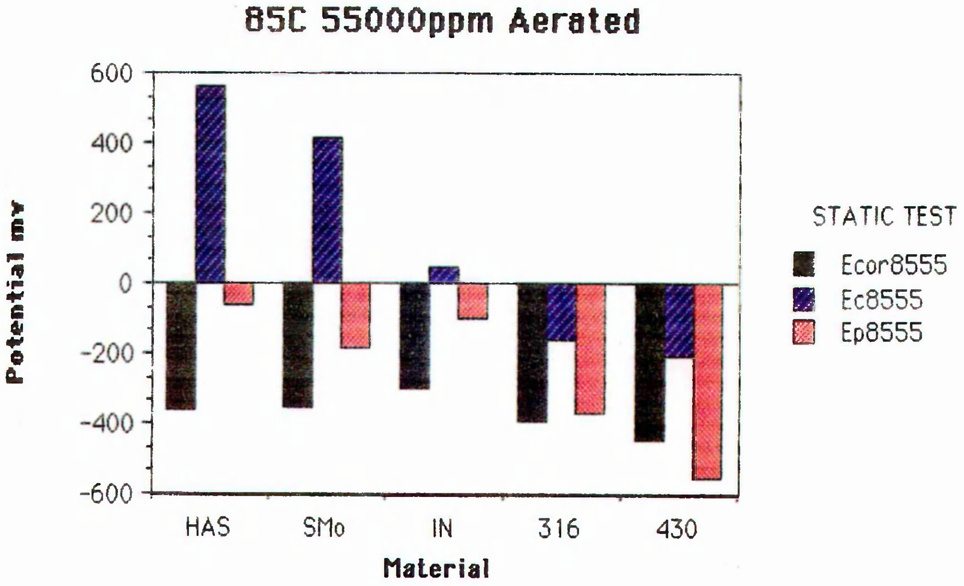

65C 35000ppm Aerated
Potential mv
800
600
400
200
0
-200
-400
-600
HAS
SMo
IN
316
430
Material
Static test
Ecor6535
Ec6535
Ep6535

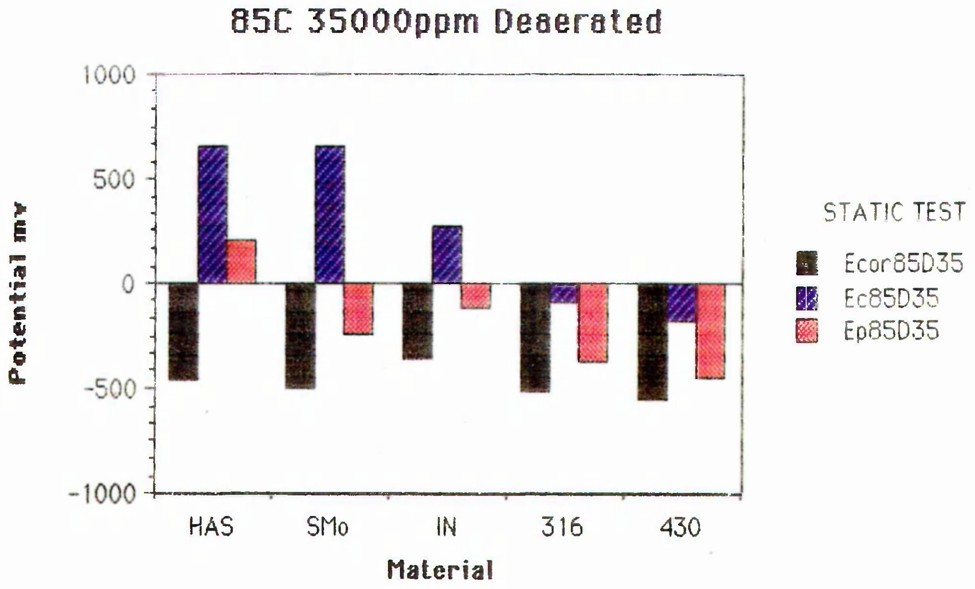

65 C 55000 PPM AERATED
Ecor6555
600
400
200
0
-200
-400
HAS
SMo
IN
316
430
Mat
Ecor6555
Ec6555
Ep6555

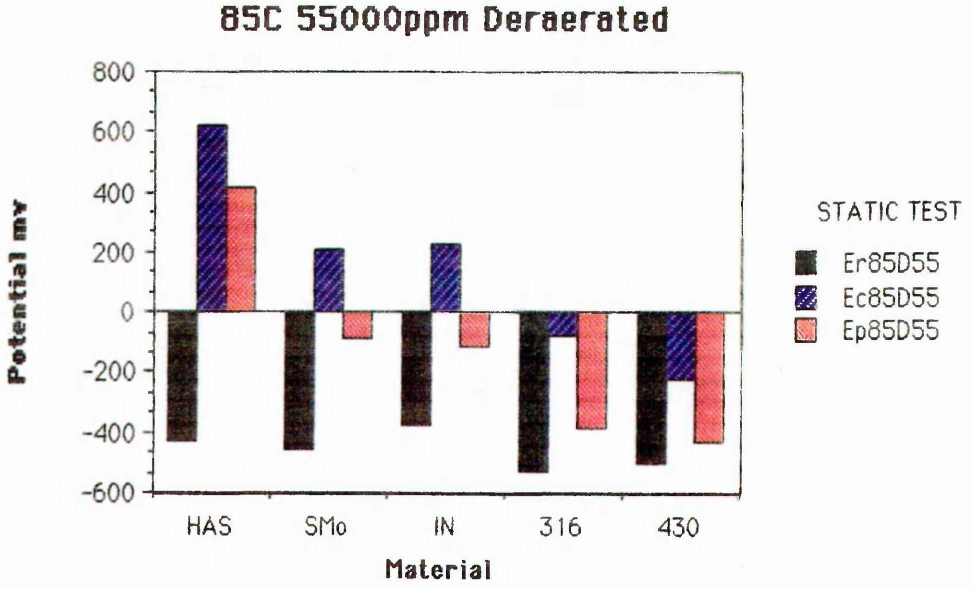

65C 35000ppm Deaerated
800
600
400
200
0
-200
-400
-600
Potential mV
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor65D35
Ec65D35
Ep65D35

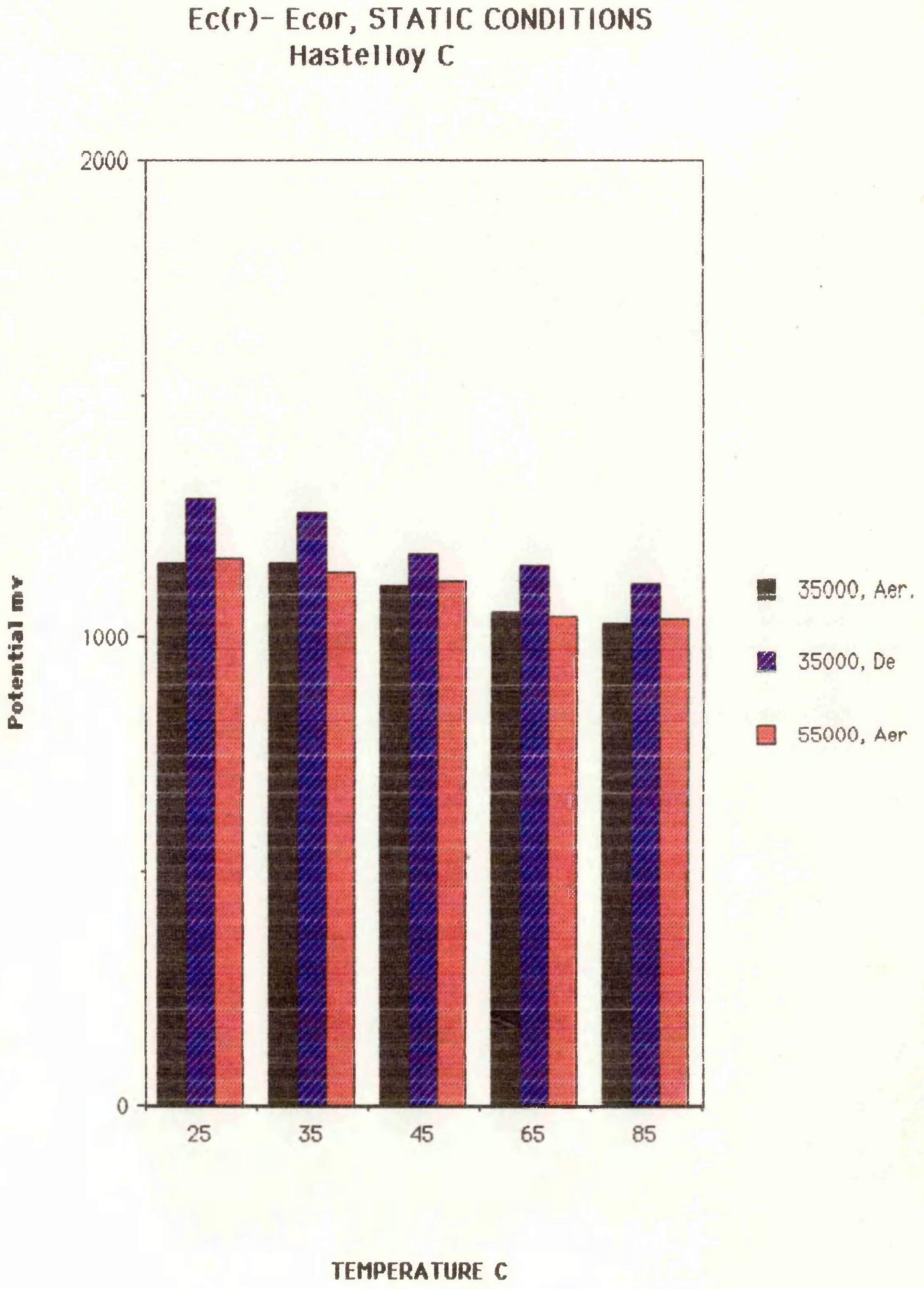

65C 55000 ppm Deaerated
1000
0
-1000
Potential mV
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor65D55
Ec65D55
Ep65D55

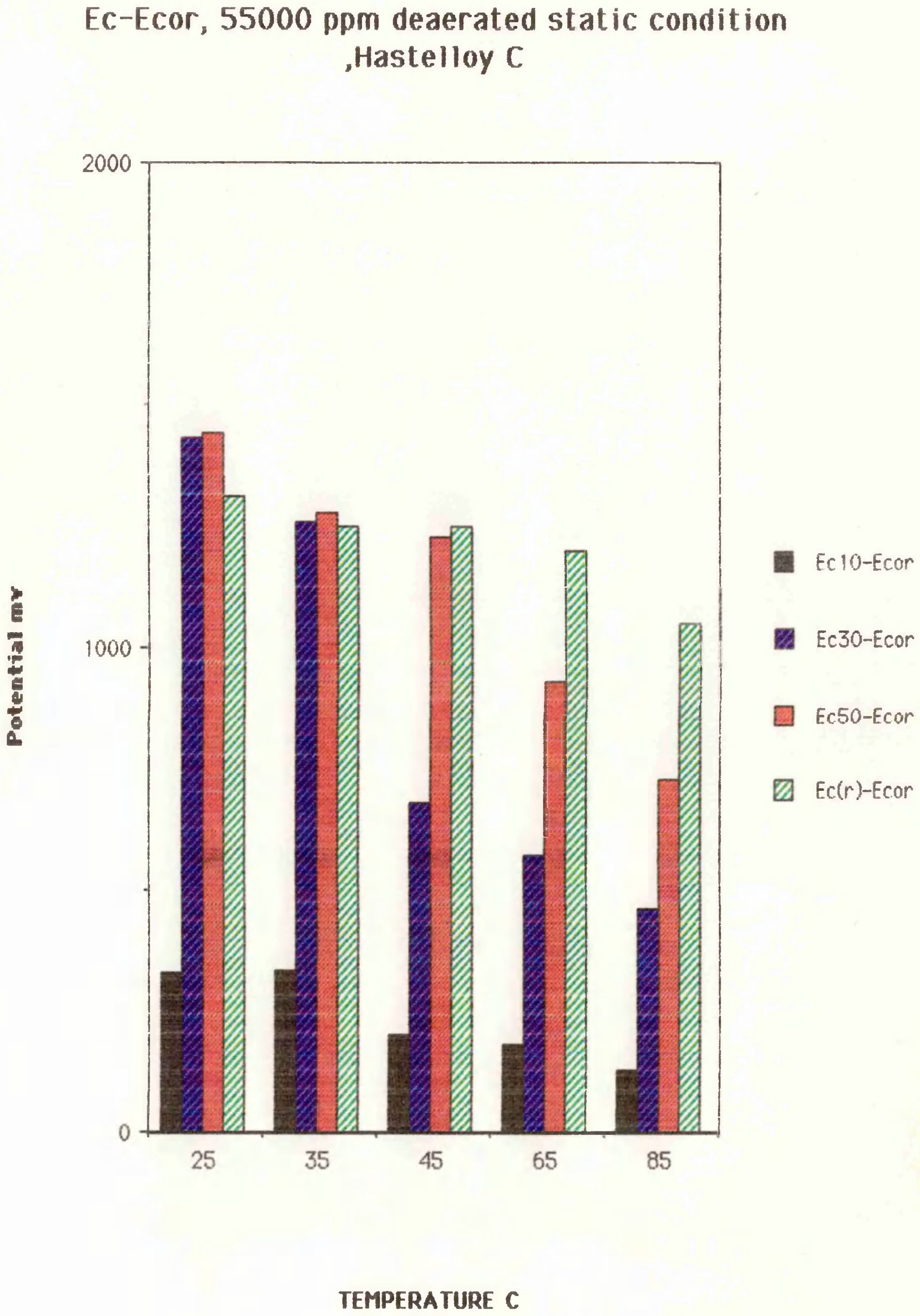

85C 35000ppm AERATED
Potential mv
800
600
400
200
0
-200
-400
-600
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor8535
Ec8535
Ep8535

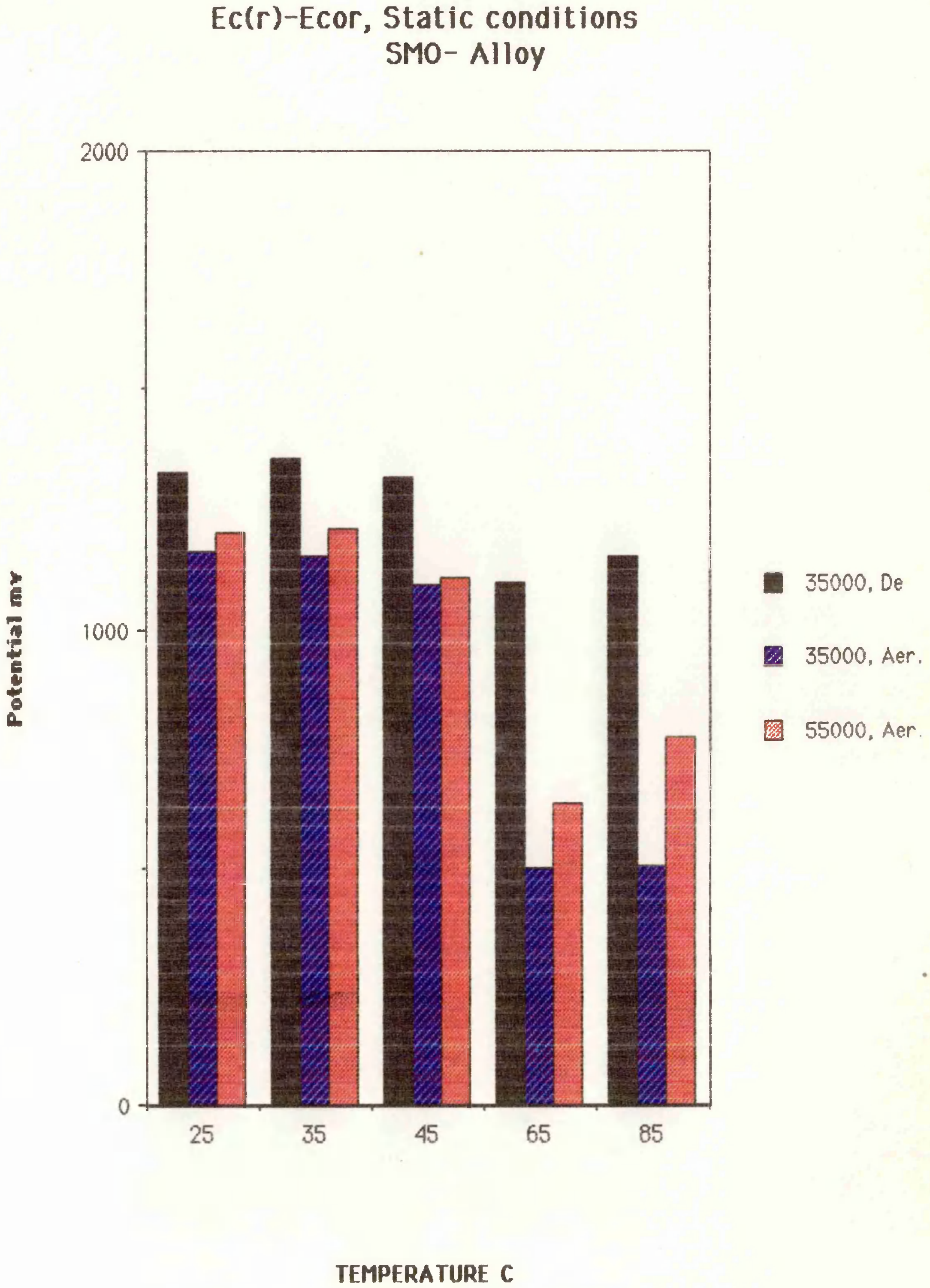

85C 55000ppm Aerated
Potential mv
600
400
200
0
-200
-400
-600
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor8555
Ec8555
Ep8555

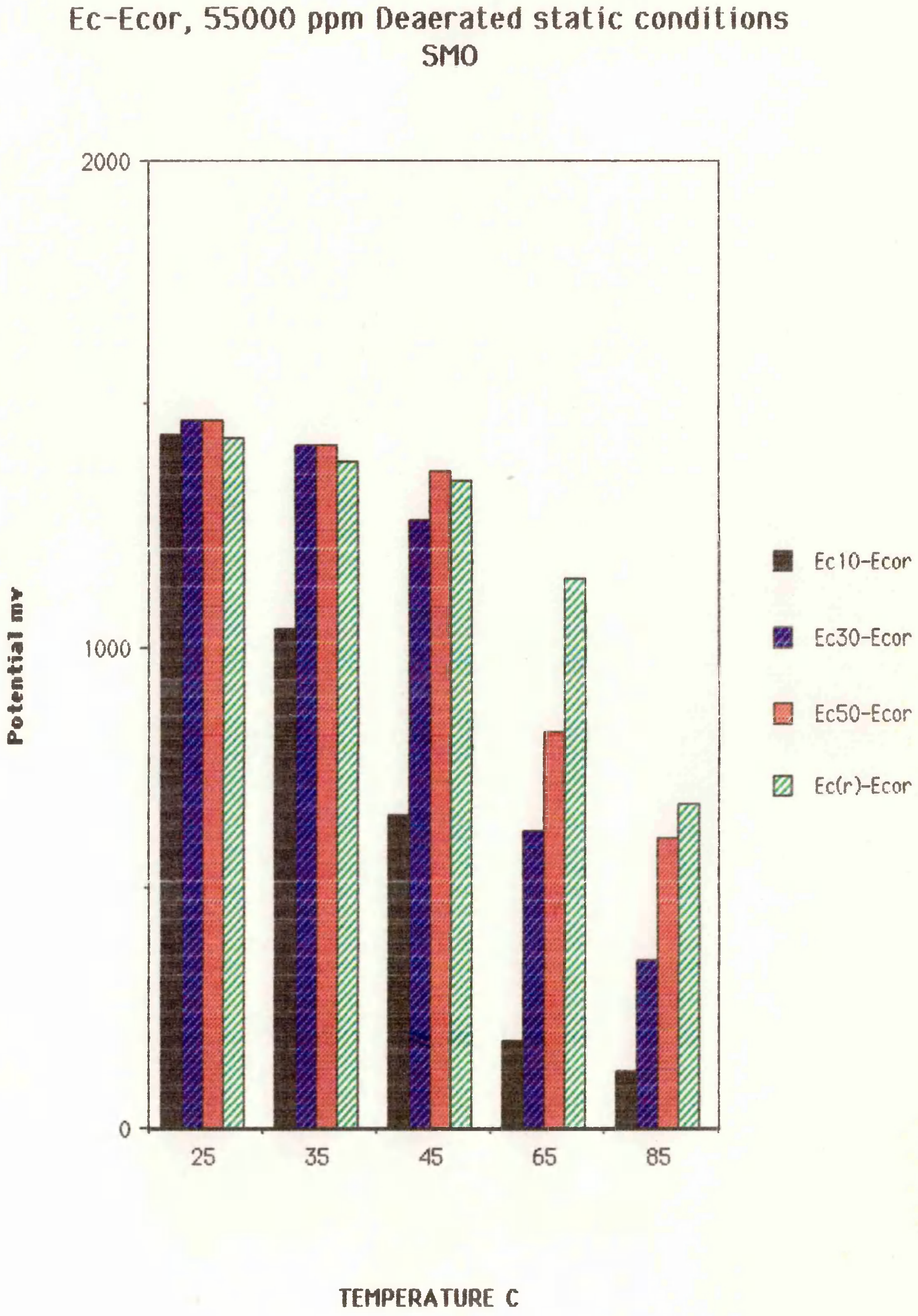

85C 35000ppm Deaerated
1000
500
0
-500
-1000
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Ecor85D35
Ec85D35
Ep85D35

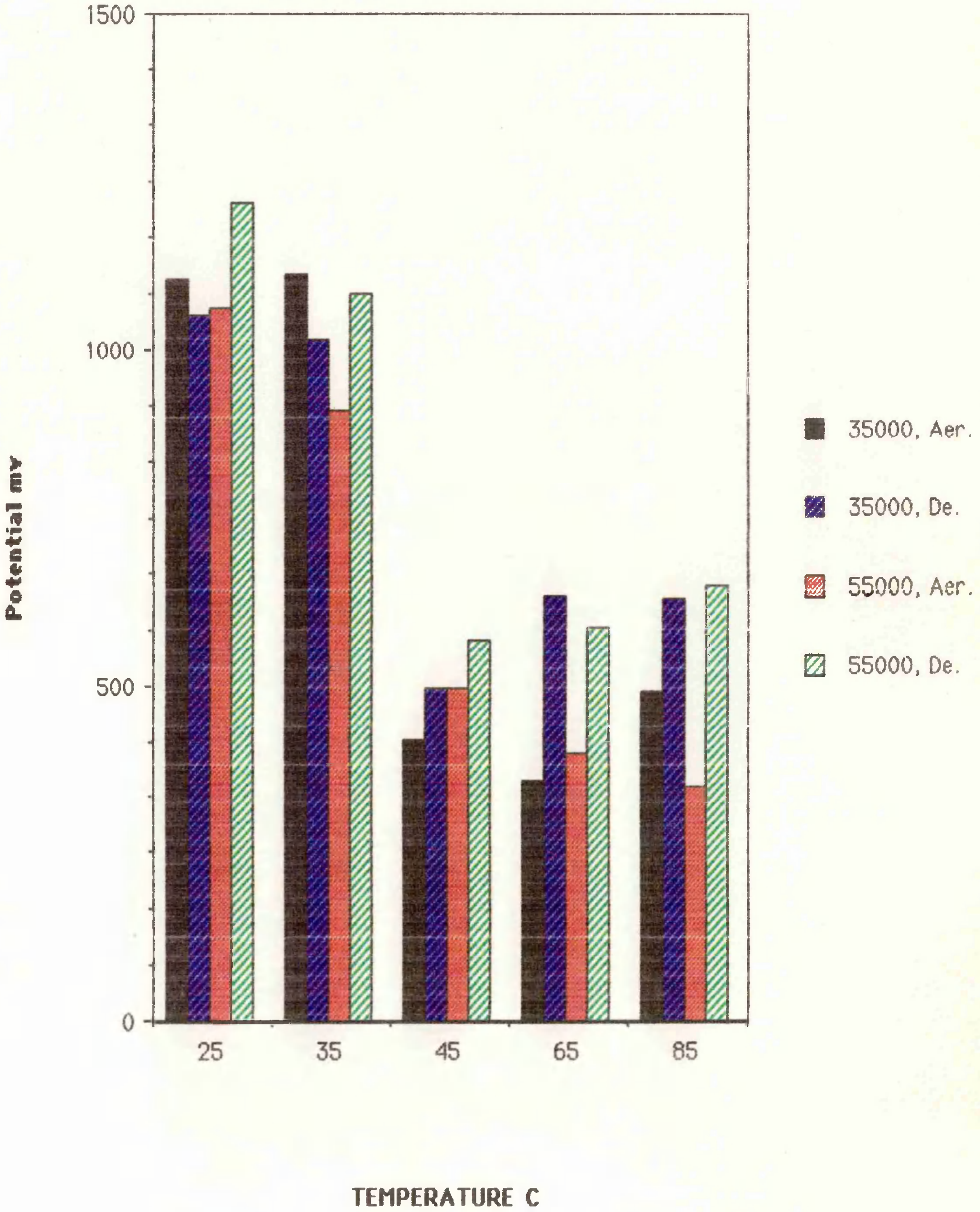

85C 55000ppm Deraerated
800
600
400
200
0
-200
-400
-600
Potential mv
HAS
SMo
IN
316
430
Material
STATIC TEST
Er85D55
Ec85D55
Ep85D55


Ec(r)- Ecor, STATIC CONDITIONS
Hastelloy C
Potential mV
2000
1000
0
25
35
45
65
85
TEMPERATURE C
35000, Aer.
35000, De
55000, Aer

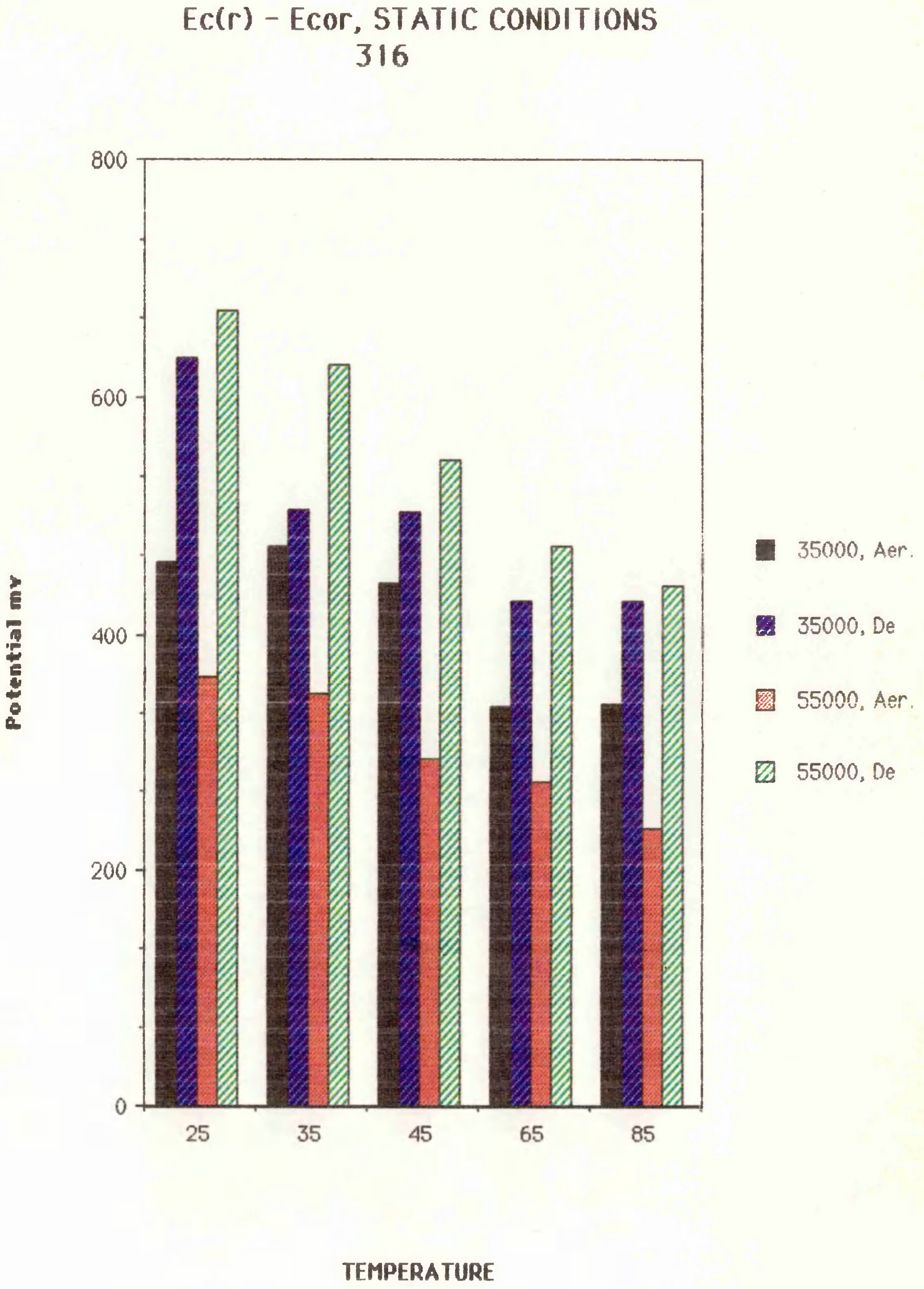

Ec-Ecor, 55000 ppm deaerated static condition ,Hastelloy C
2000
1000
0
Potential mv
25
35
45
65
85
TEMPERATURE C
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec(r)-Ecor, Static conditions
SMO- Alloy
2000
1000
0
Potential mv
25
35
45
65
85
35000, De
35000, Aer.
55000, Aer.
TEMPERATURE C

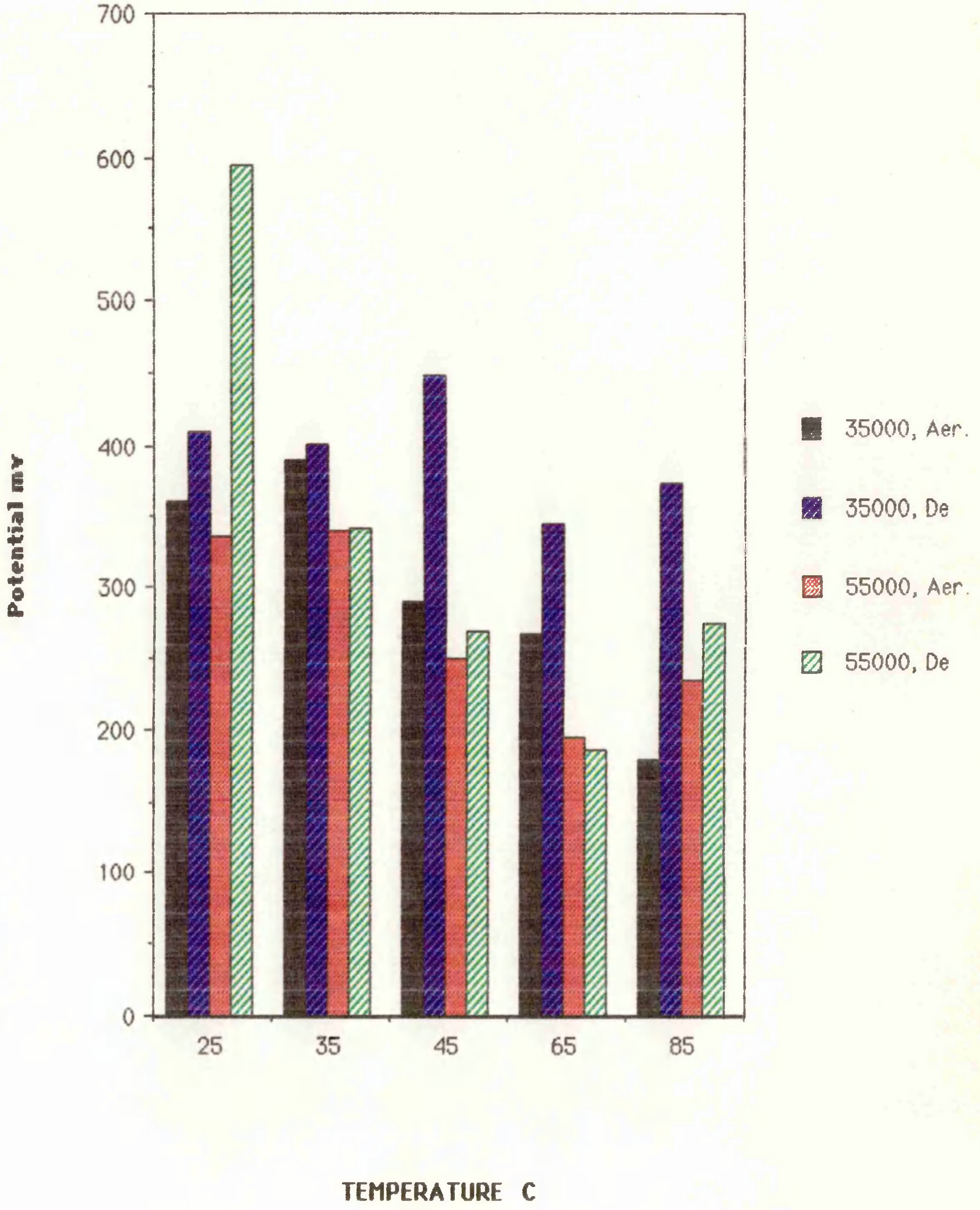

Ec-Ecor, 55000 ppm Deaerated static conditions
SMO
Potential mv
2000
1000
0
25
35
45
65
85
TEMPERATURE C
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor



Ec(r)- Ecor, STATIC CONDITIONS
IN-ALLOY


Ec(r) - Ecor, STATIC CONDITIONS
316
Potential mv
800
600
400
200
0
25
35
45
65
85
TEMPERATURE
35000, Aer.
35000, De
55000, Aer.
55000, De

Ec(r)- Ecor, STATIC CONDITIONS
430



LONG TERM IMMERSION TESTS RESULTS ANALYSIS

NOTATION:

35 >>>> 35000 PPM

55 >>>> 55000 PPM

D , De. >>>> Deaerated

A, Aer. >>>> Aerated

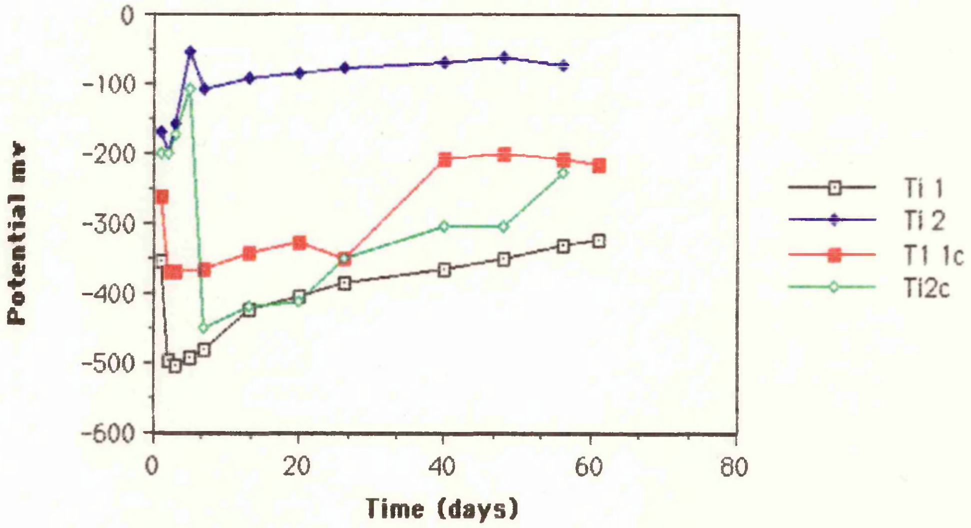
25 >>>> 25°C

45 >>>> 45°C

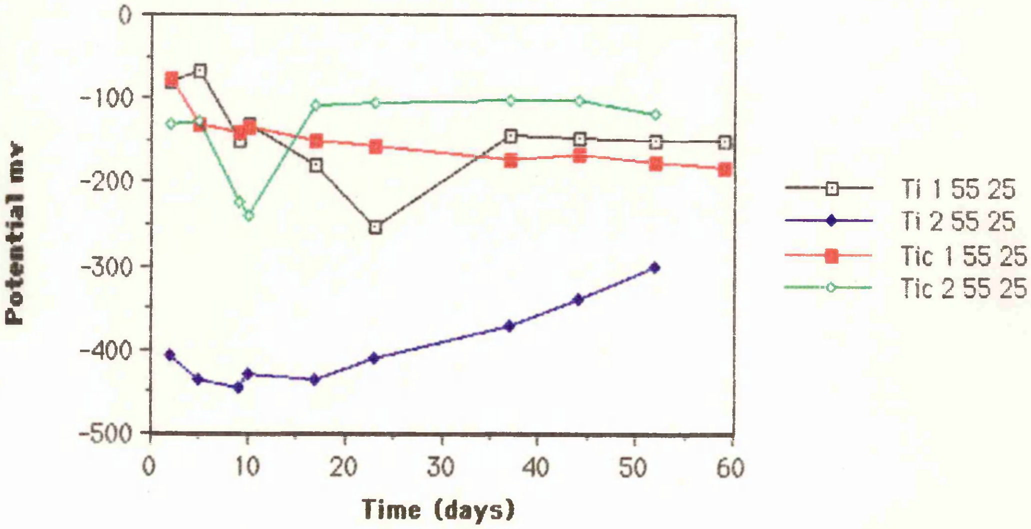
IN >>>> Plain specimen

INc >>>> Creviced Specimen

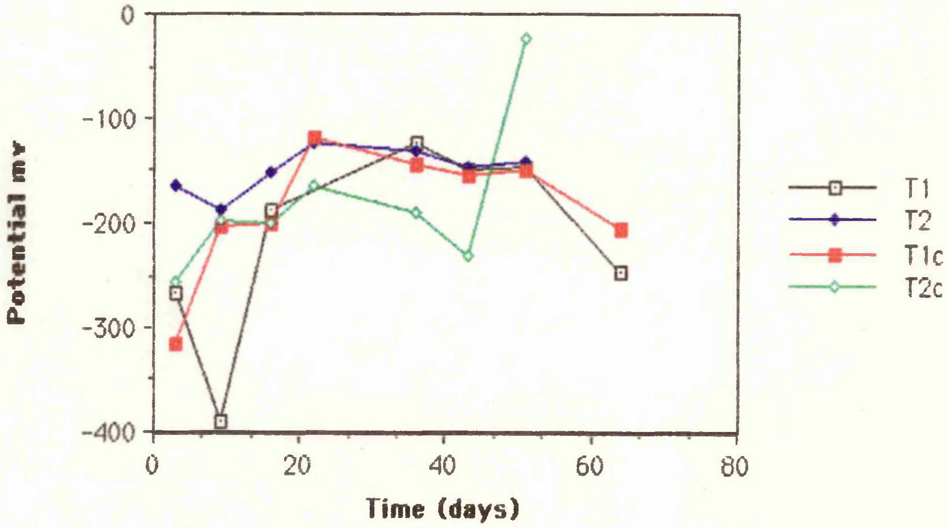
Ecor of Ti under 25 C, 35000 Aerated condition



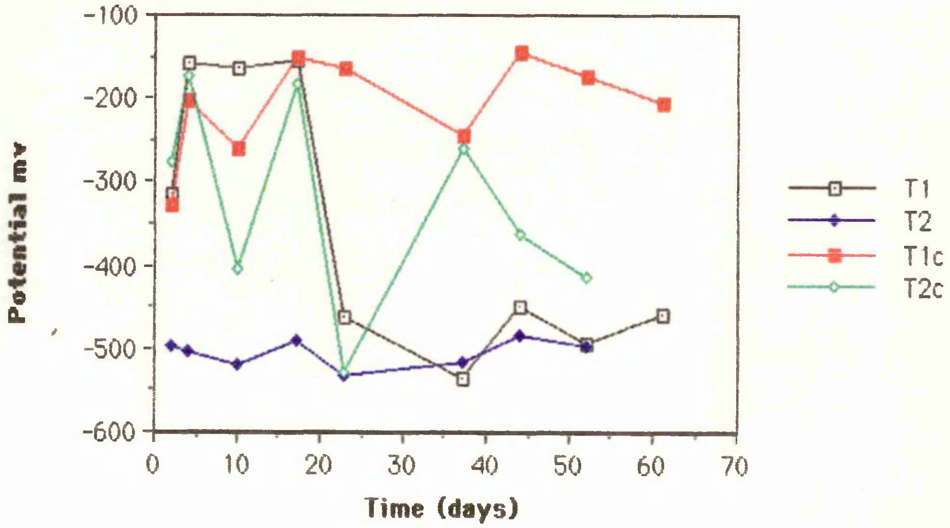
Ecor of Ti under 25 C 55000 ppm Aerated condition

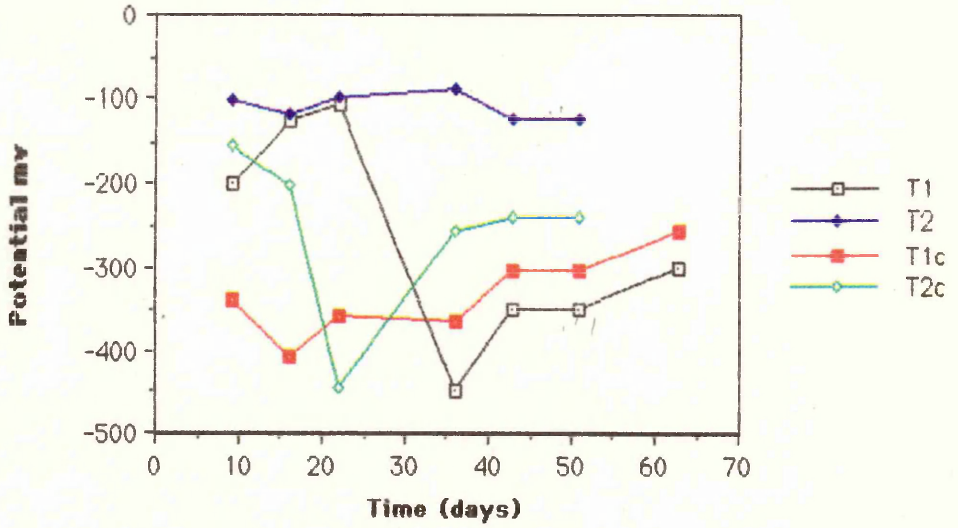


Ecor of Ti under 25C 35000 ppm Deaerated condition

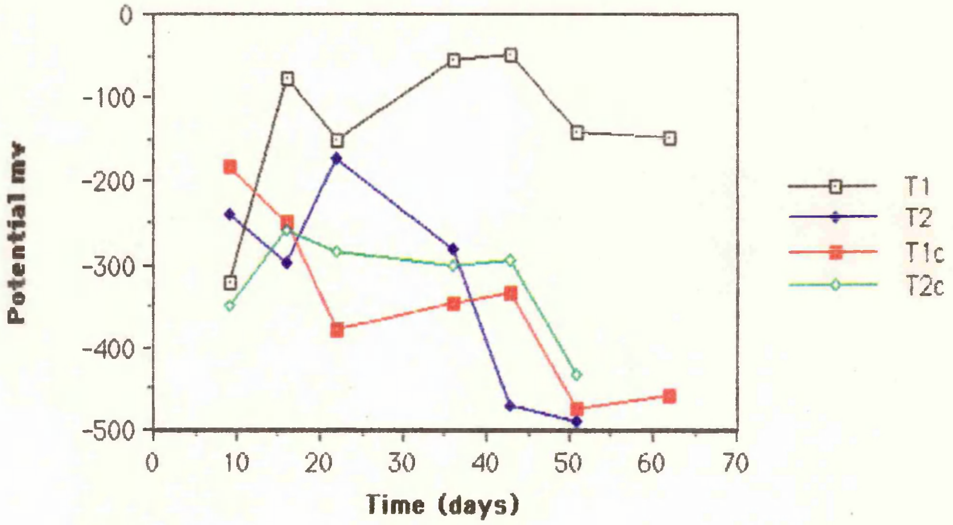


Ecor of Ti under 25C 55000 ppm Deaerated condition

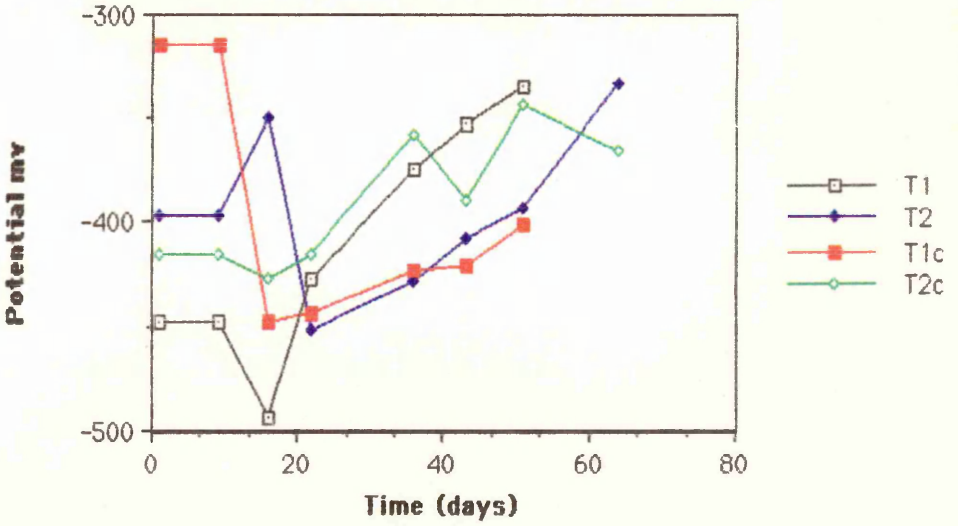




Ecor of Ti under 45C 35000 ppm Aeration condition

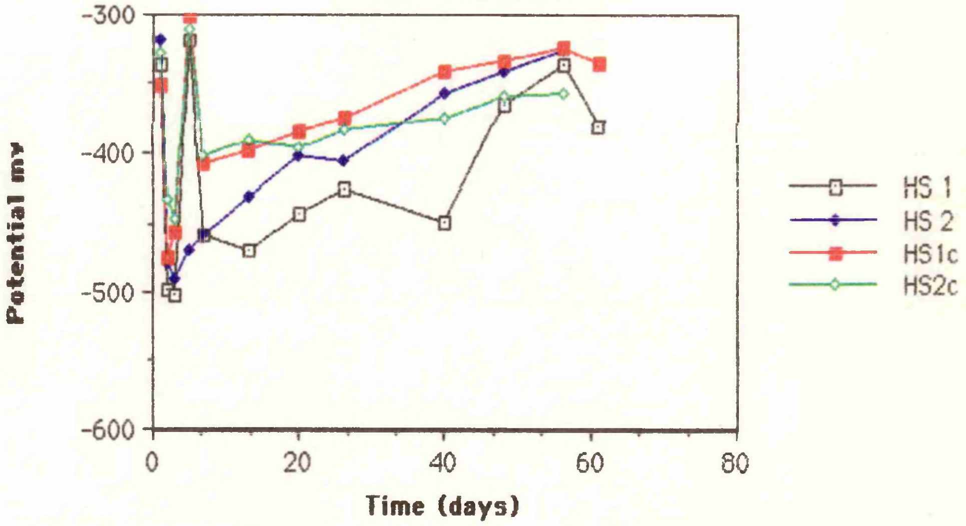


Ecor of Ti under 45C, 55000 ppm, Aerated condition

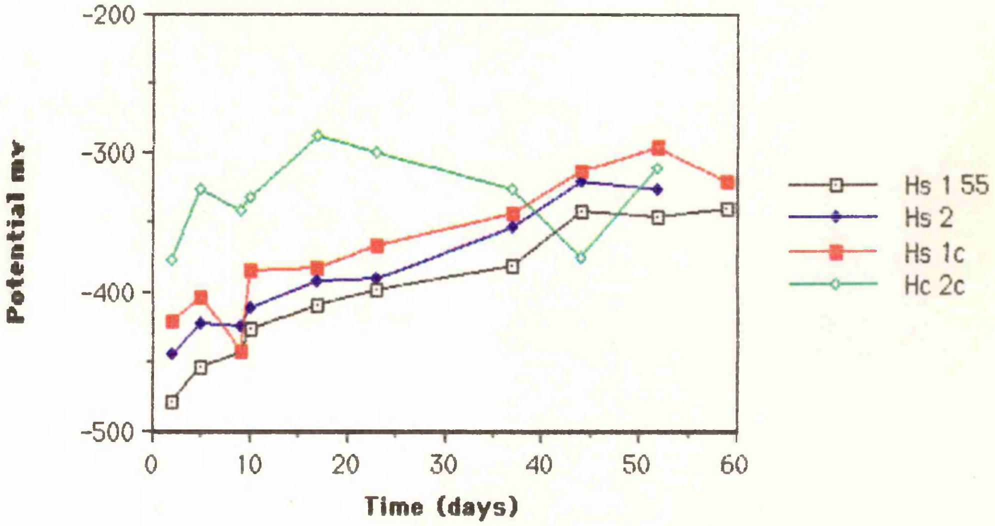


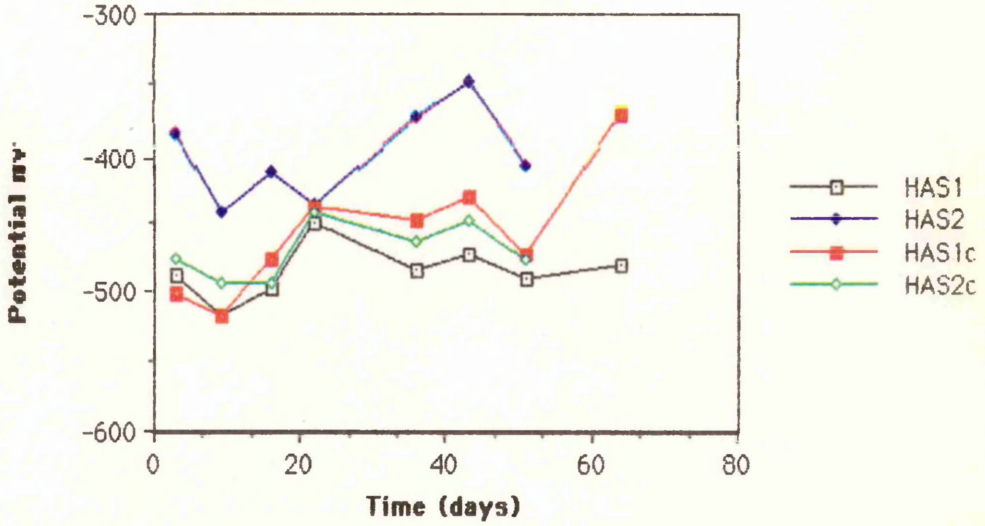
Ecor of Ti under 45C, 35000 ppm, Deaerated condition

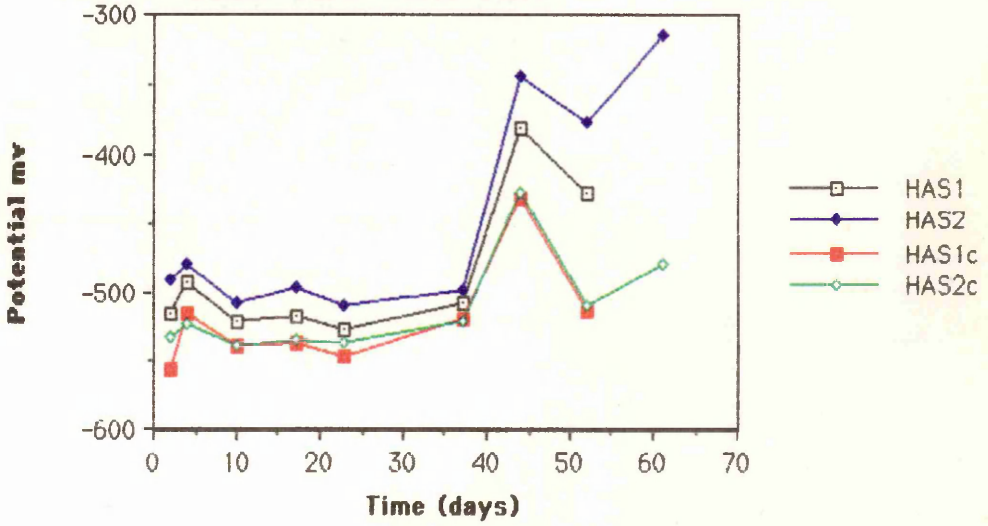
Ecor of Hastelloy C under 25 C,35000ppm
Aerated condition



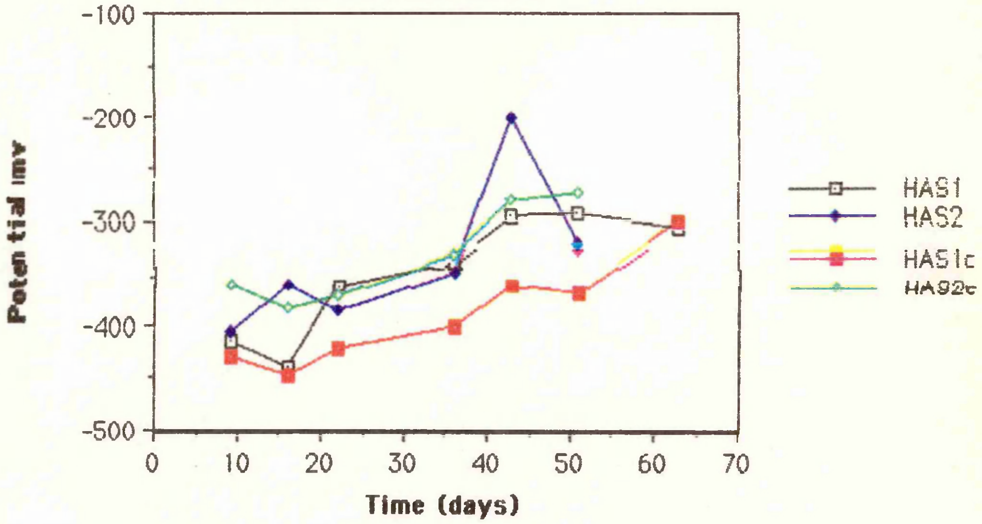
Ecor of Hastelloy C under 25C, 55000 ppm,
Aerated condition



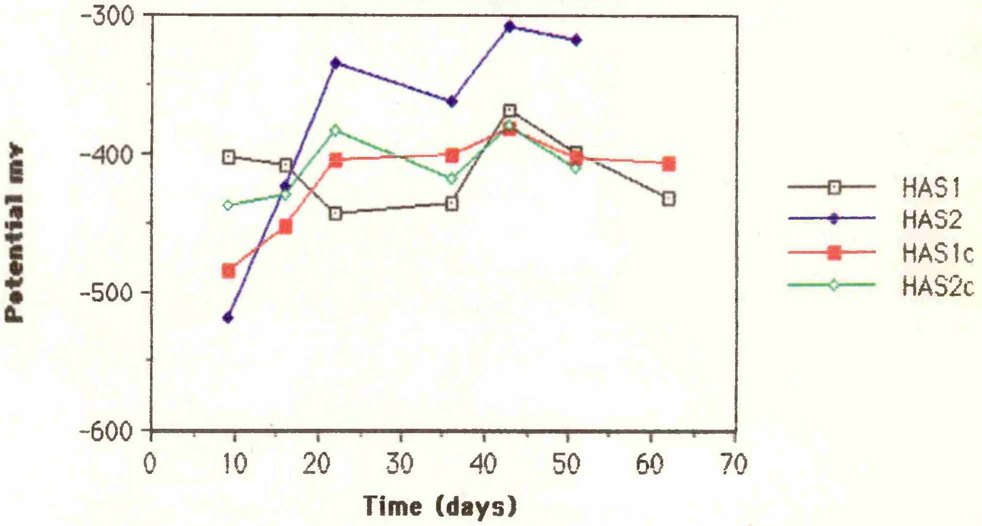

Ecor of Hastelloy C under 25 C, 35000ppm, Deaerated condition


Ecor of Hastelloy C under 25C, 55000ppm, Deaerated condition

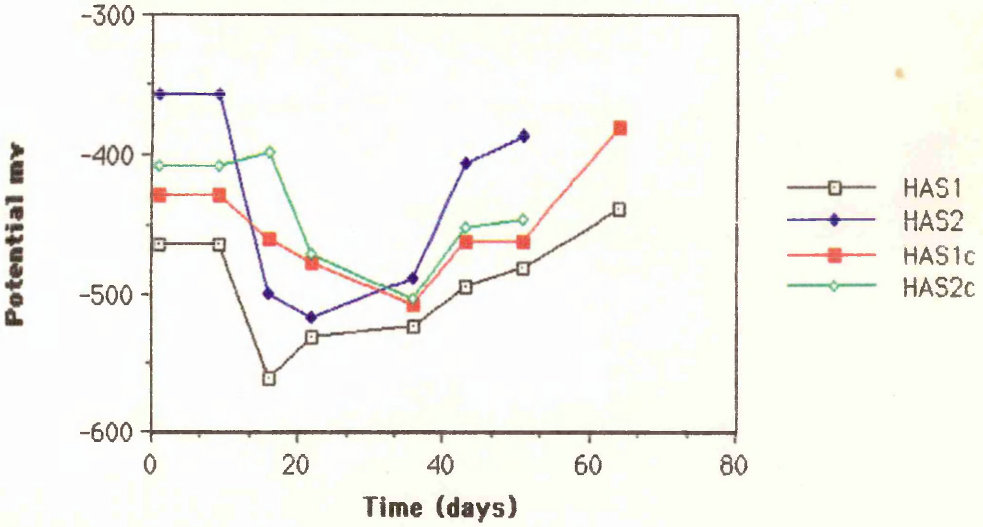
Ecor of Hastelloy C under 45C, 35000 pmm, Aerated condition



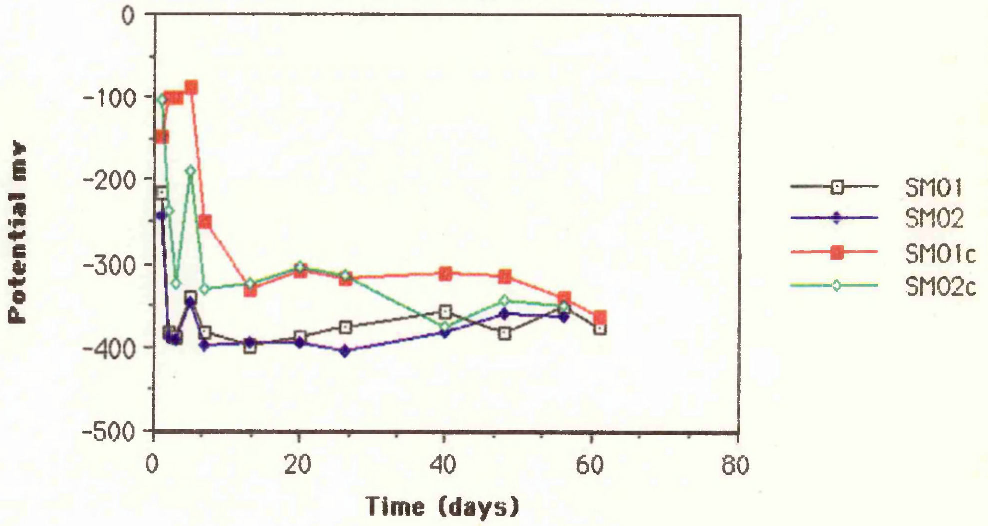
Ecor Hastelloy C under 45C, 55000 ppm, Aerated condition



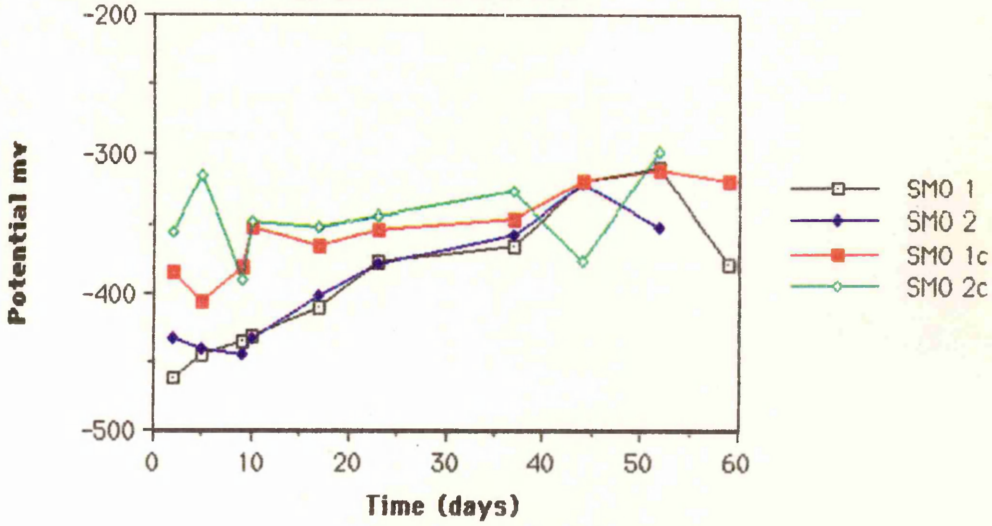
Ecor of Hastelloy C under 45C, 35000 ppm, Deaerated condition

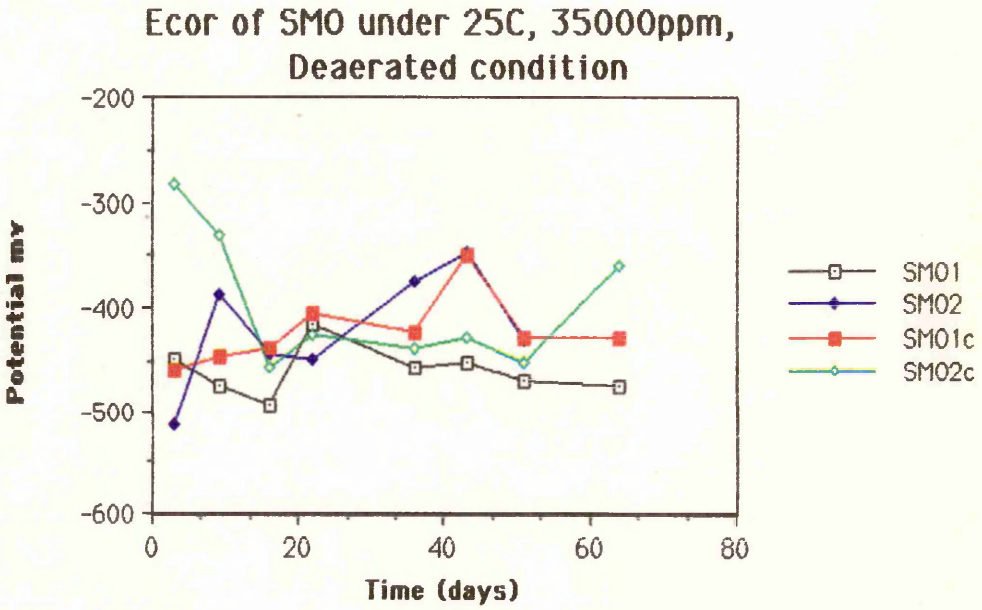


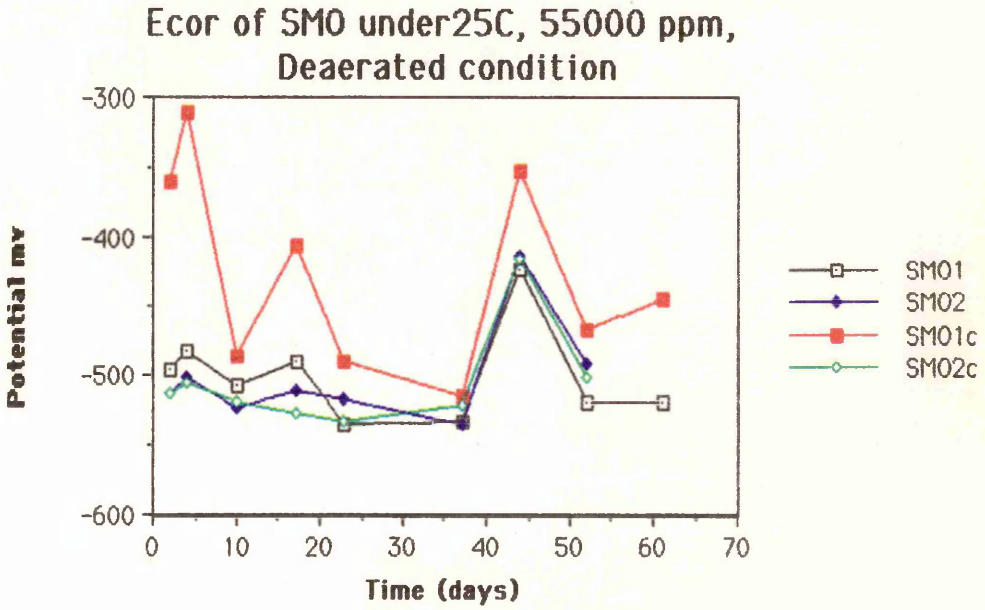
ECOR OF SMO under 25 C, 35000 PPM, Aerated condition



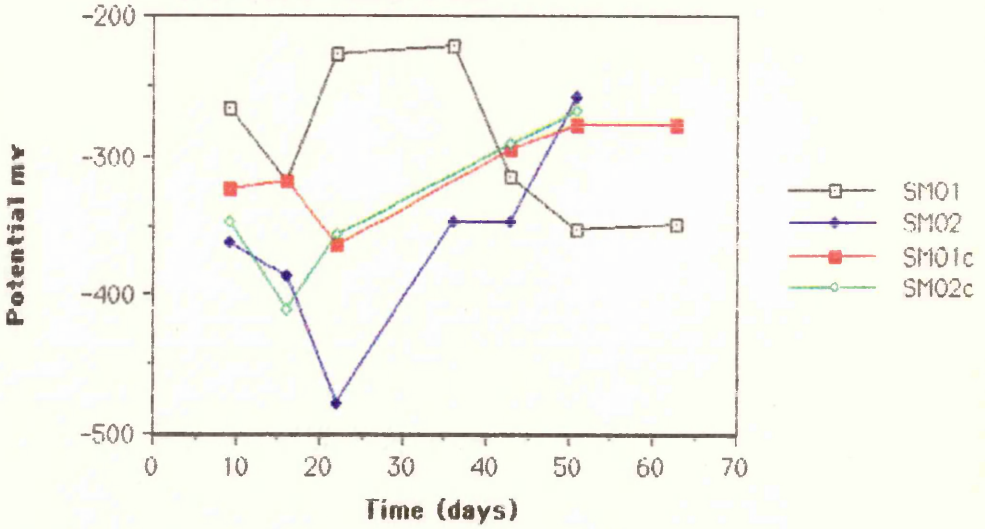
Ecor of SMO under 25C, 55000 ppm, Aerated condition



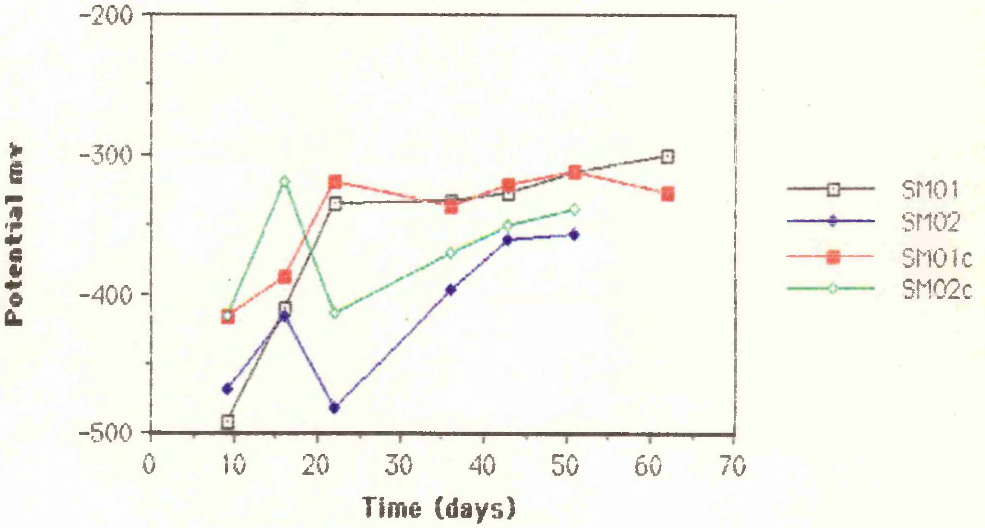

Ecor of SMO under 25C, 35000ppm,
Deaerated condition
Potential mv
-200
-300
-400
-500
-600
0
20
40
60
80
Time (days)
SM01
SM02
SM01c
SM02c


Ecor of SMO under25C, 55000 ppm,
Deaerated condition
Potential mv
-300
-400
-500
-600
0
10
20
30
40
50
60
70
Time (days)
SM01
SM02
SM01c
SM02c

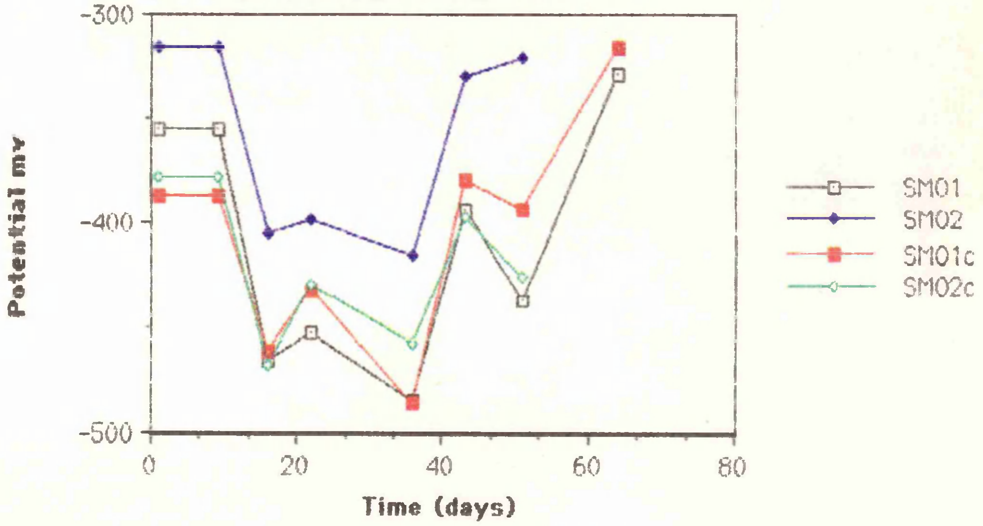
Ecor of SMO under 45 C, 35000ppm
Aerated condition

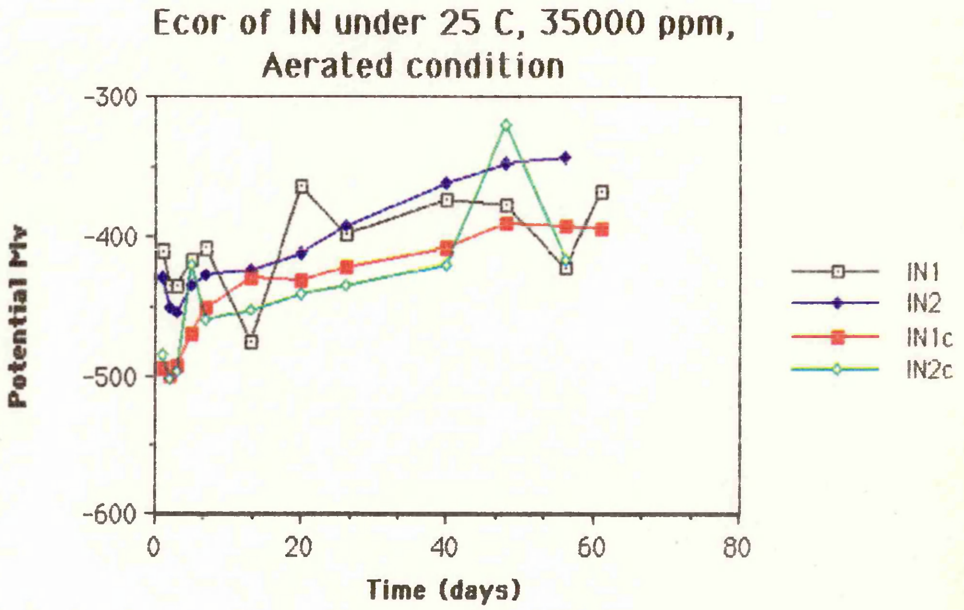


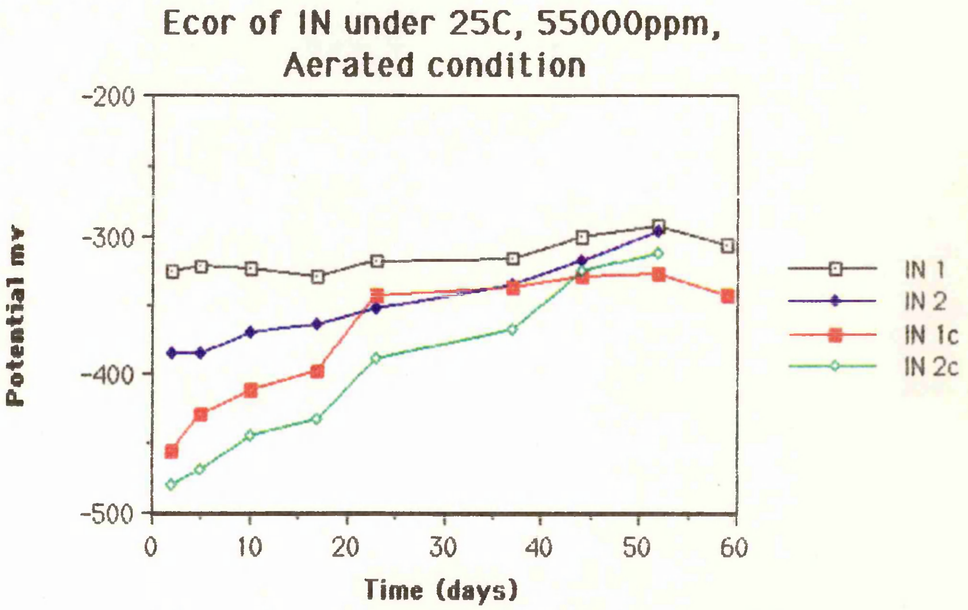
Ecor of SMO under 45C, 55000 PPM,
Aerated condition



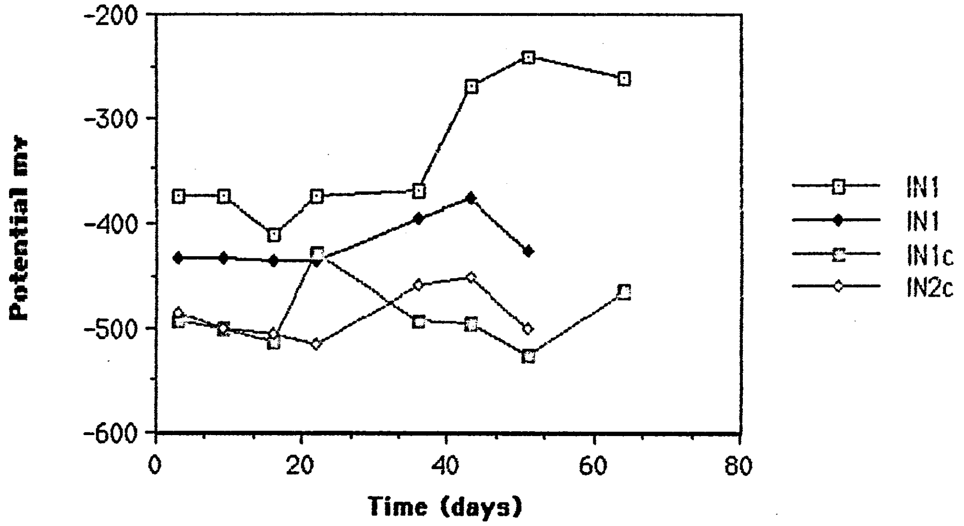
Ecor of SMO under45 C, 35000 ppm,
Deaerated condition



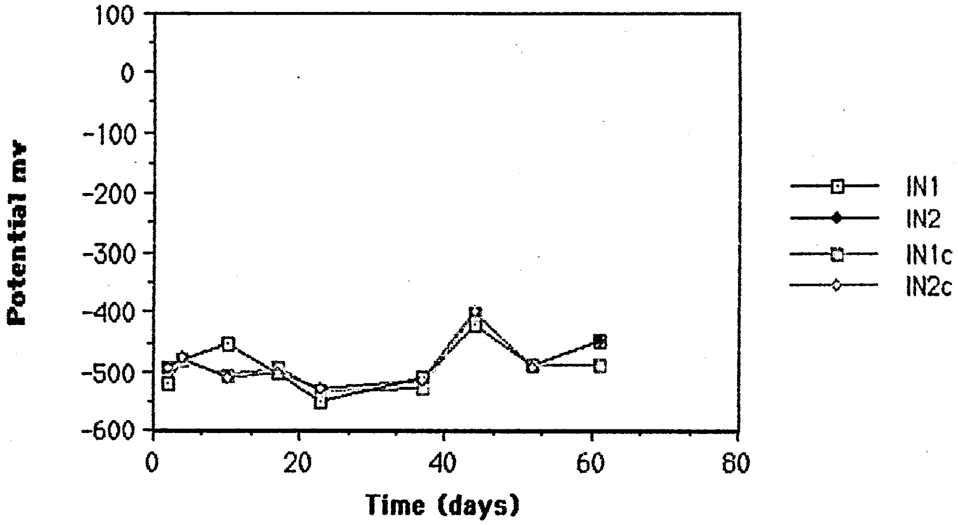

Ecor of IN under 25 C, 35000 ppm, Aerated condition
Potential Mv
-300
-400
-500
-600
0
20
40
60
80
Time (days)
IN1
IN2
IN1c
IN2c

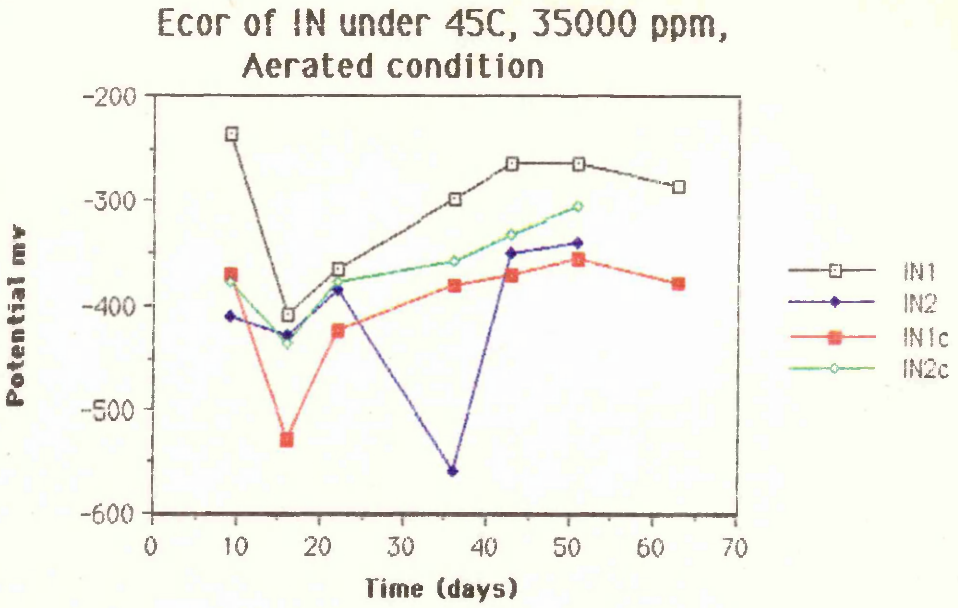

Ecor of IN under 25C, 55000ppm, Aerated condition
Potential mv
-200
-300
-400
-500
0
10
20
30
40
50
60
Time (days)
IN 1
IN 2
IN 1c
IN 2c

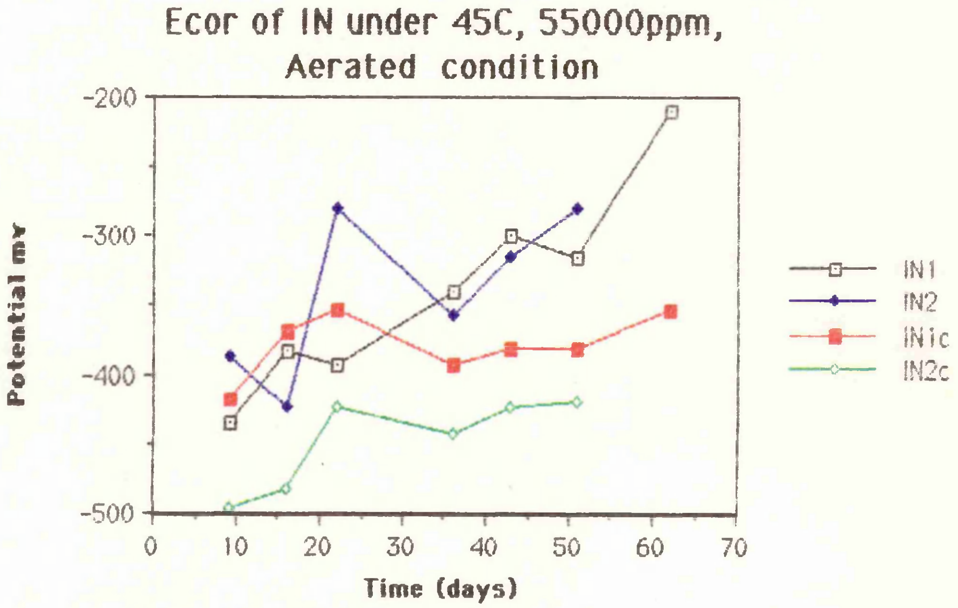
Ecor of IN under 25C, 35000 ppm, Deaerated condition

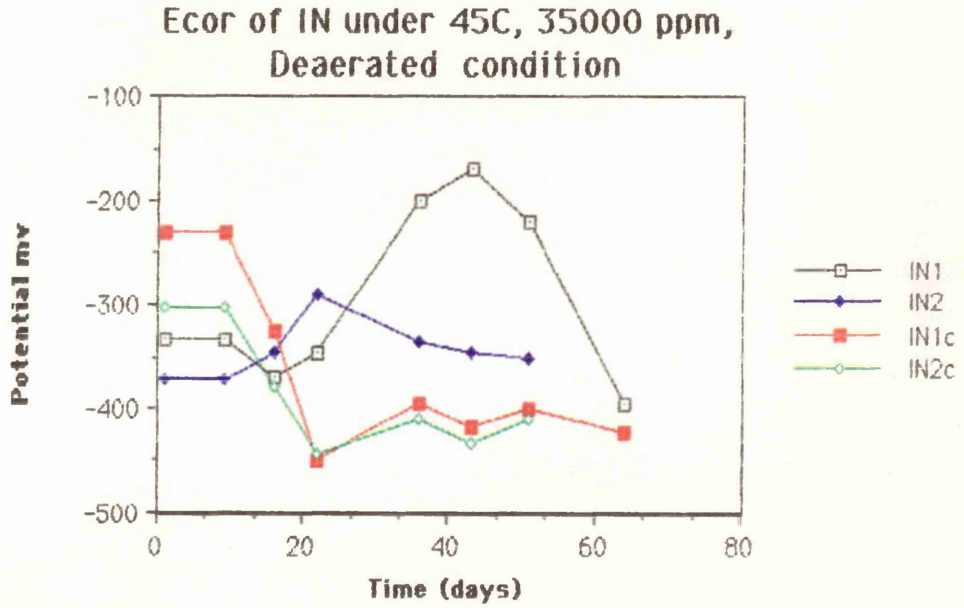


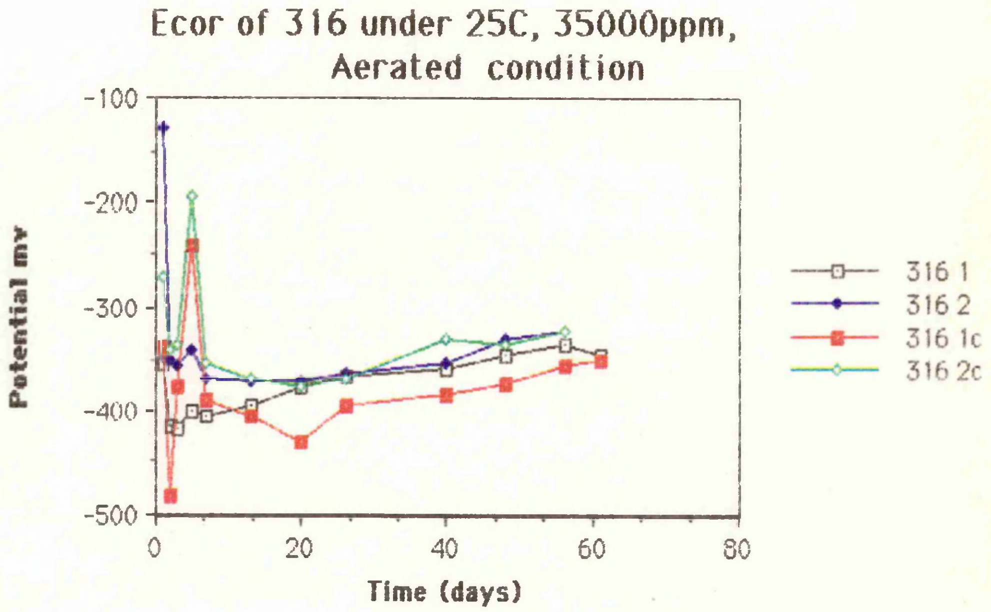
Ecor of IN under 25C, 55000 ppm, Deaerated condition

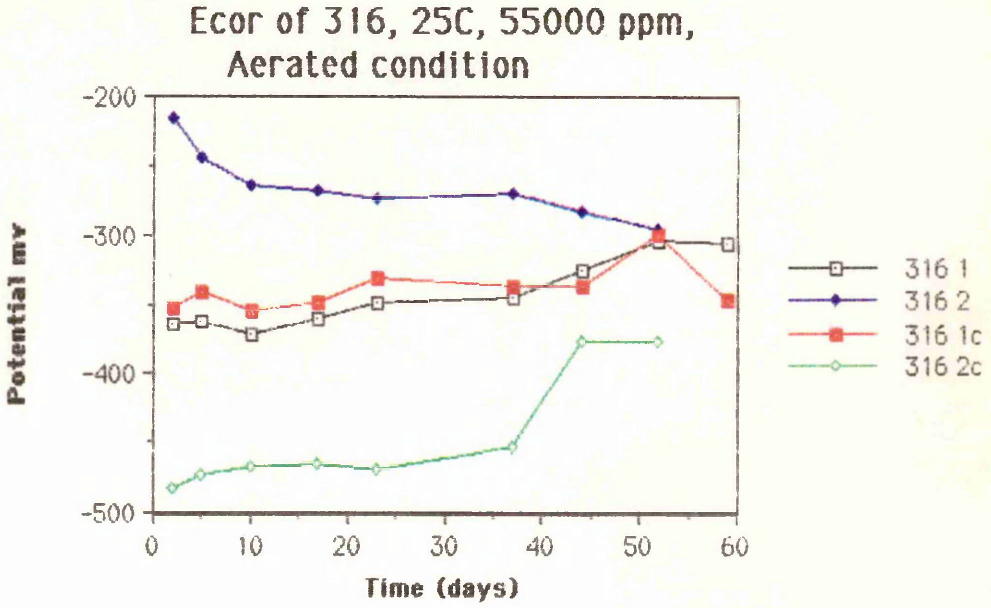


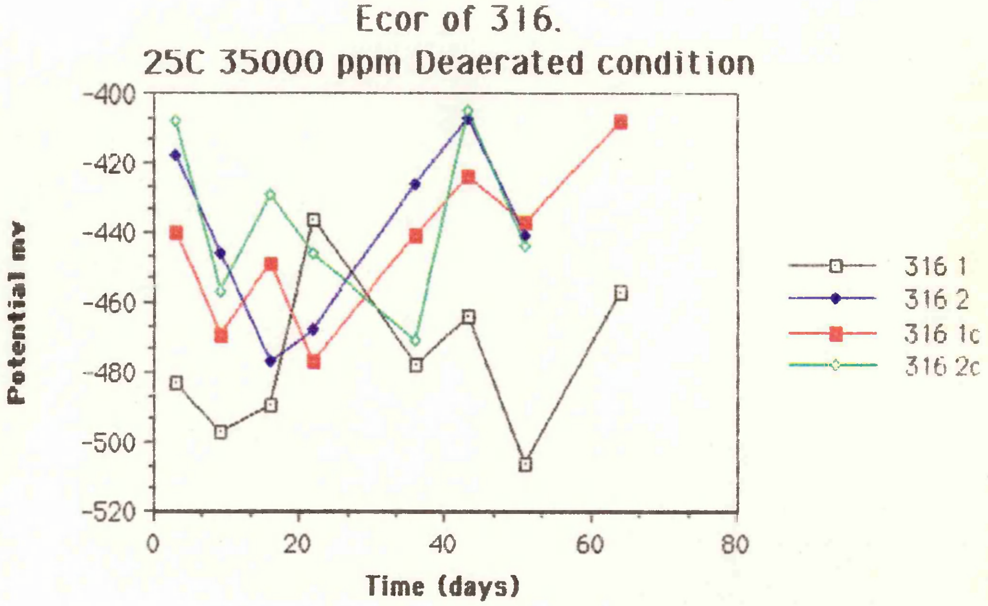

Ecor of IN under 45C, 35000 ppm, Aerated condition

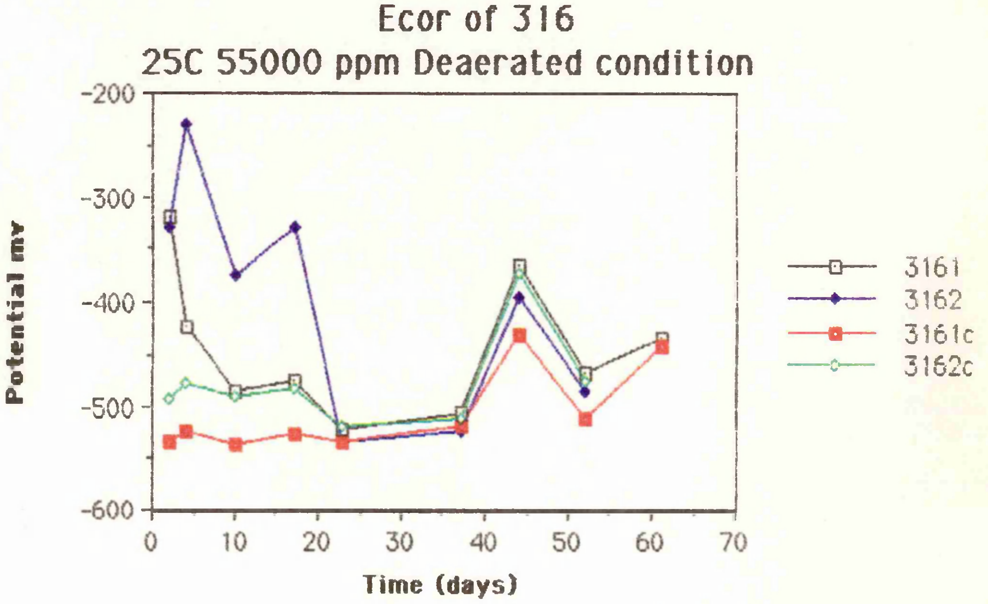

Ecor of IN under 45C, 55000ppm, Aerated condition

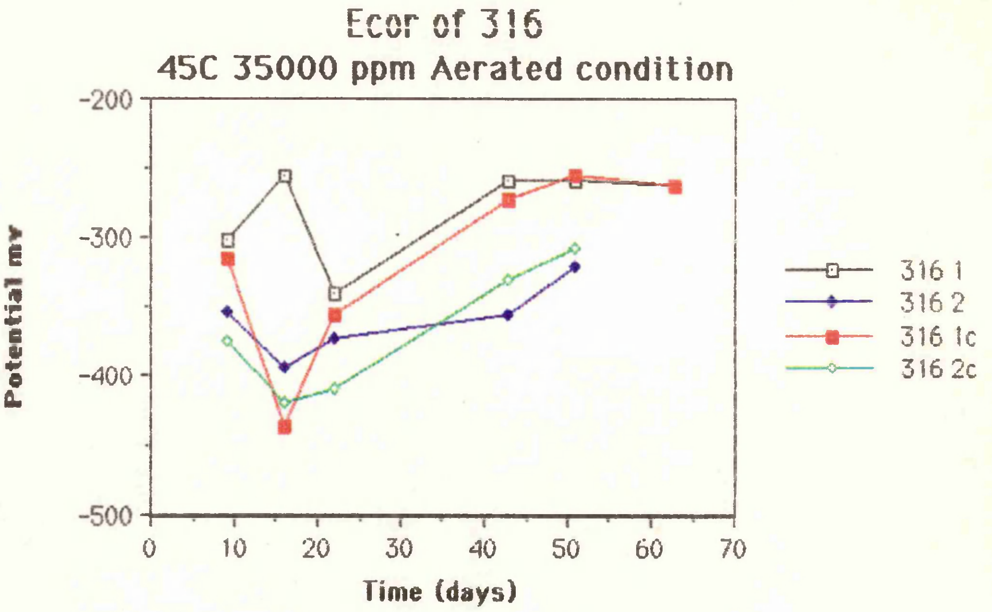

Ecor of IN under 45C, 35000 ppm, Deaerated condition


Ecor of 316 under 25C, 35000ppm, Aerated condition
Potential mV
-100
-200
-300
-400
-500
0
20
40
60
80
Time (days)
316 1
316 2
316 1c
316 2c

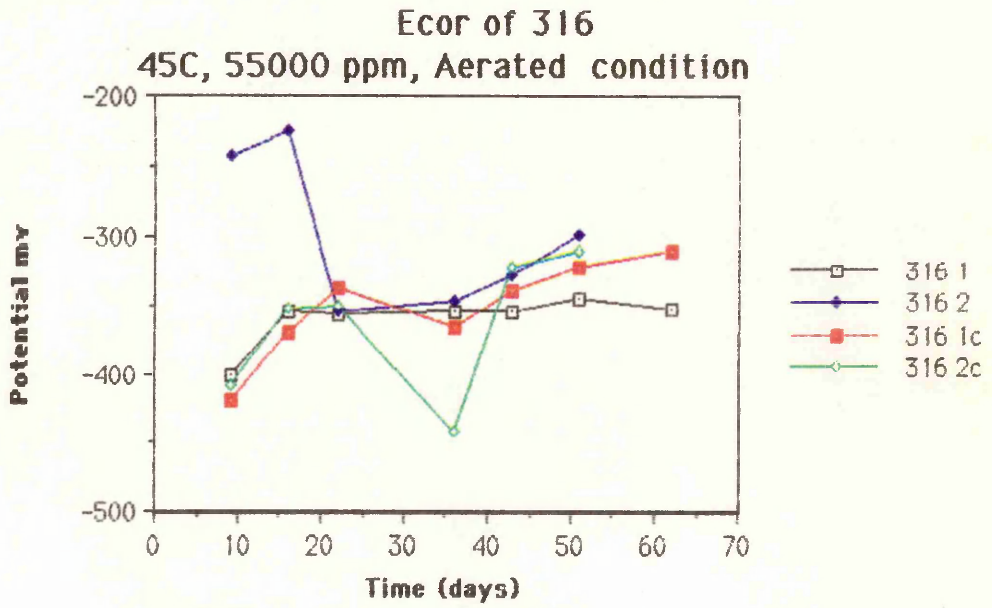

Ecor of 316, 25C, 55000 ppm, Aerated condition
Potential mV
-200
-300
-400
-500
0
10
20
30
40
50
60
Time (days)
316 1
316 2
316 1c
316 2c


Ecor of 316.
25C 35000 ppm Deaerated condition
Potential mv
-400
-420
-440
-460
-480
-500
-520
0
20
40
60
80
Time (days)
316 1
316 2
316 1c
316 2c

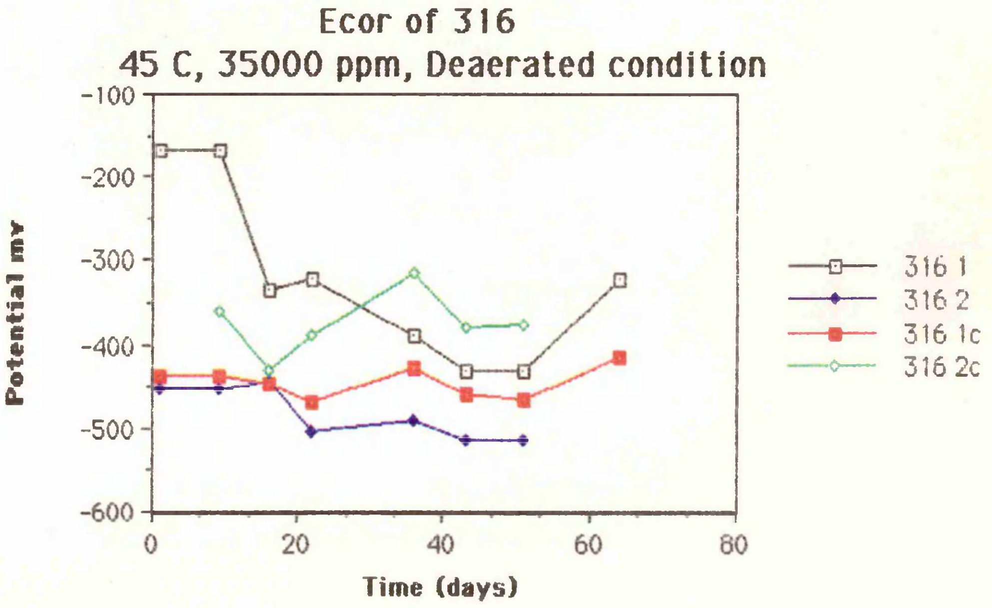

Ecor of 316
25C 55000 ppm Deaerated condition
Potential mv
-200
-300
-400
-500
-600
0
10
20
30
40
50
60
70
Time (days)
3161
3162
3161c
3162c



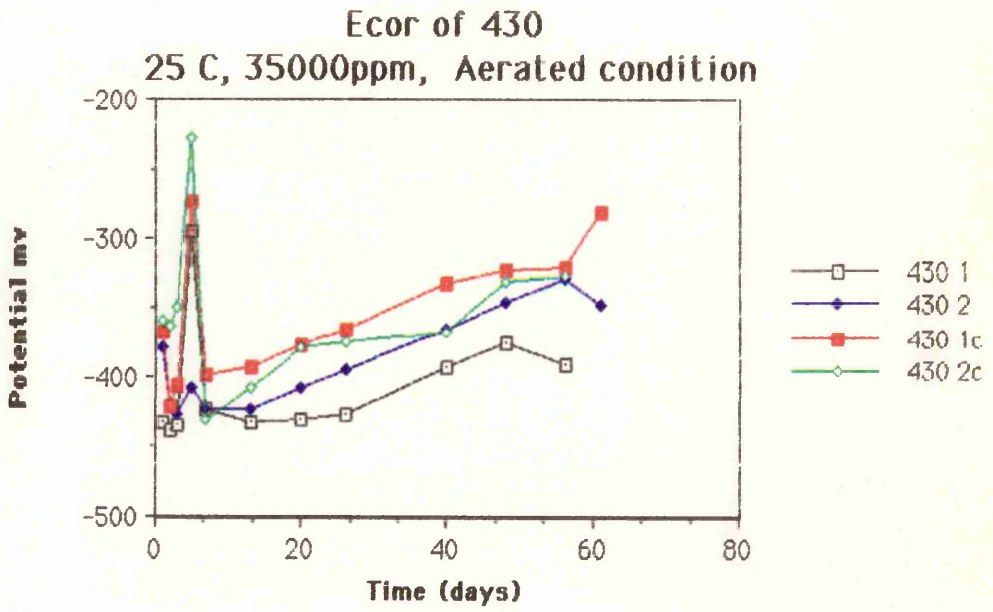
Ecor of 316
45C 35000 ppm Aerated condition

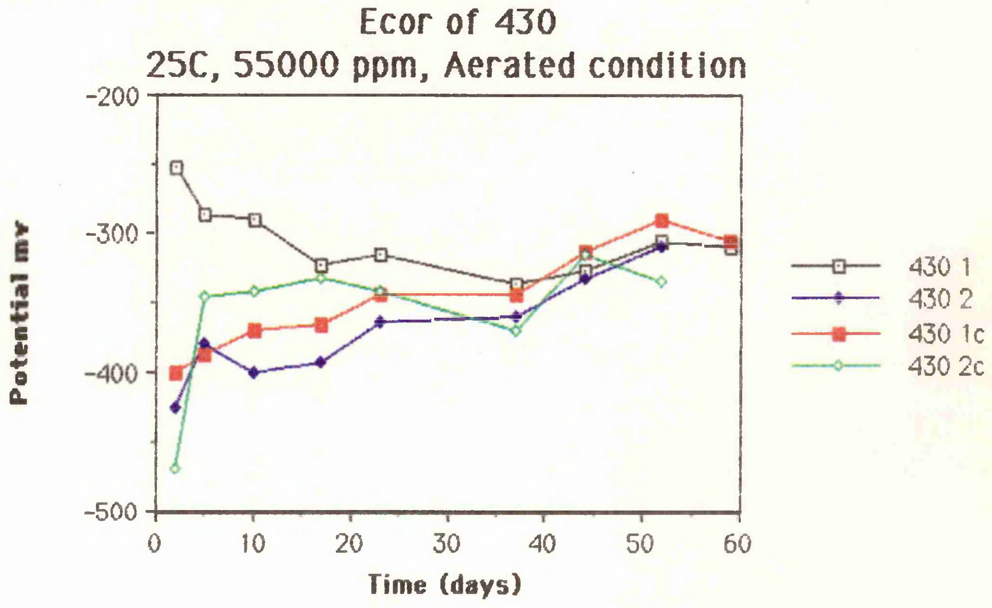


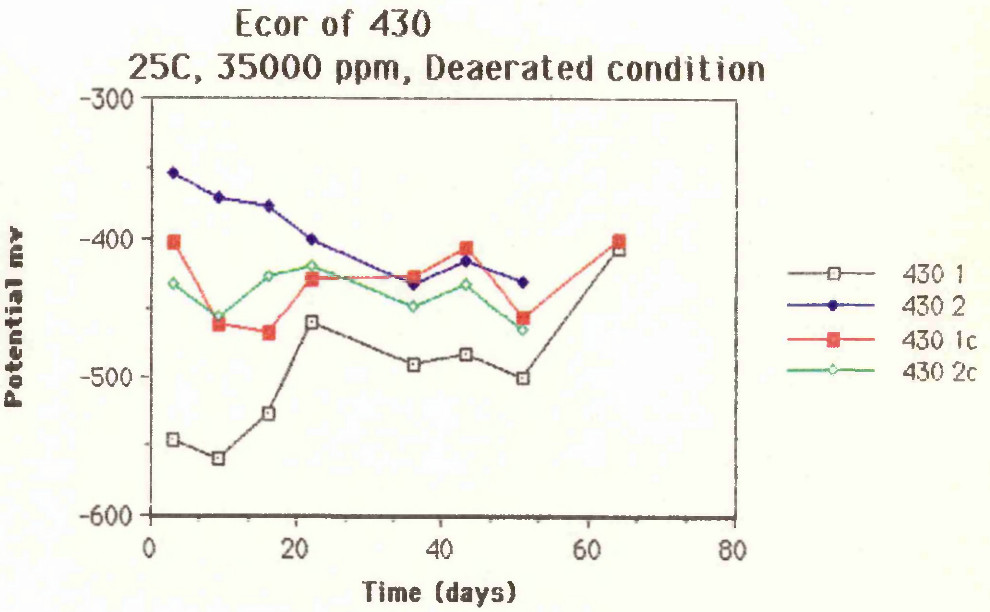
Ecor of 316
45C, 55000 ppm, Aerated condition

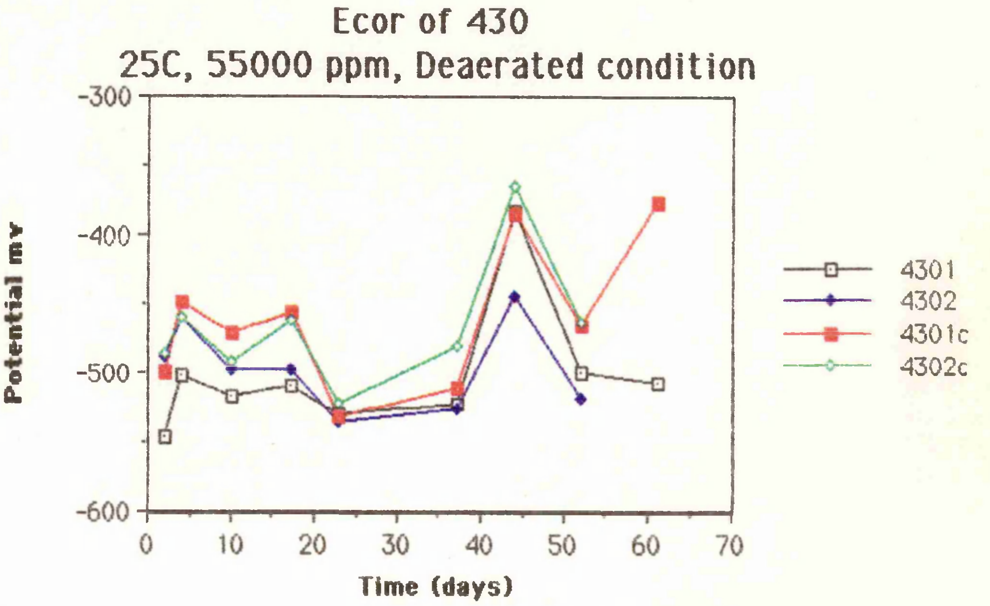


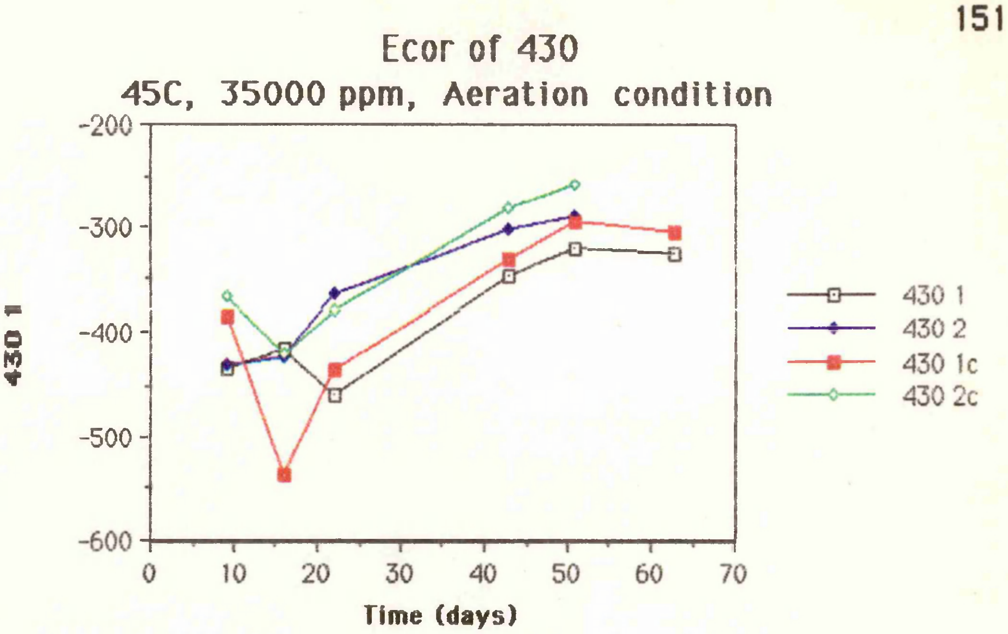
Ecor of 316
45 C, 35000 ppm, Deaerated condition

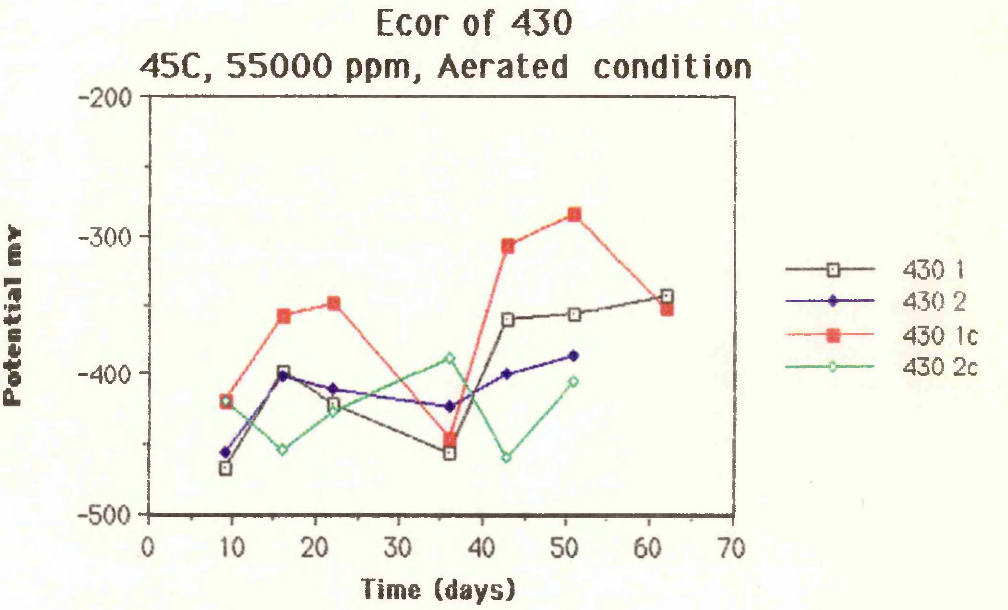

Ecor of 430
25 C, 35000ppm, Aerated condition
Potential mV
-200
-300
-400
-500
0
20
40
60
80
Time (days)
430 1
430 2
430 1c
430 2c

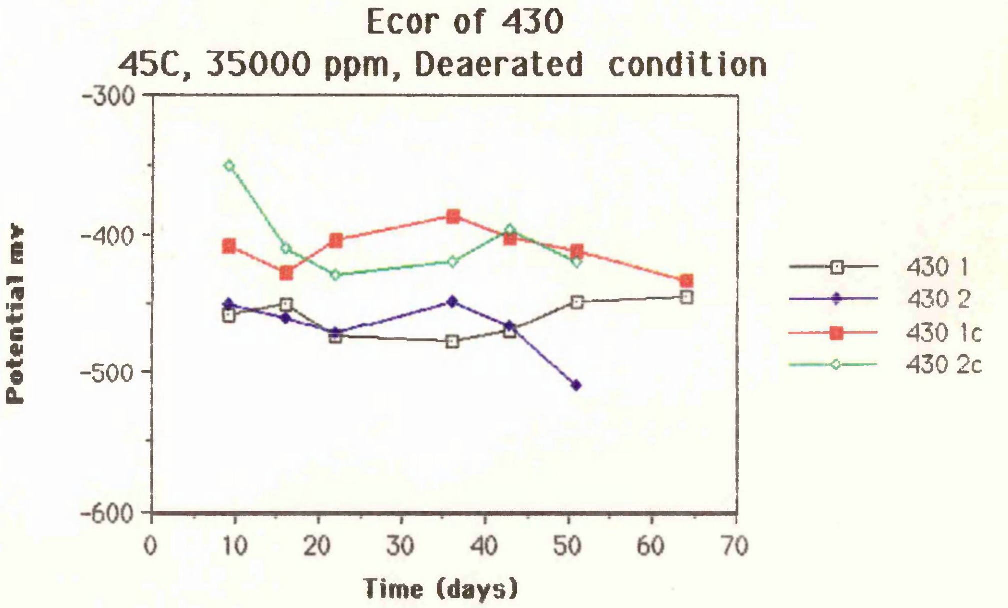

Ecor of 430
25C, 55000 ppm, Aerated condition
Potential mV
-200
-300
-400
-500
0
10
20
30
40
50
60
Time (days)
430 1
430 2
430 1c
430 2c

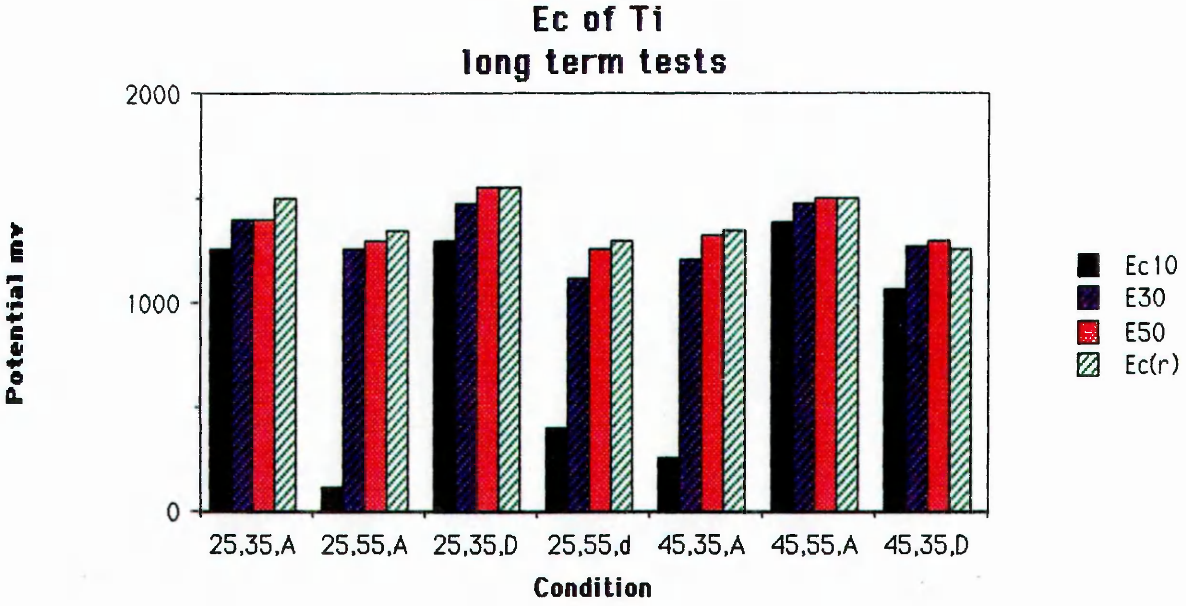

Ecor of 430
25C, 35000 ppm, Deaerated condition
Potential mV
-300
-400
-500
-600
0
20
40
60
80
Time (days)
430 1
430 2
430 1c
430 2c

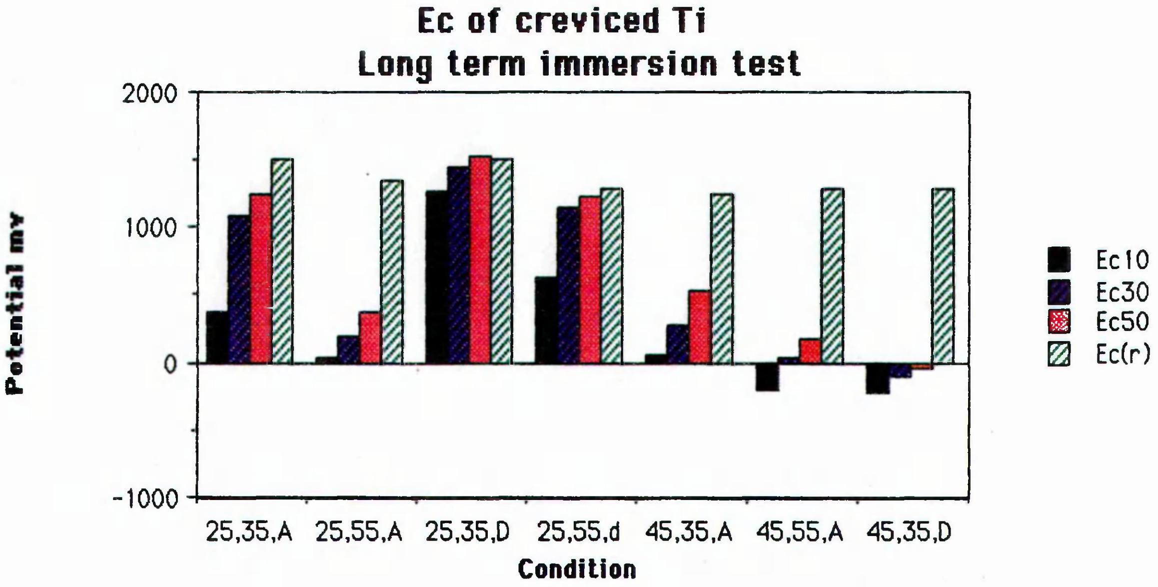

Ecor of 430
25C, 55000 ppm, Deaerated condition
Potential mV
-300
-400
-500
-600
0
10
20
30
40
50
60
70
Time (days)
4301
4302
4301c
4302c

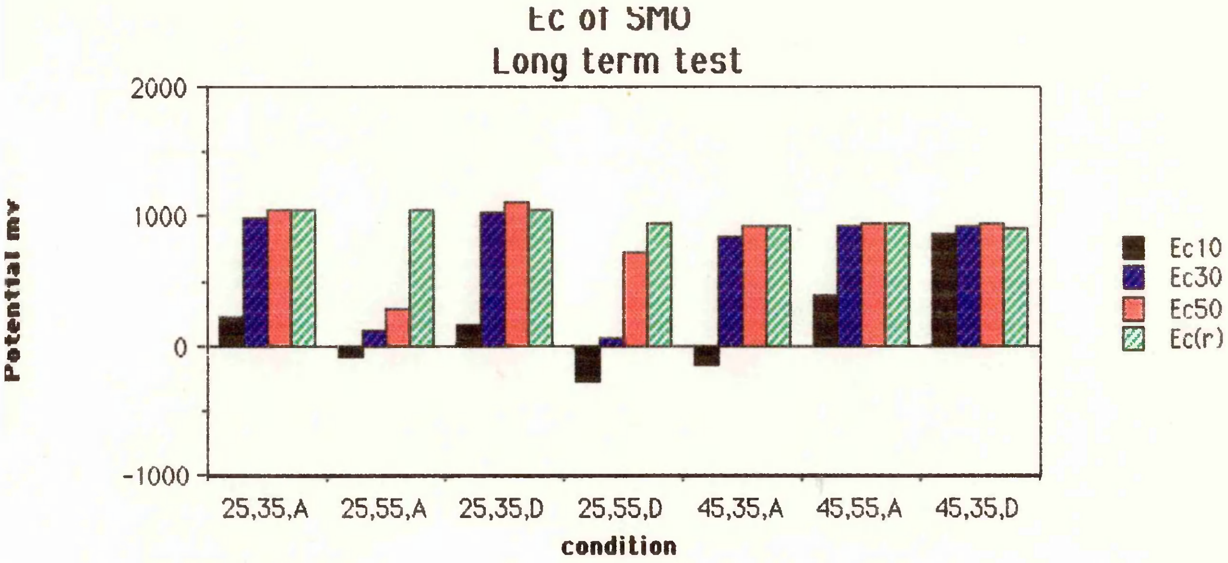

Ecor of 430
45C, 35000 ppm, Aeration condition
430 1
-200
-300
-400
-500
-600
0
10
20
30
40
50
60
70
Time (days)
430 1
430 2
430 1c
430 2c

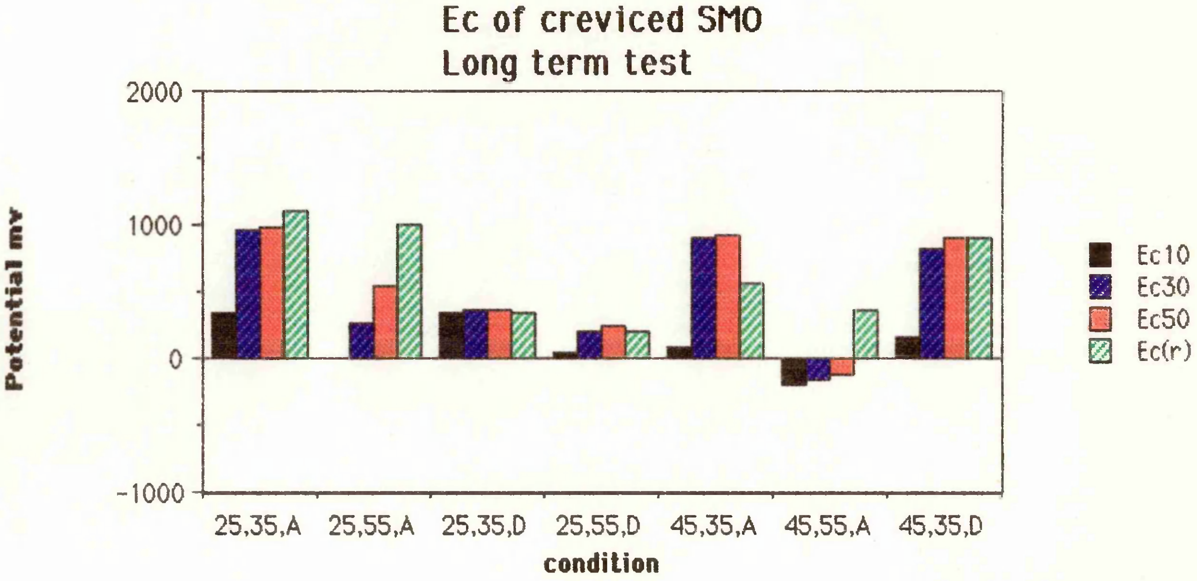

Ecor of 430
45C, 55000 ppm, Aerated condition
Potential mV
-200
-300
-400
-500
0
10
20
30
40
50
60
70
Time (days)
430 1
430 2
430 1c
430 2c

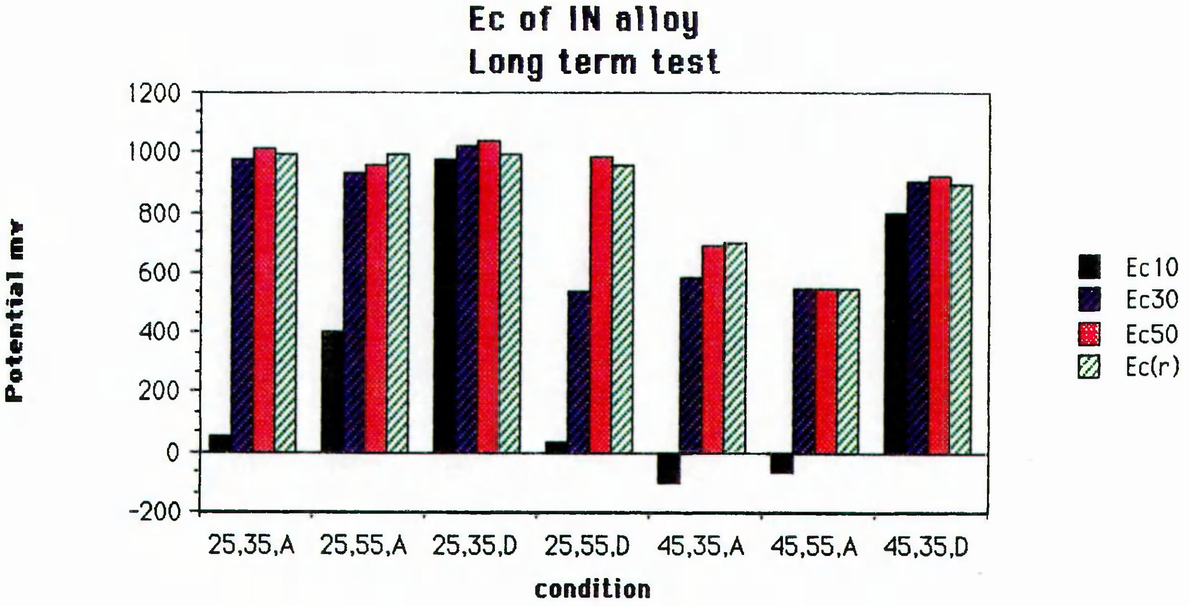

Ecor of 430
45C, 35000 ppm, Deaerated condition
Potential mV
-300
-400
-500
-600
0
10
20
30
40
50
60
70
Time (days)
430 1
430 2
430 1c
430 2c


Ec of Ti
long term tests
Potential mv
2000
1000
0
25,35,A
25,55,A
25,35,D
25,55,d
45,35,A
45,55,A
45,35,D
Condition
Ec10
E30
E50
Ec(r)

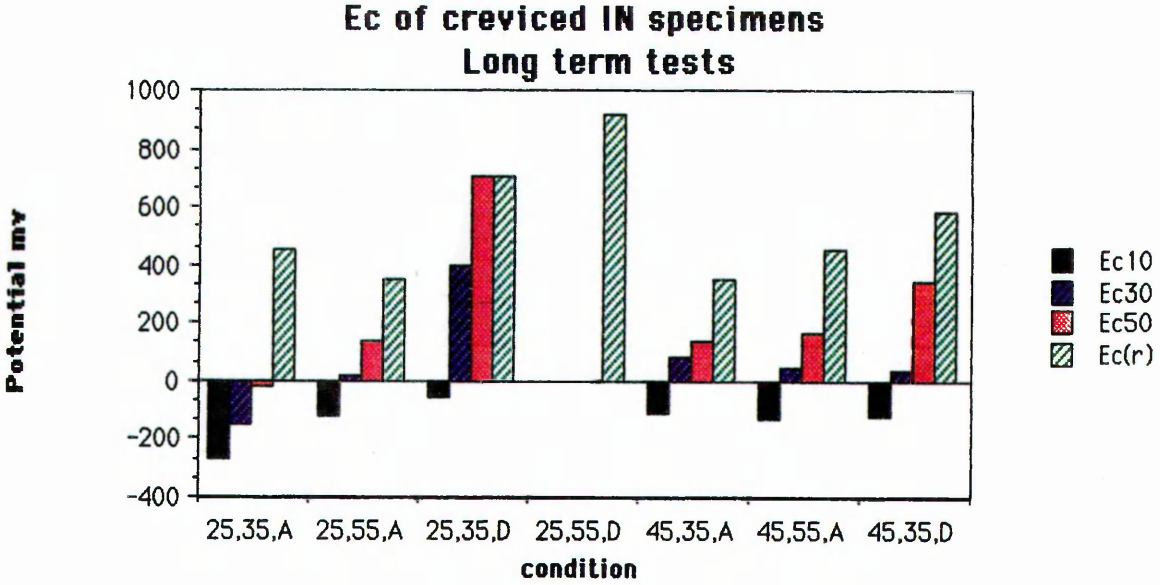

Ec of creviced Ti
Long term immersion test
Potential mv
2000
1000
0
-1000
25,35,A
25,55,A
25,35,D
25,55,d
45,35,A
45,55,A
45,35,D
Condition
Ec10
Ec30
Ec50
Ec(r)


Ec of SMO
Long term test
Potential mv
2000
1000
0
-1000
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
condition
Ec10
Ec30
Ec50
Ec(r)

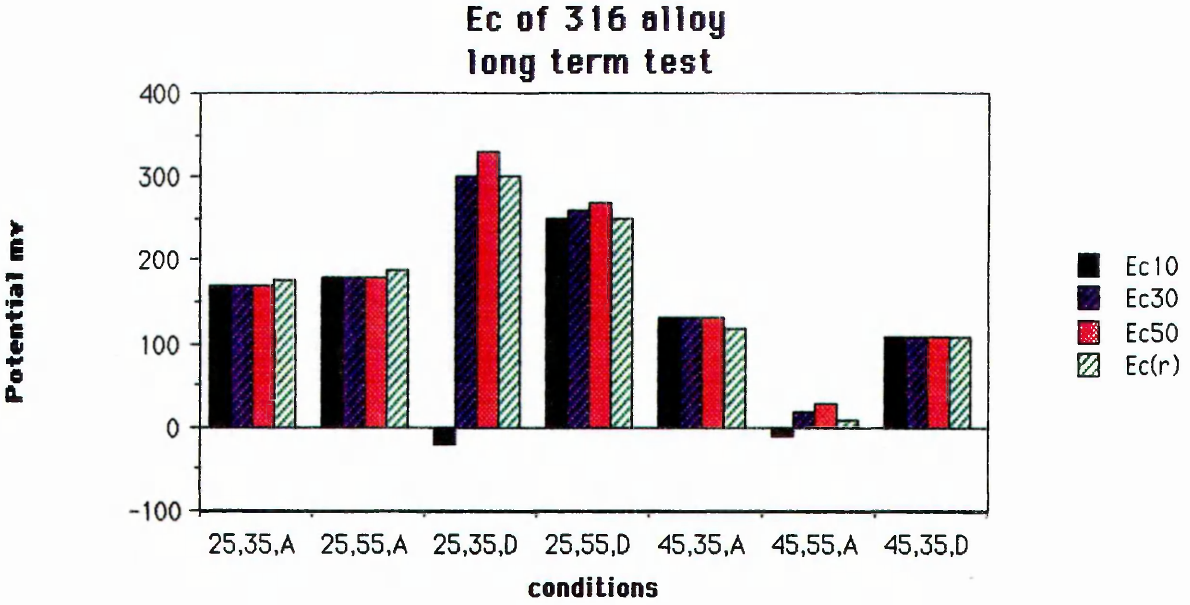

Ec of creviced SMO
Long term test
Potential mv
2000
1000
0
-1000
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
condition
Ec10
Ec30
Ec50
Ec(r)

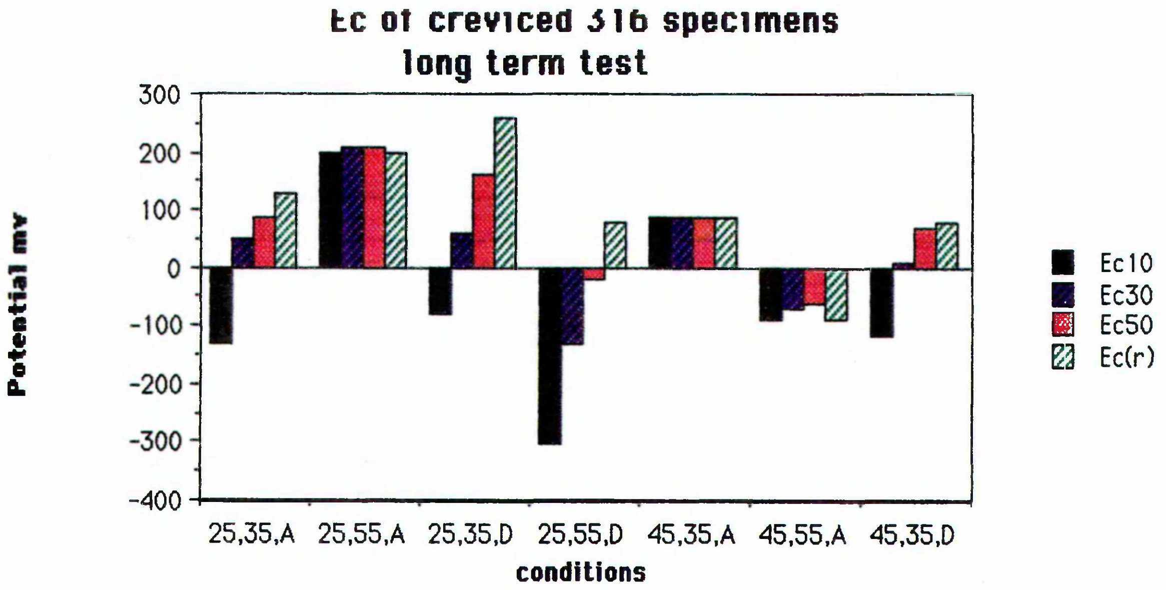


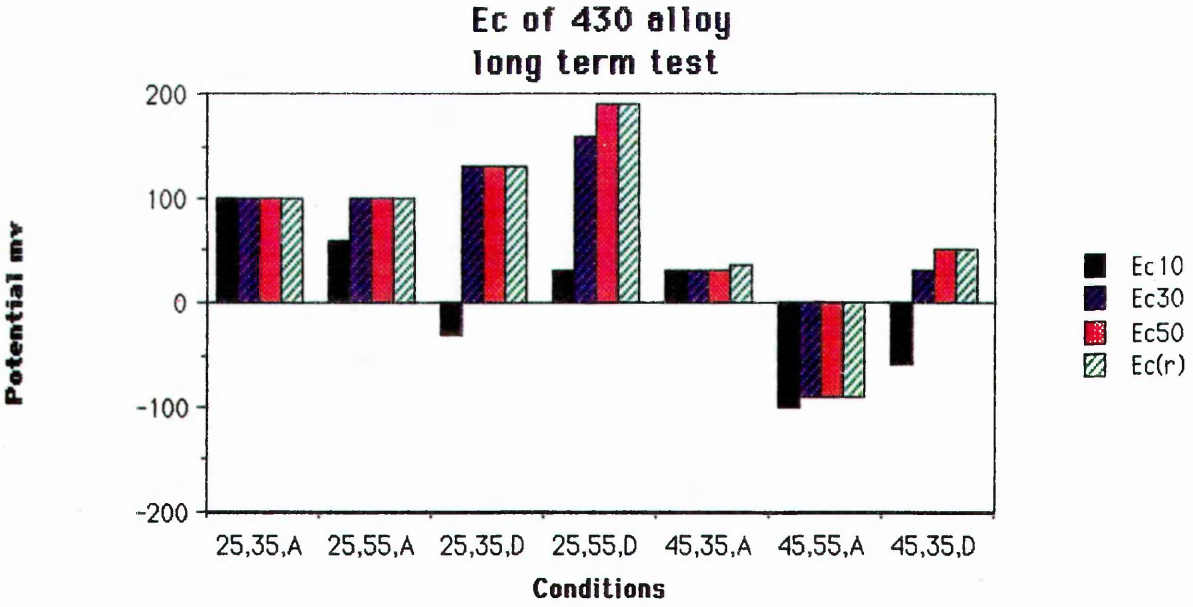
Ec of IN alloy
Long term test

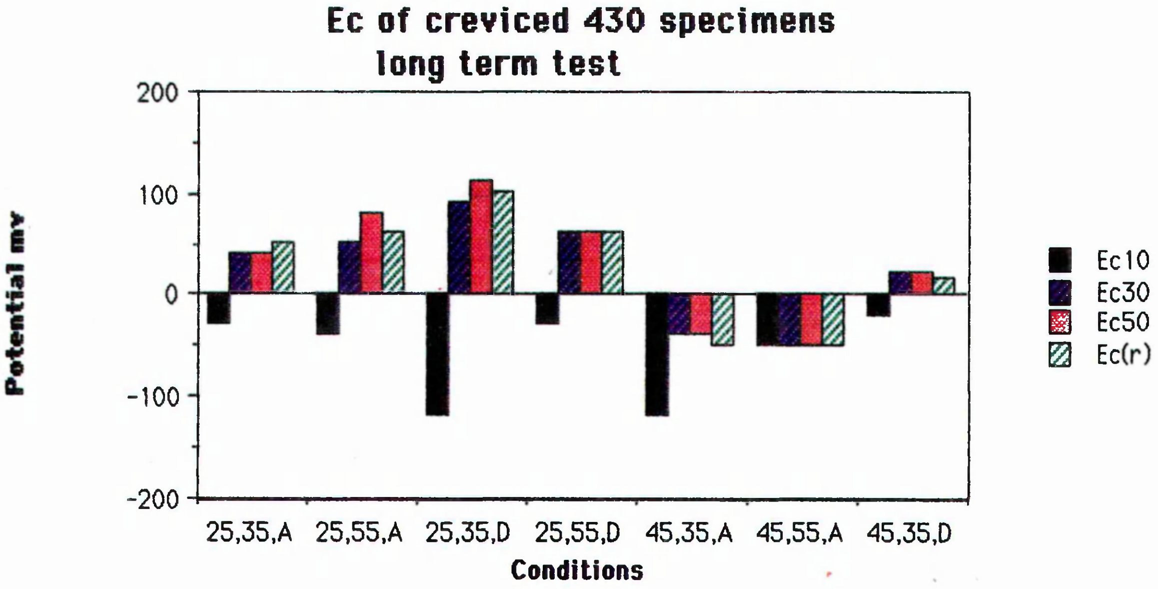


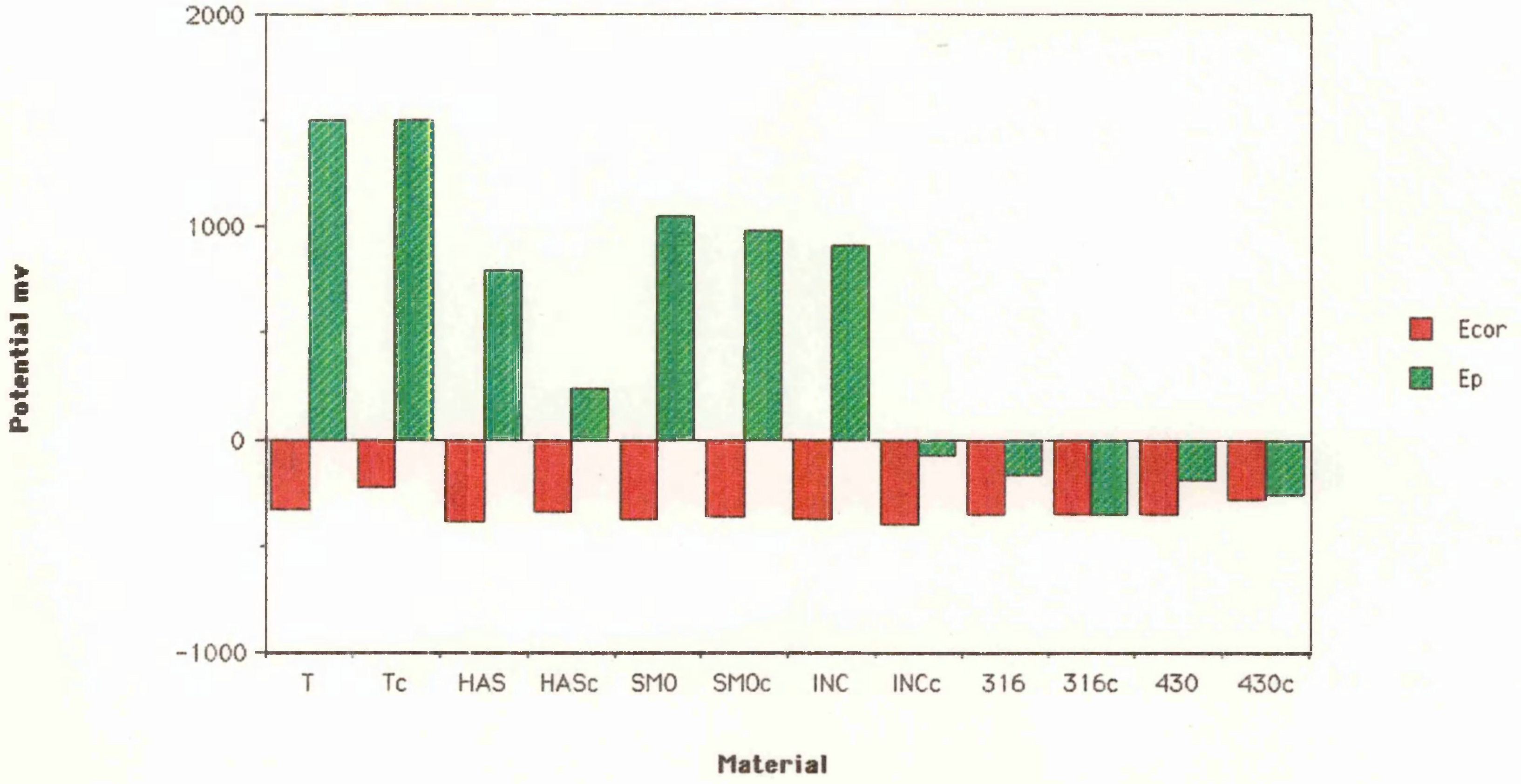
Ec of creviced IN specimens
Long term tests


Ec of 316 alloy
long term test
Potential mv
400
300
200
100
0
-100
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
conditions
Ec10
Ec30
Ec50
Ec(r)

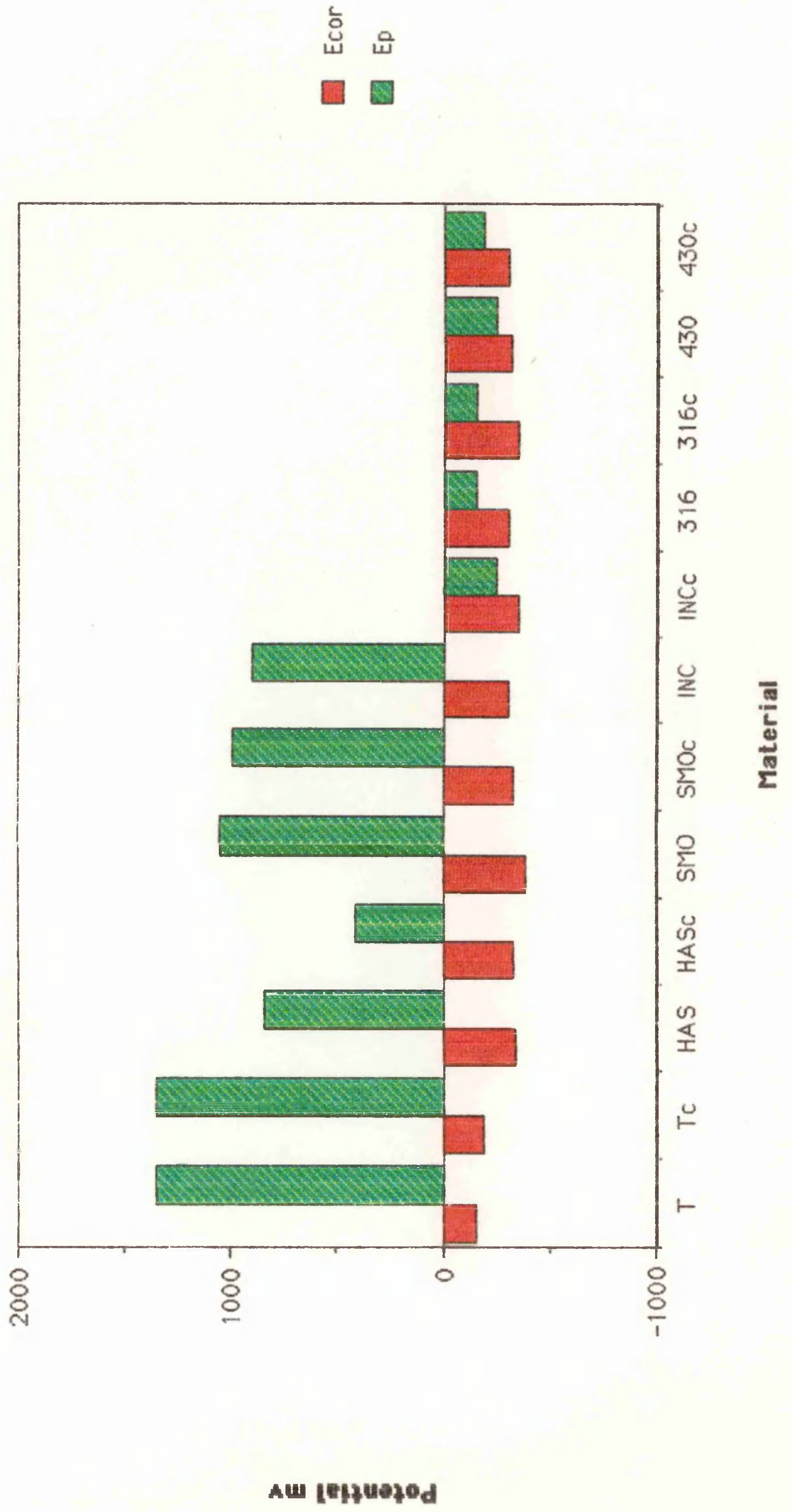

Ec of creviced 316 specimens
long term test
Potential mv
300
200
100
0
-100
-200
-300
-400
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
conditions
Ec10
Ec30
Ec50
Ec(r)


Ec of 430 alloy
long term test
Potential mv
200
100
0
-100
-200
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
Conditions
Ec10
Ec30
Ec50
Ec(r)

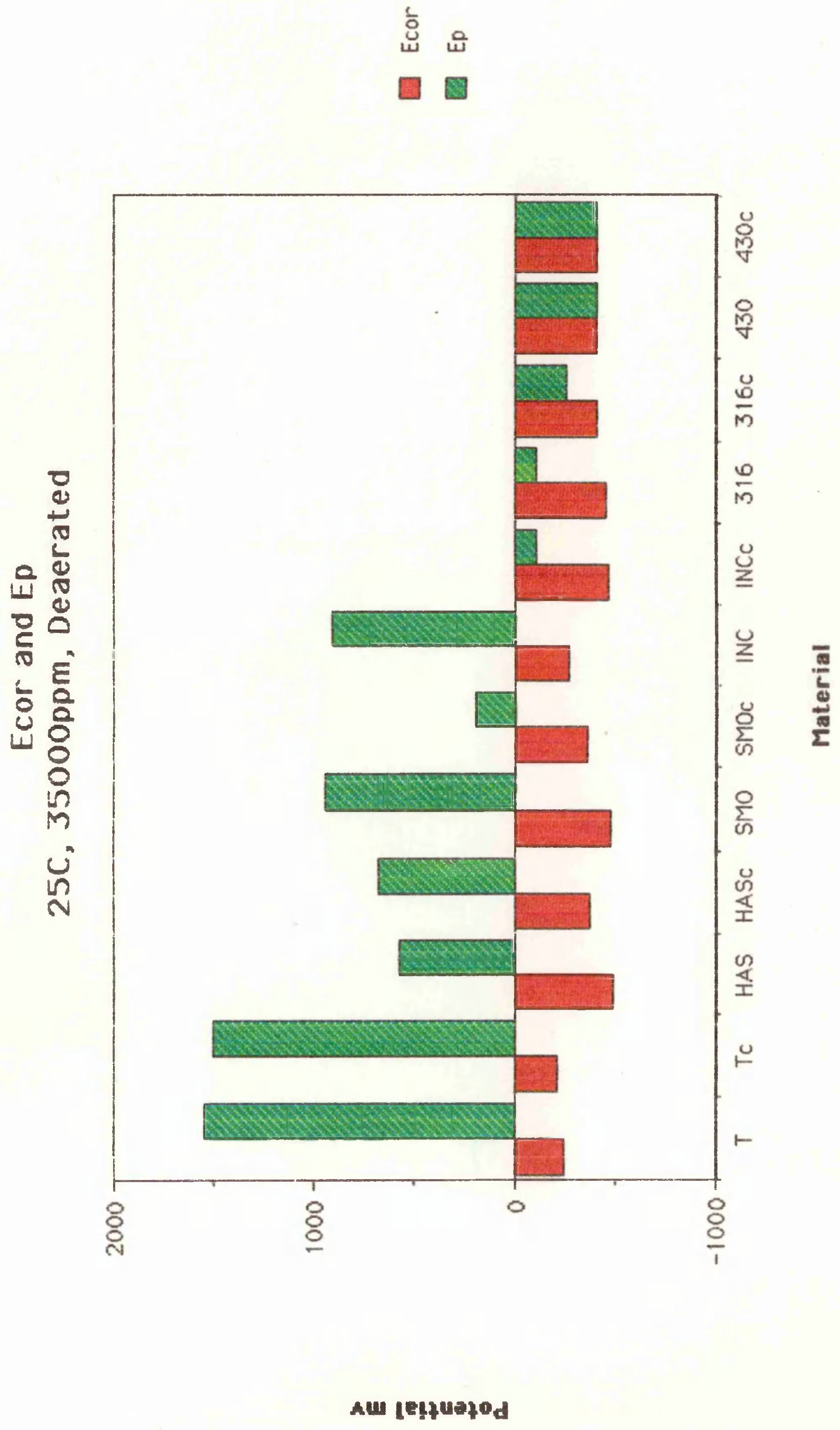

Ec of creviced 430 specimens
long term test
Potential mv
200
100
0
-100
-200
25,35,A
25,55,A
25,35,D
25,55,D
45,35,A
45,55,A
45,35,D
Conditions
Ec10
Ec30
Ec50
Ec(r)



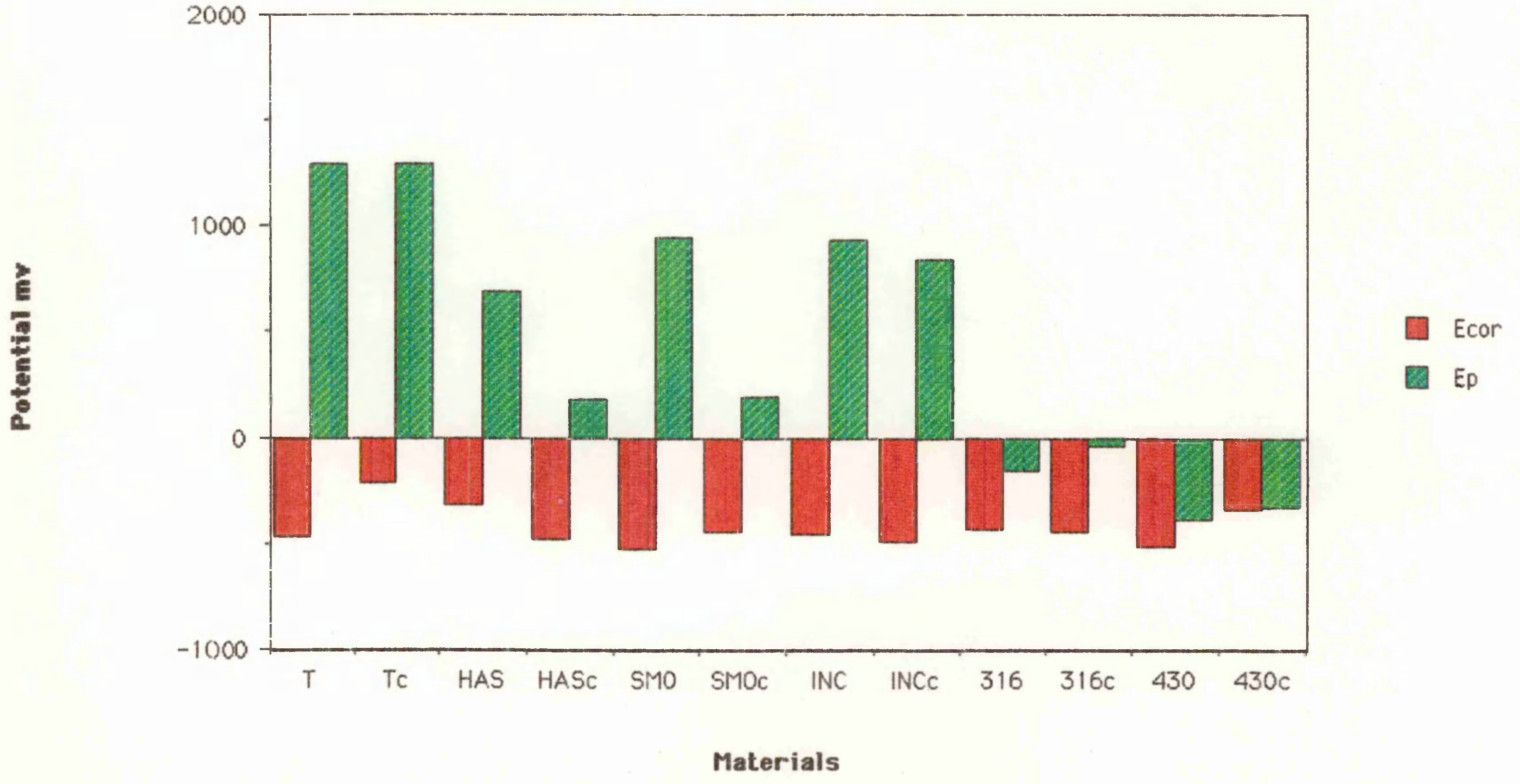
Ecor and Ep
25 C, 35000 ppm, Aerated condition



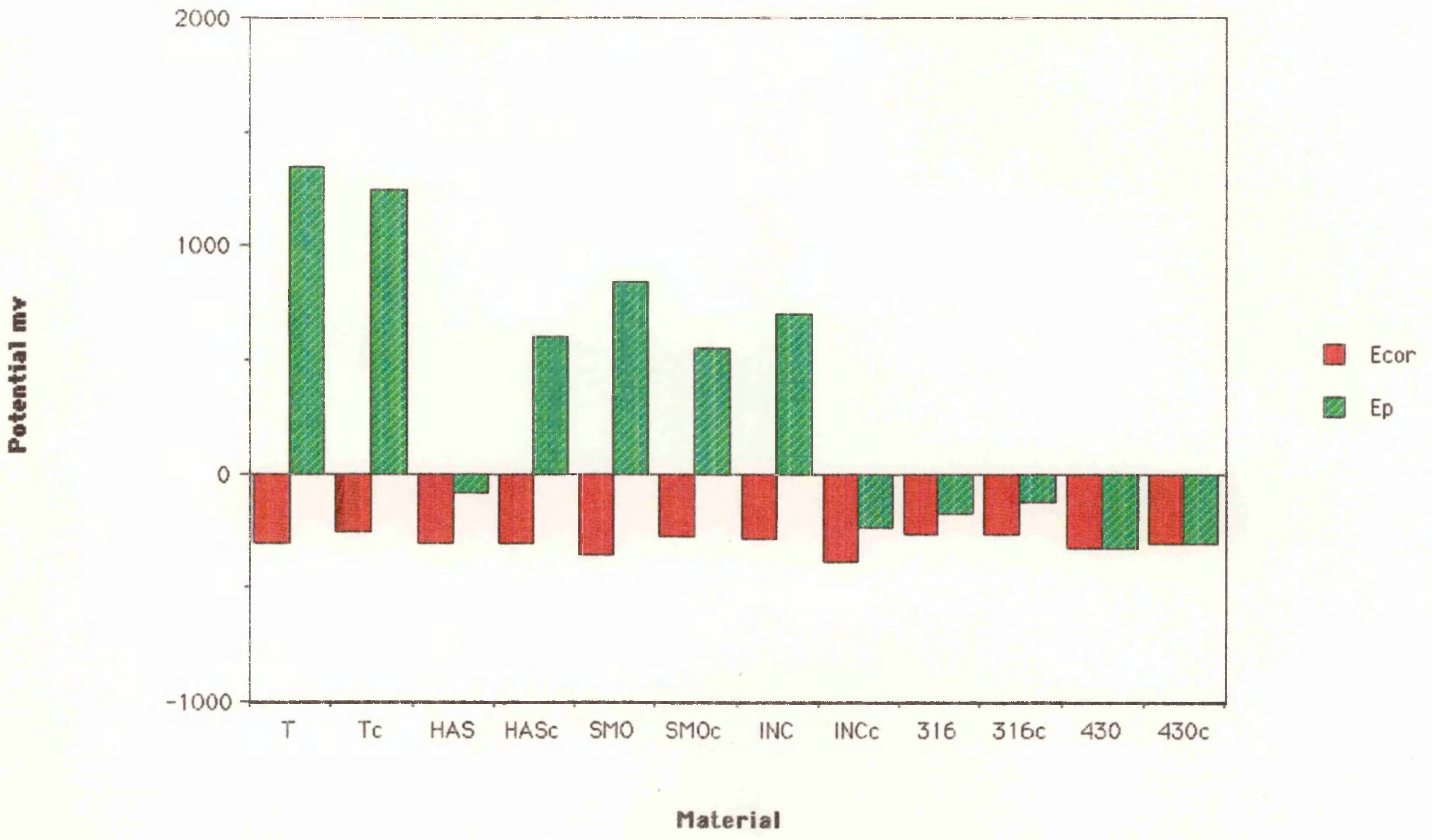
Ecor and Ep
25 C, 55000 ppm, Aerated condition

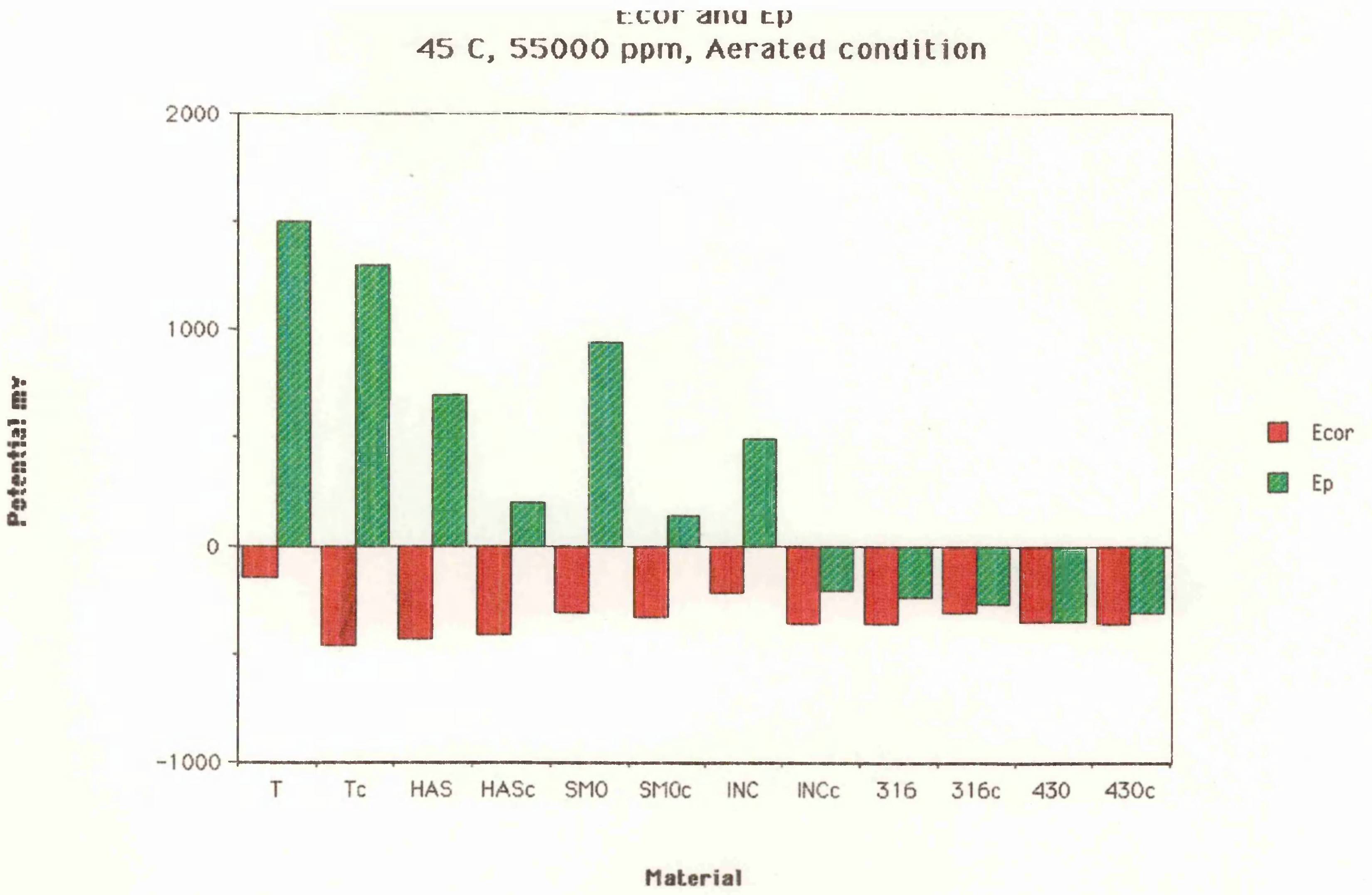

Ecor and Ep
25C, 35000ppm, Deaerated
Potential mv
2000
1000
0
-1000
T
Tc
HAS
HASc
SMO
SMOc
INC
INCc
316
316c
430
430c
Material
Ecor
Ep

Ecor and Ep
25 C, 55000 ppm, Deaerated condition

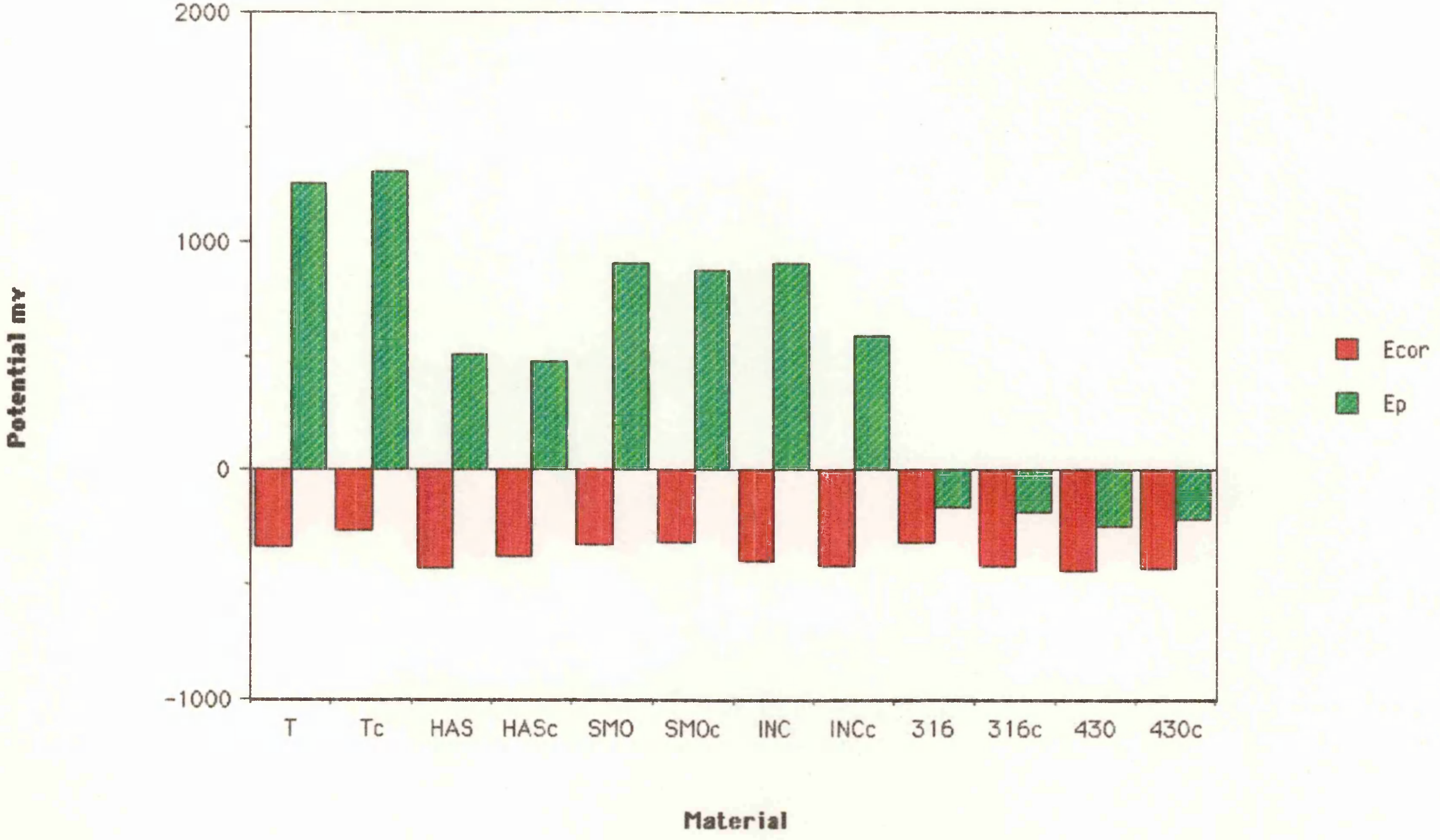


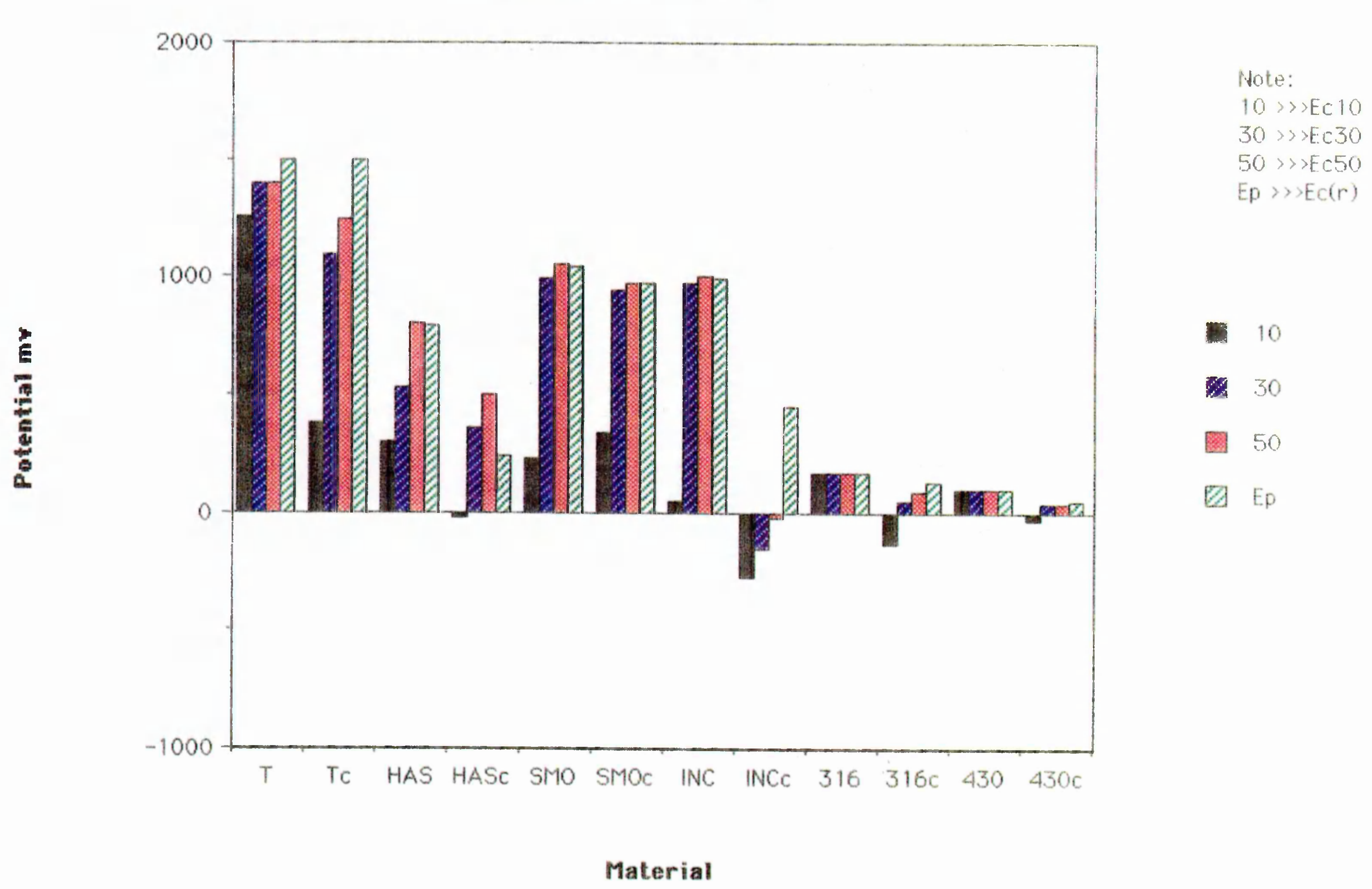
45 C, 35000ppm, Aerated condition



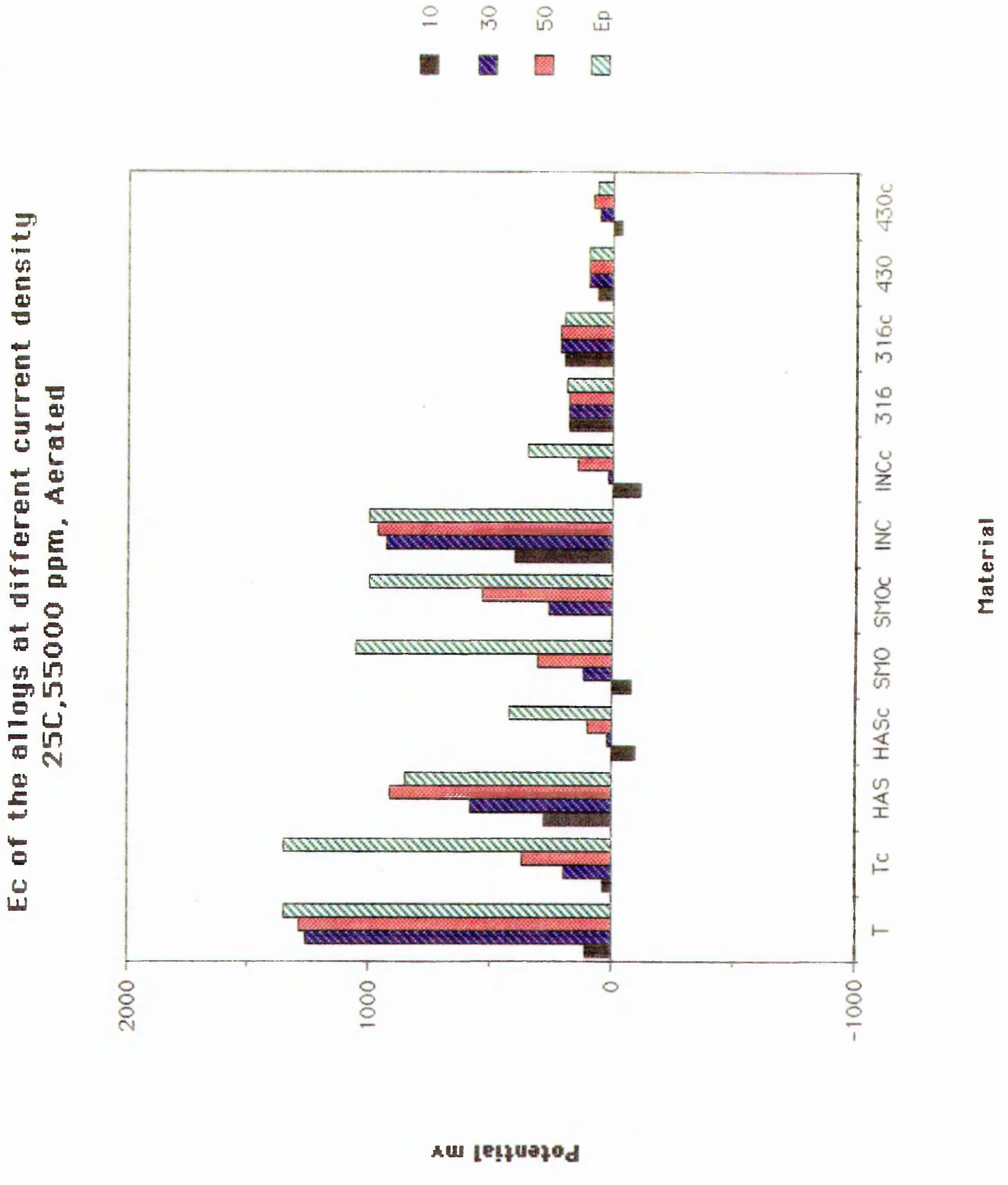

Ecor and Ep
45 C, 55000 ppm, Aerated condition
Potential mv
2000
1000
0
-1000
T
Tc
HAS
HASc
SMO
SMOc
INC
INCc
316
316c
430
430c
Material
Ecor
Ep

Ecor and Ep
45 C, 35000 ppm, Deaerated condition

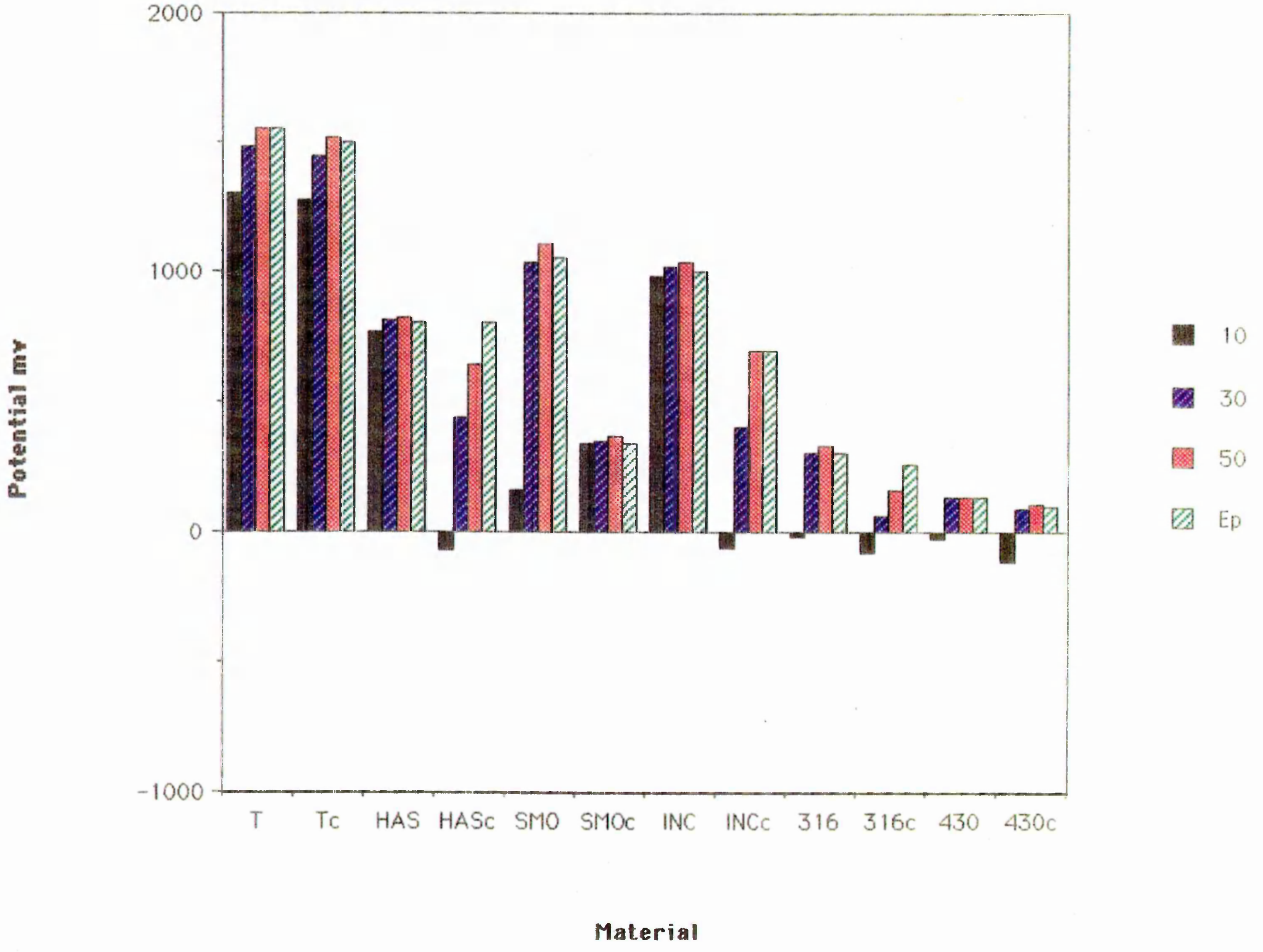




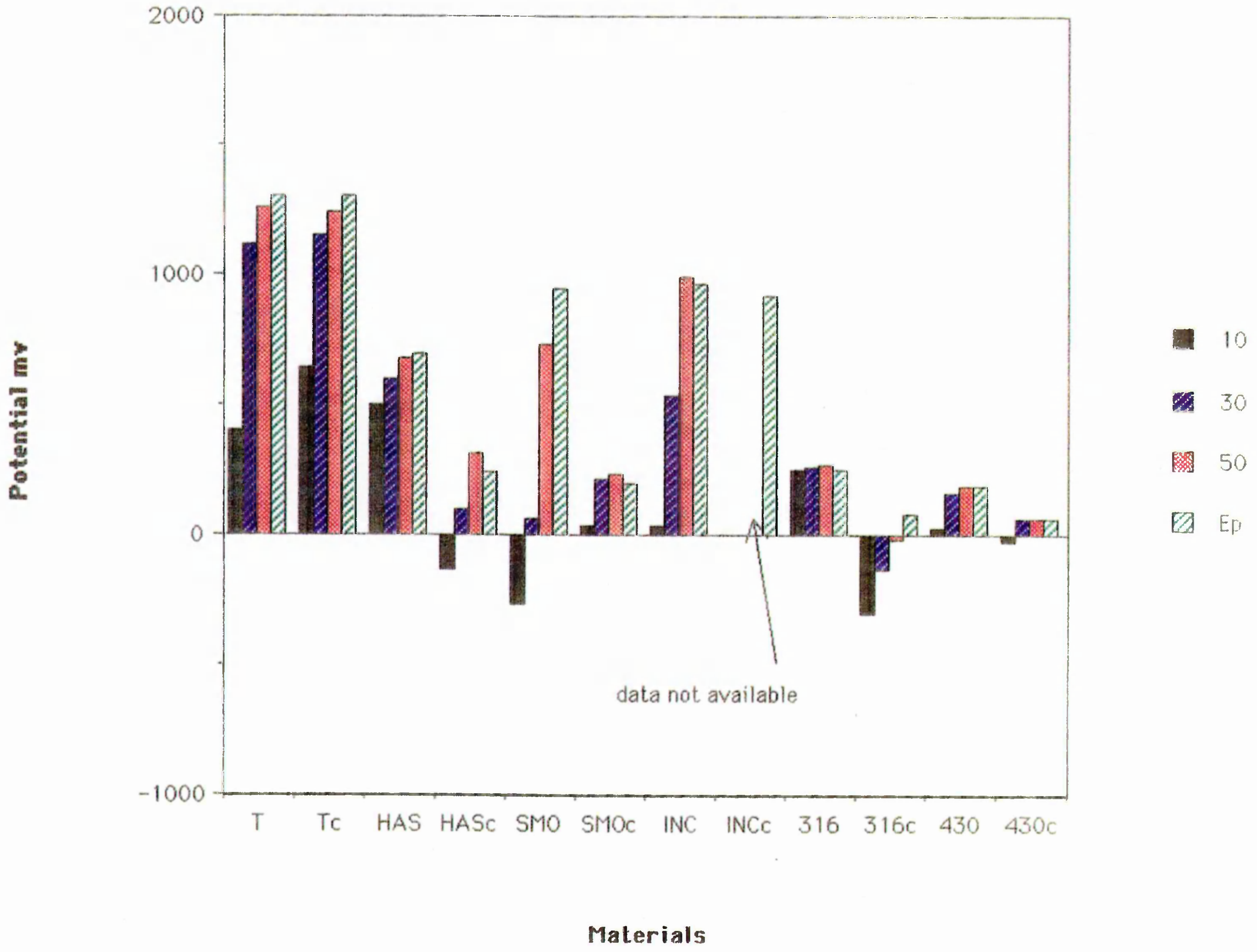
Ec of the alloys at different current density
25C,35000 ppm, Aerated



Ec of the alloys at different current density
25C,55000 ppm, Aerated

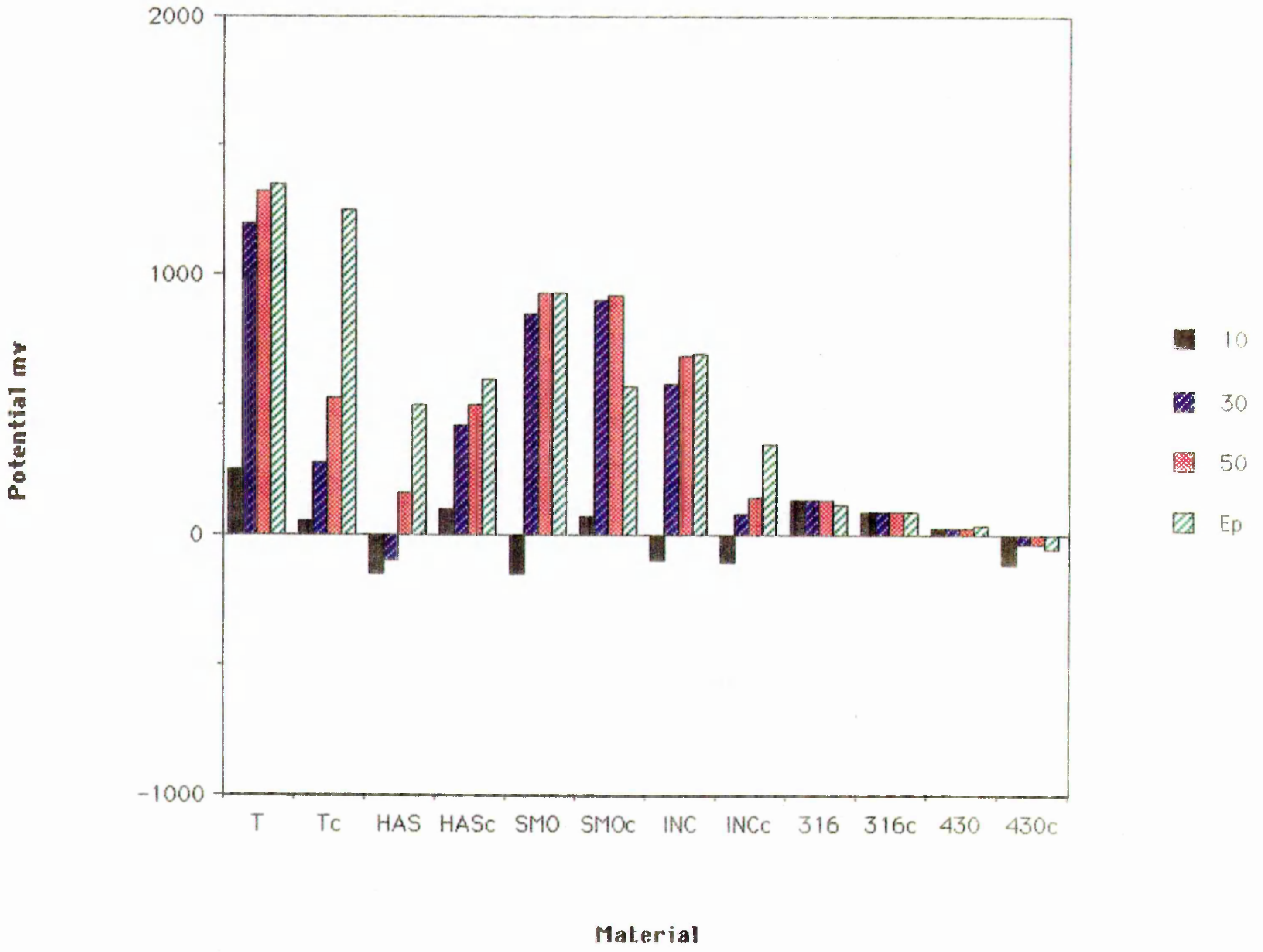


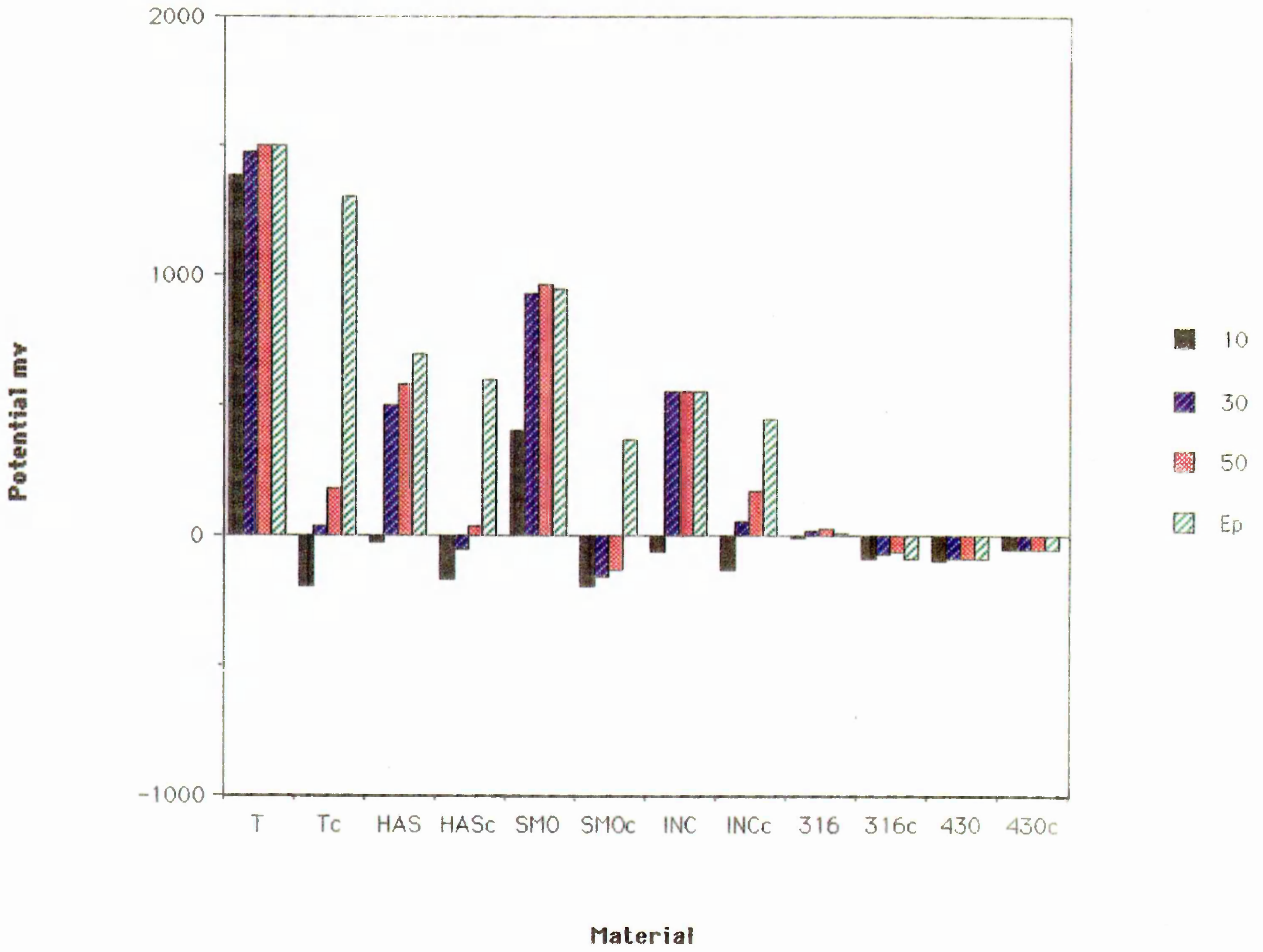
Ec of the alloys at different current density
25C,35000 ppm,Deaerated



Ec of the alloys at different current density
25C,55000 ppm, Deaerated

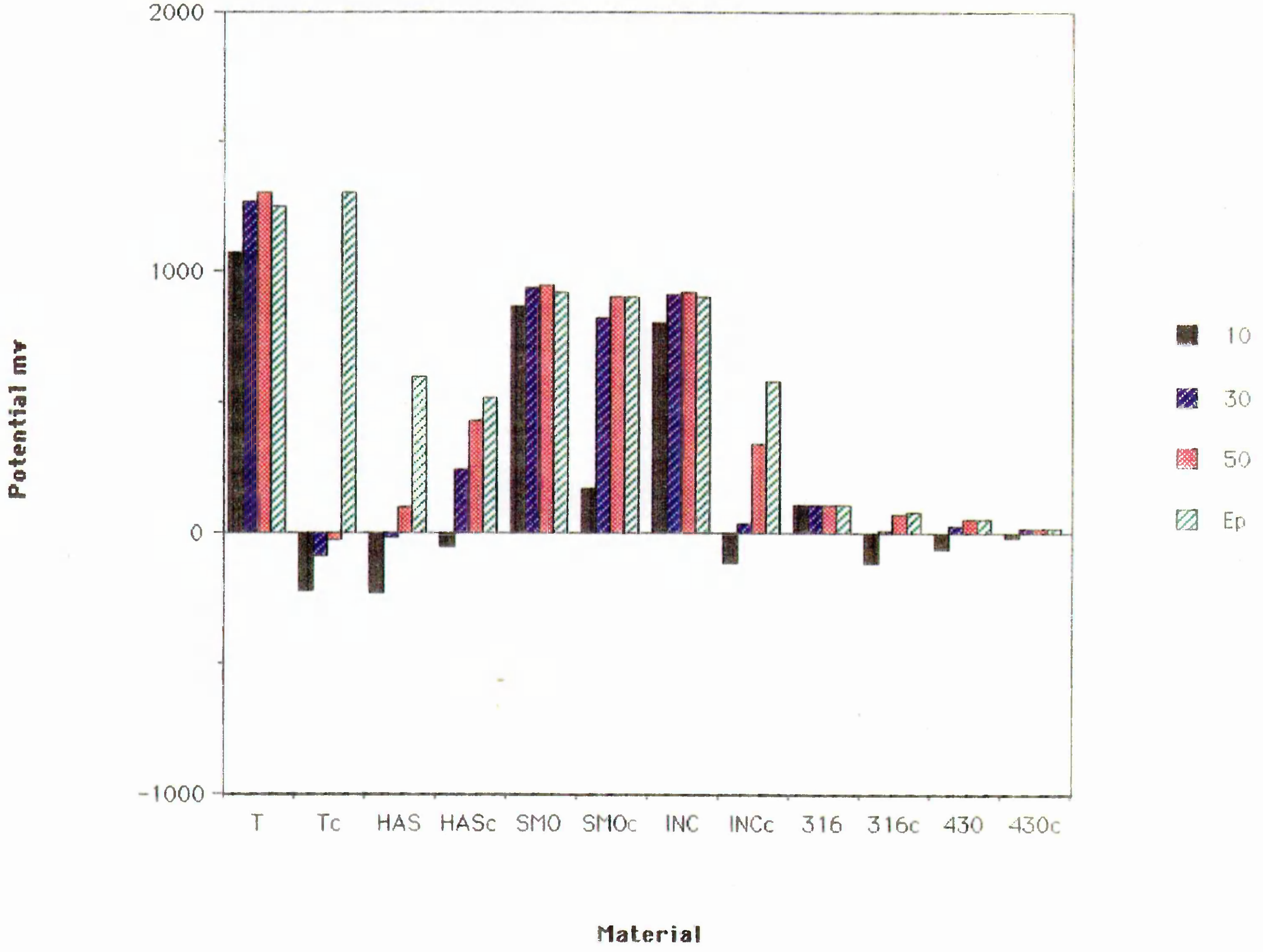
Ec of the alloys at different current density
- 45C,35000 ppm, Aerated

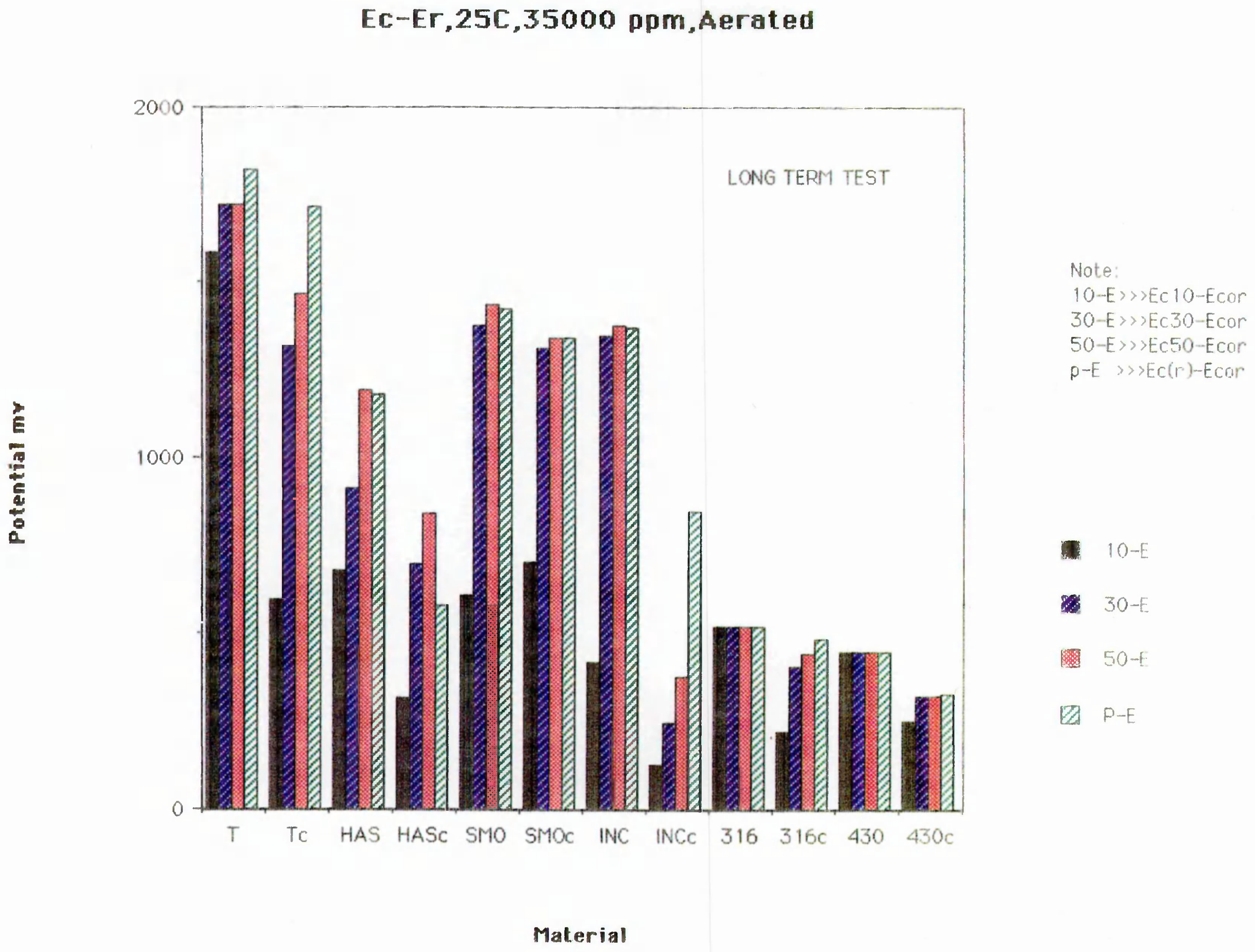




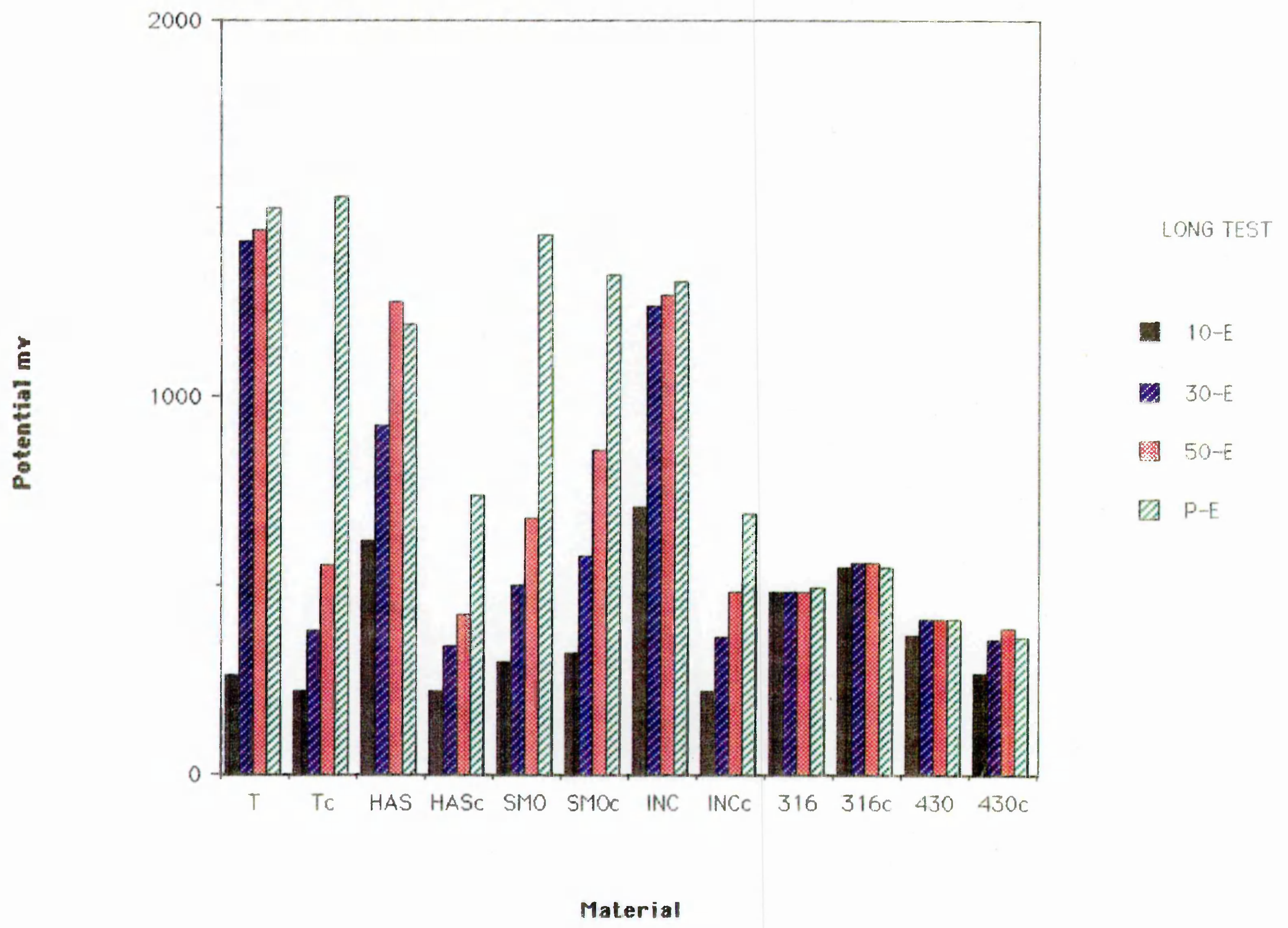
Ec of the alloys at different current density
45C,55000 ppm,Aerated

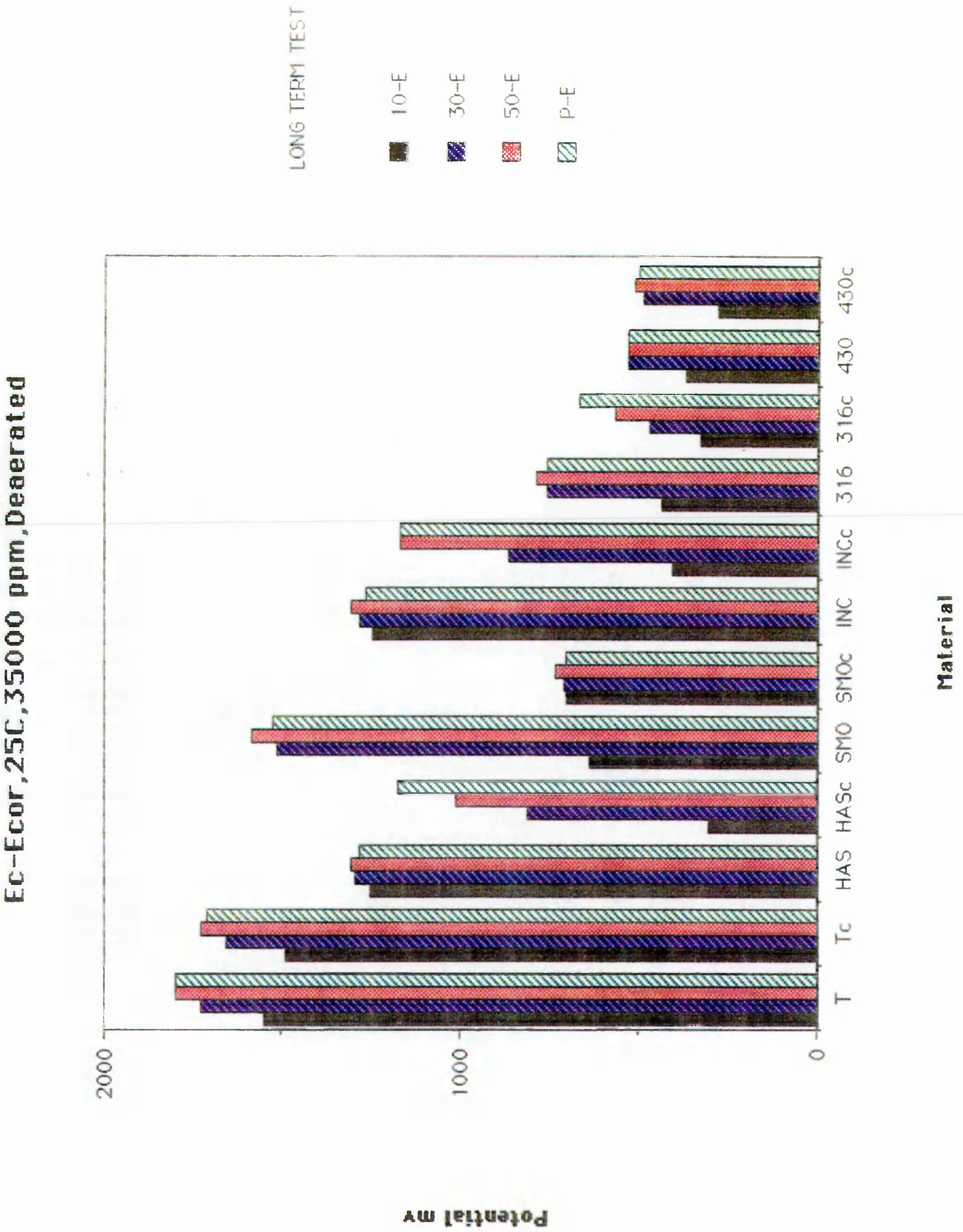
Ec of the alloys at different current density
45C,35000 ppm,Deaerated

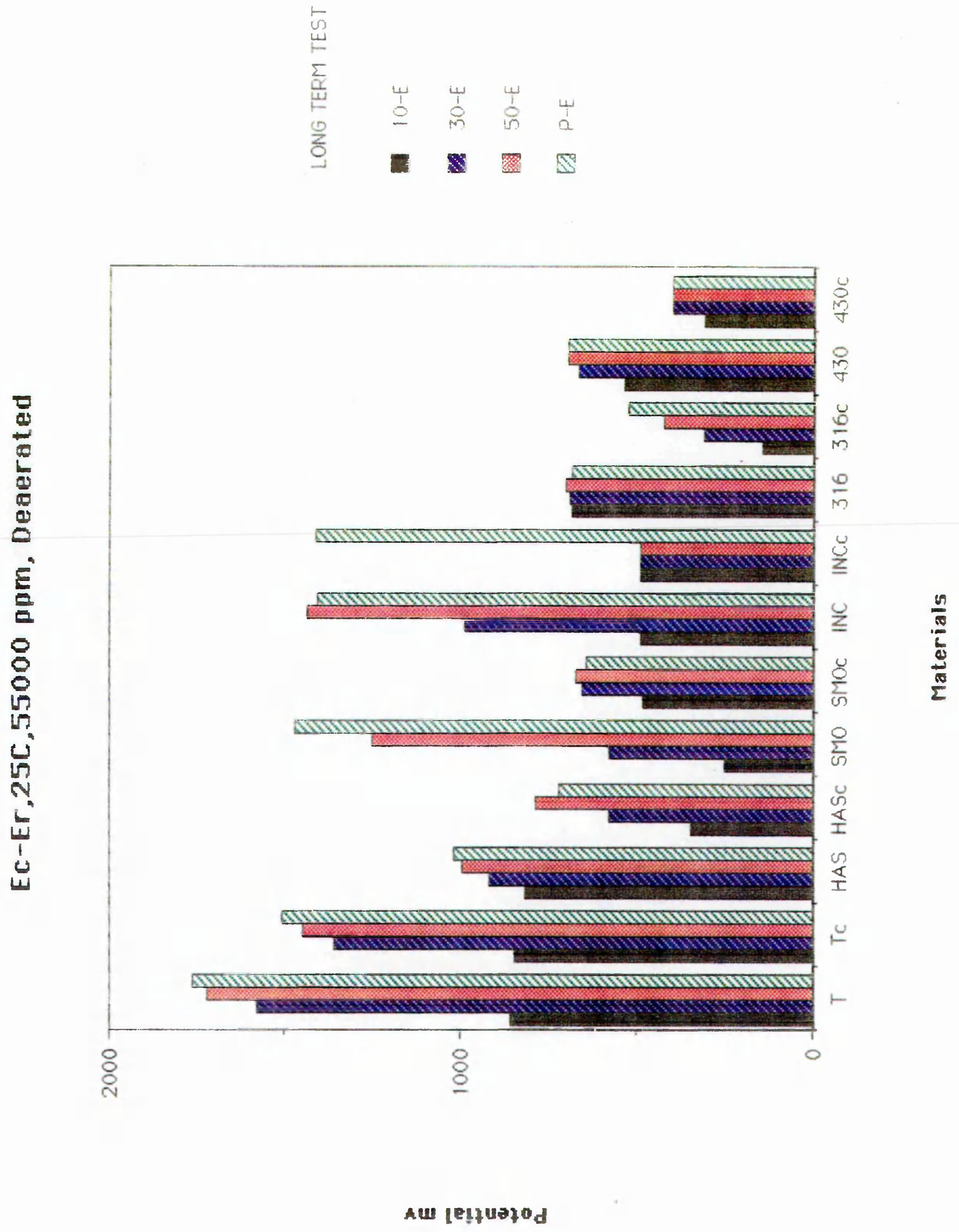



Ec-Er,25C,35000 ppm,Aerated
LONG TERM TEST
Potential mv
2000
1000
0
T
Tc
HAS
HASc
SMO
SMOc
INC
INCc
316
316c
430
430c
Material
Note:
10-E>>>Ec10-Ecor
30-E>>>Ec30-Ecor
50-E>>>Ec50-Ecor
p-E >>>Ec(r)-Ecor
10-E
30-E
50-E
P-E

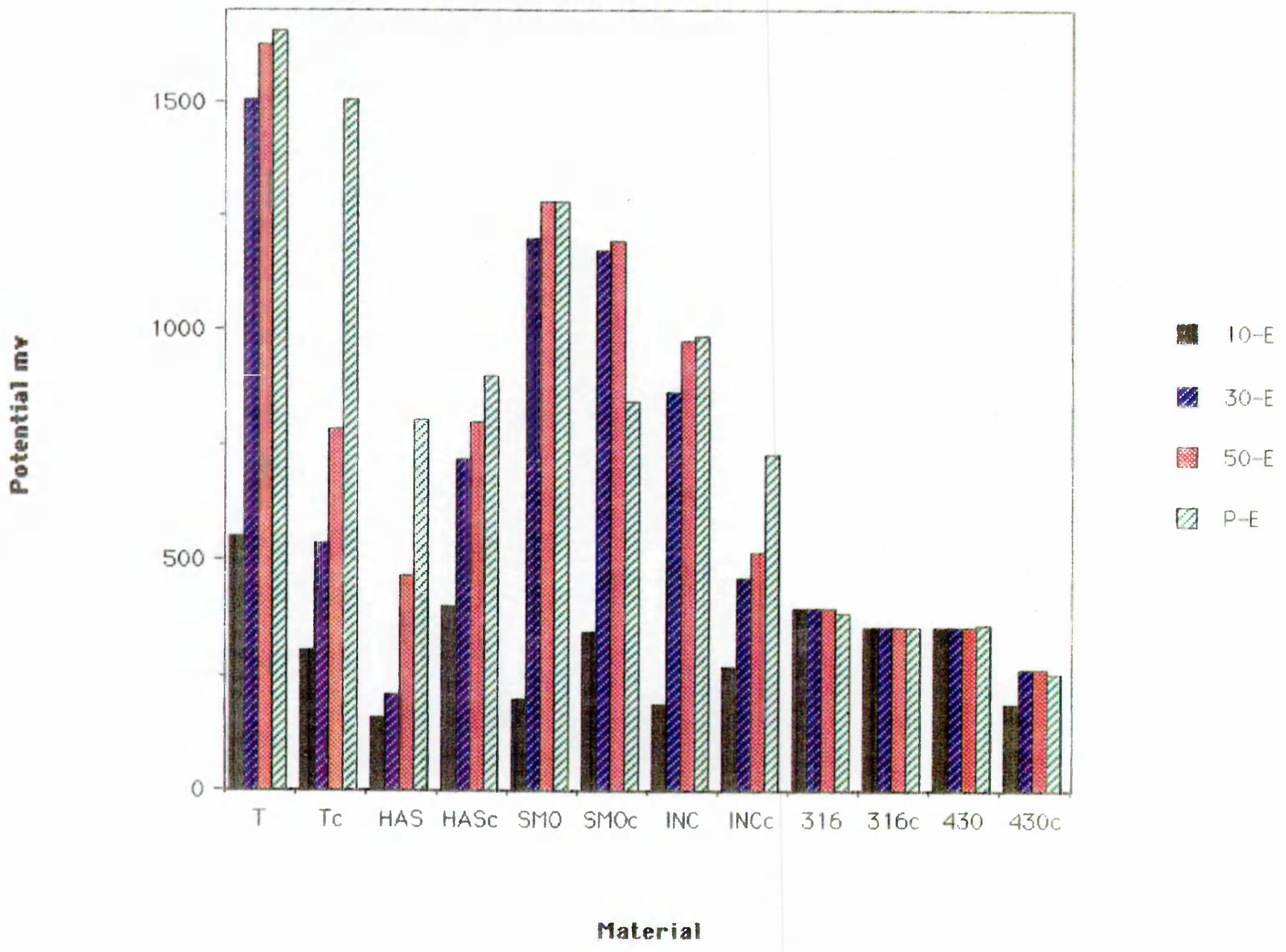
Ec-Er,25C,55000 PPM , Aerated

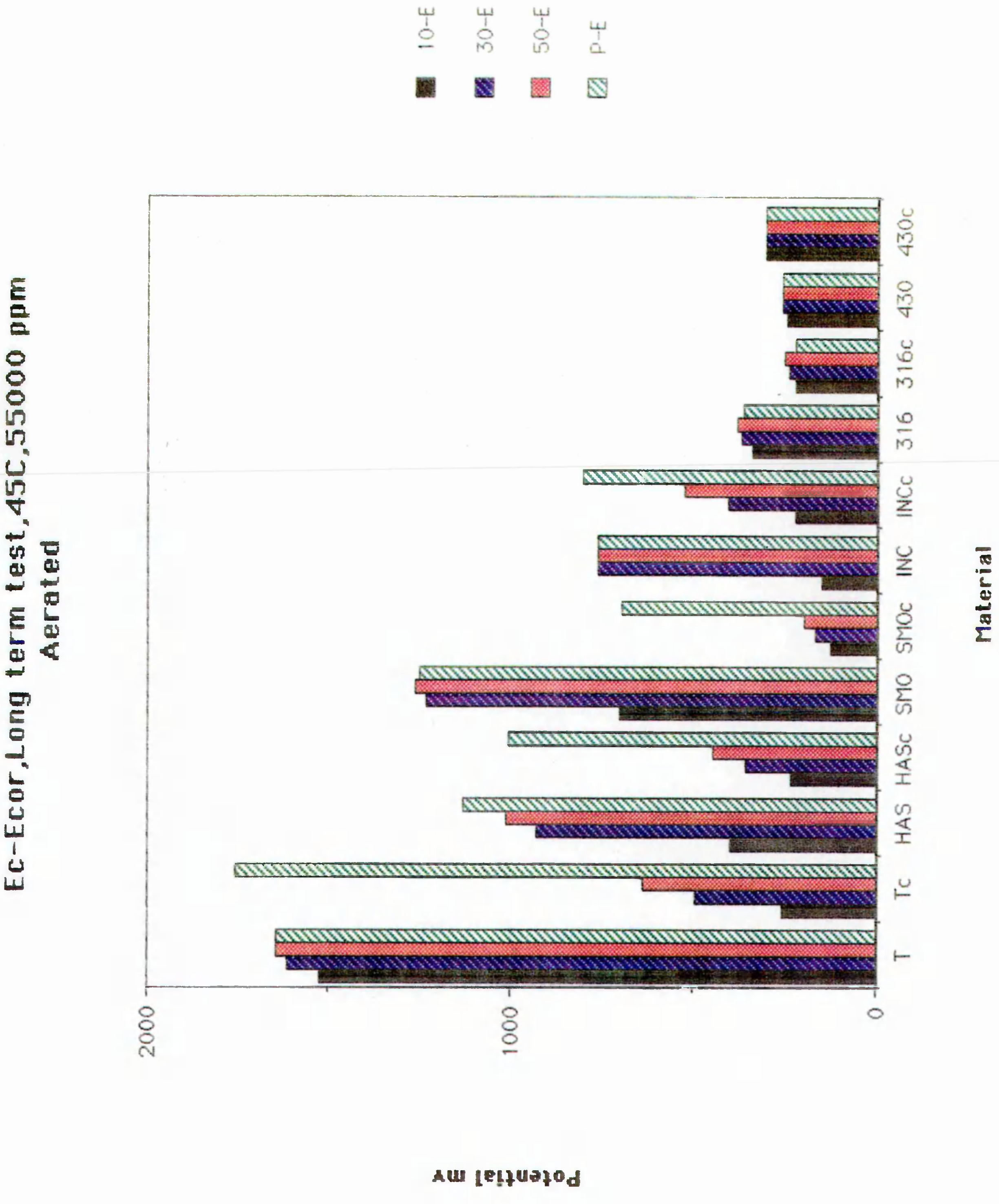



Ec-Ecor,25C,35000 ppm,Deaerated
Potential mv
2000
1000
0
T
Tc
HAS
HASc
SMO
SMOc
INC
INCc
316
316c
430
430c
Material
LONG TERM TEST
10-E
30-E
50-E
P-E


Ec-Er,25C,55000 ppm, Deaerated
Potential mv
2000
1000
0
T
Tc
HAS
HASc
SMO
SMOc
INC
INCc
316
316c
430
430c
Materials
LONG TERM TEST
10-E
30-E
50-E
P-E

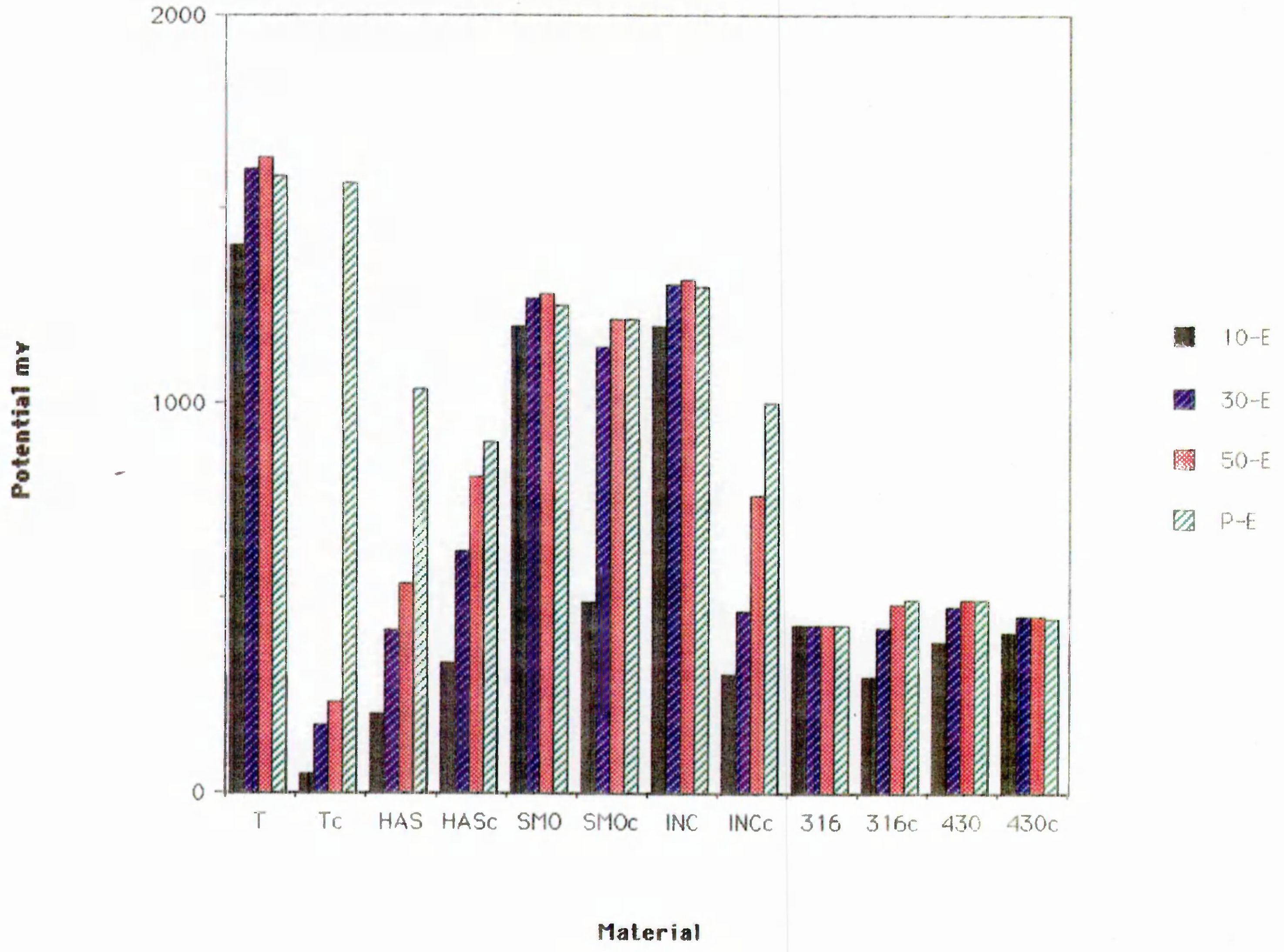
Ec-Ecor,Long term test,45C,35000 ppm
Aerated





Ec-Ecor,Long term test,45C,55000 ppm
Aerated

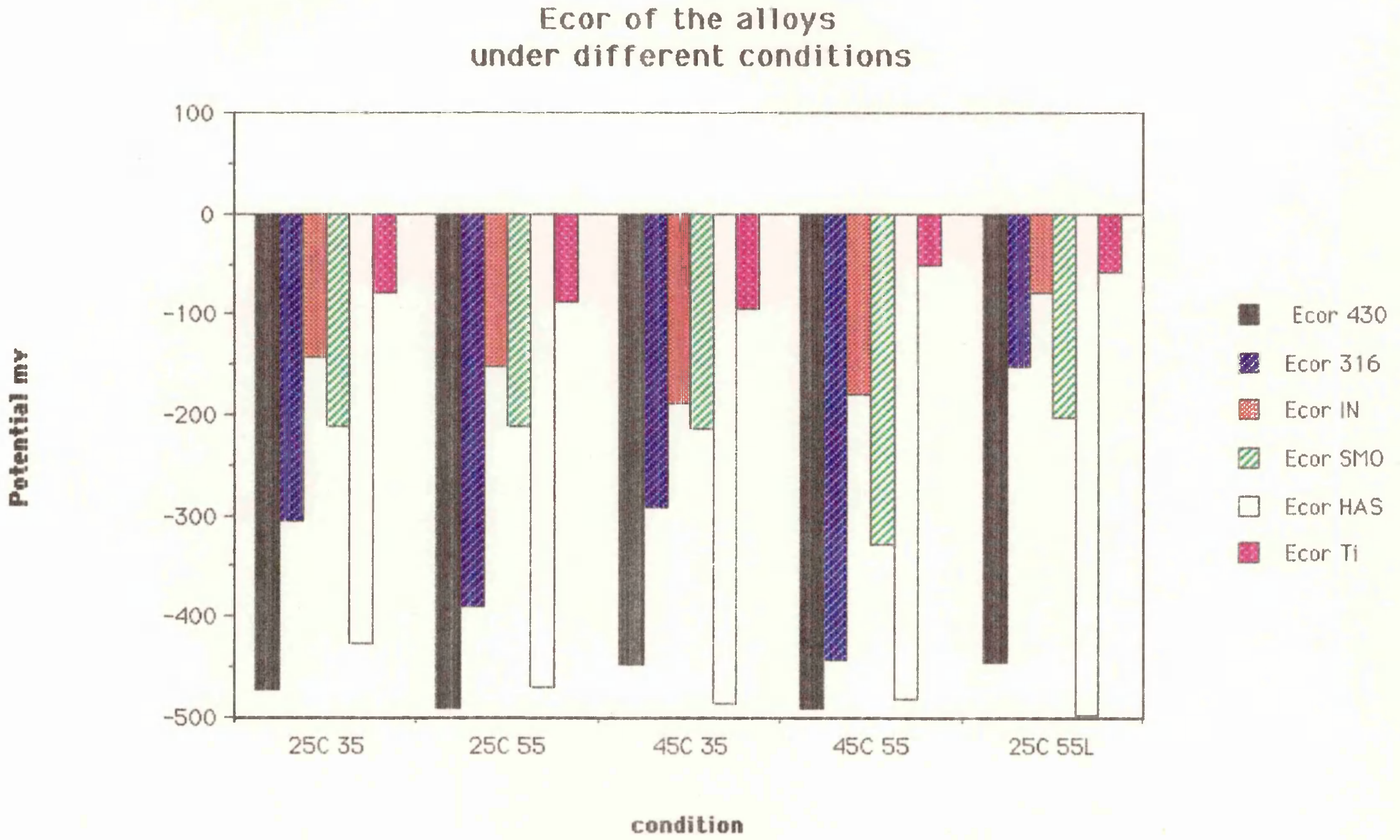
Ec-Ecor,Long term test,45C,35000 ppm
Deaerated

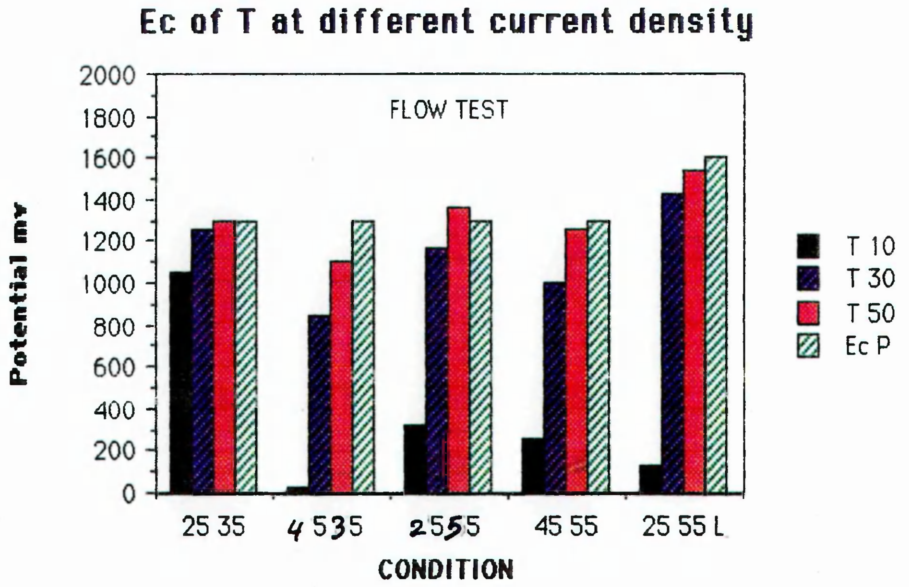


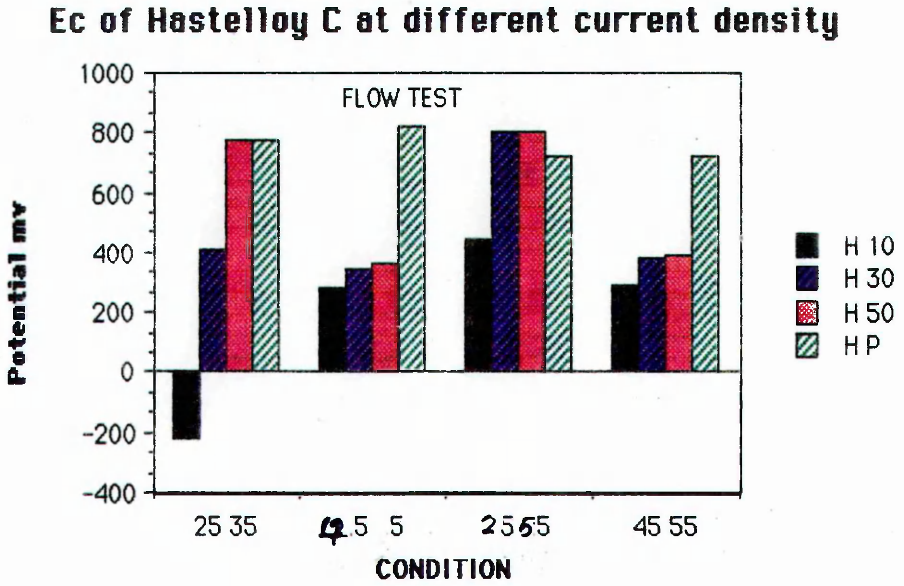
FLOW TEST RESULTS ANALYSIS

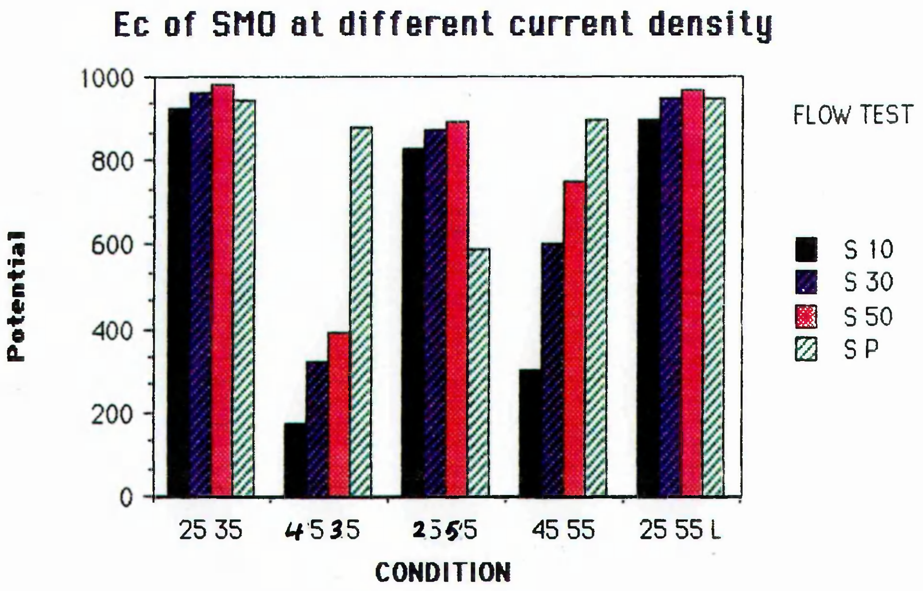
NOTATION:

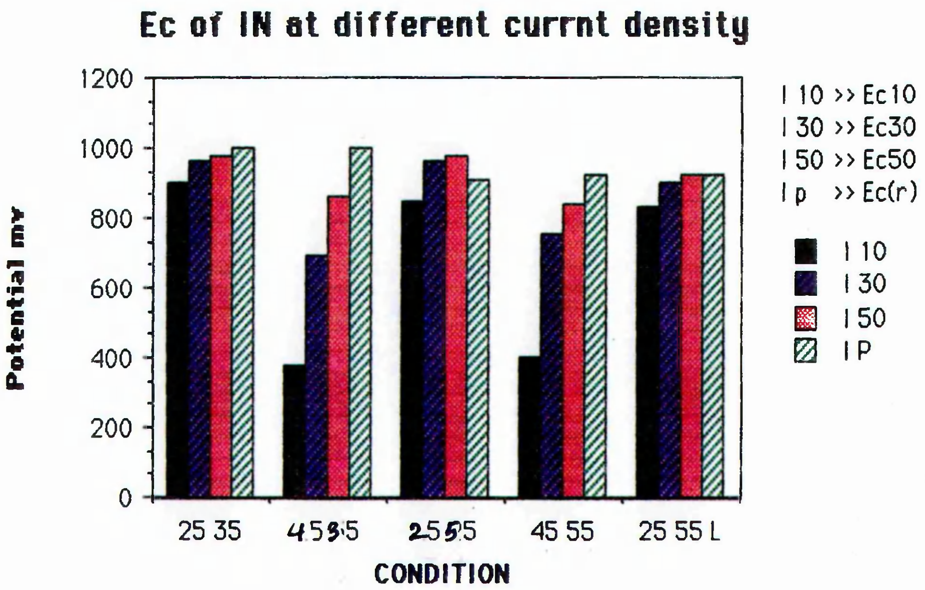
25 >>>> 25°C
45 >>>> 45°C
35 >>>> 35000 ppm
55 >>>> 55000 ppm
10 >>>> Ec10
30 >>>> Ec30
50 >>>> Ec50
p >>>> Ec(r)

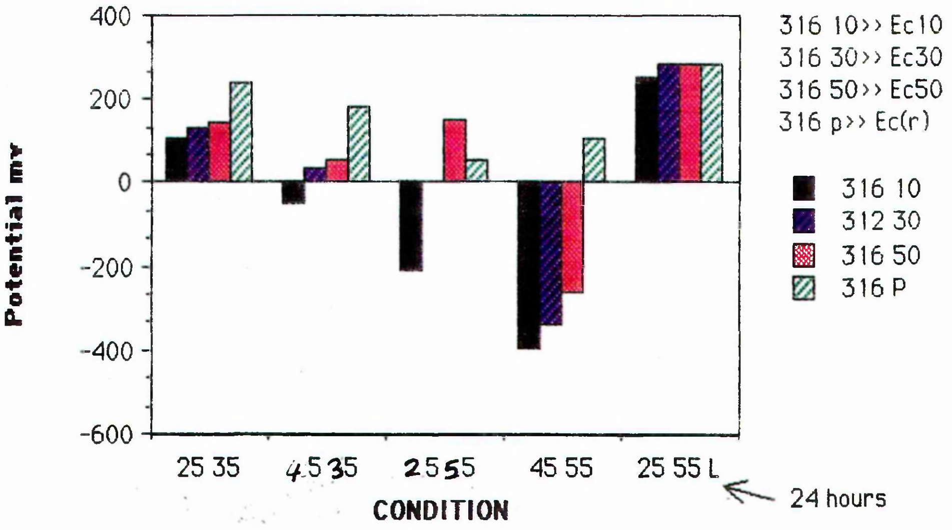

Ecor of the alloys
under different conditions
Potential mv
100
0
-100
-200
-300
-400
-500
25C 35
25C 55
45C 35
45C 55
25C 55L
condition
Ecor 430
Ecor 316
Ecor IN
Ecor SMO
Ecor HAS
Ecor Ti


Ec of T at different current density
FLOW TEST
Potential mv
2000
1800
1600
1400
1200
1000
800
600
400
200
0
25 35
4535
2555
45 55
25 55 L
CONDITION
T 10
T 30
T 50
Ec P

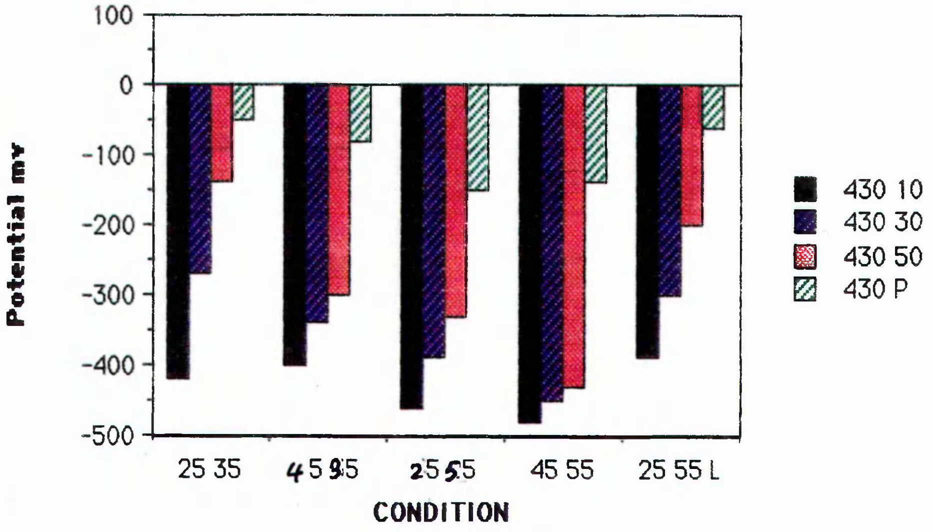

Ec of Hastelloy C at different current density
FLOW TEST
Potential mv
1000
800
600
400
200
0
-200
-400
25 35
4.5 5
2555
45 55
CONDITION
H 10
H 30
H 50
H P


Ec of SMO at different current density
Potential
1000
800
600
400
200
0
25 35
45 35
25 55
45 55
25 55 L
CONDITION
FLOW TEST
■ S 10
■ S 30
■ S 50
▨ S P


Ec of IN at different currnt density
Potential mv
1200
1000
800
600
400
200
0
25 35
45 35
25 55
45 55
25 55 L
CONDITION
I 10 >> Ec10
I 30 >> Ec30
I 50 >> Ec50
I p >> Ec(r)
■ I 10
■ I 30
■ I 50
▨ I P

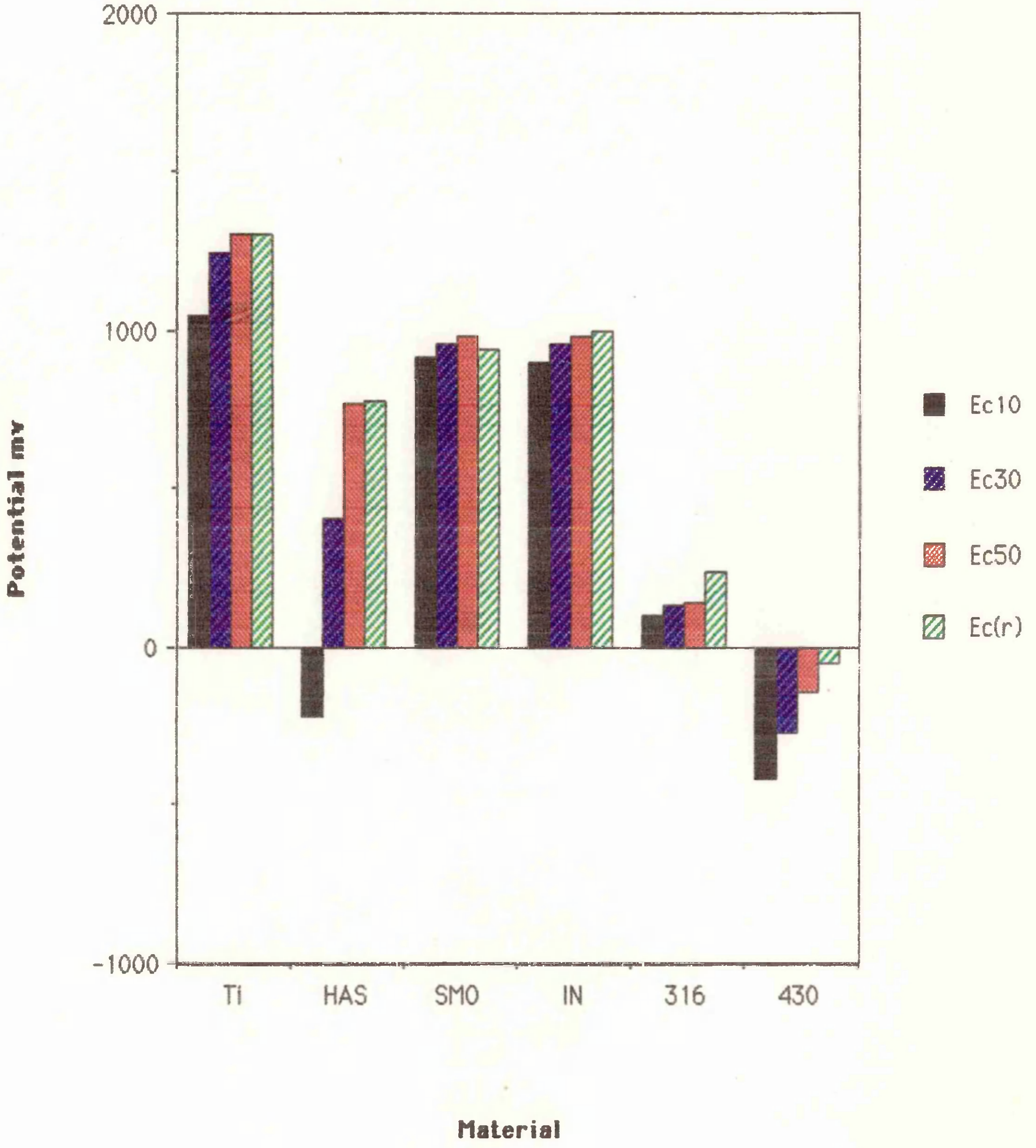


Ec of 316 at different current density

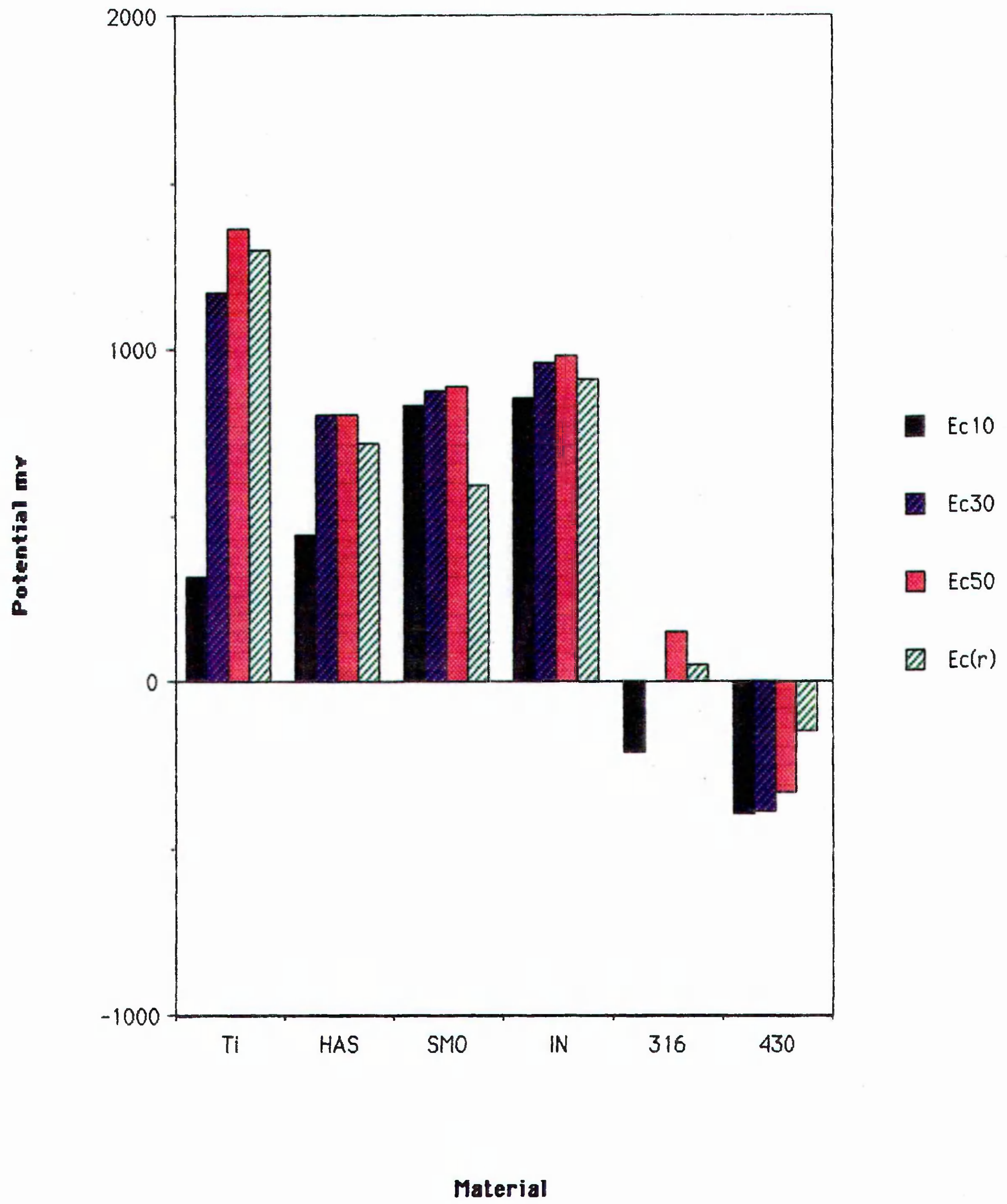


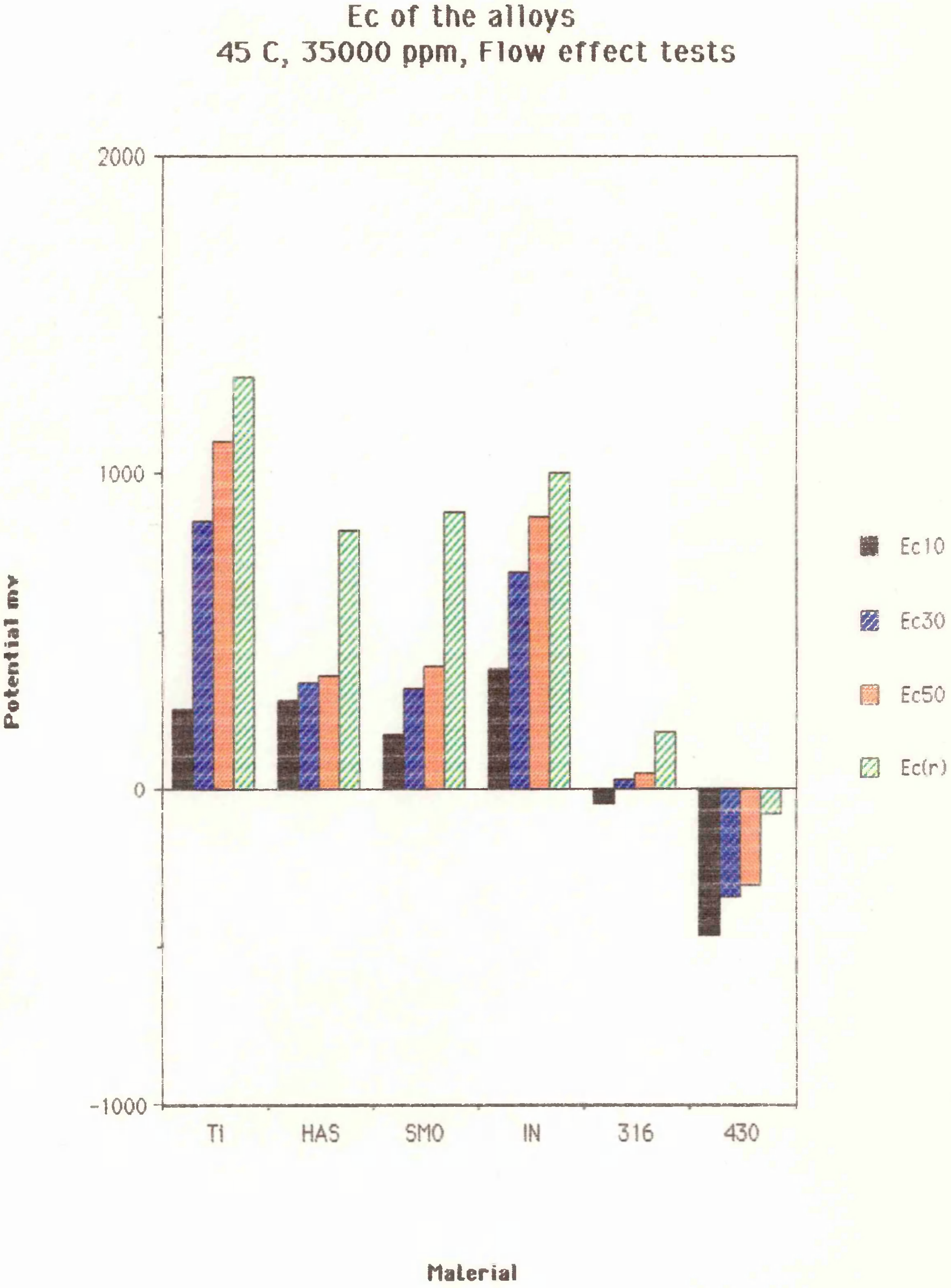
Ec of 430 at different current density

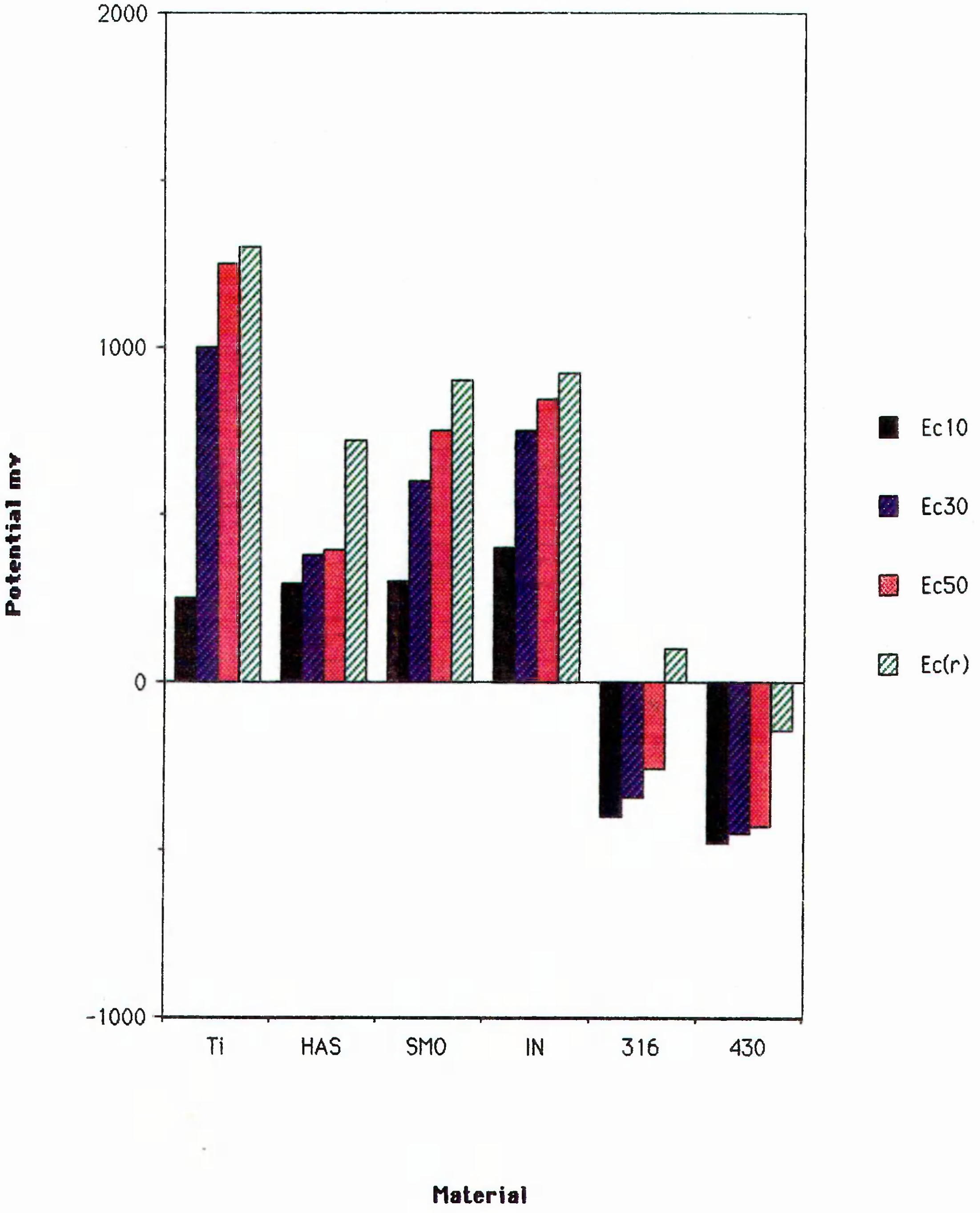
Ec of the alloys
25 C, 35000 ppm, Flow test



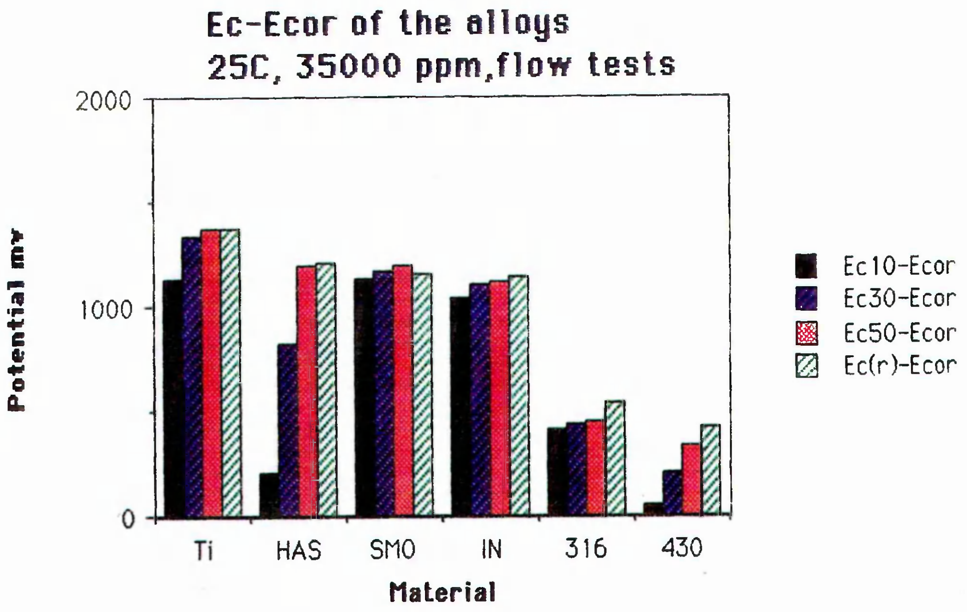
Ec of the alloys
25 C, 55000 ppm, Flow tests.

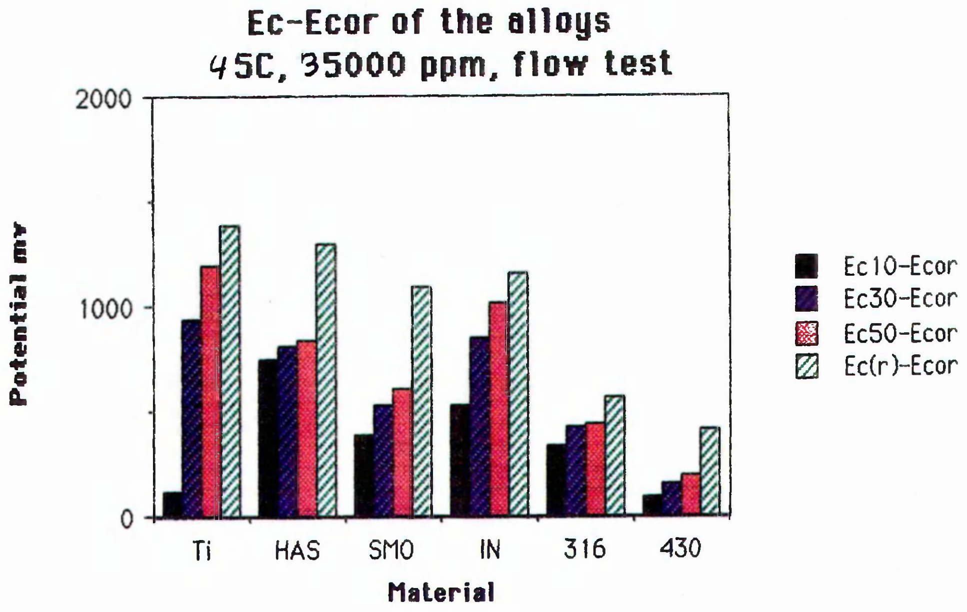


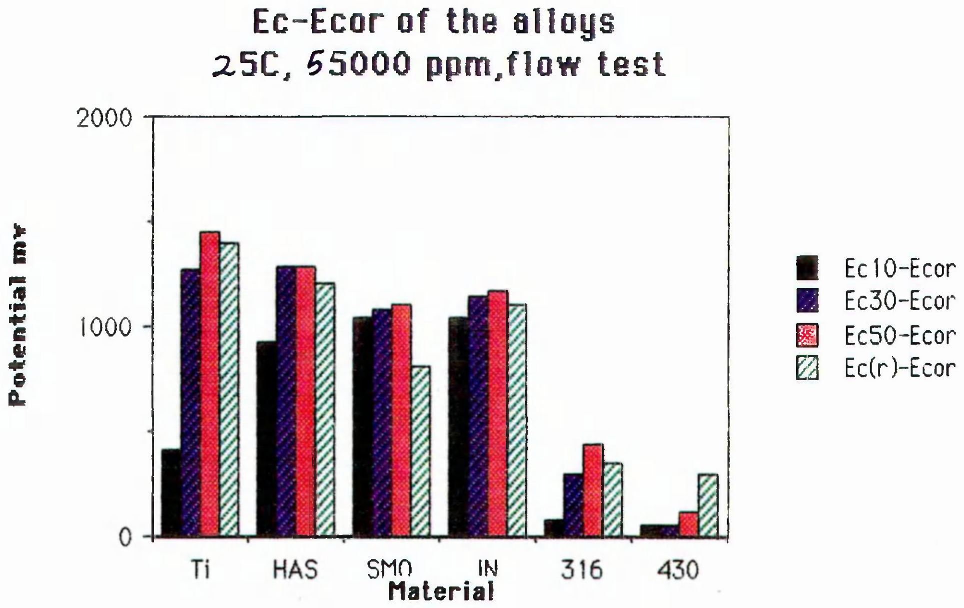

Ec of the alloys
45 C, 35000 ppm, Flow effect tests
2000
1000
0
-1000
Potential mv
Ti
HAS
SMO
IN
316
430
Material
Ec10
Ec30
Ec50
Ec(r)

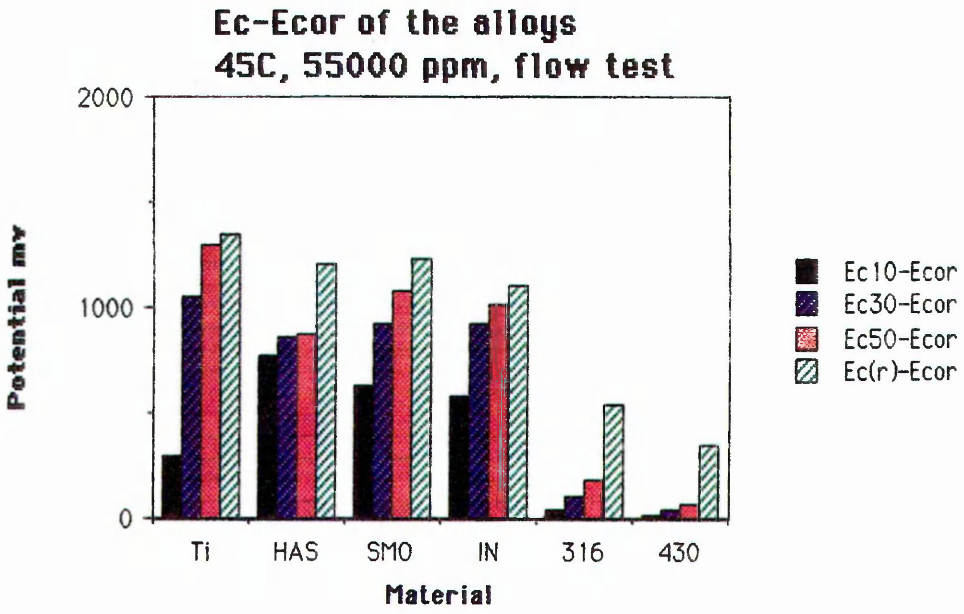


Ec of the alloys
45 C, 55000 ppm,Flow tests


Ec-Ecor of the alloys
25C, 35000 ppm,flow tests
Potential mv
2000
1000
0
Ti
HAS
SMO
IN
316
430
Material
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of the alloys
45C, 35000 ppm, flow test
Potential mv
2000
1000
0
Ti
HAS
SMO
IN
316
430
Material
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of the alloys
25C, 55000 ppm,flow test
Potential mv
2000
1000
0
Ti
HAS
SMO
IN
316
430
Material
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of the alloys
45C, 55000 ppm, flow test
Potential mv
2000
1000
0
Ti
HAS
SMO
IN
316
430
Material
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor

JET EFFECT TESTS RESULTS ANALYSIS

NOTATION:

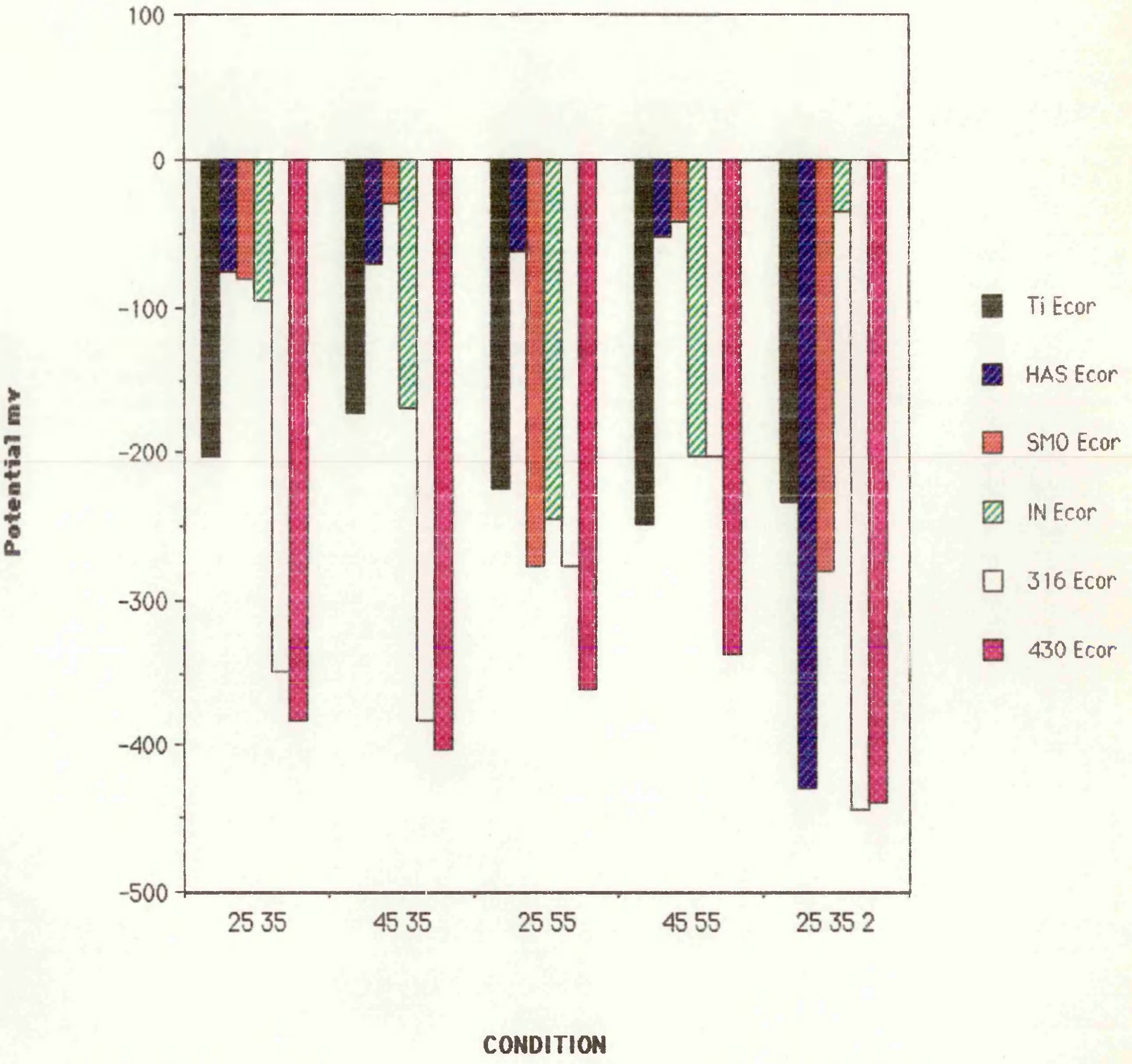
35 >>>> 35000 PPM

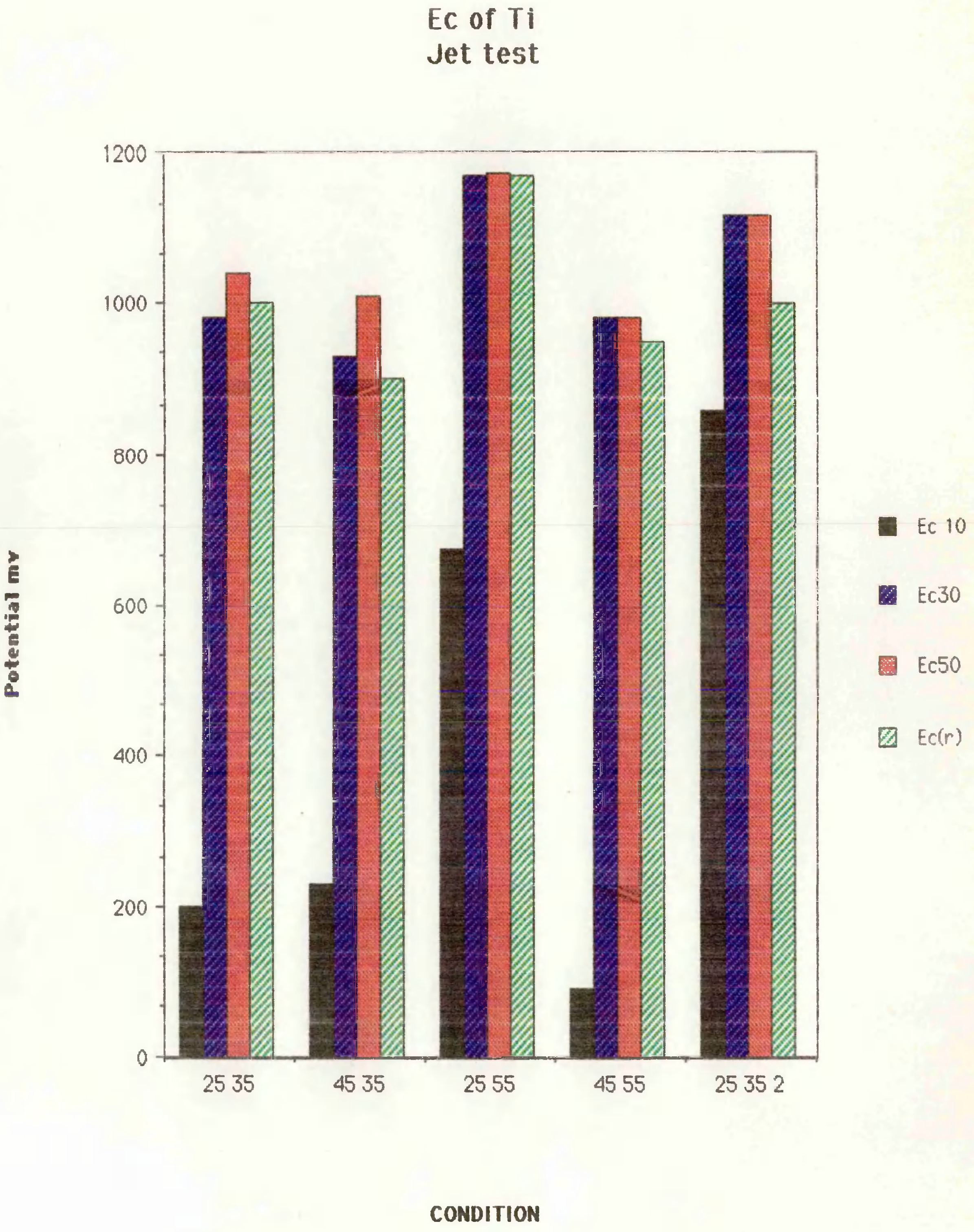
55 >>>> 55000 PPM

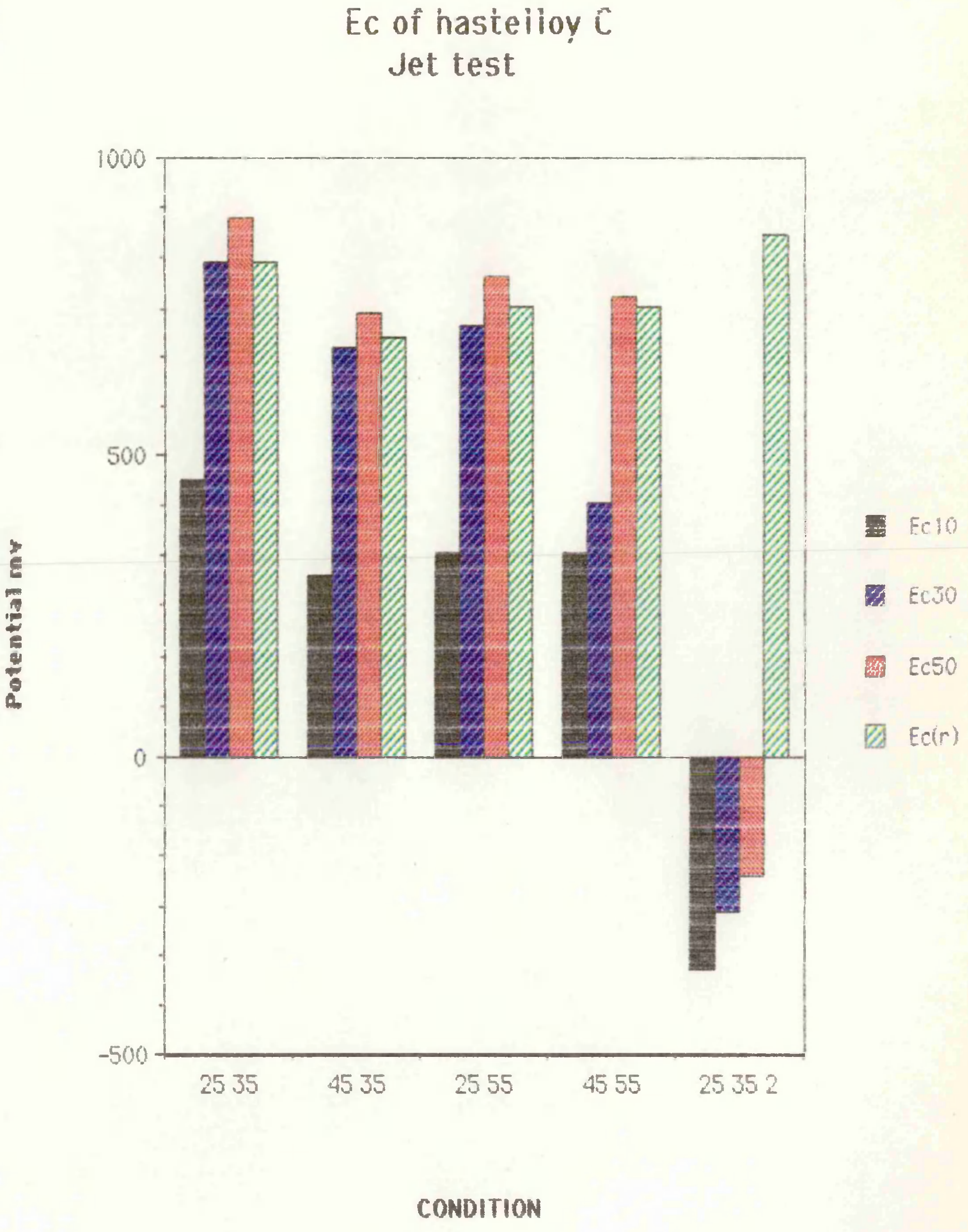
25 >>>> 25°C

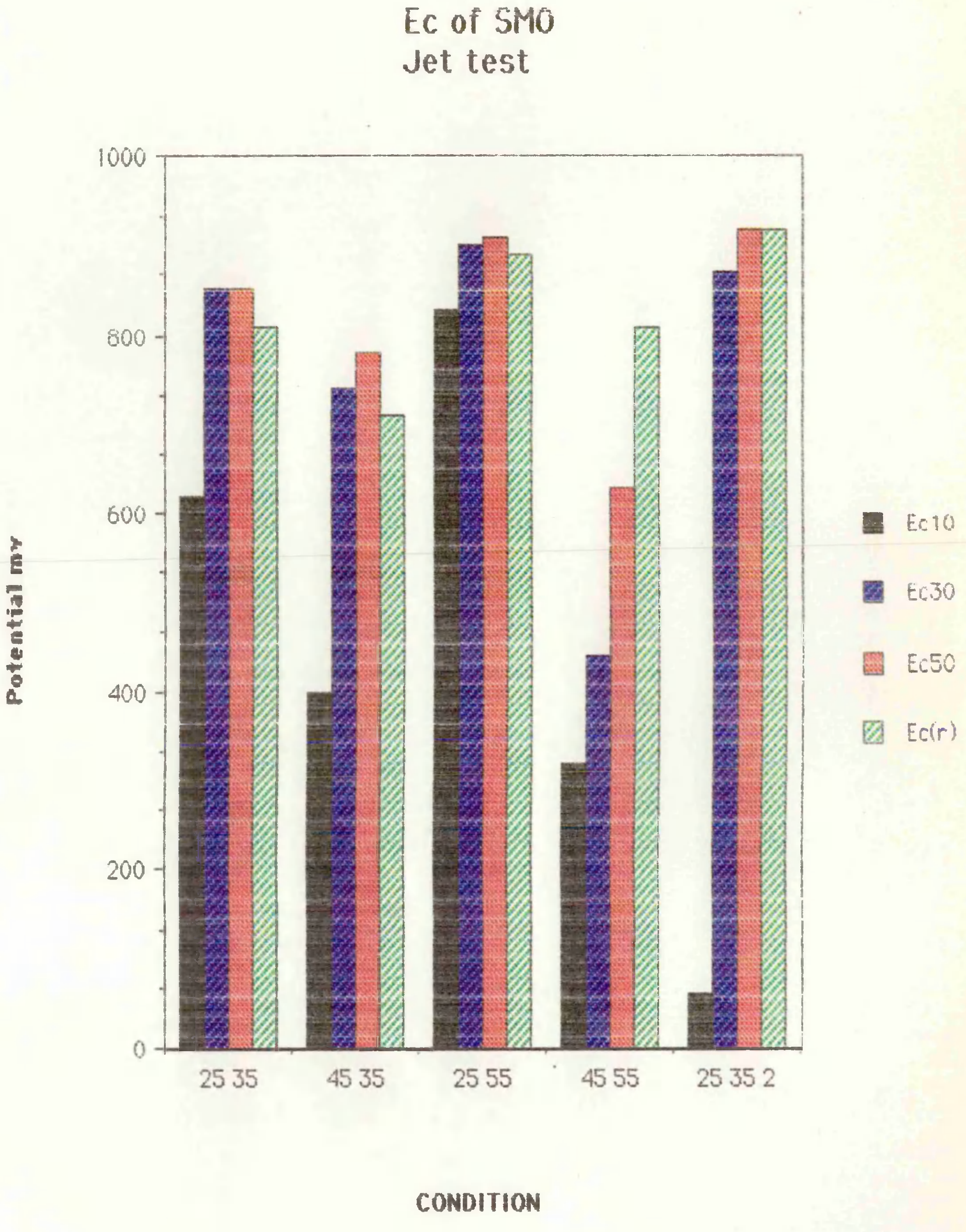
45 >>>> 45°C

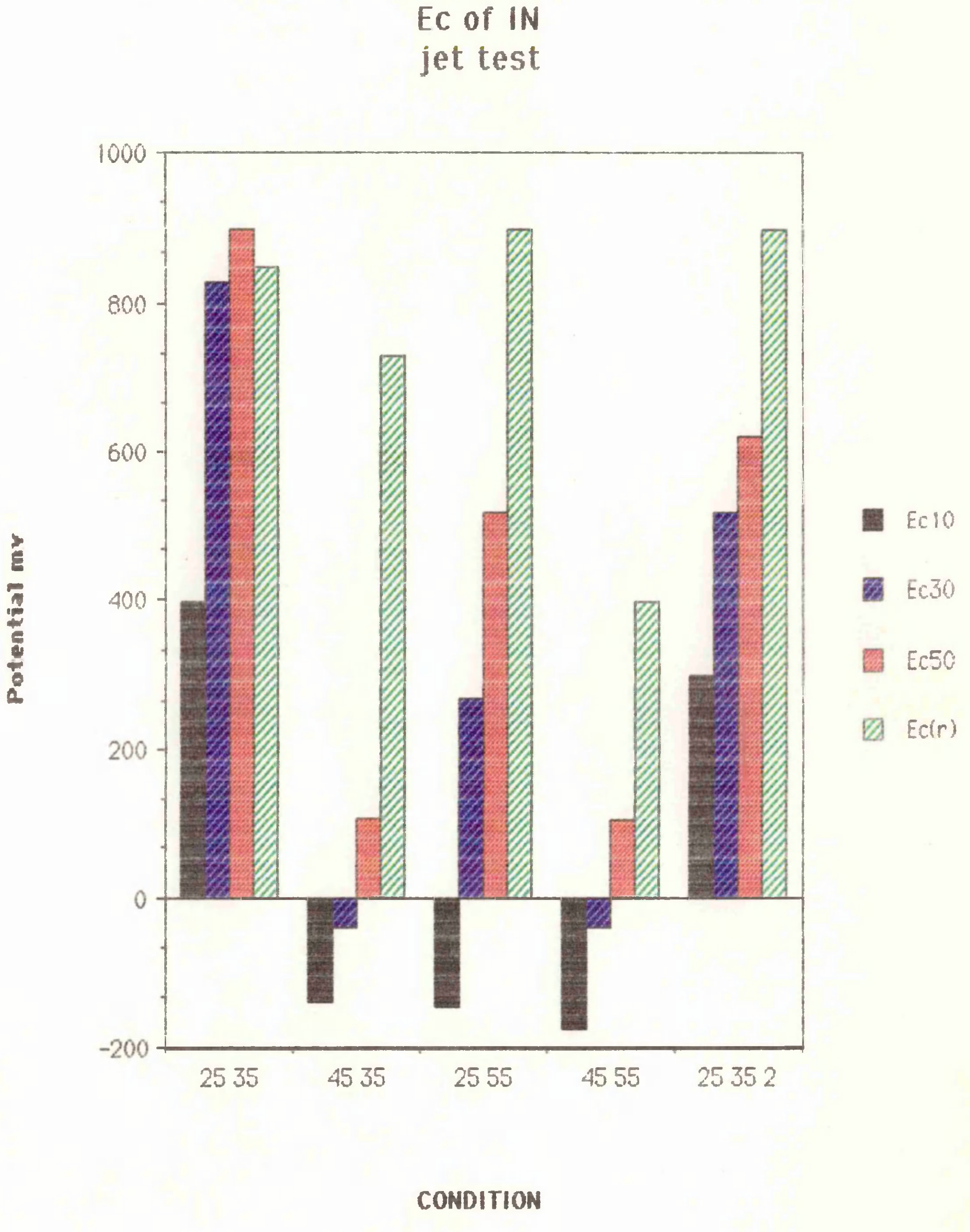
Ecor of the alloys
JET tests

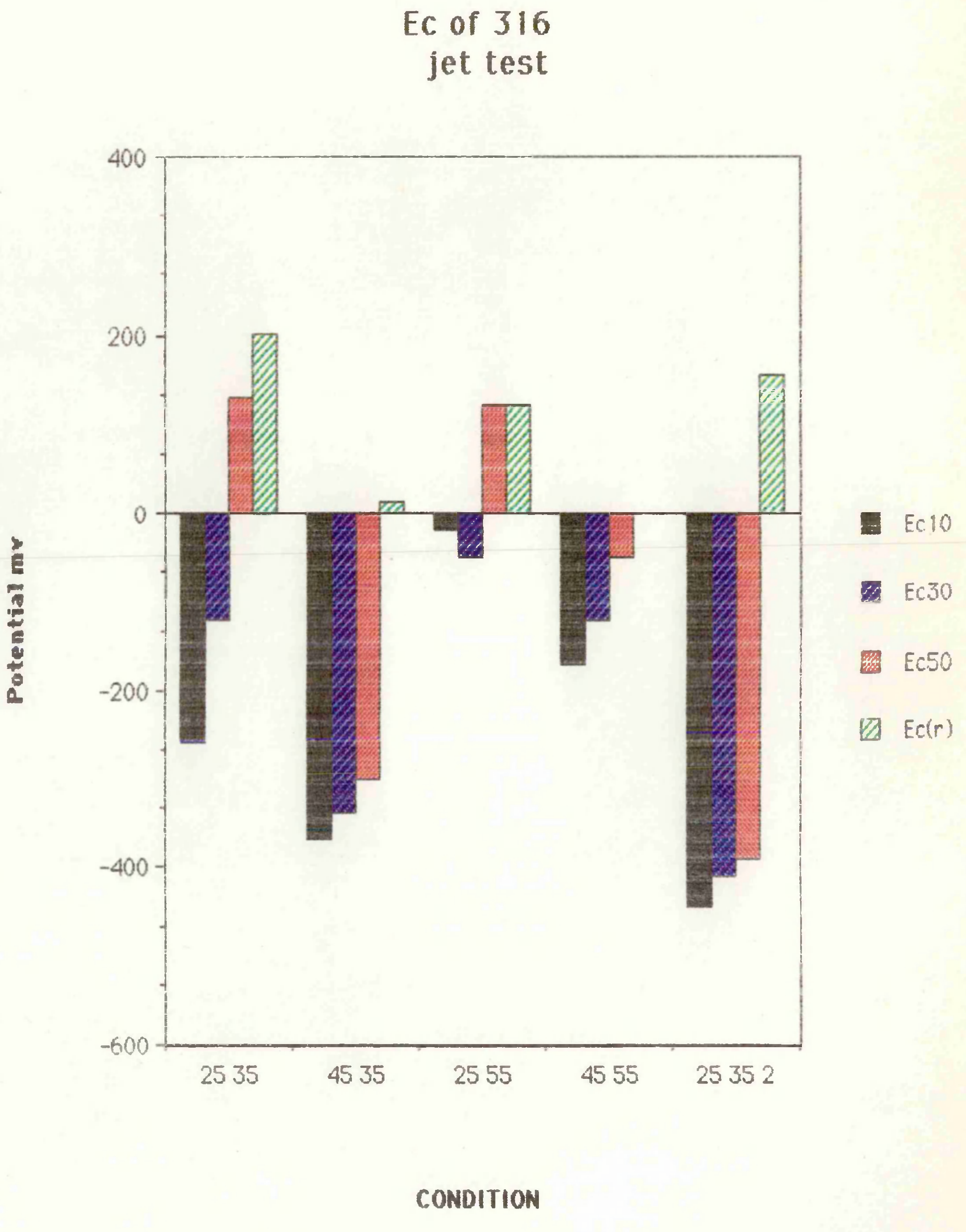


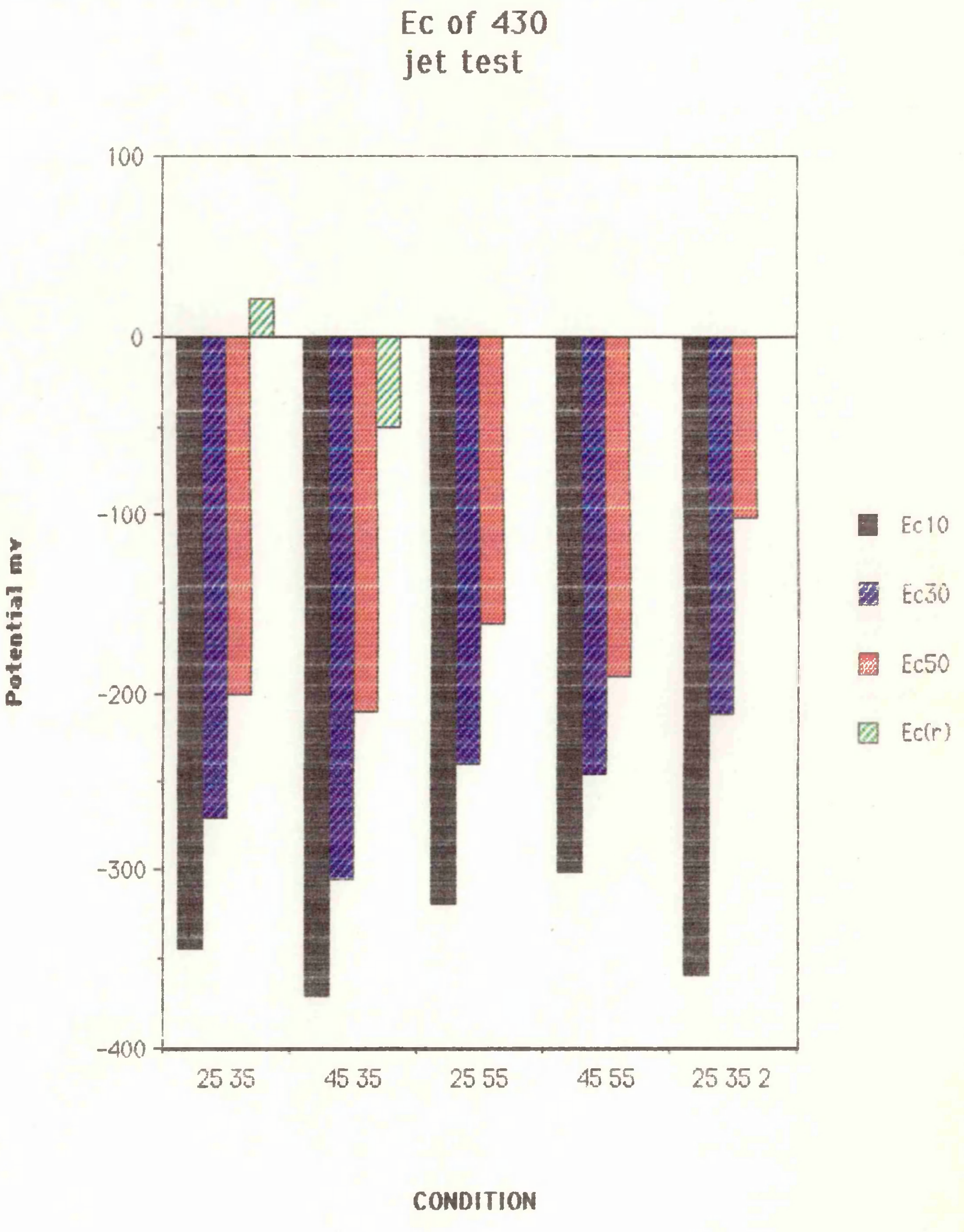

Ec of Ti
Jet test
Potential mv
1200
1000
800
600
400
200
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec 10
Ec30
Ec50
Ec(r)

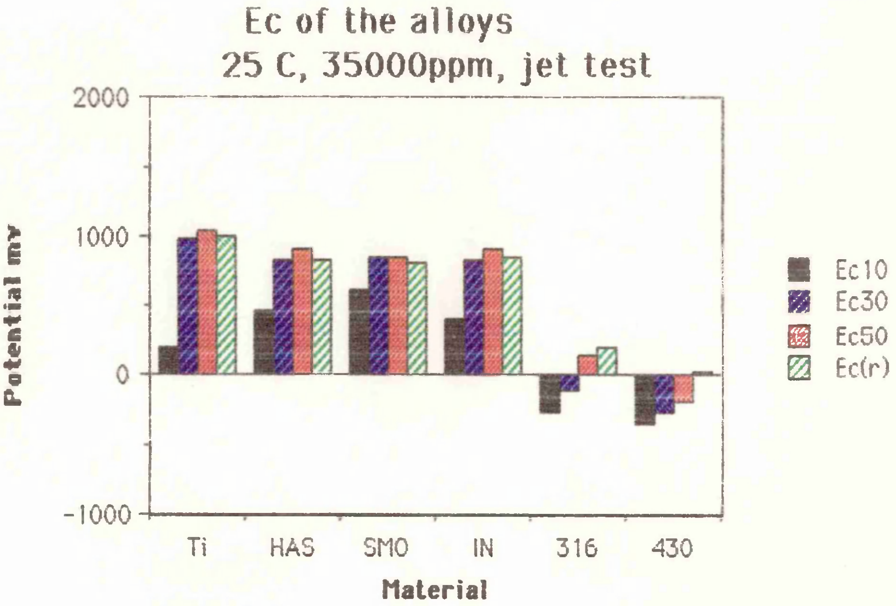

Ec of hastelloy C
Jet test
1000
500
0
-500
Potential mv
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10
Ec30
Ec50
Ec(r)

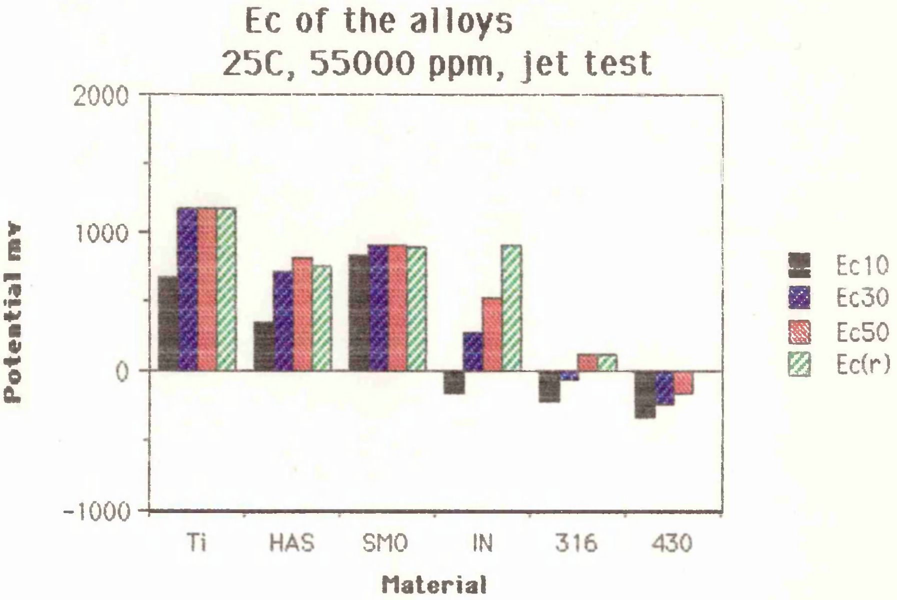

Ec of SMO
Jet test
1000
800
600
400
200
0
Potential mv
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10
Ec30
Ec50
Ec(r)

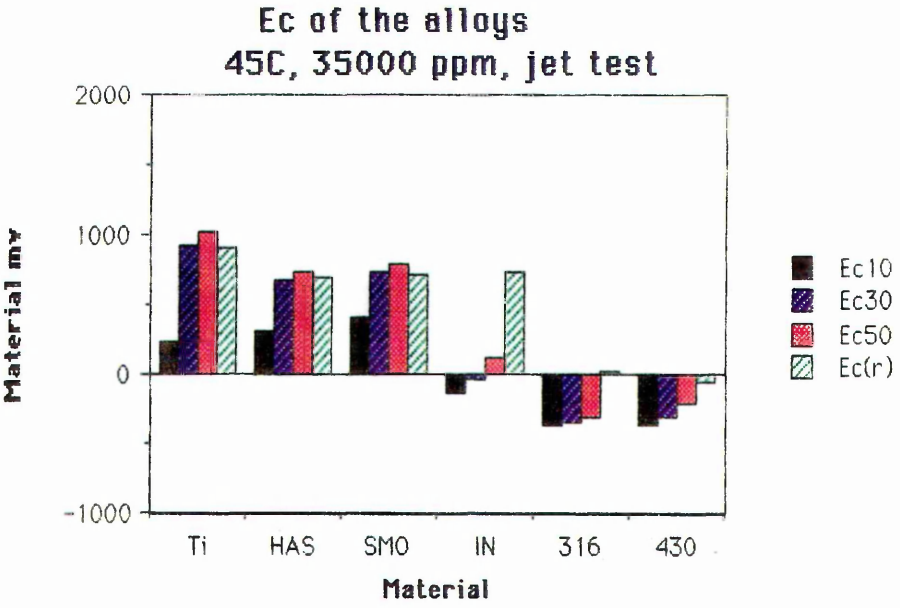

Ec of IN
jet test
Potential mv
1000
800
600
400
200
0
-200
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10
Ec30
Ec50
Ec(r)

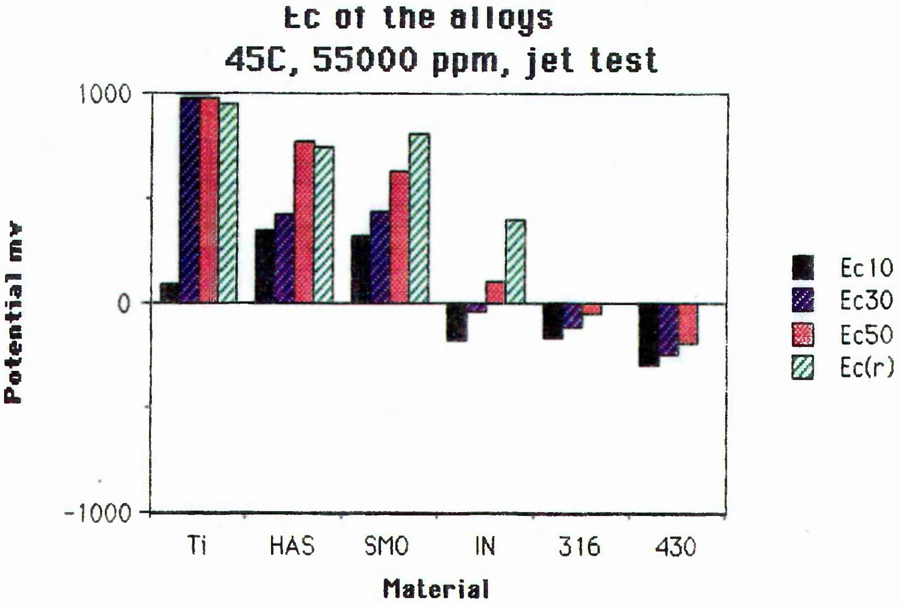

Ec of 316
jet test
400
200
0
-200
-400
-600
Potential mv
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10
Ec30
Ec50
Ec(r)

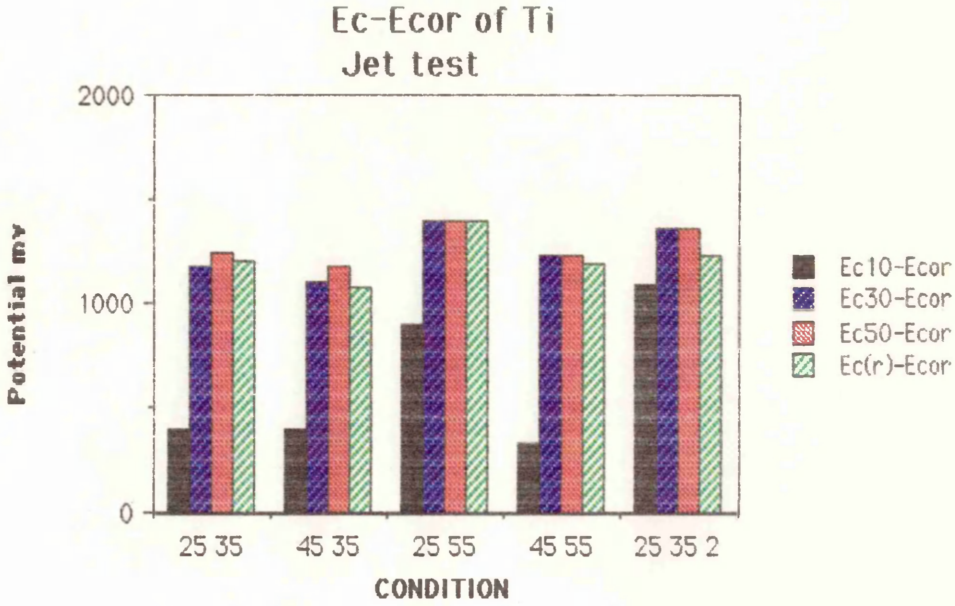

Ec of 430
jet test
100
0
-100
-200
-300
-400
Potential mv
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10
Ec30
Ec50
Ec(r)

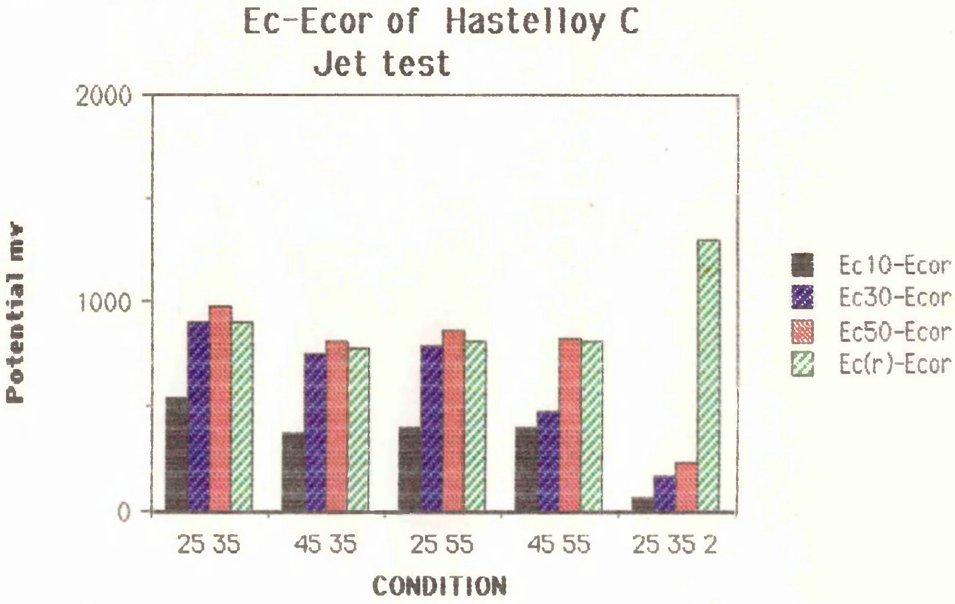

Ec of the alloys
25 C, 35000ppm, jet test
2000
1000
0
-1000
Potential mv
Ti
HAS
SMO
IN
316
430
Material
Ec10
Ec30
Ec50
Ec(r)

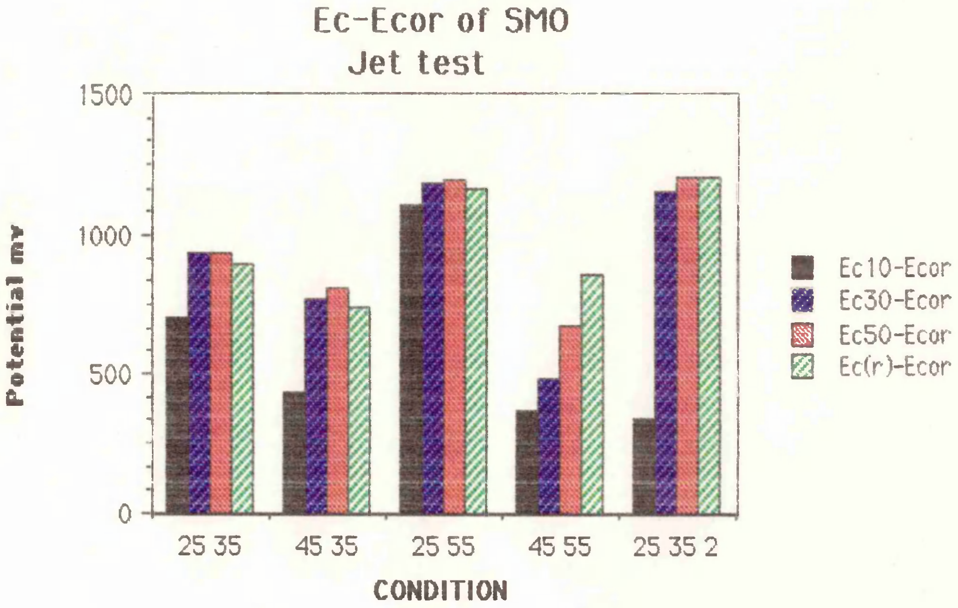

Ec of the alloys
25C, 55000 ppm, jet test
2000
1000
0
-1000
Potential mv
Ti
HAS
SMO
IN
316
430
Material
Ec10
Ec30
Ec50
Ec(r)

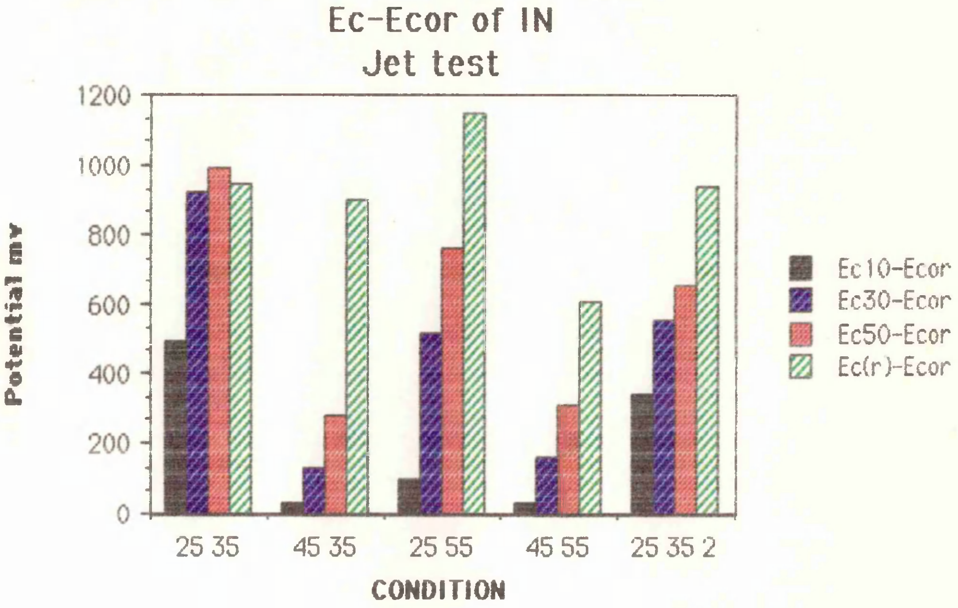

Ec of the alloys
45C, 35000 ppm, jet test
Material mv
2000
1000
0
-1000
Ti
HAS
SMO
IN
316
430
Material
Ec10
Ec30
Ec50
Ec(r)

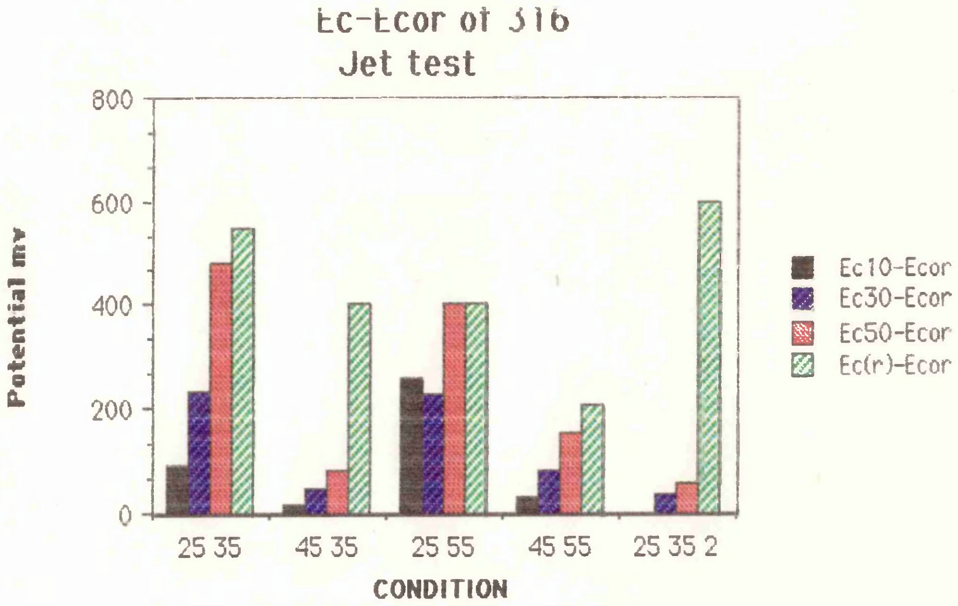

Ec of the alloys
45C, 55000 ppm, jet test
Potential mv
1000
0
-1000
Ti
HAS
SMO
IN
316
430
Material
Ec10
Ec30
Ec50
Ec(r)

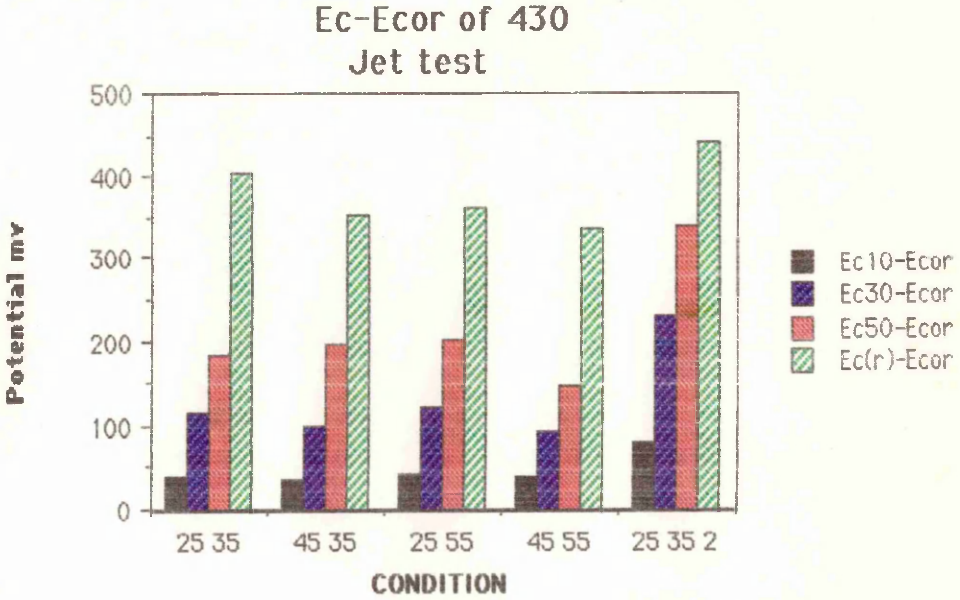

Ec-Ecor of Ti
Jet test
Potential mV
2000
1000
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of Hastelloy C
Jet test
Potential mV
2000
1000
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of SMO
Jet test
Potential mv
1500
1000
500
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of IN
Jet test
Potential mv
1200
1000
800
600
400
200
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of 316
Jet test
Potential mv
800
600
400
200
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor


Ec-Ecor of 430
Jet test
Potential mv
500
400
300
200
100
0
25 35
45 35
25 55
45 55
25 35 2
CONDITION
Ec10-Ecor
Ec30-Ecor
Ec50-Ecor
Ec(r)-Ecor

WEIGHT LOSS TESTS RESULTS

Weight loss results

	A	B	C	D	E	F	G
1	Condition	T before	T after	Loss	HAS before	HAS after	Loss
2	25 35 1	1.9975	1.9975	.0000	4.0530	4.0523	.0007
3	25 35 2	1.9975	1.9975	.0000	4.2525	4.2525	.0000
4	25 35 1c	1.8899	1.8892	.0007	4.0541	4.0534	.0007
5	25 35 2c	1.9089	1.9088	.0001	3.8540	3.8537	.0003
6							
7	25 55 1	1.9908	1.9904	.0004	4.2277	4.2274	.0003
8	25 55 2	2.0878	2.0868	.0010	4.2719	4.2715	.0004
9	25 55 1c	1.9577	1.9571	.0006	3.9137	3.9108	.0019
10	25 55 2c	1.9230	1.9214	.0016	3.8515	3.8515	.0000
11							
12	25 35 d 1	1.9840	1.9833	.0007	4.1417	4.1413	.0004
13	25 35 d 2	1.9448	1.9447	.0001	4.2450	4.2444	.0006
14	25 35 d 1c	1.9458	1.9447	.0011	4.0180	4.0180	.0000
15	25 35 d 2c	1.9956	1.9945	.0011	3.9264	3.9260	.0004
16							
17	25 55 d 1	2.0469	2.0469	.0000	4.2390	4.2390	.0000
18	25 55 d 2	2.0972	2.0967	.0005	4.3745	4.3745	.0000
19	25 55 d 1c	1.8855	1.8855	.0000	4.0504	4.0504	.0000
20	25 55 d 2c	1.9258	1.9253	.0005	3.8364	3.8364	.0000
21							
22	45 35 1	1.9533	1.9521	.0012	4.1736	4.1721	.0015
23	45 35 2	1.9396	1.9384	.0012	4.2986	4.2974	.0012
24	45 35 1c	1.8485	1.8470	.0015	4.0353	4.0337	.0016
25	45 35 2c	1.9872	1.9854	.0018	4.0659	4.0642	.0017
26							
27	45 55 1	2.0193	2.0178	.0015	4.2627	4.2627	.0000
28	45 55 2	1.9472	1.9460	.0012	4.1707	4.1696	.0011
29	45 55 1c	1.8718	1.8703	.0015	4.1427	4.1415	.0012
30	45 55 2c	1.9707	1.9692	.0015	4.1481	4.1468	.0013
31							
32	45 35 d 1	1.8903	1.8894	.0009	4.2758	4.2746	.0012
33	45 55 d 2	1.9710	1.9695	.0015	4.3187	4.3177	.0010
34	45 55 d 1c	1.9683	1.9668	.0017	3.8607	3.8588	.0009
35	45 55 d 2c	1.9225	1.9208	.0017	4.0485	4.0470	.0015
36							
37	75 35 1	2.0608	2.0608	.0000	4.4023	4.4020	.0003
38	75 35 2	1.9940	1.9940	.0000	4.1541	4.1541	.0000
39	75 35 1c	1.8924	1.8924	.0000	4.8052	4.8050	.0002
40	75 35 2c	1.9187	1.9184	.0003	4.0782	4.0780	.0002
41							
42	75 55 1	1.9160	1.9155	.0005	4.0407	4.0403	.0004
43	75 55 2	1.9185	1.9180	.0005	4.1900	4.1898	.0002
44	75 55 1c	1.8816	1.8805	.0011	3.9570	3.9569	.0001
45	75 55 2c	1.8452	1.8452	.0000	3.8200	3.8190	.0010

25 >> 25°C , 45 >> 45°C, 75 >> 75°C
35 >> 35000 ppm, 55 >> 55000 ppm
d >> deaerated condition
1 >> specimen No. 1,
2 >> specimen No. 2,
1c>> creviced specimen No. 1,
2c>> creviced specimen No. 2.

Table 6-1
Weight Loss Tests Results

	H	I	J	K	L	M	N
1	Condition	SMO before	SMO after	Loss	INCO before	INCO after	Loss
2	25 35 1	4.9307	4.9307	.0000	15.8100	15.8090	.0010
3	25 35 2	4.6515	4.6512	.0003	16.0210	16.0210	.0000
4	25 35 1c	4.5477	4.5473	.0003	15.4886	15.4879	.0007
5	25 35 2c	4.3792	4.3790	.0002	15.5968	15.5965	.0003
6							
7	25 55 1	4.7338	4.7334	.0004	16.6320	16.6318	.0002
8	25 55 2	4.8380	4.8376	.0004	15.8600	15.8600	.0000
9	25 55 1c	4.5782	4.5776	.0006	15.3851	15.3845	.0006
10	25 55 2c	4.5756	4.5750	.0006	15.2788	15.2985	.0003
11							
12	25 35 d 1	4.7487	4.7479	.0008	16.3629	16.3621	.0008
13	25 35 d 2	4.7677	4.7669	.0008	15.6200	15.6200	.0000
14	25 35 d 1c	4.5947	4.5939	.0008	15.2138	15.2132	.0006
15	25 35 d 2c	4.5100	4.5093	.0007	15.2100	15.2027	.0073
16							
17	25 55 d 1	4.5513	4.5513	.0000	16.4772	16.4772	.0000
18	25 55 d 2	4.6129	4.6129	.0000	16.2779	16.2779	.0000
19	25 55 d 1c	4.6765	4.6765	.0000	15.3076	15.3076	.0000
20	25 55 d 2c	4.5589	4.5589	.0000	15.7562	15.7562	.0000
21							
22	45 35 1	4.7804	4.7789	.0015	15.9771	15.9765	.0006
23	45 35 2	4.6197	4.6185	.0012	15.8485	15.8476	.0009
24	45 35 1c	4.3852	4.3834	.0018	15.3008	15.2991	.0017
25	45 35 2c	4.6455	4.6434	.0021	15.2812	15.2758	.0054
26							
27	45 55 1	4.7990	4.7977	.0013	15.7652	15.7652	.0000
28	45 55 2	4.6782	4.6770	.0012	16.1616	15.1616	.0000
29	45 55 1c	4.5056	4.5042	.0014	15.3758	15.3736	.0022
30	45 55 2c	4.6147	4.6131	.0016	15.3883	15.3859	.0024
31							
32	45 35 d 1	4.7068	4.7059	.0009	16.0870	16.0864	.0006
33	45 55 d 2	4.5200	4.5191	.0009	15.8108	15.8076	.0032
34	45 55 d 1c	4.6291	4.6281	.0010	15.7103	15.7087	.0016
35	45 55 d 2c	4.3904	4.3891	.0013	15.2121	15.2112	.0009
36							
37	75 35 1	4.8472	4.8472	.0000	16.0700	16.0700	.0000
38	75 35 2	4.6311	4.6311	.0000	16.3635	16.3635	.0000
39	75 35 1c	4.4038	4.4038	.0000	14.8635	14.8630	.0005
40	75 35 2c	4.5517	4.5503	.0014	14.8591	14.8540	.0051
41							
42	75 55 1	4.7282	4.7271	.0011	16.0827	16.0827	.0000
43	75 55 2	4.7053	4.7047	.0006	16.2176	16.2176	.0000
44	75 55 1c	4.5364	4.5353	.0011	15.6267	15.6259	.0008
45	75 55 2c	4.4754	4.4744	.0010	15.6713	15.6593	.0120

25 >> 25°C , 45 >> 45°C, 75 >> 75°C
35 >> 35000 ppm, 55 >> 55000 ppm
d >> deaerated condition
1 >> specimen No. 1,
2 >> specimen No. 2,
1c>> creviced specimen No. 1,
2c>> creviced specimen No. 2.

Weight loss results

	O	P	Q	R	S	T	U
1	Condition	316 before	316 after	Loss	430 before	430 after	Loss
2	25 35 1	2.1165	2.1162	.0003	2.7053	2.0748	.6305
3	25 35 2	2.0605	2.0600	.0005	2.5760	2.5766	.0000
4	25 35 1c	2.0010	2.0000	.0010	2.6136	2.6128	.0008
5	25 35 2c	1.9768	1.9764	.0004	2.5137	2.5130	.0007
6							
7	25 55 1	2.1483	2.1478	.0005	2.6431	2.6424	.0007
8	25 55 2	2.1523	2.1520	.0003	2.5856	2.5849	.0007
9	25 55 1c	1.9294	1.9283	.0011	2.4845	2.4824	.0021
10	25 55 2c	2.0309	2.0306	.0003	2.5253	2.5245	.0008
11							
12	25 35 d 1	2.0417	2.0409	.0008	2.7985	2.7974	.0011
13	25 35 d 2	2.0800	2.0790	.0010	2.6008	2.5996	.0012
14	25 35 d 1c	2.0210	2.0199	.0011	2.4481	2.4470	.0011
15	25 35 d 2c	1.9632	1.9619	.0013	2.4424	2.4415	.0009
16							
17	25 55 d 1	2.1157	2.1157	.0000	2.5862	2.5860	.0002
18	25 55 d 2	2.1076	2.1076	.0000	2.6333	2.6333	.0000
19	25 55 d 1c	2.0340	2.0340	.0000	2.4613	2.4612	.0001
20	25 55 d 2c	1.9865	1.9865	.0000	2.4989	2.4989	.0000
21							
22	45 35 1	2.1070	2.1056	.0014	2.6635	2.6620	.0015
23	45 35 2	2.0894	2.0880	.0014	2.6057	2.6045	.0012
24	45 35 1c	2.0170	2.0155	.0015	2.4786	2.4767	.0019
25	45 35 2c	2.0551	2.0533	.0018	2.6224	2.6208	.0016
26							
27	45 55 1	2.1817	2.1296	.0521	2.5661	2.5587	.0074
28	45 55 2	2.0572	2.0559	.0013	2.5618	2.5609	.0009
29	45 55 1c	1.9776	1.9763	.0013	2.4510	2.4492	.0018
30	45 55 2c	1.9825	1.9819	.0006	2.1174	2.1165	.0009
31							
32	45 35 d 1	2.0300	2.0296	.0004	2.0664	2.6050	-1.0000
33	45 55 d 2	2.1338	2.1326	.0012	2.7373	2.7357	.0016
34	45 55 d 1c	1.9662	1.9647	.0015	2.4837	2.4820	.0017
35	45 55 d 2c	2.0295	2.0280	.0015	2.4872	2.4858	.0014
36							
37	75 35 1	2.1121	2.1117	.0004	2.5311	2.5297	.0014
38	75 35 2	2.1239	2.1238	.0001	2.6536	2.6531	.0005
39	75 35 1c	2.0050	2.0050	.0000	2.6358	2.6344	.0014
40	75 35 2c	2.0727	2.0719	.0008	2.6917	2.6905	.0012
41							
42	75 55 1	2.1193	2.1186	.0007	2.6683	2.6635	.0048
43	75 55 2	2.1317	2.1309	.0008	2.6690	2.6657	.0033
44	75 55 1c	2.0333	2.0324	.0009	2.5987	2.5848	.0139
45	75 55 2c	2.0402	2.0390	.0012	2.4469	2.4340	.0129

25 >> 25°C , 45 >> 45°C, 75 >> 75°C
35 >> 35000 ppm, 55 >> 55000 ppm
d >> deaerated condition
1 >> specimen No. 1,
2 >> specimen No. 2,
1c>> creviced specimen No. 1,
2c>> creviced specimen No. 2.

TABLE 6-2
Crevice Corrosion Measured Visually
-Weight Loss tests-

		25,35, A	25,55, A	25,35, D	25,55, D	45,35, A	45,55, A	45,35, D	75,35	75,55
Ti	1									
	2									
	1c									
	2c									
Has	1									
	2									
	1c									
	2c								△	
Smo	1									
	2									
	1c	△		△	△	△				△
	2c		△	△	△	△	△			◮
IN	1									
	2									
	1c	◮*								
	2c									
316	1									
	2									
	1c									△
	2c								△	◮
430	1						◮		△	▲
	2									◮
	1c	◮	▲		◮	◮	◮	◮		▲
	2c					◮		◮		▲

△ >>> Low corrosion
◮ >>> Moderate corrosion
▲ >>> High corrosion
25 >>> 25^{o}C
45 >>> 45^{o}C.
75 >>> 75^{o}C.
35 >>> 35000ppm.
55 >>> 55000ppm
* corrosion remarked on the side of the specimen.

CHAPTER SEVEN

DISCUSSION

7-1 Introduction

The results obtained in the previous chapter raise some interesting points. These points will be discussed through the following policy. First, some discussion about those experiments in which the measured currents between Ecor and Ec were relatively high (i.e. >10 micro amps.) will be done. Second, the effect of the environment conditions will be discussed for each alloy. Finally, the behaviour of the alloys under the same condition will be compared. Before starting the discussion of the results, it should be stressed again that the conditions selected in this thesis are relevant to the R.O. desalination plant conditions, also the alloys used were selected according to their application in desalination industries.Of course one material studied, titanium, is very expensive, hence not used in R.O. desalination plant, but as mentioned before it was used as an ideal reference for the other alloys. Consequently, the results obtained can be used as a guide to the material selection for the R.O. plants. For example the flow test was made for the effect of the flow of the corrodent on the pipe material, while jet test made to study the effect of the nozzle jet on the impulse turbine buckets used as energy recovery turbine, also long term test were used for the vessels and tanks material , while the static test was considered to be the base for comparisons.

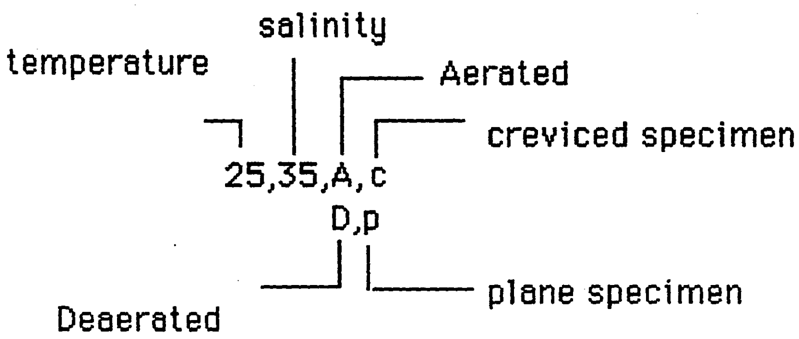
7-2 Occurence of relatively-higher currents in passive potential range.

In some of the experiments, rather higher currents were observed in potential region between Ecor and the potential, Ec(r), at which the much-more rapid increase in current occured. This behaviour was quite prevalent (table 7-1) in the long term experiments but was alomst completely absent from the short term static tests being observed in two materials only exposed to the most saline water under deaerated conditions at higher temperatures.

Table 7-1
High current measred during the polarization tests

		Ti	HAS	SMO	IN	316	430
Static test	25,35,A						
	55,A						
	35,D						
	55,D						
	35,35,A						
	55,A						
	35,D						
	55,D						
	45,35,A						
	55,A						
	35,D						
	55,D		●	●			
	65,35,A						
	55,A						
	35,D						
	55,D		●	●			
	85,35,A						
	55,A						
	35,D						
	55,D		●	●			
long term	25,35,A,p		●		●		
	,35,A,c	●	●		●	●	
	,55,A,p		●	●	●		
	,55,A,c	●	●	●	●		
	,35,D,p					●	
	,35,D,c		●		●	●	●
	,55,D,p			●	●		●
	,55,D,c	●	●		●	●	
	45,35,A,p		●	●	●		
	,35,A,c	●	●		●		
	,55,A,p		●				
	,55,A,c	●	●	●	●		
	,35,D,p	●	●				
	,35,D,c		●	●	●	●	

		Ti	HAS	SMO	IN	316	430
Flow test	25,35		●				●
	,55	●		●	●		●
	45,35		●			●	●
	,55			●	●	●	●
Jet test	25,35				●	●	●
	,55				●	●	●
	45,35				●	●	●
	,55		●	●	●	●	●



● high- current test
blank low current test

The currents recorded in this "passive- potential range" must be indicating something about the corrosion behaviour of the materials and this is why, in the comparison of the materials, the potentials corresponding to different currents have been quoted in the previous chapter.

Nevertheless it should be emphasized that these rather higher currents sometimes did not arise until the potential in the anodic polarization scan was significanly more positive than Ecor. Also, the rates of current increase withrespect to potential, in the relevant potential range below Ec(r), were considerably lower (by a factor of 20 times or greater) than those recorded at potentials at, and more positive to, Ec(r). Thus the events occuring when these relatively high currents are observed below Ec(r) are clearly of far less significance in determining the basic resistance to passive film breakdown then, these events at potential at and more positive to Ec(r).

It is likely that this " high-current behaviour" between Ecor and Ec is associated with crevice corrosion occuring at localised regions of the specimen. These regions could either be under the deliberately induced central crevice in the model crevice specimens or at the interface between the specimen and the sorrounding polymer resin. Such crevice corrosion would be expected to be more prevalent in specimens subjected to long exposures in the corrosive environment. This is in line both with visual observation (see e.g. photographs in previous chapter) and also with the observation of a much greater tendency for the " high-current phenomenon" in the long term experiments (table 7-1).

7-2-1. Behaviour more typical of active corrosion.

In some of the tests(table 7-1) involving the 430 and 316 grades of stainless steel, the anodic polarization curves exhibited rapidly increasing current immediately upon commencing the sweep, i.e. at potentials immediately positive to Ecor. This is indicative of essentially active corrosion,i.e. either non-passive behaviour during natural corrosion at the free corrosion potential or of very easy breakdown of any passive film. Indeed, the current: potential gradients in such circumstances were of the same order as those recorded, at potentials more positive to Ec, in other experiments when the more normal passive-to- active transition occured.

It thus appears that the tow lowest-grade materials in the expeimental programme, type 430 and 316, were undergoing essentially non-protective corrosion even at Ecor under the most-severe exposure conditions provided by the jet-impingement tests (and also, with respect to type 430 alloy, in some circumstances in the flow experiments).

7-3. The corrosion behaviour of each alloy:

7-3-1 Titanium.

As mentioned before, this material was considered to possess excellentcorrosion resistance in seawater environments. Different papers considered this alloy on their comparisons studies, such as references [52,55,61,62,63,69,70].

The results of this alloy under short term static tests showed a very good corrosion resistance under the different conditions tested, i,e up to +1500 mv no passive-film breakdown was obtained under short static tests, with only a few micro amperes being measured(<10 micro amps). Temperature rises from 25°C to 85°C did not increase the current, also the level of dissolved oxygen in the environment and the salinity level didn't affect the value of Ec, only Ecor was affected by the level of oxygen and temperatures. Under aerated conditions Ecor was -220 mv while under the deaerated condition it became -400mv as would be expected due to the oxygen concentration polarization effect,. Also at lower temperatures (25°C) it was more positive that it at higher temperatures (65°C,85°C). Such results were obtained in laboratory by T. Hodgkiess ref.[61,62,70] and A. Tuthill ref.[52,55] , also T. Hodgkiess ref.[63] made the test in three desalination plants and he observed the Ti to be un attacked in all conditions of the three plants.

It can be noticed from the results on pages(134-136) that after long term immersion of Ti on seawater, Ecor of Ti was not a unique value under each environment, for example Ecor of the plain specimen number 1 under 25°C and

35000ppm aerated condition was about -400 mv after 60 days immersion while Ecor of specimen number 2 under the same condition was about -100 mv after the same period of immersion, also the creviced specimens had the same different between each other under the same environment. The value of Ecor of Ti under flow tests were between -50mv (45°C, 55000ppm) and -100 (25°C,35000ppm). And the value of Ecor of Ti under jet tests were between -170mv(45°C,35000ppm) and -250mv (45°C,55000ppm).

For the Ec value after long term immersion it was less positive than in short static test(1200 mv), and the currents measured at this potential were higher(>50 micro amps) than the currents measured under the short static tests, which implies slightly lower corrosion resistance after long term immersion. And the other important effect was the high current measured during the passive range for the most creviced specimens (see table 7-1) . Under flow test, Ti showed a good corrosion resistance, where the Ec was about 1200mv and only under one test, high current was observed during the passive range as shown in table 7-1. But under jet tests the values of Ec were between 900mv (under 45°C and 35000ppm) and 1150mv (under 25°C and 55000ppm). In general it can be remarked from page (192) that the jet of the fluid reduce the value of Ec specially at 45°C, this may means that at moderate temperatures and under jet imingement condition the passivity is slightely reduced.

As a conclusion of the behaviour of titanium, it can be said that it has an excellent corrosion resistance under RO desalination plant conditions. despite its slightly reduced corrosion resistance in long term tests and in jet impingement conditions, and the small effect of crevice. Weight loss test results agree with the electrochemical tests results in this conclusion, that extremely small weight loss and no observation for crevice corrosion takes place in the weight loss tests.As mentioned above most of the previous work done on this alloy showed good behaviour with presence of artificial crevices as in ref.[70].

7-3-2 Hastelloy-C.

For the hastelloy-C it should be pointed out that some of the anodic polarization test results obtained had two peaks as shown in fig. (1) and (2) and mainly occured in short term static tests under temperatures lower than 65°C. Possibly these two peaks means one oxide film is stable at low potential and breaks down at moderately low potential, then at even more positive potential, a new different oxide film is formed and again breaks down at high potential. When two peaks are observed, the value of potential at which the current rises at the higher potential peak is rather similar to Ec values for a single peak. This gives some indication that it is the lower potential peak which is not observed when single peak exist. Table 7-2 shows the results of the two peaks tests. The above gives a possible indication that at short term times and lower temperatures, an oxide film forms at Ecor which is less resistant to breakdown but with longer exposure and/or high temperatures, an oxide film is atblilised which is more resistant to breakdown , thus a better indication of long term behaviour from the anodic polarization curves of short term tests is obtained from the potential of breakdown of the high potential oxide i.e. the more positive peak. J. Postlethwaite et al paper [71] provided most indication of salinity effect with poss more tendency to two peaks at salinity around 1% NaCl and less tendency at 20% NaCl. Jet tests repeat observation of short term static (and in any cast jet conditions are severe and might cause easy breakdown). but flow tests do not give two peaks and this emphasizes :

a) complexity of anodic polarization behaviour of the Hastelloy C.

b) particularly the complicated influence of hydrodynamics on corrosion behaviour of this alloy.

Oxygen is not affecting these two peaks formation. It can be also said that the crevices may avoid the two peaks to be formed, also this can be seen through the results obtained by B. Wilde[58], he tested hastelloy C specimens with artificial crevice under 35000ppm and 25°C , the Ec he obtained was about 900mv with one peak. It may be possible to say that the lower peak does not represent the potential at which corrosion resistance of this material be suspect, becaus in case of one peak

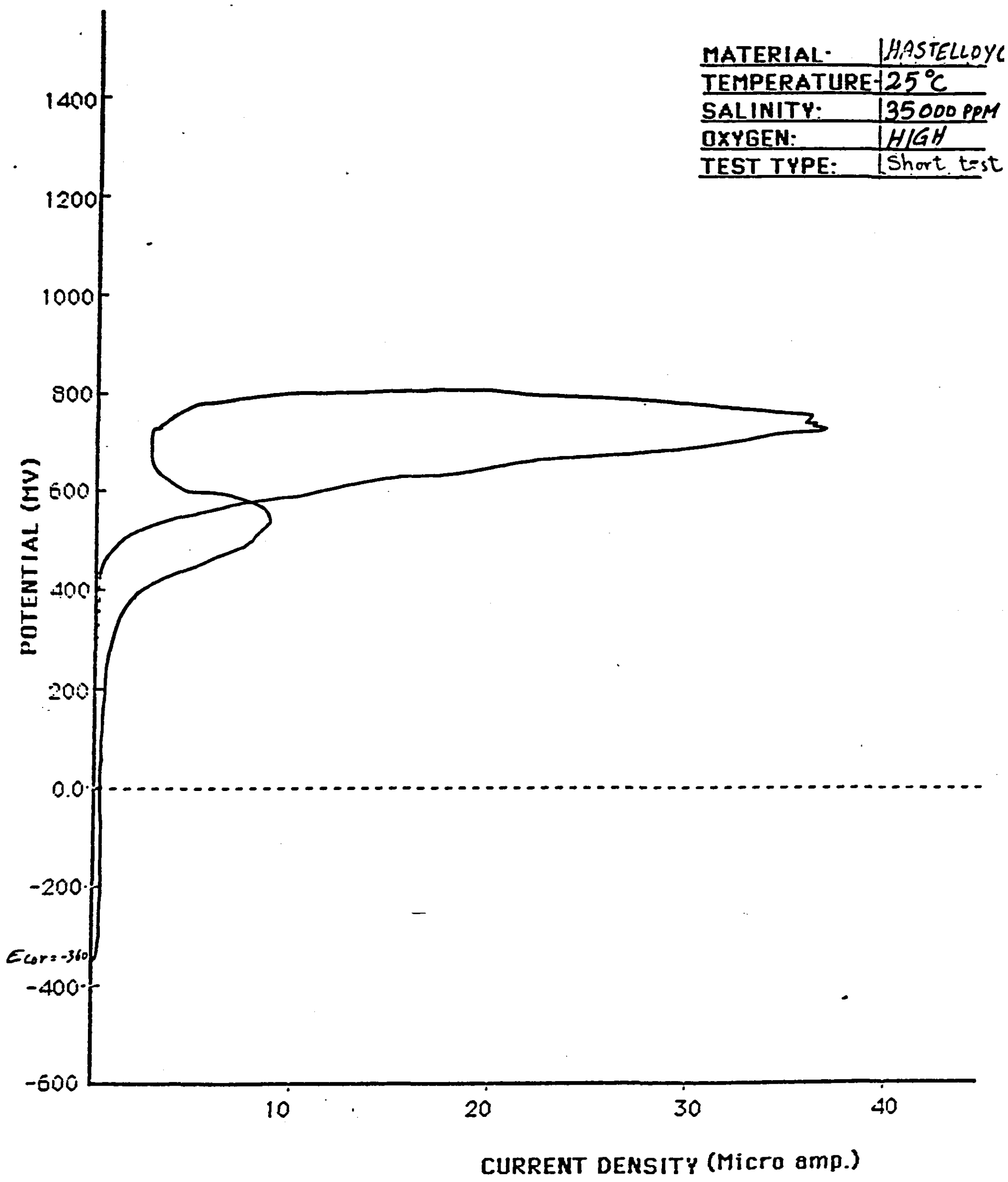

MATERIAL: HASTELLOYC
TEMPERATURE: 25 °C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: Short test

Figure 1

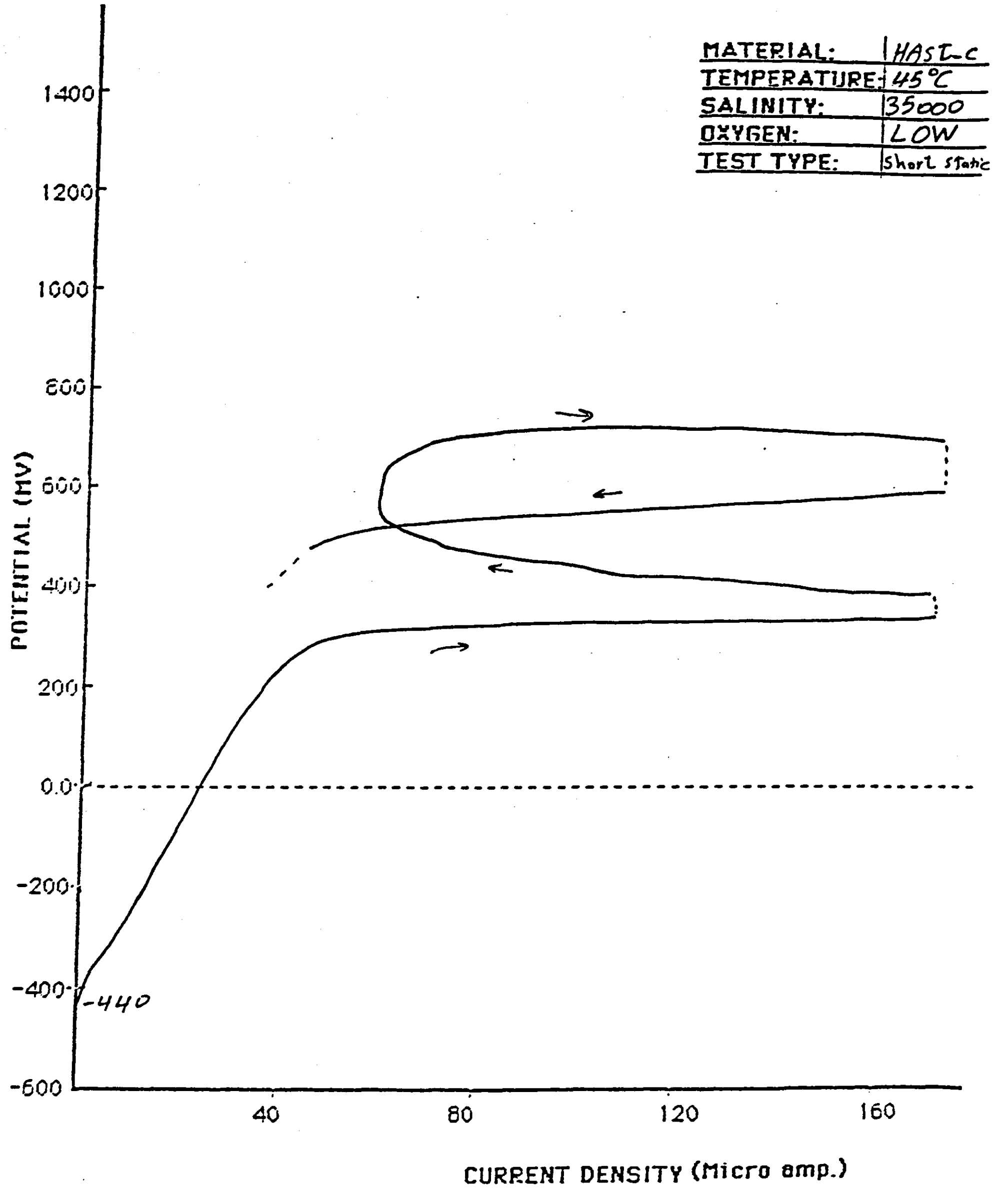

MATERIAL: HAST-C
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN: LOW
TEST TYPE: Short static
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-440
40
80
120
160
CURRENT DENSITY (Micro amp.)

Figure 2

Table 7-2
Two peaks measured on Hasteeloy-C tests

		peaks	Potential at fist peak(mv)	Current at first peak	Potential at second peak mv
Static test	25,35,A	●	550	9(micro amp)	820
	55,A	●	550	14	800
	35,D	●	530	14	780
	55,D	●	530	37	820
	35,35,A	●	520	20	810
	55,A	●	510	18	800
	35,D	● (small)	450	8	800
	55,D	●	490	<60	800
	45,35,A	●	500	30	800
	55,A	●	480	23	850
	35,D	●	410	<50	730
	55,D	●	390	95	800
	65,35,A				730
	55,A				580
	35,D	● (small)	350	23	750
	55,D	● (small)	370	50	770
	85,35,A				700
	55,A				590
	35,D				650
	55,D				620
long term	25,35,A,p	●	600	45	810
	,35,A,c				500
	,55,A,p	●			910
	,55,A,c				100
	,35,D,p				820
	,35,D,c				640
	,55,D,p				680
	,55,D,c				310
	45,35,A,p				160
	,35,A,c				500
	,55,A,p				580

		peaks	Potential 1	Current	Potential 2
	,55,A,c				40
	,35,D,p				100
	,35,D,c				430
Flow test	25,35				770
	,55				800
	45,35				360
	,55				390
Jet test	25,35	●	530	15	825
	,55				750
	45,35	●	460	30	700
	,55	●	500	60	750

●	Two peaks
blank	One peak

which usually under more sever condition the Ec potential will be more positive than the first peak.

Now let us discuss the effect of each factor on the specimens used:

7-3-2-1 Temperature:

Generally Ecor was not affected by the temperature increasing under static conditions as shown in fig. page (106). For Ep it was reduced by increasing the temperature specially when the environment was aerated and had 55000ppm salinity. Ec was slightly decreased by increasing the temperature. As shown in the figs. page(111-112) Ec30 decreased from more than 900 mv at ambient temperature to 600 mv at 85°C in 55000ppm aerated, and from 800 mv (25°C) to 700 mv (85°C) in 35000ppm aerated , while in the deaerated media Ec30 decreased from 800mv (25°C) to 50mv (85°C) with 35000ppm. With 55000ppm deaerated media Ec30 decreased from 970mv (25°C) to 20mv at 85°C. If Ec(r) is considered, it will be found that Ecs were decreased from about 800 mv at ambient temperature to 650mv at 85°C for all the environments used and this implies a reduced stability of passive film as the temperature rises. Long term immersion tests showed that as the temperature increase, the Ec30 and Ec(r) decreases as shown in figures. page (153). The temperatures applied in flow effect tests were only 25 and 45°C and the results showed no effect on the value of Ecs due to the temperature change as shown in figures page(181). Also temperature change doesn't affect Ec value under jet condition as shown in figures page(193).

It can be concluded that upto 45°C under short static tests, Ec was not affected by the temperature increasing, but the effect of this difference in temperature appeared after long term of immersion by reducing the value of Ec, while at higher temperatures the pitting potential Ec was decreased . J. Postlethwaite[71] had similar behaviour of Ec at higher temperatures(i.e 900 mv at 100°C and about 150 mv at 175°C).

7-3-2-2 Salinity:

In general it was found that the effect of the salinity change-from 35000ppm to 55000ppm-on Ecor and Ep very low(about 50 mv) . For Ec, if it is considered at 50 micro ampere -under flow condition- then it can be noticed that high salinity may decrease the pitting potential Ec as shown in figs. page(181). Possibly the reason for this decrease of Ec value is due to the increase of the fluid density. In jet conditions it was observed that there wasn't effect due to the change of the fluid salinity. It should be pointed out that the comparisons on this study were between 35000ppm and 55000ppm, and it may be that the salinity will affect the value of Ec under different range of salinities, for example J. Postlethwaite[71] showed that Ec was reduced from 900 mv at 1% NaCl to 500 mv at 20% NaCl, and both were under 100^{o}C and short term static conditions.

7-3-2-3 Oxygen

Ecor is influenced by the level of dissolved oxygen in the environments. It becomes more positive as the dissolved oxygen increase. In static tests it was about -300 mv with aeration (8mg/lit.) and when dissolved oxygen reduced, Ecor became -500 mv. This reduction is expected on account of more severe concentration polarization of oxygen- reduction cathodic reaction at lower levels. For Ec it was observed that oxygen level effects the passive range slope. In other words, as the dissolved oxygen level decrease the current measured increase in the passive range under short static conditions. After long immersion of the specimens in the fluid, no effect appeared due to the dissolved oxygen level, which possibly means that the oxide film formed after long period from immersion is more stable and is not affected by the oxygen level in the environment.

7-3-2-4 Time Effect:

By comparing the static (short period) test results and long term immersion test (60 days) results under the same condition, some differences were observed. First the two peaks disappeared in most of the long term test results. Second, high current was measured during the passivity of the alloy, which implies somewhat greater electrochemical activity. Finally, at temperatures 45°C and more, pitting potential Ec reduced from about 800 mv at static tests to about 100 mv with 35000 ppm and 500mv with 55000 ppm after long term immersion. It is clear that the corrosion resistance of this alloy may reduced after long term immersion in seawater at elevated temperatures (45°C or more).

7-3-2-5 Flow Effect:

To study the flow effect, a comparison between the static test results and the flow test results under the same other conditions had been done. Table(7-3) shows that the flow does not affect Ec value under ambient temperature, but at 45°C the flow reduces the breakdown potential Ec from about 800 mv to 350 mv. This might mean that the oxide film is not strong enough at 45°C, hence the flow can introduce pitting at lower potential. and generally this implies that corrosion resistance behaviour of this alloy under flowing conditions at elevated temperatures may be adversely affected. Finally it should be pointed out that in the flow tests there wasn't two peaks.

7-3-2-6 Jet Effect:

Comparison of the various Ec values indicates that only in the 25°C,55000ppm condition does jet impingement represent clearly more severe circumstances for hastelloy C Than either static or flow tests. In two of the other conditions, the corrosion resistance appeared worse in impingement compared to static conditions (i.e. lower Ec). Although in these other 3 tests, table (7-3) indicates that flow condition appears worse than jet imingement, it must be point out that a current peak was obtained in jet tests at potential less positive than Ec for the corresponding flow tests. Thus these experiments do not provide a clear demonstration that jet impingement is more severe than simple flow. This implies that the influence of hydrodynamics on the corrosion of hastelloy C is complex and probably does need further study.

TABLE 7-3
Some Comparisons Between Ec(mv) of Hastelloy-C under different conditions

	STATIC	TEST	FLOW	TEST	JET	TEST
	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)
25°C,35000ppm	810	810	400	770	825	900
25°C,55000ppm	880	900	800	800	720	750
45°C,35000ppm	800	800	340	360	680	700
45°C,55000ppm	840	850	380	390	420	750

7-3-2-7 Crevice Effect:

From the results available it is clear that at 25^{o}C the presence of a crevice apparently reduced the corrosion resistance of Hastelloy-C . This conclusion can be noticed from the figs. shown in pages (153). However from the weight loss specimens (tables 6-1, 6-2), there did not appeare to be much difference between the behaviour of plain and creviced specimens. Indeed these specimens provided good evedince of the good corrosion resistance of hastelloy C at ambient and moderately elevated temperatures.

7-3-3 SMO-254 Stainless Steel.

This alloy has been identified in many investigations to be one of the best corrosion resistance stainless steels in aerated seawater at ambient temperatures. This alloy will be discussed as in the above discussion procedure,

7-3-3-1 Temperature Effect:

All SMO specimens exhibit very small weight losses even at 75^{o}C. this indicates that the excellent general surface corrosion resistance of this material is retained up to highest temperatures tested in this work. However, the weight losses were in fact greater at the higher temperatures thus providing an indication of possible greater susceptibility to corrosion at higher temperatures. And, the superior sensitivity of the electrochemical tests in indicating on the susceptibility to localised corrosion provided more precise information on the effect of temperature as described below.

Free corrosion potential Ecor was not affected by the temperature changes under static conditions. Repassivation potential Ep shows significant changes at elevated temperatures. At 25 and 35^{o}C Ep was almost the same as Ec (950 mv), while at 45^{o}C and more they reduced to about -100 mv. This indicates that at temperatures 45^{o}C and more, once pitting corrosion take place it is not easy to reform oxide film again. Breakdown potentials Ec were also affected by the temperature changes. At lower temperatures 25,35 and 45°C Ec values were about 950 mv while at 65 and 85°C they were between 200 and 600 mv (page 107). These results are in general agreement with those obtained by T. Hodgkiess[70] who found that the value of Ec at 22°C was 1060 mv and reduced to 65 mv at 95°C. Whilst he[70] observed that the critical pitting potential temperature is between 85°C and 90°C, A. Garner[51] measured that the critical crevice corrosion temperature of this alloy at 50°C in seawater. While at lower temperature, J.Olsson[66] found that there was no corrosion present on the specimens under field tests-MSF plant- for 10 months, the temperatures was 36°C. Both long term test and flow test show the same behaviour that up to 45°C pitting potential is not affected. In the jet test, the pitting potential was reduced due to the temperature change from 25 to 45°C. For example at 25°C Ec was about 820 mv while at 45°C it was reduced to about 620 mv. In summary, this work has demonstrated significant affect of temperature upon the localised corrosion behaviour of this material.

7-3-3-2 Salinity

Salinity effect appears in the long term test, flowing test and jet test. In the long term immersion test salinity effect is clear specially at the ambient temperature, for example under deaerated conditions Ec30 was 1000mv under 35000 ppm, and it became 120mv under 55000ppm. as shown in table (7-4). In case of flow tests Ec30 was reduced from 960mv at 35000ppm and 25°C to 870 mv at 55000ppm, but under 45°C Ec30 under 35000ppm was 320, while it became 600mv at 55000ppm, actually this is unexpected results, it may be possible to say that the oxide films formed under each condition are different and the oxide film of this alloy under 45°C and 55000ppm is better than the oxide film formed under 45°C and 35000ppm. For the jet test results, almost the same habit happened under 25°C, where Ec30 was 850mv under 35000ppm and it became 900mv under 55000ppm, while at 45°C Ec30 of 35000ppm was 740mv and at 55000ppm it was 440mv.

TABLE 7-4

Some Comparisons Between Ec(mv) of SMO alloy under different tests

	STATIC	TEST	LONG	TEST	FLOW	TEST	JET	TEST
	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)
25^oC,35000ppm	810	810	1000	1060	960	980	850	850
25^oC,55000ppm	880	900	120	30	870	890	900	910
25^oC,35000ppm, deaerated	800	800	1040	1110				
25^oC,55000ppm, deaerated	940	940	60	730				
45^oC,35000ppm	800	800	850	930	320	390	740	780
45^oC,55000ppm	840	850	930	960	600	750	440	810
45^oC,35000ppm deaerated	760	760	940	950				

7-3-3-3 Oxygen:

Aerated environments shows higher value of Ec at elevated temperatures(65, 85°C) as shown in page(107), also histogrames in page 144 shows evidence of significant worse behaviour in deaerated conditions in long term tests. This may implies that the presence of oxygen is improving the corrosion resistant of this alloy specially after long time of exposure. For the free corrosion potential Ecor also aerated environments shows more positive potential than deaerated environments as shown in page (107).

7-3-3-4 Time effect:

From table (7-4), it is possible to conclude that the time increase positively the breakdown potential of this alloy. In general about 150 mv is the increased in Ec due to two months immersion. Possibly the reason of this behaviour is the oxide film nature and it is required long time to be more stable, hence more strong.

7-3-3-5 Flow Effect:

Flow at ambient temperatures increases the value of Ec, for example Ec30 at static test was 810mv and became 960mv with flow condition. At 45°C temperature reduces the pitting potential, as shown in table (7-4), Ec reduced from about 800 mv to about 350 mv under 45°C and 35000ppm environment condition,also it increase the slope of the passive range. It is possible that the same behaviour of hastelloy-C happened to SMO alloy.

7-3-3-6 Jet Effect:

Under ambient temperature condition, jet does not affect the breakdown potential value. But at 45°C jet reduced the breakdown potential, for example Ec30 reduced from 840 mv under static condition to 440 mv under jet condition both were at 45°C and 55000ppm.

7-3-3-7 Crevice Effect:

As the figures on page 144 reveal, by testing the specimens immersed in 25°C, 35000ppm and 55000ppm deaerated tanks and 45°C 55000ppm tank, they show a significant reduction in the breakdown potentials with compared to the plain specimens under the same conditions. Hoever, in the remaining conditions in the long term tests there are no remarkable differences between creviced and plain specimens. (see the table below).

	25, 35A		25, 55A		25, 35D		25, 55D		45, 35A		45, 55A		45, 35D	
	Ec30	Ecr*	Ec30	Ecr	Ec30	Ecr	Ec30	Ecr	Ec30	Ecr	Ec30	Ecr	Ec30	Ecr
plain	1000	1060	120	300	1040	1110	60	730	850	930	930	960	940	950
crevicd	950	980	260	540	350	370	210	230	900	920	-160	-130	825	900

* Ecr >>> Ec(r).

7-3-4 IN-Stainless Steel

In general this alloy has a good passive range with low current during the passivity.

7-3-4-1 Temperature Effect:

As for the previous alloys, the free corrosion potential was not affected by the temperatures. At 45°C and above temperatures repassivation potential was affected significantly. Ep reduced from about 800 mv at 25 and 35°C to lower than 0 mv at 45°C and above temperatures (see page 108). breakdown potential was also affected by increasing the temperature by the same manner as Ep potential. At 25 and 35°C the breakdown potential was about 800 mv, while at 45°C and above was between 50 and 550 mv as indicated in pages (108). This effect of temperature can be also observed in the long-term test results on page 145, Ec value was reduced from 980 mv at 25°C to 580°C at 45°C when both were measured under 35000ppm salinity and both were aerated. The same behaviour happened for jet tests, high temperatures reduces the Ec values (see page 195). Hence both initiation of localised corrosion and repassivation are adversely affected at elevated temperatures.

7-3-4-2 Salinity Effect:

The corrosion resistance of this alloy seams to be not affected by the salinity. Only under jetting conditions there were different in Ec values due to changing the salinity, for example the value of Ec30 with 35000ppm salinity Ec was 830 mv, while with 55000ppm it was reduced to 270 mv.

7-3-4-3 Oxygen Effect:

Free corrosion potential was slightly affected by the dissolved oxygen level.The range of Ecor when the environment aerated was between -200 and -350 mv, and when the environment deaerated its value was between -250 and -450 mv (page 108). If the pitting potential Ec considered to be occured at 30 micro ampere then, the presence of oxygen in high percent will reduce the Ec at elevated temperatures as shown in page 108. This is also clear in the long term test results under 45°C and 35000ppm conditions, Ec was 940 mv with low level of oxygen and became 580 mv with aerated environment.

7-3-4-4 Effect of Time:

By analysing the long term test results, they show that, in case of deaerated conditions,the time increase more positive the value of the breakdown potential (for example at 25°C and 35000ppm Ec was 800 mv in shoert term test and became 1040 mv after long time immersion under the same condition), while in aerated conditions and at 45°C the breakdown potential reduced with the time (see table 7-5).

7-3-4-5 Flow Effect:

Table 7-5 shows that flow does not affect the behaviour of the corrosion resistance of this alloy, it is clear that there is no big differences between the results

TABLE 7-5
Some Comparisons Between Ec(mv) of IN alloy under different tests

	STATIC	TEST	LONG	TEST	FLOW	TEST	JET	TEST
	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)
25°C,35000ppm	810	820	980	1010	980	980	830	900
25°C,55000ppm	880	900	930	960	960	970	270	520
25°C,35000ppm, deaerated	800	800	1020	1040				
25°C,55000ppm, deaerated	940	940	540	900				
45°C,35000ppm	800	800	580	690	690	860	-40	110
45°C,55000ppm	840	850	550	550	750	840	-40	105
45°C,35000ppm deaerated	760	760	910	920				

under short static tests and the flow tests. This implies that the flow of the fluid tangentially does not change the behaviour of this alloy.

7-3-4-6 Jet Effect:

Both salinity and temperature conditions might reduce the breakdown potential in combination with jet effect. At ambient temperature and 35000ppm, Ec was similar to the results under static conditions, while increasing the temperature to 45°C the value of Ec reduced from 900 mv at 25°C to 110 mv and also incresing the salinity from 35000 ppm to 55000 ppm reduced the value of Ec from 900 mv to 520 mv at ambient temperature. This may implies that this alloy is affected by the severe conditions such as the high salinity ant temperatures with the conjunction of the jet.

7-3-4-7 Crevice Effect:

This alloy is very sensitive to crevice. All the results obtained shows that, a major reduction in Ec value happened when the specimens creviced. This is clearly shown on pages (155).

7-3-5 316 Stainless Steel.

316 austenitic stainless steel is the common grade used in industries, and in so many corrosive media. The results of this alloy showed that it has lower resistance to the corrosion than the previous alloys, this also can be found through the references [51,52,54,57,58,61,62,63,66,70].

7-3-5-1 Temperature Effect:

As the previous alloys Ecor is not affected by the temperature rises. In case of high salinity Ep slightly affected by rising the temperature (page 109). Pitting potential is dramatically reduced by increasing the temperature as shown in pages (109) . Also T.Hodgkiess[62] showed the same temperature effect on Ec value.

But in general 316 S.S Ec value was low compared with Ec of the previous alloys. For example most Ecs of the previous alloys were in order of 900 mv, while Ec for 316 was in order of 100 mv.

7-3-5-2 Salinity Effect:

Salinity effect may be appeared in the repassivation potential Ep. As shown in page (109) Ep decrease by increasing the temperature only in case of 55000ppm salinity. Also under Aeration conditions high salinity reduce pitting potential , and vice versa happened under deaeration conditions, that high salinity increase the pitting potential. In long term immersion, there wasn't a remarkable change due to the salinity, only at 45°C, where Ec reduced from 130 mv at 35000ppm salinity to 20 mv at 55000ppm. Also salinity effect appeared in the flow test at 45°C and reduced from 30 mv at 35000ppm to -340 mv at 55000ppm salinity as shown in table (7-6).

7-3-5-3 Oxygen Effect:

It can be noticed from table 7-6 that the presence of oxygen reduced the breakdown potential Ec values. For example under short static tests at 25°C and 35000 ppm aerated condition the value of Ec was 90 mv and became 165 mv under the same conditions but with deaerated evironment. and the same behaviour can be noticed in the long term test results shown in table 7-6. This gives an evidence that this common stainless steel and as the previous work done is affected by the presence of oxygen and became have more resistance to corrosion in absence of the oxygen.

7-3-5-4 Time Effect:

The results listed in table (7-6) shows that the time is helping the pitting potential to be more positive. This gives an indication that in anodic polarization tests, the oxide film became more stable after long time exposur to the seawater.

TABLE 7-6
Some Comparisons Between Ec(mv) of 316 S.S. under different tests

	STATIC	TEST	LONG	TEST	FLOW	TEST	JET	TEST
	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)
25°C,35000ppm	80	90	170	170	130	140	-120	130
25°C,55000ppm	10	20	180	180	0.0	150	-120	0.0
25°C,35000ppm, deaerated	165	165	300	320				
25°C,55000ppm, deaerated	135	160	260	270				
45°C,35000ppm	-60	-30	130	130	30	50	-340	15
45°C,55000ppm	-52	-35	20	30	-340	-260	-410	150
45°C,35000ppm deaerated	7	40	110	110				

7-3-5-5 Flow Effect:

By comparing the results of the flow test with static test, it is possible to notice that flow of the fluid enhanced the breakdown potential positively, for example under short test Ec was 90 mv at 25^{o}C and 35000 ppm and became 140 mv with the flow (see table 7-6). Generally a lot of evidence to suggest that in ambient temperature seawater, stainless steel have good erosion/corrosion resistance (i.e good resistance to flow conditions).

7-3-5-6 Jet Effect:

On this alloy the jet exerts on it aggressively. Table (7-6) and page (196) shows how the jet makes this alloy to be active. This implies that the oxide film of this alloy is not strong enough to stand againest such severe conditions, and also proves that this alloy has lower corrosion resistance than the previous alloys under the severe conditions.

7-3-5-7 Crevice Effect:

Except 25^{o}C and 55000ppm environments, all the specimens show that crevices reduce the pitting potential. The degree of pitting potential reduction is different depending on the environment. The environments at 25^{o}C had a big reduction in Ec, while in 45^{o}C environments less reduction took place.

7-3-6 430 Stainless Steel

This type of alloy is ferritic stainless steel.

7-3-6-1 Temperature Effect:

Free corrosion potential observed to be reduced by increasing the temperature, only under aerated conditions. Repassivation potential can't be reformed under aeration conditions as well (see page 110). Pitting potential is also affected by rising the temperature and reduced from about +0 mv to -250 mv.

7-3-6-2 Salinity Effect:

From the curves shown on pages (110) it can be observed that salinity reduce the value of Ec.

7-3-6-3 Oxygen:

After long term immersion and under ambient condition oxygen reduced the pitting potential as shown in table (7-7). Ec was reduced from 130 mv with low oxygen to 100 mv with aerated environment. One of the most important related to oxygen content in the environment is its effect on Ep. From curves shown on page (110) it is clear that Ep almost the same as Ecor in case of aeration, while it has higher value in absence of oxygen.

7-3-6-4 Time Effect:

From table (7-7) it is clear that the time increase the breakdown potential. Of course not all the environments has the same behaviour in increasing Ec. For example environment with 25^{o}C and 35000ppm aerated, the Ec increased from 17 to 100 mv by the two months immersion. This may implies that the oxide film improved with the time and have better corrosion resistance in anodic polarization test cases. But comparing this conclusion with the weight loss tests which showed severe corrosion after the same period of exposure, it can be said that not all the anodic polarization tests showed the same behaviour as the weight loss tests.

7-3-6-5 Flow and Jet Effects:

From table (7-7) it is possible to notice that both flow and jet conditions are making this stainless alloy to be active and there was not any indication that oxide film has any resistance. Comparing this with the 316 stainless steel it can be noticed that

TABLE 7-7
Some Comparisons Between Ec(mv) of 430 S.S. under different tests

	STATIC	TEST	LONG	TEST	FLOW	TEST	JET	TEST
	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)	Ec30	Ec(r)
25°C,35000ppm	17	17	100	100	-270	-140	-270	-200
25°C,55000ppm	-45	-40	100	100	-390	-330	-240	-160
25°C,35000ppm, deaerated	-100	-100	130	130				
25°C,55000ppm, deaerated	65	120	160	190				
45°C,35000ppm	-58	-58	30	30	-340	-300	-304	-210
45°C,55000ppm	-155	-145	-90	-90	-450	-430	-240	-190
45°C,35000ppm deaerated	-115	-100	30	50				

this material is much worse than 316, and both of these alloys are the lowest grade of the materials testedand this is what most of the leratures proves.

7-3-6-6 Crevice Effect:

Generally crevices reduces the pitting potential.This can be observed in figures shown on pages(157). Only at 45°C,55000ppm environment which show increase in Ec due to crevice.

7-4 Comparisons between the results of the alloys used:

7-4-1 Free Corrosion Potential (Ecor):

It should be mentioned that all the alloys used showed a negatively shift in the value of Ecor in deaerated conditions. And this implies that free corrosion potential of the materials in the passive state is determined largely by the concentration of dissolved oxygen in the seawater.

Except for Ti and IN alloy, the alloys had almost the same value of Ecor, under aeration and deaeration conditions. Ti and IN alloys showed more positive value of Ecor in both cases aeration and deaeration environments than the others as shown in table (7-8) and figures in pages (pages 106-110). In general, under long term immersion tests, most of the alloys showed an increase in the value of Ecor with the time. Most of Ecor of the specimens of each alloy used were closer to each other with the time as shown in the figures (pages 134-151).

Under flow conditions and as shown in pages (180), Ecor of Hastelloy C and 430 alloys were negatively decreased, for example Ecor of Hastelloy C became -460 mv under 25°C and 55000ppm, while it was -300 mv under the same condition in the short static test. On the other hand Ecor of Ti and SMO alloy increased positively to about -70mv and -150mv respectively.

In case of jetting conditions, Hastelloy-C didn't show changes in Ecor under the different environments used. SMO show more negative value of Ecor under ambient temperatures as shown in page (191).

7-4-2 Repassivation Potential (Ep):

Repassivation potentials Ep of titanium under all the tests conditions were equal to Ec indicating that the oxide film can reformed instantaneously after reversing the swept potential negatively.

At ambient temperatures up to 35°C and sort static tests, the two stainless steel alloys IN and SMO show a good and fast reforming oxide films. The film reformed just after reversing the sweep potential, In case of Hastelloy-C it was require more reduction in the applied potential to form the film once again, the film was reformed at about 600 mv. 316 Stainless steel alloy was in the range between -150 mv and -400 mv. For 430 alloy, the film couldn't reform under aeration while it could under deaeration conditions. The above discussion can be observed in table (7-9) and figures shown in pages (106-110). At 45°C and higher temperatures the behaviour of the high grade alloys was changed. Ep of Hastelloy-C was decreased up to -100 mv under 550000ppm aeration conditions and high temperatures. Also Ep of IN and SMO was noticed to be decreased under the environments used with temperatures 45°C and above. The behaviour of the above alloys gives an indication that, in general, hastelloy C oxide film has the best ability to be reformed under the most conditions applied, then SMO and IN alloys have good behaviour to reform the oxide film but at 25°C and 35°C temperatures, while 316 and 430 stainless steel alloys shows worse behaviour in repassivation.

7-4-3 Breakdown Potential (Ec):

This parameter is the most important parameter, because it gives the indication about the strength of the oxide film of the alloys. Under ambient temperatures (i,e 25°C,35°C) it is easy to classify alloys used in this project into low grade and high

TABLE 7-8
Some Comparisons between Ecor of the alloys short static tests

	430	316	IN	SMO	HastelloyC
35000ppm aerated	-350 to -450	-350 to -400	-150 to -250	about -250	-300 to -350
55000ppm Aerated	-350 to -450	-350 to -400	-200 to -250	-250 to -300	-300 to -350
35000ppm Deaerated	-450 to -550	about -500	-250 to -400	about -500	about -500
55000ppm Deaerated	-450 to -500	about -500	-250 to -450	about -500	about -500

TABLE 7-9
Some Comparisons between Ep of the alloys short static tests

	430	316	IN	SMO	HastelloyC
35000ppm aerated	--	-200 to -300	800 to 500	900	400
55000ppm Aerated	--	-150 to -350	850 to 600	900	650 to 500
35000ppm Deaerated	-350 to -450	-260 to -350	850 to 700	500	500
55000ppm Deaerated	-400	-250 to -400	800	900	600

grade materials. Titanium, Hastelloy-C, SMO and IN alloys can be considered as the high grade alloys ,while 316 and 430 were the low grade alloys. Referreing to the curves shown in pages (106-110), it is possible to notice the above classification. Ec of 316 was between 0 mv and 180 mv. 430 has Ec between 0 mv and 150 mv. For Hastelloy-C, SMO and IN pitting potentials at ambient temperatures were between 800 mv and 900 mv, while Ec of titanium were between 1200mv and more. After long term immersion it can be observed that SMO and IN has almost the same Ec as the short tests, while Ec of Hastelloy-C alloy reduced to about 700 mv. Crevices reduced the Ec value of Hastelloy-C, 316 and 430 alloys, and titanium also affected by the crevice with the time, that higher current observed during the passivity range of the alloys, as shown in figures pages (152) and table 7-1. In flow and jet tests, 430 was observed to be an active material. Also Ec of Hastelloy-C reduced under flow tests. IN alloy Ec value reduced under jet 55000ppm conditions. Breakdown potential of IN alloy didn't change very much under 45°C temperature and flow conditions.

At 45°C, breakdown potential of IN alloy decreased to about 200 mv in aeration conditions and about 350 mv in deaeration environments, both in short term tests and jet tests, but in long term tests and flow tests conditions, the Breakdown potential of IN alloy didn't change very much under 45°C temperature. While at 45°C SMO showed a good pitting potential, and there wasn't a remarkable change in Ec value from that at 25°C, only a slight reduction took place under jet tests. But at 65°C, Ec reduced to about 300 mv in aerated environments only, while in deaerated conditions it was reduced slightly. Hastelloy-C was almost stable, and seems to be not affected by the temperature changes under the short tests, but in case of long term tests, its Ec was reduced at 45°C conditions., specially under 35000ppm aerated and deaerated conditions.. Ec of titanium were stable as mentioned above, and only under jetting conditions the values of Ec were reduced to about 900mv.

Generally it can be said that Ec of Ti is not affected by the temperature rises, hence indicating an excellent resistance to corrosion at all temperatures tested in this work. Also the oxide film breakdown of Hastelloy C alloy, it was not affected by temperature rising. SMO showed good breakdown potential value under deaerated conditions and up to 45^oC under aerated conditions. Also IN alloy maintained good resistant to oxide film break down up to 35^oC only. Finally 316 and 430 alloys were the worst alloys at ambient temperature, also showed the most reduction in corrosion reduction as the temperature increased.

Table 7-10 classify the breakdown potential behaviour of all materials tested in this work under each condition applied. There are three materials used in this work have the same psition in table 7-10, these material are Ti which exhibit the best behaviour through out all the conditions applied, and this agree with the work done before by most of the literaures. The other two mateials are 316 and 430 stainless steels, and this due to the low percentage of Cr and Mo presented in these alloys, of course 316 exhibits better behaviour than 430 because there is about 2.5% Mo in 316 and while no Mo in 430.

Also the table implies that SMO has the best value of Ec - after Ti- under static condition and temperature range between 25 and 45^oC. Also under these conditions (i.e static and temperatures 25-45^oC) it can be noticed that IN has better breakdown potential than hastelloy C. At 65^oC and more hastelloy C shows better corrosion resistance than SMO and IN alloys. In general under the hydrodynamic conditions it is clear that IN exhibit better behaviour than SMO, and SMO was better than hastelloy C. It must mentioned that the value of the difference between alloys in table 7-10 is not constnt, but some times the different is about 30 mv and in some cases the difference is couple of hundreds of millivolts.

7-4-4 (Ec-Ecor) Comparisons:

The aim of these comparisons was to measure the potential range above Ecor required oxide film breakdown to occur.

None of the previous works seen in the literature did these comparisons. Looking the histograms of Ec-Ecor of Hastelloy C shown in pages(126), it can be seen that the difference between the values of Ec-Ecor at ambient temperatures and elevated temperatures was very low (approximately 100mv) compared to the values of Ec(900mv) which may exhibit nearly the same difference as Ec values at the same temperatures. Also the same behaviour found for the rest alloys. For example 316 alloy under short static ,35000ppm, aerated test condition:

Ec(25^{o}C)-Ec(85^{o}C)=100-(-100)=200mv

[Ec-Ecor(25^{o}C)]-[Ec-Ecor(85^{o}C)]=460-320=140mv.

7-5 Weight Loss Test:

After testing the alloys for about 60 days, under the different environments mentioned in the previous chapter, and from the results shown on table (6-1) and table (6-2) it can observed the following :

Titanium showes a very low weight losses through all the environments, which implies the fact that this material is one of the best corrosion resistance material under a wide range of seawater conditions, also this agree with results obtained by the electrochemical tests. The maximum weight loss recorded was 0.0017 gm and no localised corrosion observed visually. The same behaviour can be said for the Hastelloy C. Only one creviced specimen showed slight corrosion. From table 6-1 it may be noticed that Hastelloy C has good corrosion resistance at ambient and75^{o}C temperatures. For the SMO alloy it was mentioned in chapter six that only a slight discouloration and very low weight loss (max. 0.0021 gm) and the weight losss were higher at higher temperatures. No evidence for IN that it was affected by specific condition, but some of the specimens shows relatively higher weight losses such as 0.012 gm and this was creviced one under 75^{o}C and 55000 ppm. 316 also indicates good corrosion resistance in this test. only three specimens exhibited corrosion and all of them were at 75^{o}C. In general the results gives an indication that 60 days is not suffecient period to observe the difference between the corrosion behaviour of the materials tested specially Ti, Hastelloy C, INand 316. 430 alloy and as can be noticed in table 6-2 that this alloy was the worst material tested specially in the presence of the crevices. Severe corrosion obsereved visually at 75^{o}C and again this implies that this has not good corrosion resistance in seawter environments. Thus these results demonstrated that weight loss and visual observation can separate out the very best (Ti) from the worst 430 materials. However, at least for the period of the test (60 days) these parameters are not as sensitive for comparison of the other materials or for assesment of influence of environmental variables. Although these tests did provide slight indications of the deletrious effect of icreasing the temperature.

7-6 Comments on the mechanisms of localized corrosion of stainless steel:

Pit initiation results from a breakdown of passivity due to a potential controlled adsorption of chloride ions at specific sites on the metal surface[58].The nature of pit propagation is such that theories describing it are concerned mainly with geometry, mass transfer, and reaction kinetics[54].

Crevice corrosion initiation can be described as follow: at the beginning the reaction between the metal surface and the corrodent take place on both crevice and the uncrevice area, where anodic, cathodic and overall reactions exist. After time the the solurion inside the crevice becomes depleted of oxygen, because the diffusion of the oxygen into the crevice is limited, after depletion of oxygen inside the crevice, an electrochemical cell is set up with anodic reaction occuring inside the crevice and the cathodic reacion outside. This results in an increase in metal ions in the solution inside the crevice, these ions then hydrolyse and reduce the pH of the solution, at the same time Cl^- increases within the crevice to maintain the electrical neutrality of the solution. The build up of Cl^- and the reduction in the value of pH leads to breakdown the protective film of the surface. once the breakdown of the passivity occurred within the crevice, rapid dissolution takes place. This reaction is balanced by cathodic reduction of oxygen outside the crevice and, if the pH is low enough, hydrogen evolution inside the crevice. As with pitting corrosion the rate of propagation is mainly concerned with geometry, mass transfer, and reaction kinetics, and no complete model of process has been developed[54]

It should be pointed out that this work is concentrating on the initiation of the localized corrosion (Pitting, Crevice) which is important and neccessery stage of the localized corrosion, but must be followed by propagation if a practical problem is to occur. Thus the intersting evedence in this work of greater tendency to pit initiation at elevated temperatures need not neccesserily point to practical problems in engineering plant. clearly more work on pit propagation at the above-ambient temperatures would be of interest study.

7-7 Comments on the effect of flow rate on the corrosion of stainless steels:

This work provided some interesting indications of possible flow rate effects on the corrosion of stainless steel in saline environments. Literature [1,46] stated that stainless steels are not affected by the velocity of the corrodent significantly. Up to 40 m/s velocity nickel stainless steels were tested [72] and show no effect on the corrosion process. This work in agreement with the literature shown that nickel stainless steels hastelloy C and Ti have good corrosion resistant to low flow rate (3.1 m/s). However in jet tests at 25^{o}C and 95 m/s, both 430 and 316 were active in contrast to other materials which remain passive. Morever even at 3.1 m/s the lowest grade alloy type 430 showed evidence of non passive behaviour. All this provides a possible indication that there may be a critical value of velocity for each of the corrosion resistant material although such critical velocity will clearly be at very high values for most stainless steels.

7-8 Relevance of the results to Material selection in Desalination plant:

In summurising the relevence of this work to operational plant, it must be accepted that this study was conducted in artificial seawater and therefore any influences on corrosion processes caused by biological activity have not been accounted for. However such biological effects represent only one factor influencing corrosion and a number of other important parameters (temperature, oxygen concentration, flow rate, etc..) have been investigated in this project. Thus the results are likely to have

relevance to materials selection in desalination and other plants, especially taking into account that there are circumstances (such as at elevated temperature and in other circumstances (72)) where biological effects are relatively unimportant. Thus the following comments are made concerning the relevance of these results in the estimation for the selection of the material for the different parts of the desalination plants especially the R.O. plant from the corrosion resistance point of view. Since the desalination plant basically consists of, **pipework, vessels, pumps and energy recovery systems (Impulse Turbine)**, then it can be said that Ti, Hastelloy C, SMO and IN can be used for the pipework at temperature upto 45°C, Of course this is from corrosion resistance point of view. From the cost point of view no one will select Ti or Hastelloy C comparing with SMO and IN alloys. In the parts containing seawater at low oxygen and temperature it may be usefull to use 316 alloy. For the vessels that will operat over than 45°C, Hastelloy C will be the proper selection. In case of the pumps and the impulse turbine where severe conditions exists it is recommended to use IN or SMO at ambient temperatures or Hastelloy C at elevated temperatures. Finally it must be pointed out that Ti can be used in all parts mentioned above safely, but its price is stand as a restriction from its application.

Finally it should be pointed out that from the results obtained in this work it is possible to say that the failure of the energy ecovery turbine used at Ummluj plant is not due to erosion corrosion problem, this conclusion came from the results of hastelloy C and IN (which is similar to Es135 alloy) under jet impengiment test where the velocity was 95 m/s and no evidence of corrosion was found. Another study for Ummluj plant problem may be required to investigate the possibility of cavitation due to the high velocity of the brine.

Table 7-10
Classifying the material according to their behaviour

		best					worst
Static test	25,35,A	Ti	SMO	IN	HAS	316	430
	55,A	Ti	SMO	IN	HAS	316	430
	35,D	Ti	SMO	IN	HAS	316	430
	55,D	Ti	SMO	IN	HAS	316	430
	45,35,A	Ti	SMO	HAS	IN	316	430
	55,A	Ti	SMO	HAS	IN	316	430
	35,D	Ti	SMO	HAS	IN	316	430
	55,D	Ti	SMO	HAS	IN	316	430
	65,35,A	Ti	HAS	SMO	IN	316	430
	55,A	Ti	HAS	SMO	IN	316	430
	35,D	Ti	HAS	SMO	IN	316	430
	55,D	Ti	HAS	SMO	IN	316	430
	85,35,A	Ti	HAS	SMO	IN	316	430
	55,A	Ti	HAS	SMO	IN	316	430
	35,D	Ti	HAS	SMO	IN	316	430
	55,D	Ti	HAS	SMO	IN	316	430
long term	25,35,A,p	Ti	SMO	IN	HAS	316	430
	,35,A,c	Ti	SMO	IN	HAS	316	430
	,55,A,p	Ti	SMO	IN	HAS	316	430
	,55,A,c	Ti	SMO	HAS	IN	316	430
	,35,D,p	Ti	SMO	IN	HAS	316	430
	,35,D,c	Ti	HAS	IN	SMO	316	430
	,55,D,p	Ti	SMO	IN	HAS	316	430
	,55,D,c	Ti	IN	HAS	SMO	316	430
	45,35,A,p	Ti	SMO	IN	HAS	316	430
	,35,A,c	Ti	SMO	HAS	IN	316	430
	,55,A,p	Ti	SMO	HAS	IN	316	430
	,55,A,c	Ti	HAS	IN	SMO	316	430
	,35,D,p	Ti	SMO	IN	HAS	316	430
	,35,D,c	Ti	SMO	IN	HAS	316	430
Flow test	25,35	Ti	IN	SMO	HAS	316	430
	,55	Ti	IN	SMO	HAS	316	430
	45,35	Ti	IN	HAS	SMO	316	430
	,55	Ti	IN	SMO	HAS	316	430
Jet test	25,35	Ti	IN	HAS	SMO	316	430
	,55	Ti	IN	SMO	HAS	316	430
	45,35	Ti	IN	SMO	HAS	316	430
	,55	Ti	SMO	HAS	IN	316	430

CHAPTER EIGHT

CONCLUSION

This study has successfully provided indications of the corrosion behaviour over a much more extended range of environmental conditions (temperature, oxygen content, salinity) than has been generally investigated in previous researches. A particular outcome of this work relative to major problems experienced at Ummluj R.O. plant in Saudi Arabia. In this respect, the work has indicated that material suffering deterioration in the plant appear to have very good corrosion resistance in relevant conditions. This provides strong evidence that erosion corrosion has not been a factor in the practical problem at Ummluj.

In more general terms the following conclusions may be drawn from the results and data presented:

1- Comparing the breakdown potentials "Ec" obtained on this project with the practical experience of the corrosion resistance of some alloys tested, it can be noticed that the anodic polarization technique is a good method to test the corrosion resistance behaviour of the materials under the different environments.

2- In terms of the corrosion behaviour of the separate materials:-

2-1. Titanium exhibits excellent corrosion resistance over a wide range of condition in this study including R.O. seawater desalination conditions. Only the jet imingement condition may reduce the resistance to passive film breakdown specially at 45°C.

2-2. Hastelloy C also exhibits many indication of excellent corrosion resistance under static conditions at ambient temperatures. However, the anodic polarization behaviour in short term tests was complicated by the appearence of two current peaks, indicative of the stability of oxides at different conditions. This complicated the detailed interpretations of some of the results. Further investigation is required to clarify the electrochemical behaviour of this material. The influence of hydrodynamics upon corrosion behaviour was likewise not clearly evident from this study , although there

was evidence that at 45^{o}C (and possibly at even higher temperatures) the resistance to flowing seawater may be lowered.

2-3. The excellent corrosion resistance of SMO alloy at ambient temperatures shown in many previous investigation was reproduced in this work. However there was clear evidence of reduced resistant to passive film breakdown and more difficult repassivation at or above 45^{o}C. Salinity can be considered as reducing factor to the breakdown potential of this alloy. The time factor increases the breakdown potential of this alloy.Under hydrodynamic conditions (flow or jet impingement) the excellent resistance of this alloy was maintained at 25^{o}C but a greater susceptibility to protective-film breakdown was evident at 45^{o}C.The other environmental parameters, salinity and oxygen concentration, do not appear to influences corrosion behaviour of this alloy as much as temperature, but seem to have effects on increasing the tendency to film breakdown. Crevices can affect the breakdown potential by reducing its value. Oxygen also reduces the breakdown potential at 45^{o}C and more.

2-4. IN alloy is affected by the temperature rise. The oxide film potential is reduced by rising the temperature specially at 45^{o}C and higher temperatures. The results obtained shows that this alloy has better corrosion resistance behaviour under hydrodynamic conditions than both Hastelloy C and SMO. Also the salinity does not reduce its corrosion behaviour under the most conditions tested. The time improves the breakdown potential of this alloy and the SMO as well. also crevices weaken the corrosion behaviour of IN alloy.

2-5 For the 316 stainless steel, it shows a performance lowere than all the above alloys. There was a remarkable difference between the breakdown potential of this alloy and all the above alloys but this big different reduced in comparisons with some of the above alloys(i.e IN and SMO) at higher temperatures, also it can be assumed as an active material under jet imingement conditions. This material and as most of the above is sensetive to crevices and the crevice can reduce the corrosion resistance.

2-6 Finally 430 stainless steel alloy as expected was the worst material. It exhibit low breakdown potentioal through all the tests. Also it was active under hydrodynamic conditions. Severe corrosion was observed by weight loss tests after only 60 days of immersion.

3- As indicator of the relative performances of the material it can be classify them generally as follows : Titanium was the best material under all the conditions applied. The next best material appeared at higher temperatures (i.e 65 and 85°C) to be hastelloy C which exhibit a very good corrosion resistance. However, this assessment of hastelloy C is subject to some coplex on the plarisation behaviour of thia material and requires further study. But at ambient temperatures upto 45°C and static conditions SMO was the next best material, by considering the hydrodynamic effect IN was the next best material following Ti in corrosion resistance. 316 exhibit better corrosion resistance than 430 but both of these two alloys were the worst compared with all the other tested material.

4- In terms of relevance to materials selection for desalination plants componenets, this study indicates the following:

Ti excellent for most of the componenets but it is costly and not available in wide range. 430 is unacceptable alloy for the componenets of the desalination plants due to its low corrosion resistance behabviour. Type 316 stainless steel has also been demonstrated in this work to be much inferior to the remaining material except 430 stainless steel and in practice has sometimes been found to suffer from severe crevice corrosion in aerated ambient temperature seawater. However, its behaviour may be satisfactory for components under low oxygen conditions. SMO and IN can used in desalination plant componenets specially at lower temperatures. At higher temperatures Hastelloy-C can be used.

5- As a recommendation for futur works, it is preferred to make further investigation on hastelloy-C in order to clarify its polarization behaviour, espicially at lower temperatures and static conditions. Another point should be studied more, that is the weight loss on the high grade alloy tested in this work for longer period thn 60 days and compare their results with the electrochemical behaviour.

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Appendix-A

Chemical composition of some stainless alloys

	CN7M	Hastelloy C	ES 135
C	.07 max	.12 max	.05 max
Si	1.5 max	1.5 max	1.5 max
Mn	1.5 max	1.0 max	2.0 max
P		.04 max	.03 max
Ni	29	Bal	20-26
Cr	20	15-20	19-21
Mo	2.5	16-20	6.0
N			.05 min
W		5.25 max	
V		.4 max	
Co		2.5 max	
Fe	Bal.	7.5 max	Bal
Cu	3.5		
S		.03 max	.03 max

Alloys used in impulse turbine for umm-luj RO plant

	Ni	Cu	C	Mn	Fe	S	Si	P	Cb
Ni-Cu 410	62-68	26-33	.35 max	1.5 max	2.5 max	.015 max	2. max	-	-
Ni-Cu 411	60 min	26-33	.3 max	1.5 max	3.5 max	.015 max	1.0-2.0	-	1.0-3.0
Ni-Cu 505	60 min	27-33	.25 max	1.5 max	2.5 max	.015 max	3.5-4.5	-	-
Ni-Cu 506	61-68	27-33	.3 max	1.5 max	2.5 max	.015 max	2.7-3.7	-	-

Some Commercial Monel Composition

Designation	Producer	Cr%	Ni%	Mo%	Cu%	N%
AL-6XN	Allegheny	20.8	25	6.5		.2
AL-6	- -	20.3	24.5	6.3		
Uranus SB8	Creusot-Loire	25	25	5	1.5	.15
254 SMO	Avesta	20	18	6.1	.7	.2
HR 8N	Sumitomo	21	24.5	5.8	.8	.2
UNS NO8366	VDM	21	25	5.9		.14
UNS NO8925 sanicro 28	Sandvik	27	31	3.5	1.	
Alloy 20	Haynes	22	26	5		

Composition of some high alloy stainless steels
(B.Tood, Reference 2)

Chemical Composition Of Some Stainless Steels
(Introd. To Physical Metallurgy, Avner)

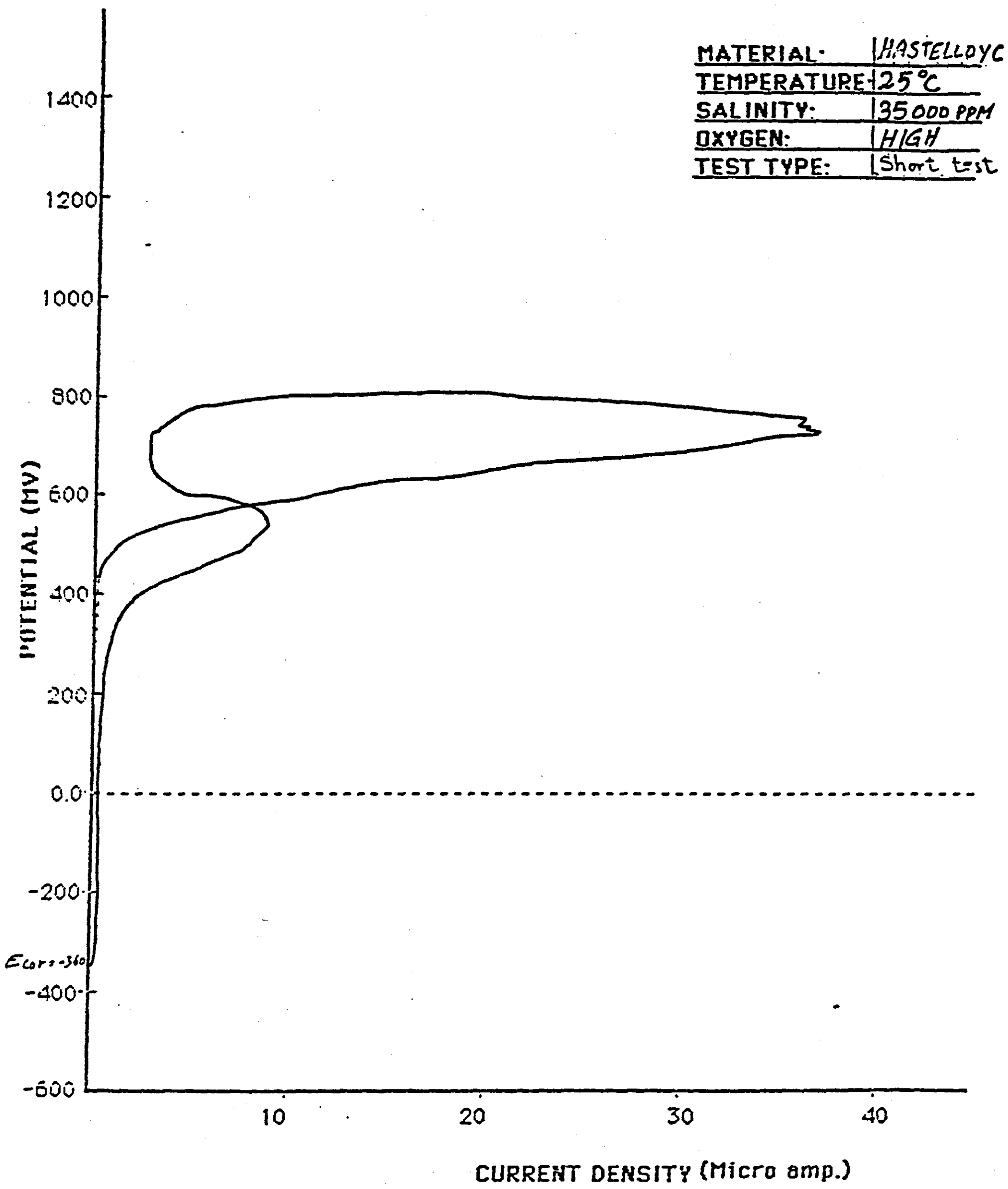
	AUSTENITIC GROUP								MARTENSITIC GROUP				FERRITIC GROUP		
	201	202	301	302	309	316	410	416	420	440A	501	502	405	430	446
Cr	16-17	17-19	16-18	17-19	22-24	16-18	11.5-13.5	12-14	12-13	16-18	4-6	4-6	11.5-14.5	14-18	23-27
Ni	3.5-5.5	4-6	6-8	8-10	12-15	10-14	.5 max			.5 max			.5 max	.5 max	.5 max
Mo						2-3				.75 max	.4-.65	.4-.65			
N_2	.25 max	.25 max													.25 max
C	.15 max	.15 max	.15 max	.15 max	.2 max	.08 max	.15 max	.15 max	.15 max	.6-.75	.1 min	.1 max	.08 max	.12 max	.20 max
Si	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max	1. max
Mn	5.5-7.5	7.5-10	2. max	2. max	2. max	2. max	1. max	1.25 max	1. max	1. max	1. max	1. max	1. max	1. max	1.5 max

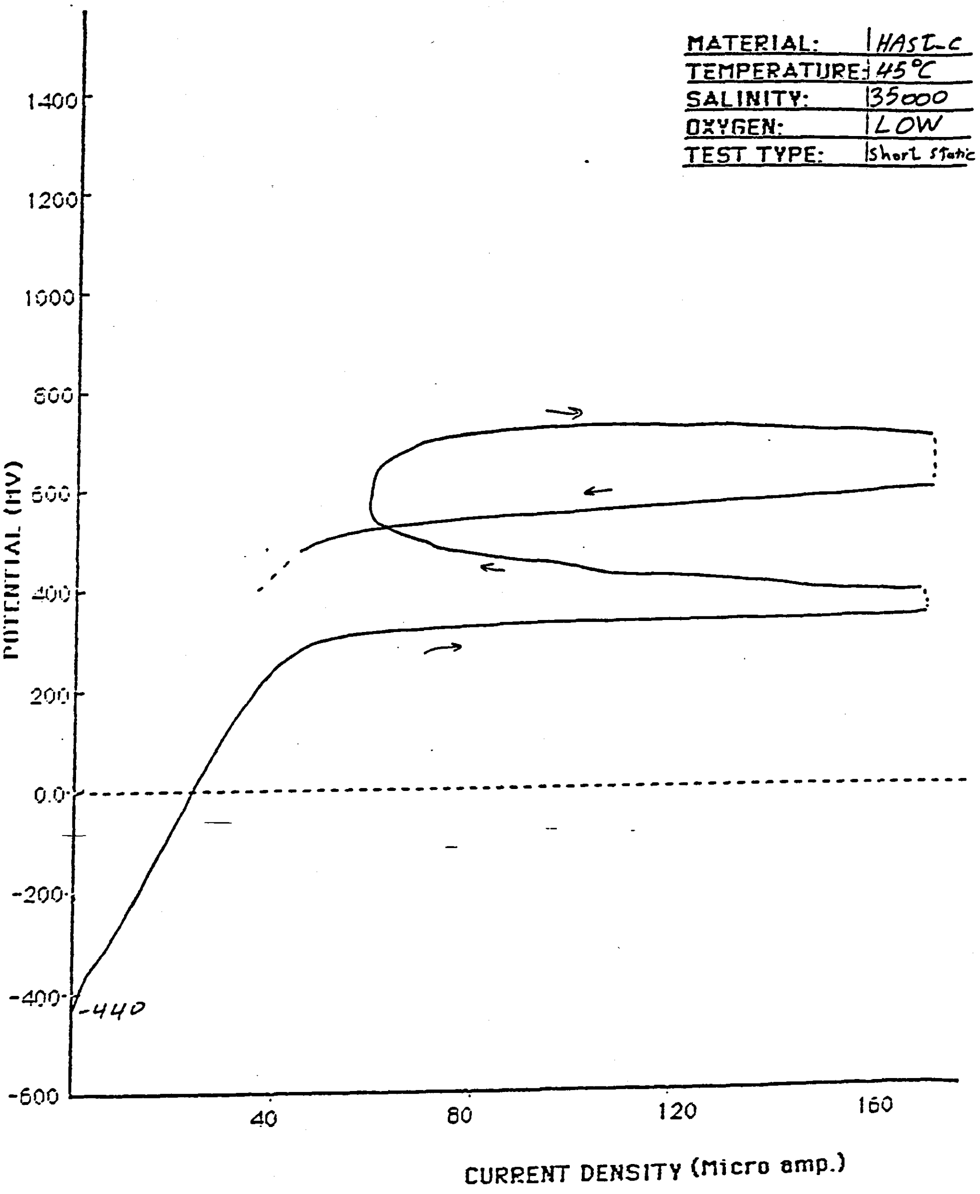
Alloy	Cr%	Ni%	Mo%	C%	Ti%	Mn%	Fe%	Si%	P%	Other
430	16			< .12			BAL.			
316	16.9	11	2.5	.03		1.5	BAL.	.36	.031	.11 Cu
IN-14529	19-21	24-26	6-7							.8-1.5 Cu
SMO 245	19.8	17.7	5.6	.02		.42	BAL			.8Cu, .19N
Hastelloy C	15-20	BAL	16-20	< .12		< .1	< 7.5			.8Cu,<.4V,<5. 25W,<2.5Co
Titanium				.02	BAL		.03			

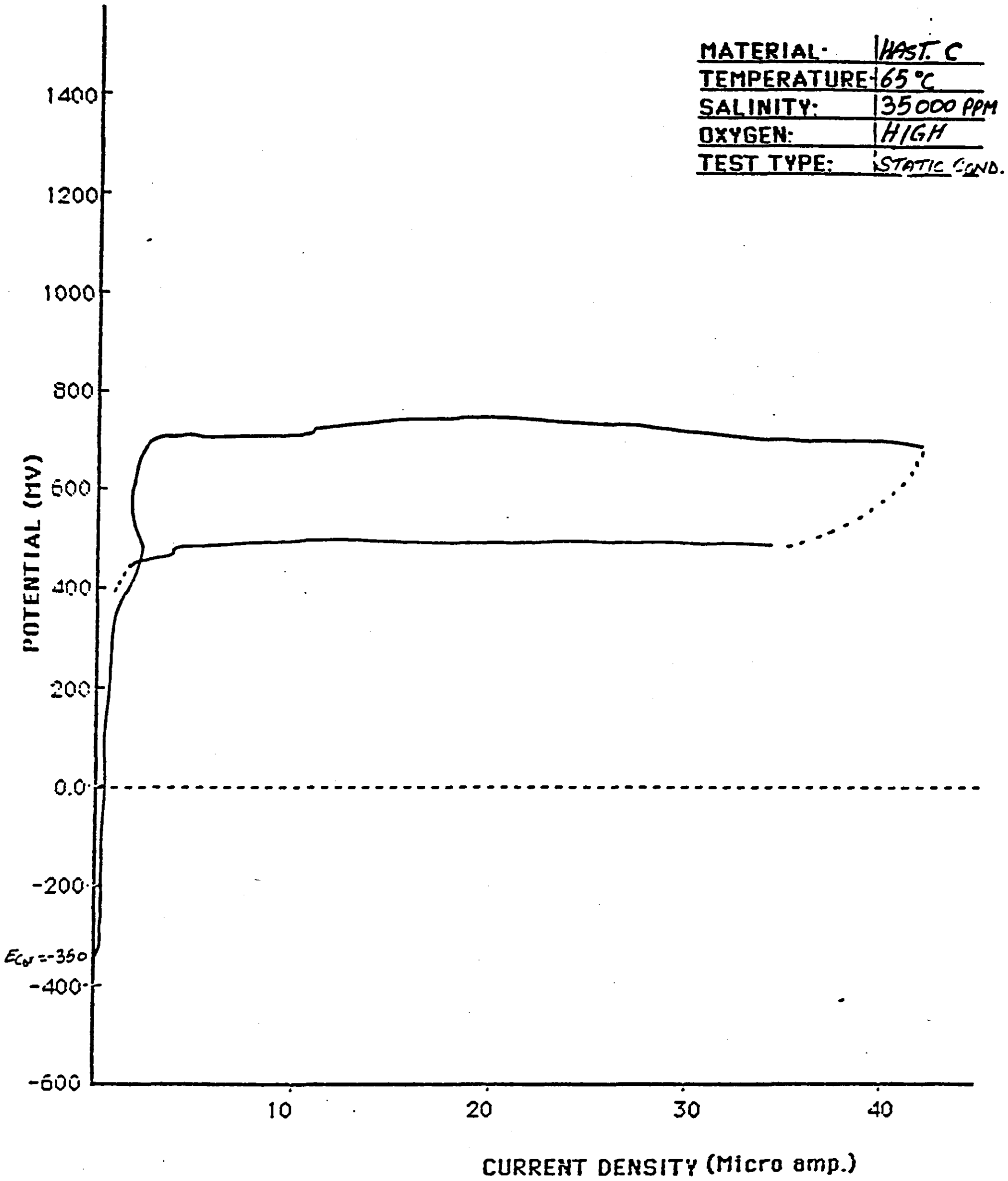
Composition of the invistigated alloys

Appendix-B

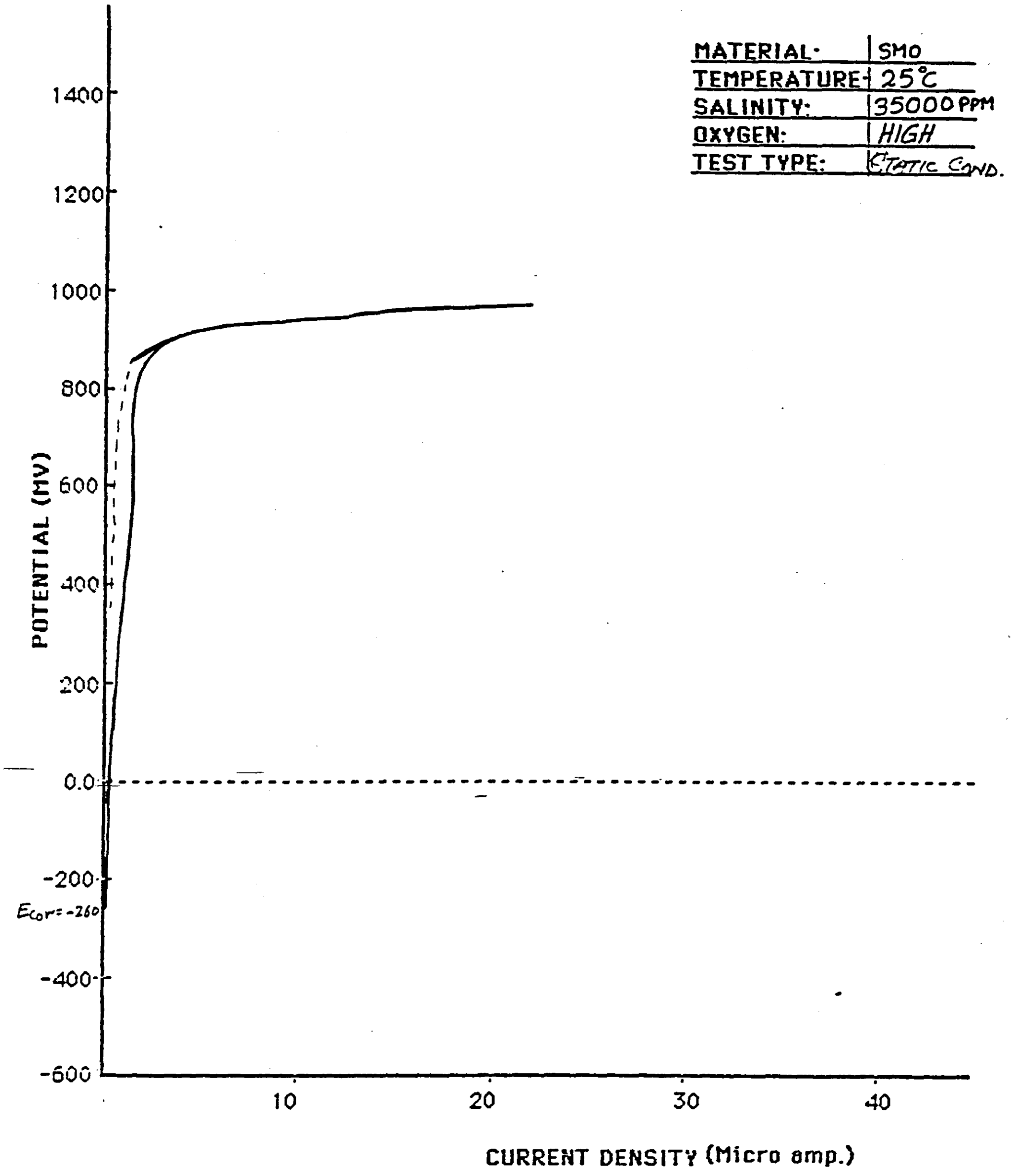
Some Static Test Rresults

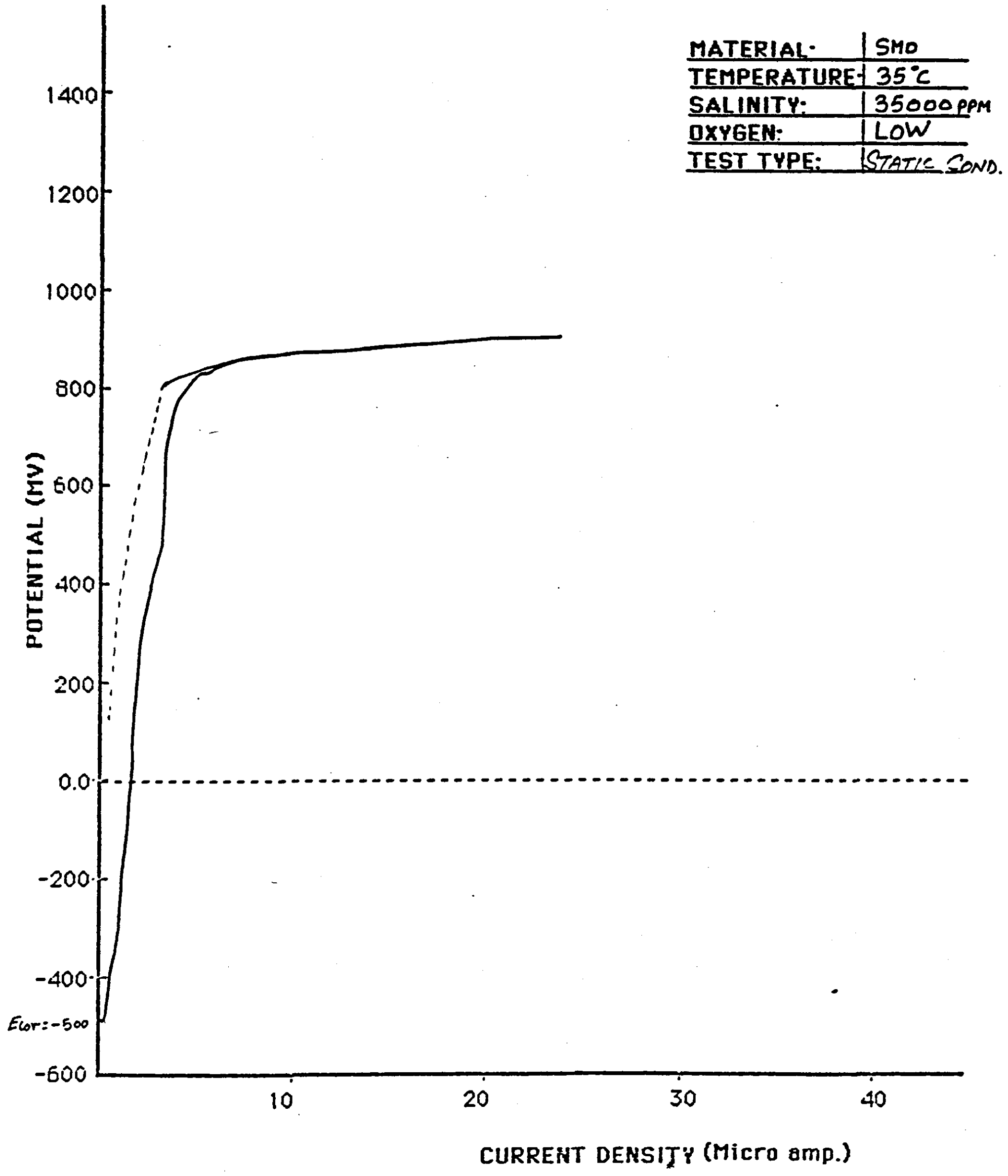

MATERIAL: HASTELLOY C
TEMPERATURE: 25°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: Short test
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
Ecorr=-360
-400
-600
10
20
30
40
CURRENT DENSITY (Micro amp.)

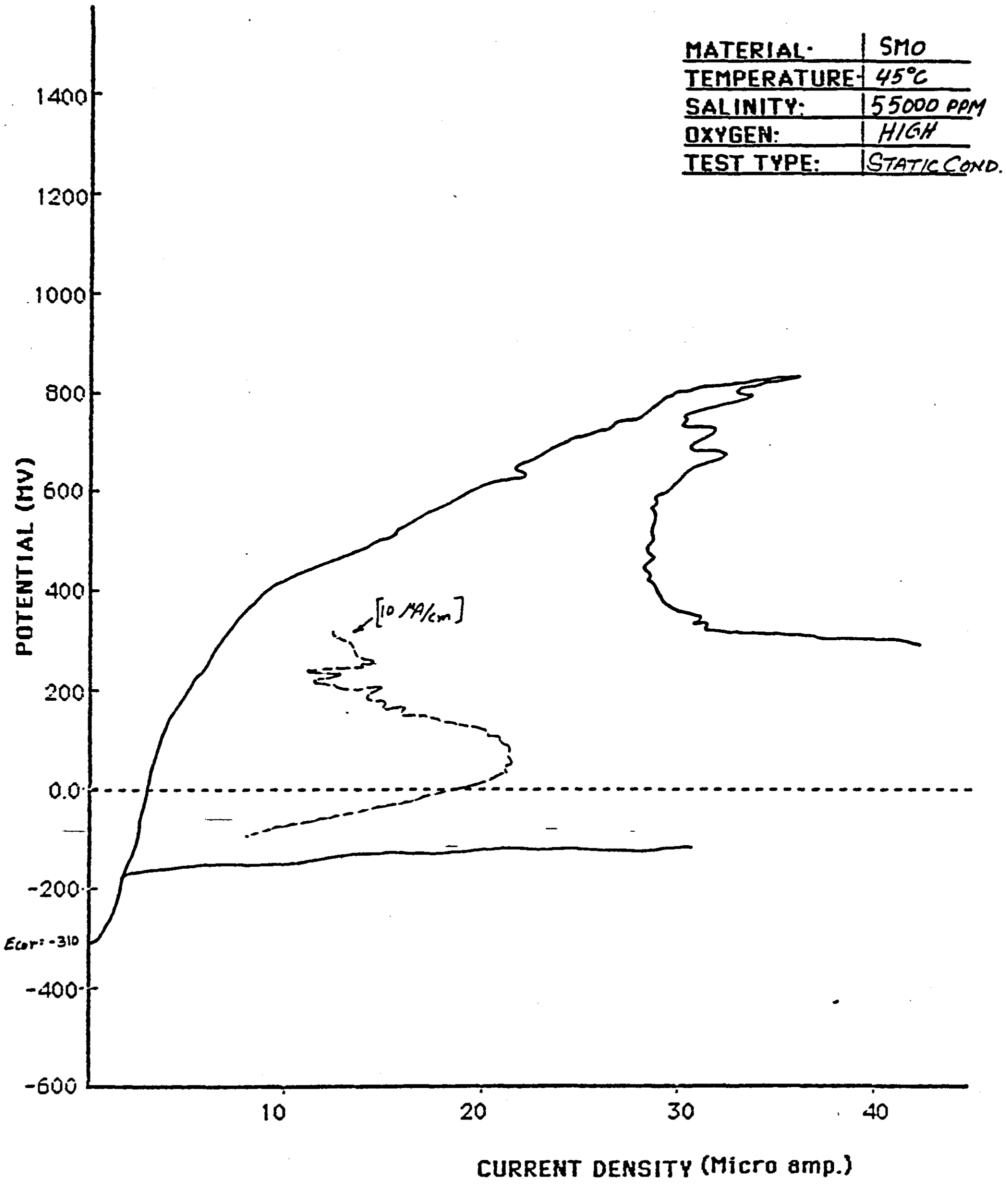

MATERIAL: HAST-C
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN: LOW
TEST TYPE: Short static
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-440
40
80
120
160
CURRENT DENSITY (Micro amp.)

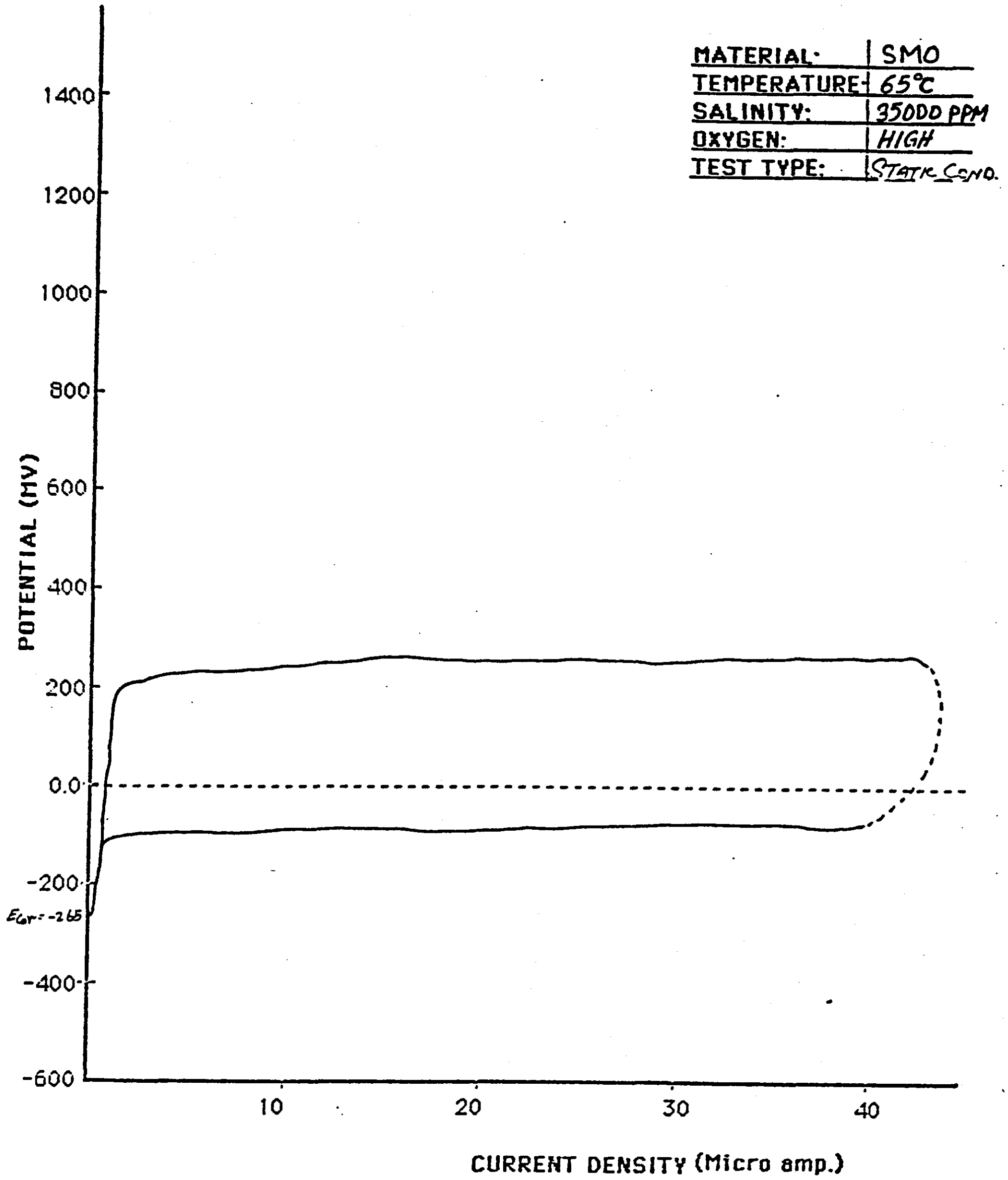


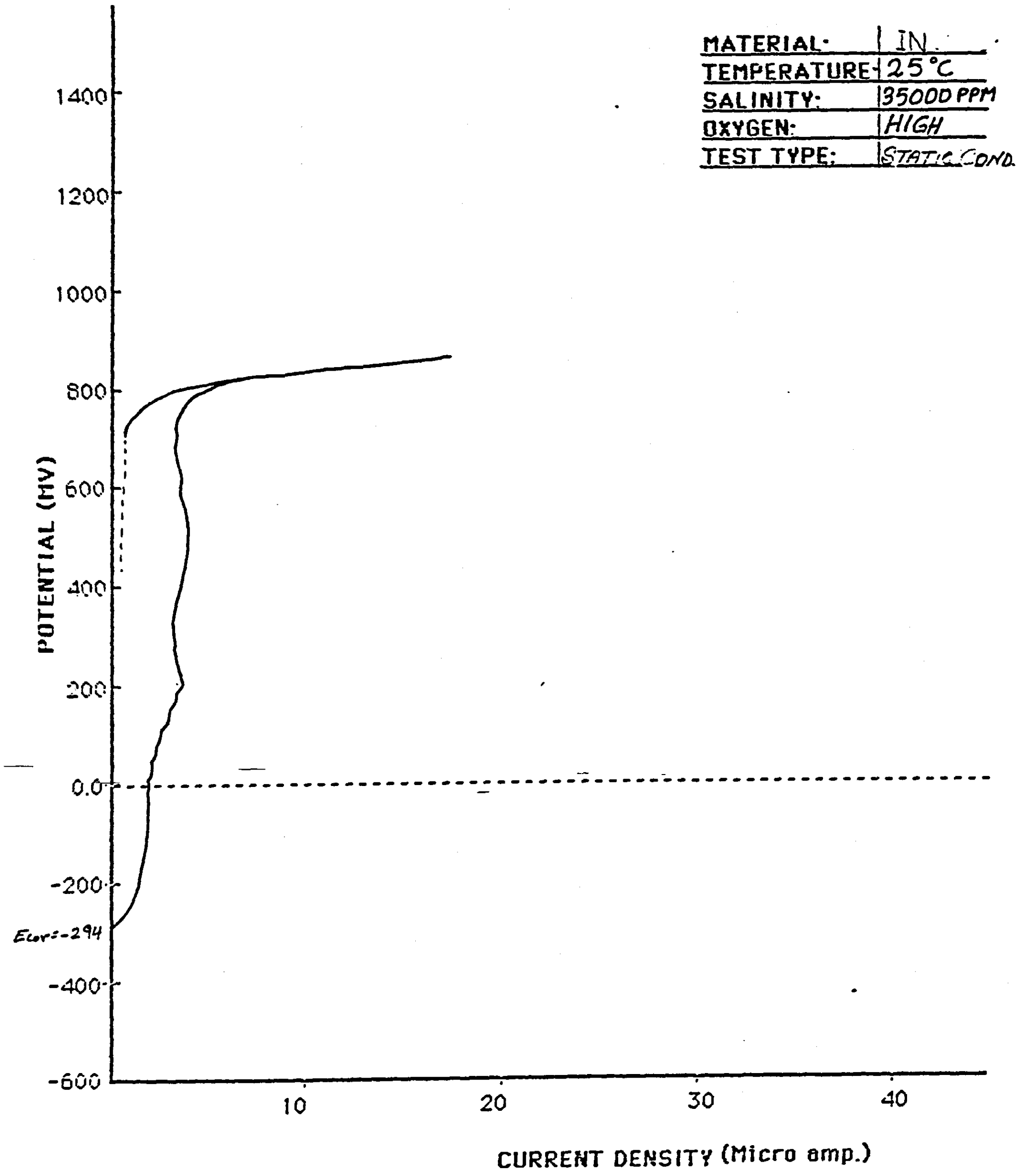
MATERIAL: HAST. C
TEMPERATURE: 65 °C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.


MATERIAL: SMO
TEMPERATURE: 25°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.
1400
1200
1000
800
600
400
200
0.0
-200
Ecor= -260
-400
-600
POTENTIAL (MV)
10
20
30
40
CURRENT DENSITY (Micro amp.)

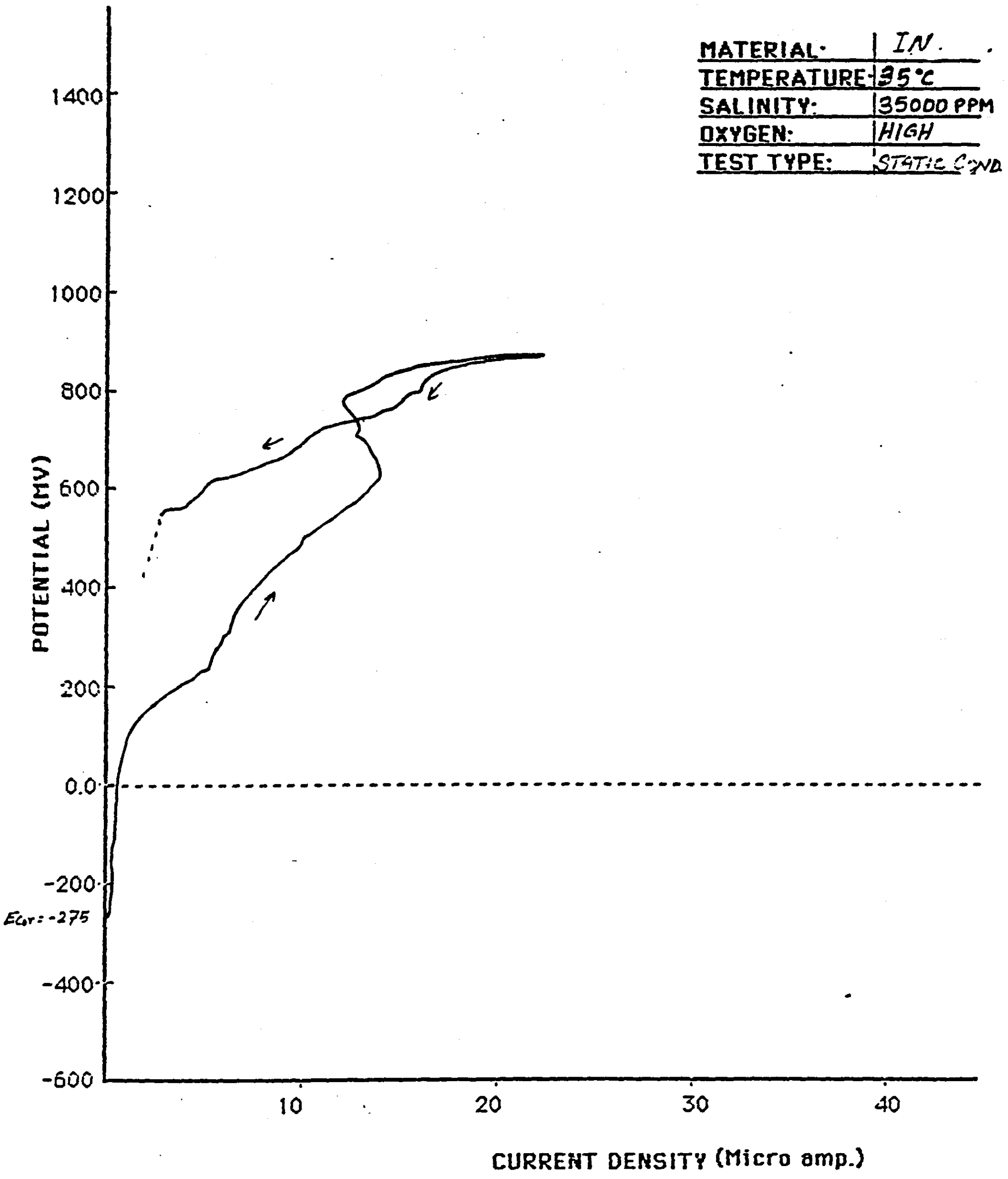

MATERIAL: SMO
TEMPERATURE: 35°C
SALINITY: 35000 PPM
OXYGEN: LOW
TEST TYPE: STATIC COND.
1400
1200
1000
800
600
400
200
0.0
-200
-400
Ecor: -500
-600
POTENTIAL (MV)
10
20
30
40
CURRENT DENSITY (Micro amp.)


MATERIAL: SMO
TEMPERATURE: 45°C
SALINITY: 55000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
Ecor: -310
-400
-600
[10 MA/cm]
10
20
30
40
CURRENT DENSITY (Micro amp.)

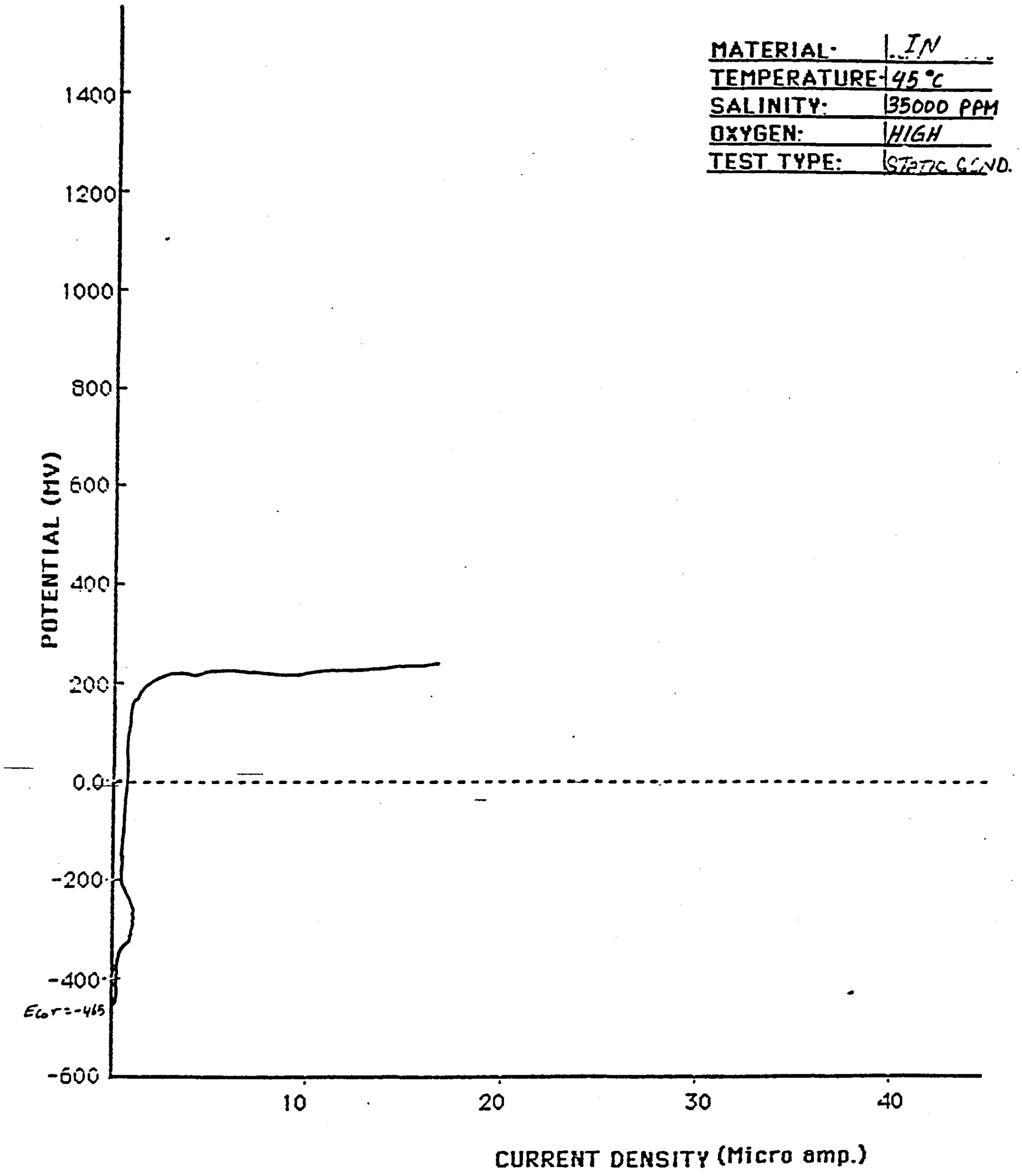

MATERIAL: SMO
TEMPERATURE: 65°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
E_{cor} = -265
-400
-600
10
20
30
40
CURRENT DENSITY (Micro amp.)

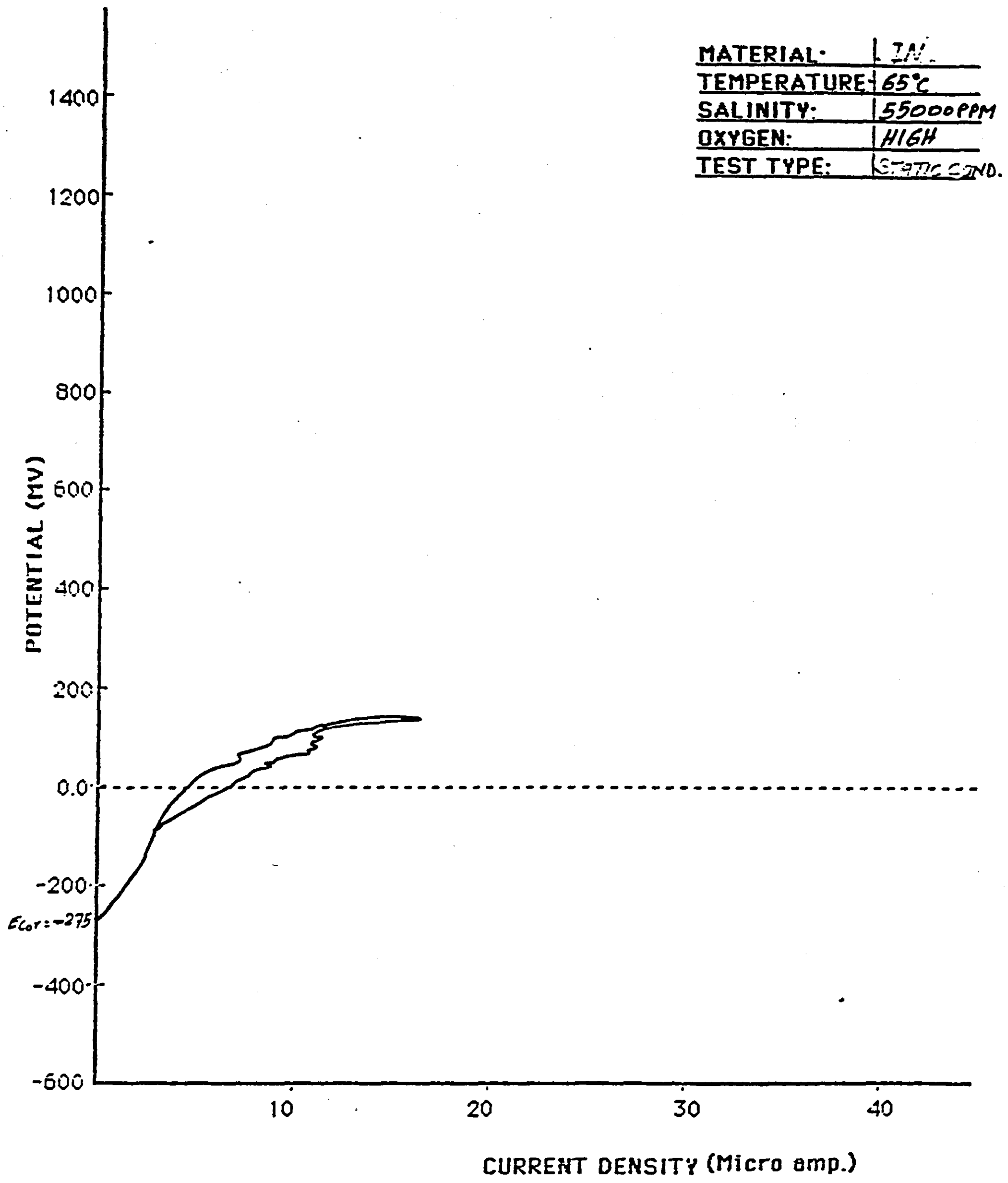


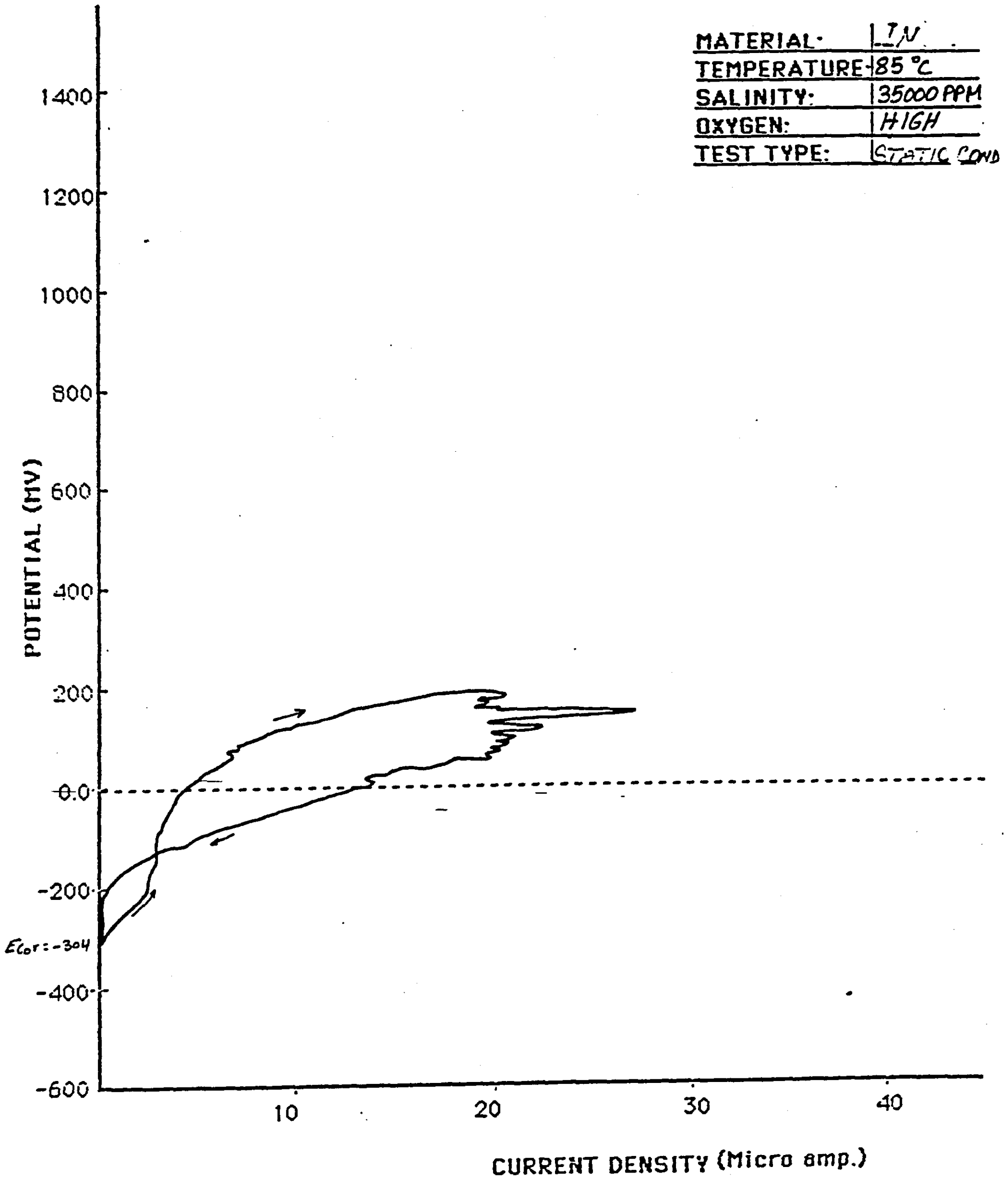
MATERIAL: IN.
TEMPERATURE: 25°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.

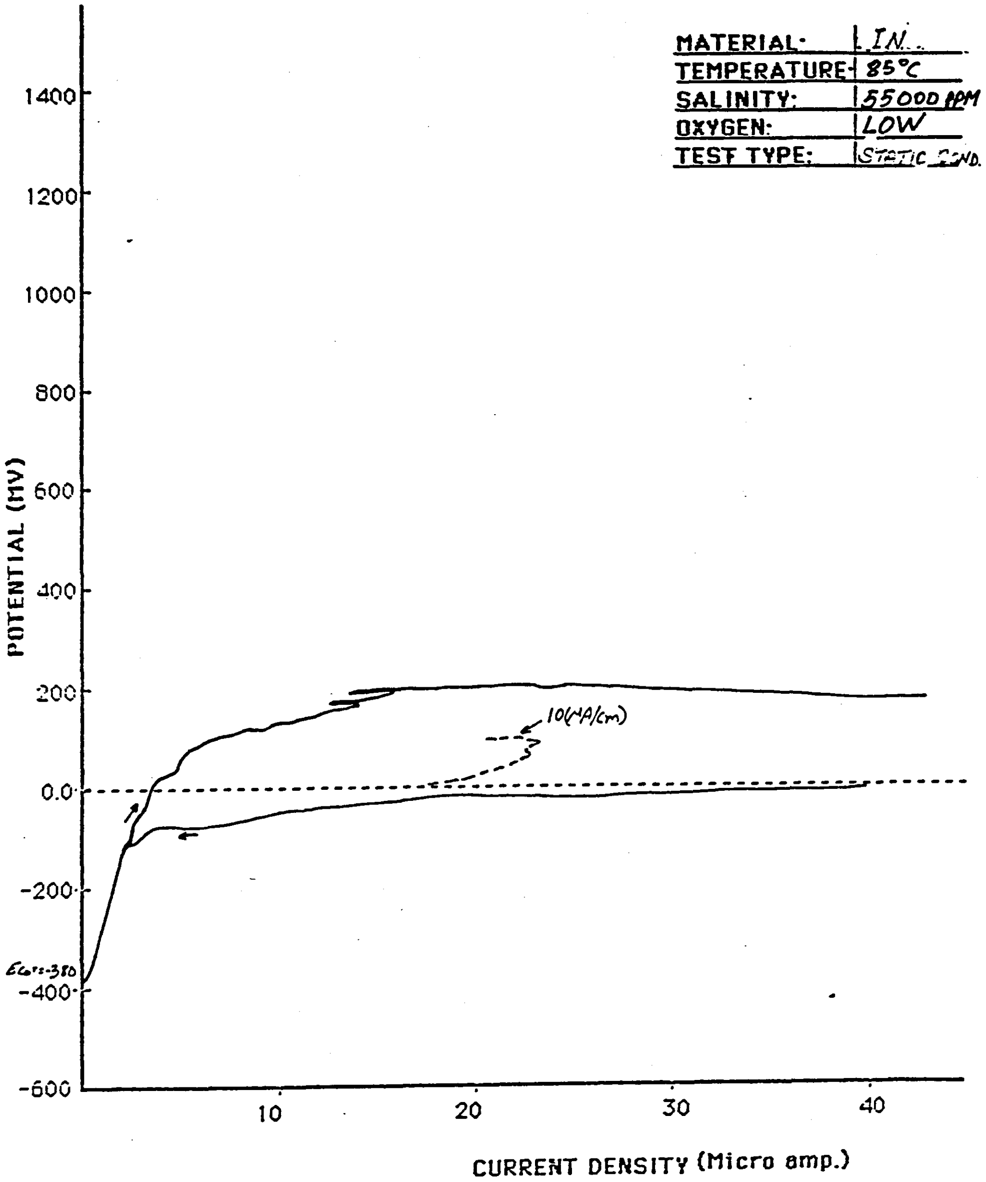


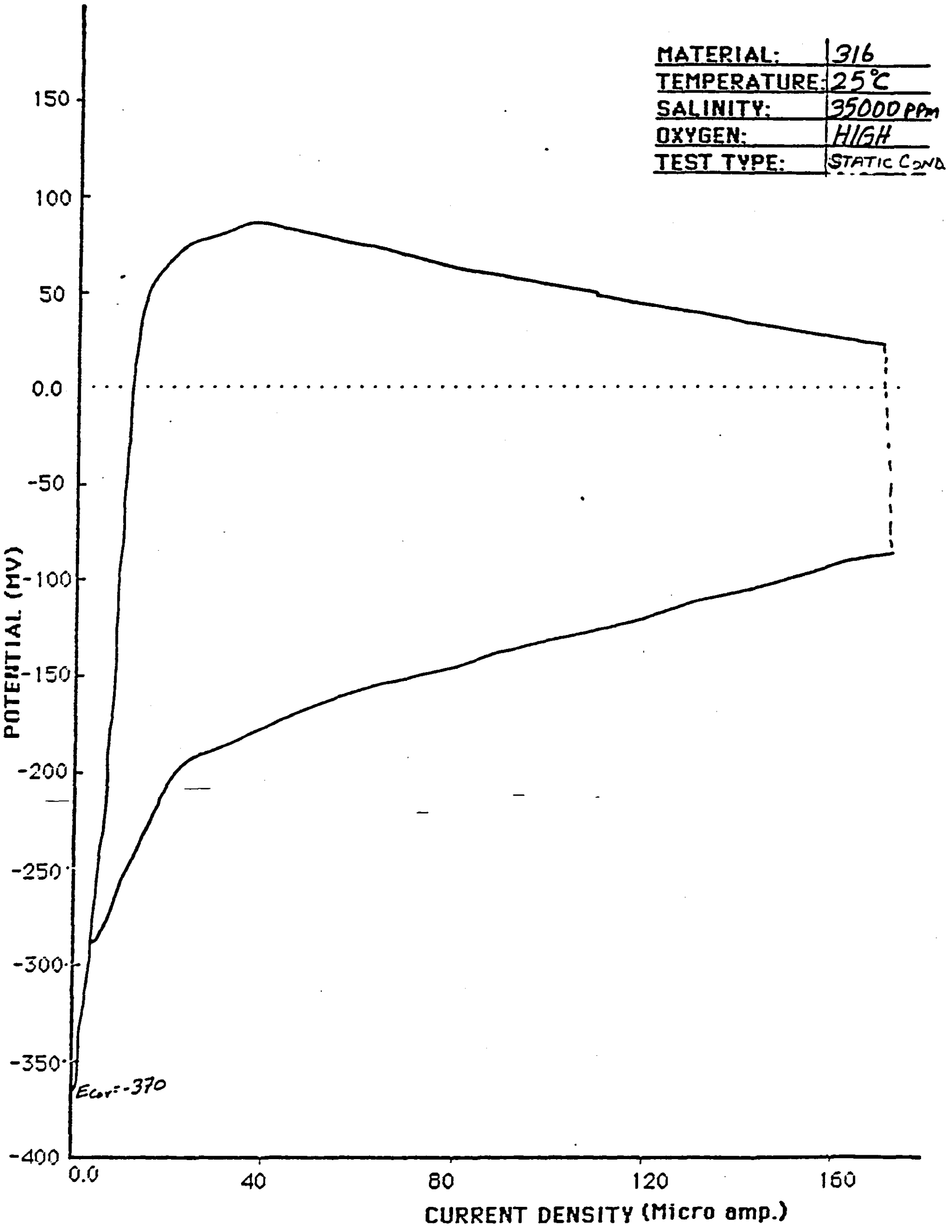
MATERIAL: IN.
TEMPERATURE: 35°C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND

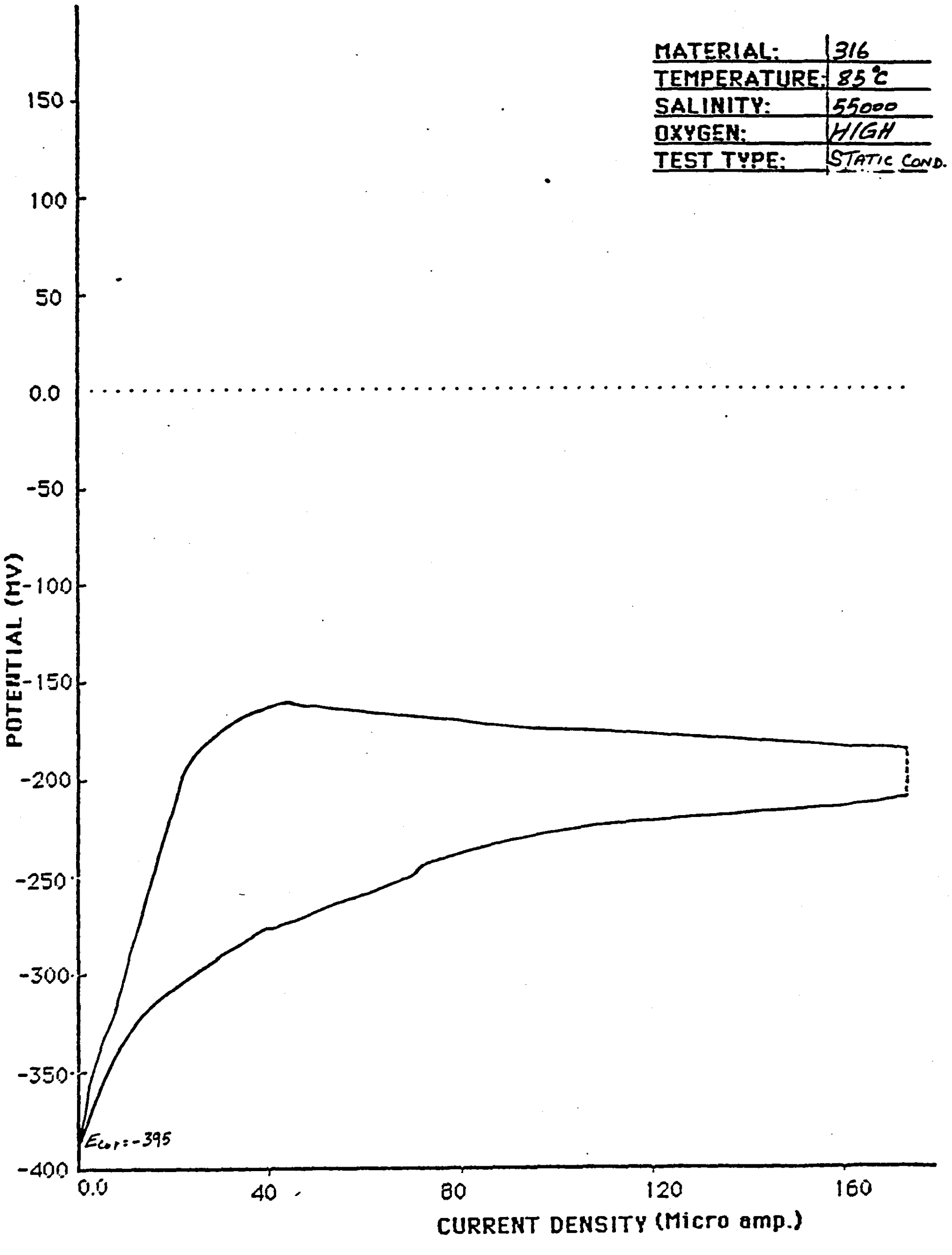

MATERIAL: IN
TEMPERATURE: 45 °C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
Ecorr=-415
-600
10
20
30
40
CURRENT DENSITY (Micro amp.)


MATERIAL: I.N.
TEMPERATURE: 65°C
SALINITY: 55000PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND.
1400
1200
1000
800
600
400
200
0.0
-200
Ecor:-275
-400
-600
POTENTIAL (MV)
10
20
30
40
CURRENT DENSITY (Micro amp.)

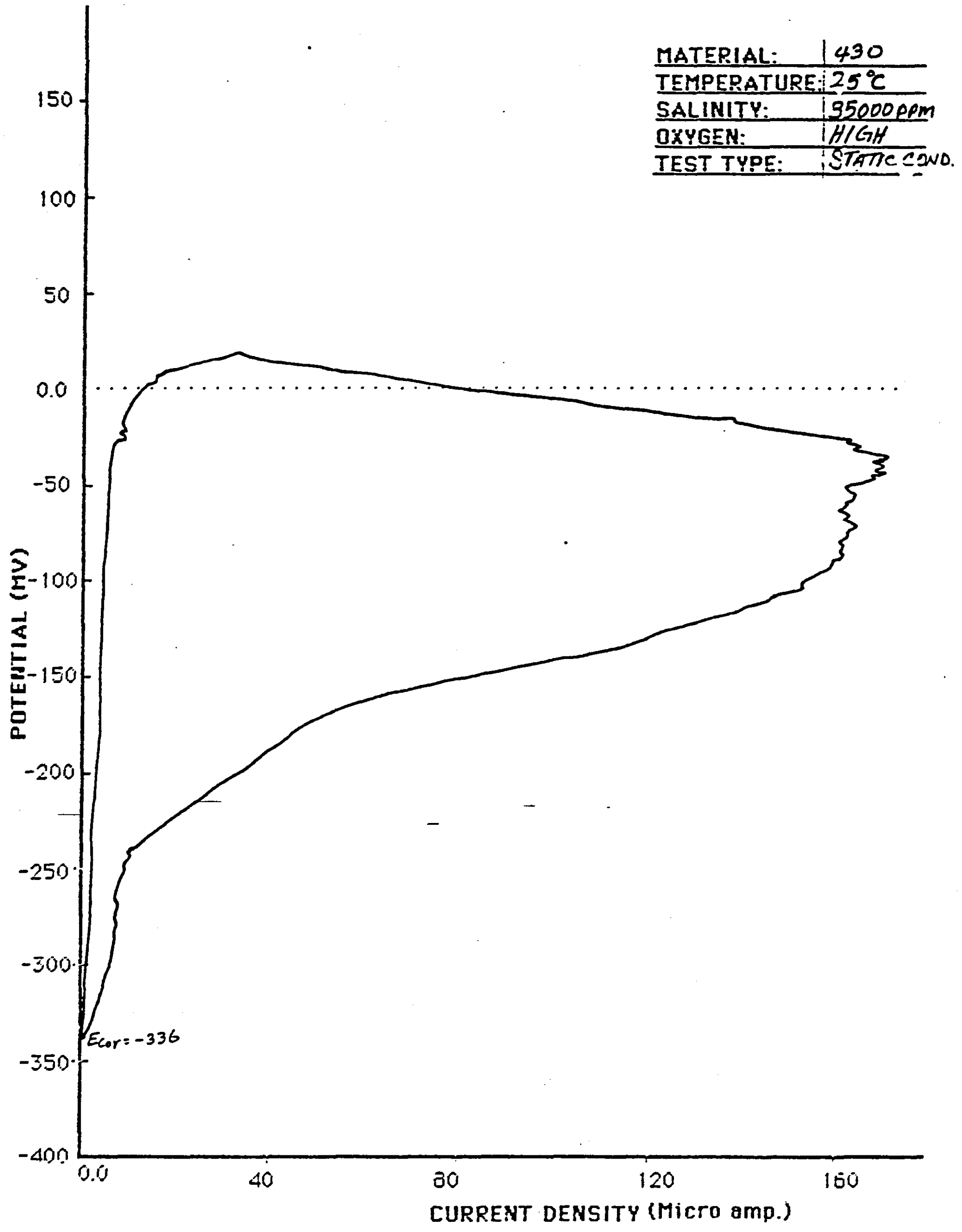

MATERIAL: IN
TEMPERATURE: 85 °C
SALINITY: 35000 PPM
OXYGEN: HIGH
TEST TYPE: STATIC COND
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecor: -304
10
20
30
40
CURRENT DENSITY (Micro amp.)

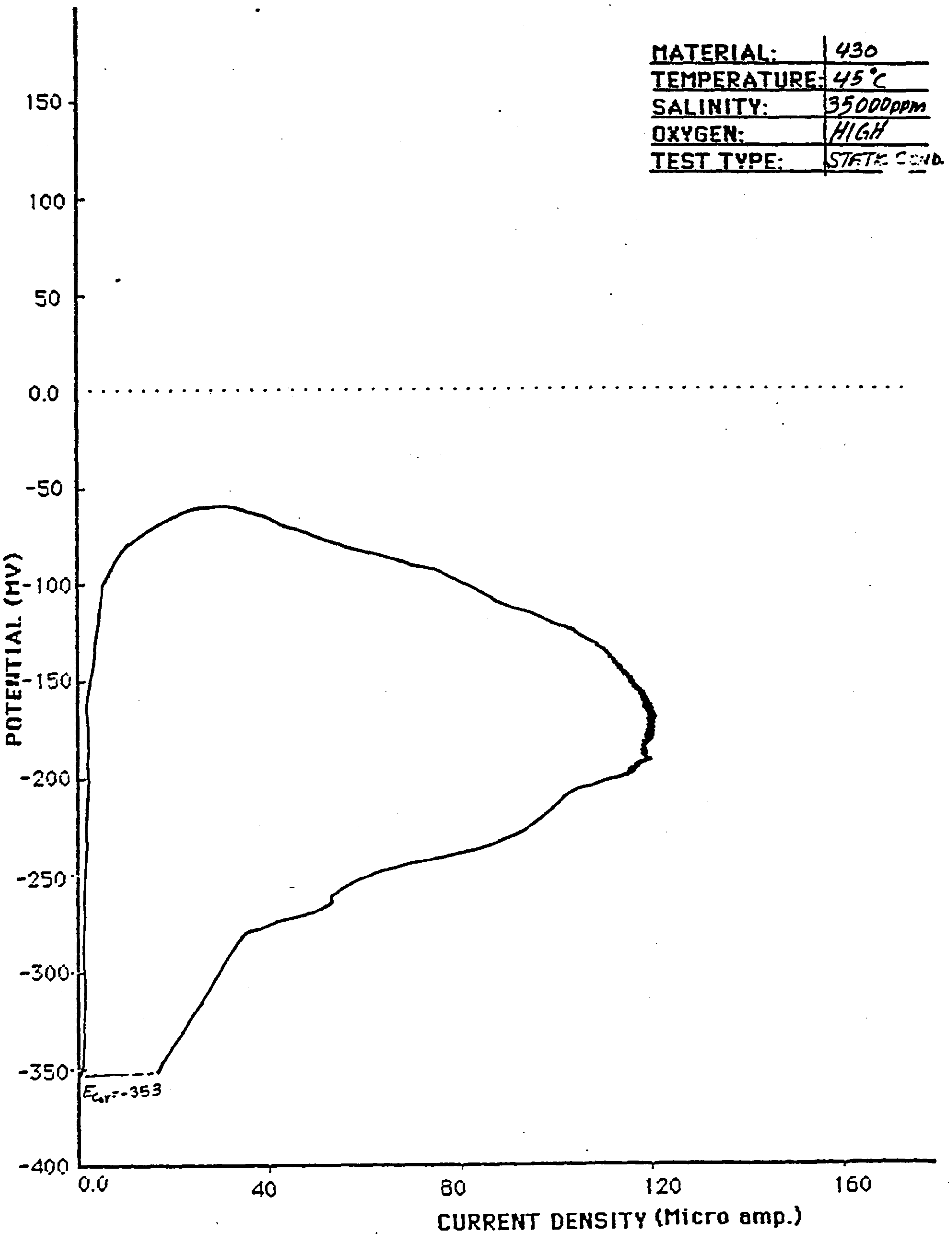

MATERIAL: IN.
TEMPERATURE: 85°C
SALINITY: 55000 PPM
OXYGEN: LOW
TEST TYPE: STATIC COND.
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecorr=-380
10(μA/cm)
10
20
30
40
CURRENT DENSITY (Micro amp.)


MATERIAL: 316
TEMPERATURE: 25°C
SALINITY: 35000 PPm
OXYGEN: HIGH
TEST TYPE: STATIC COND
150
100
50
0.0
-50
-100
-150
-200
-250
-300
-350
-400
POTENTIAL (MV)
Ecor=-370
0.0
40
80
120
160
CURRENT DENSITY (Micro amp.)

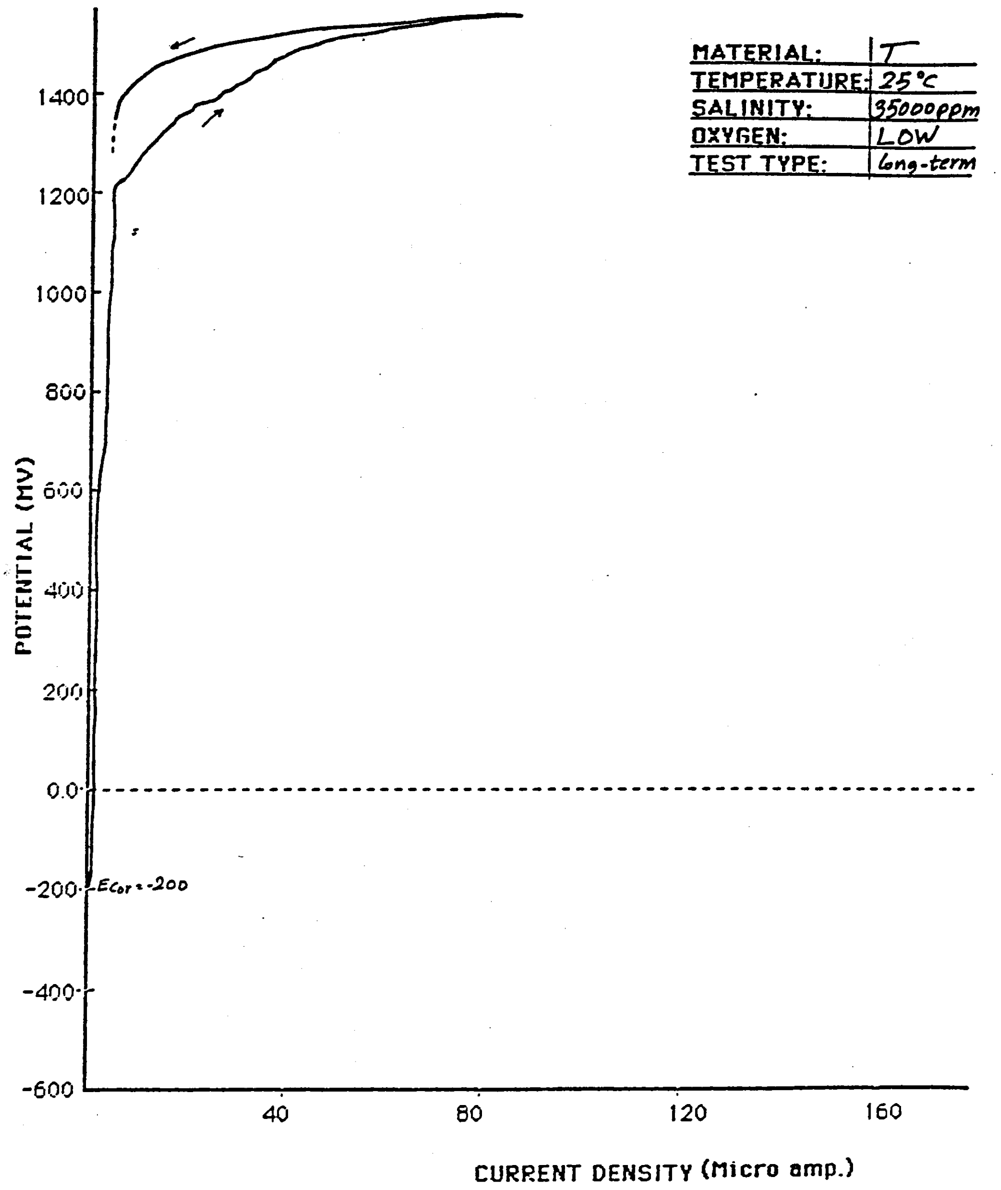


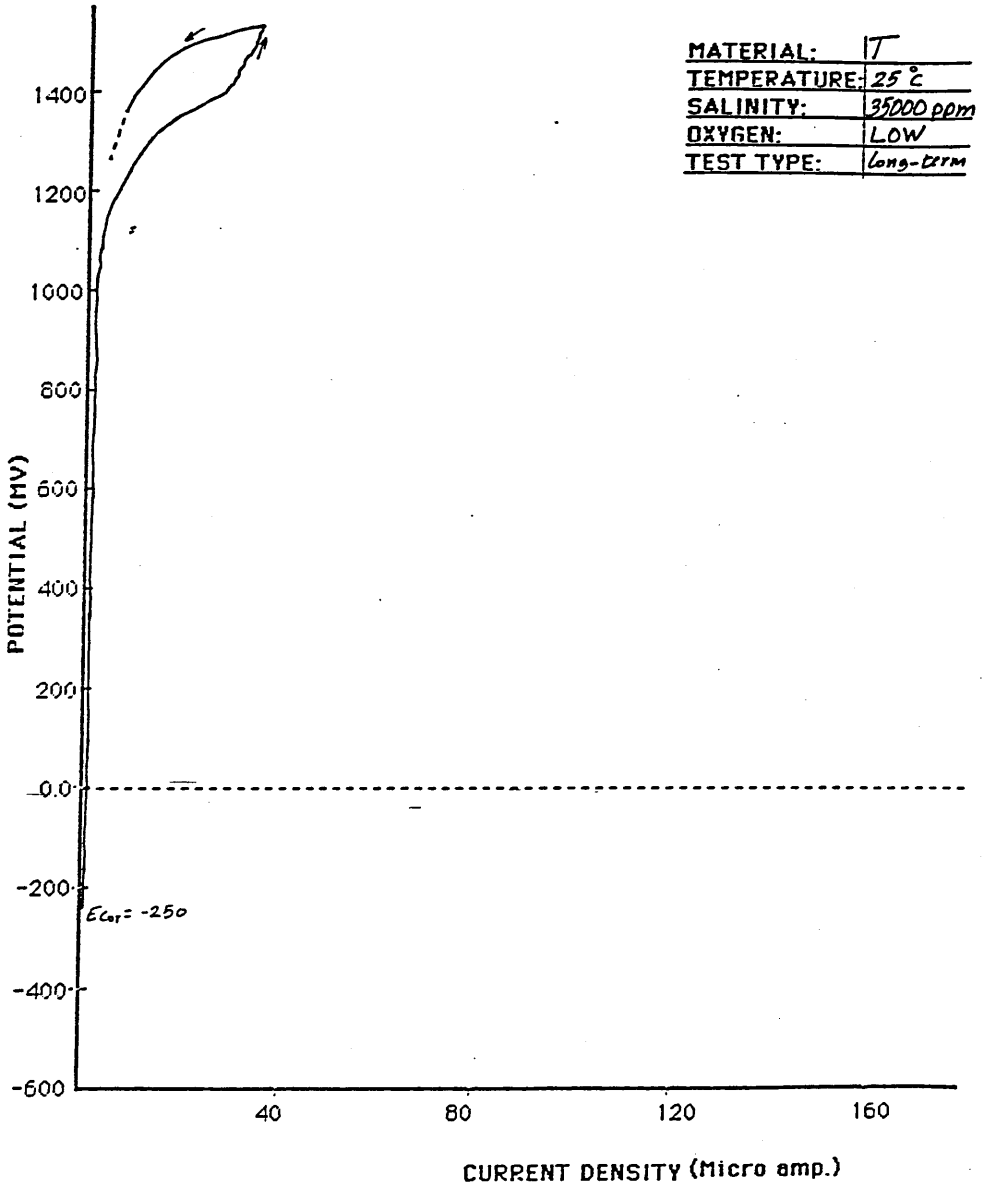
MATERIAL:	316
TEMPERATURE:	85 °C
SALINITY:	55000
OXYGEN:	HIGH
TEST TYPE:	STATIC COND.

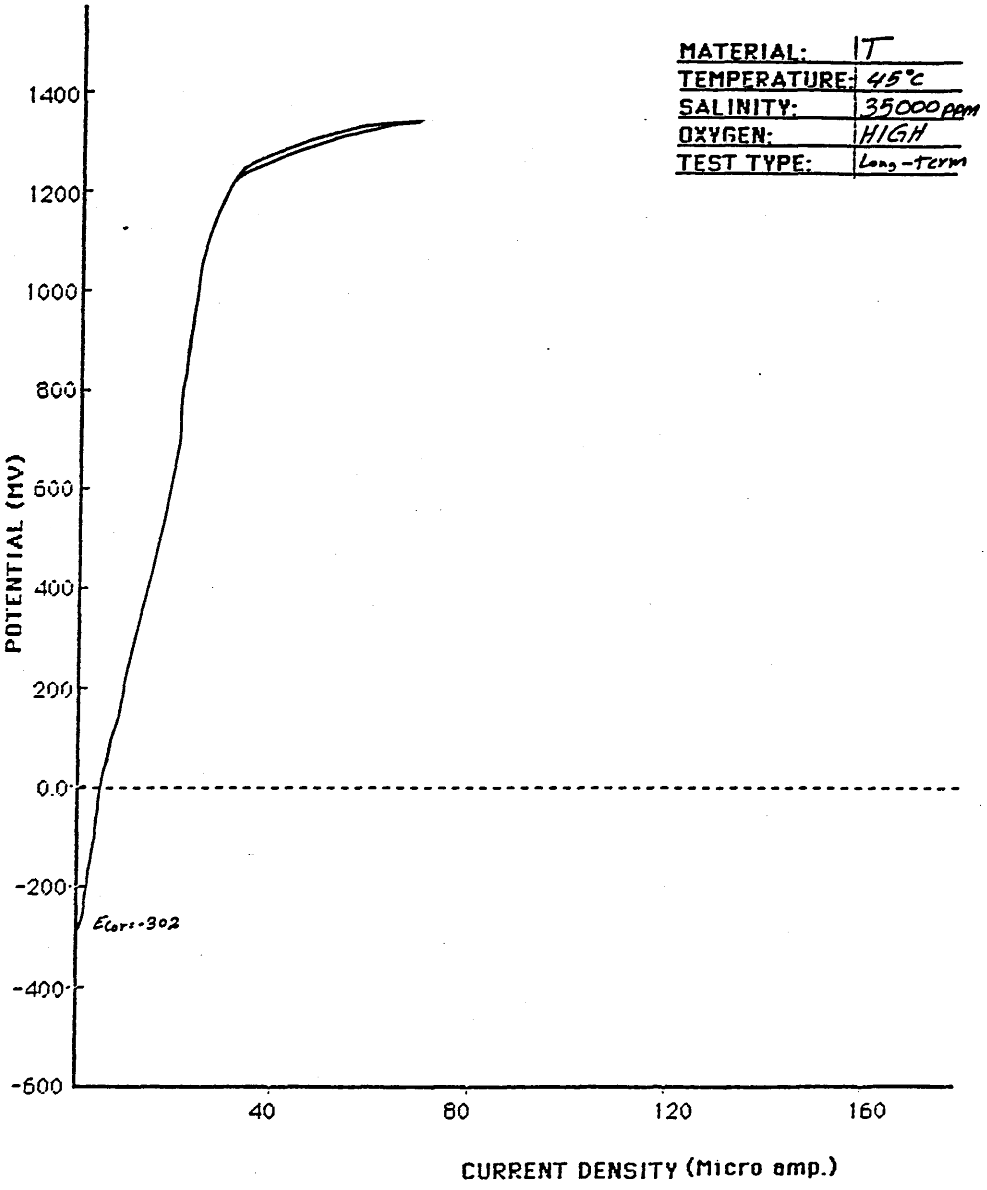

MATERIAL: 430
TEMPERATURE: 25°C
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: STATIC COND.
150
100
50
0.0
-50
-100
-150
-200
-250
-300
-350
-400
POTENTIAL (MV)
Ecor = -336
0.0
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: 430
TEMPERATURE: 45 °C
SALINITY: 35000ppm
OXYGEN: HIGH
TEST TYPE: STATIC COND.
POTENTIAL (MV)
150
100
50
0.0
-50
-100
-150
-200
-250
-300
-350
-400
E_{corr}=-353
0.0
40
80
120
160
CURRENT DENSITY (Micro amp.)

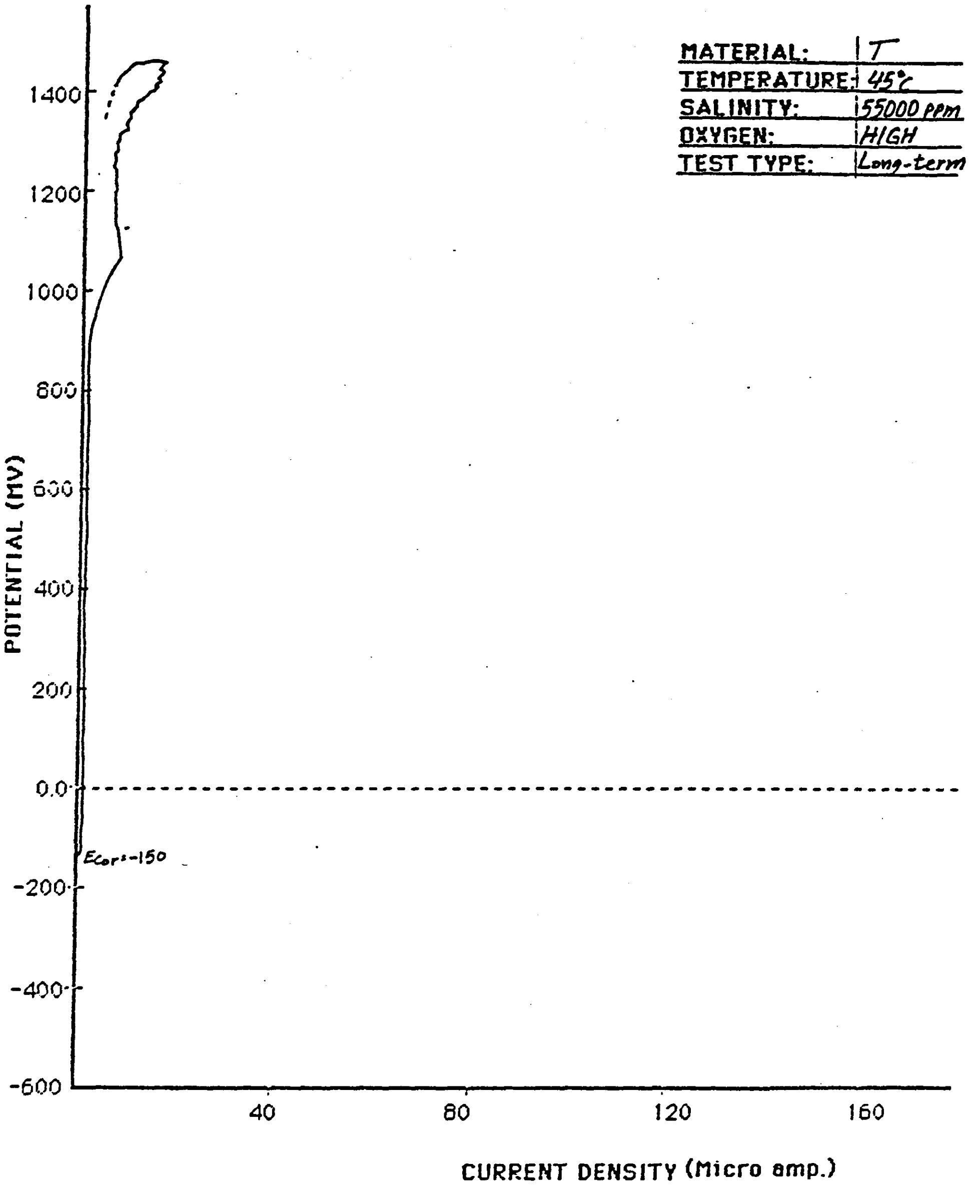
Long Term Effect Test Rresults


MATERIAL: T
TEMPERATURE: 25°C
SALINITY: 35000ppm
OXYGEN: LOW
TEST TYPE: Long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecor = -200
40
80
120
160
CURRENT DENSITY (Micro amp.)

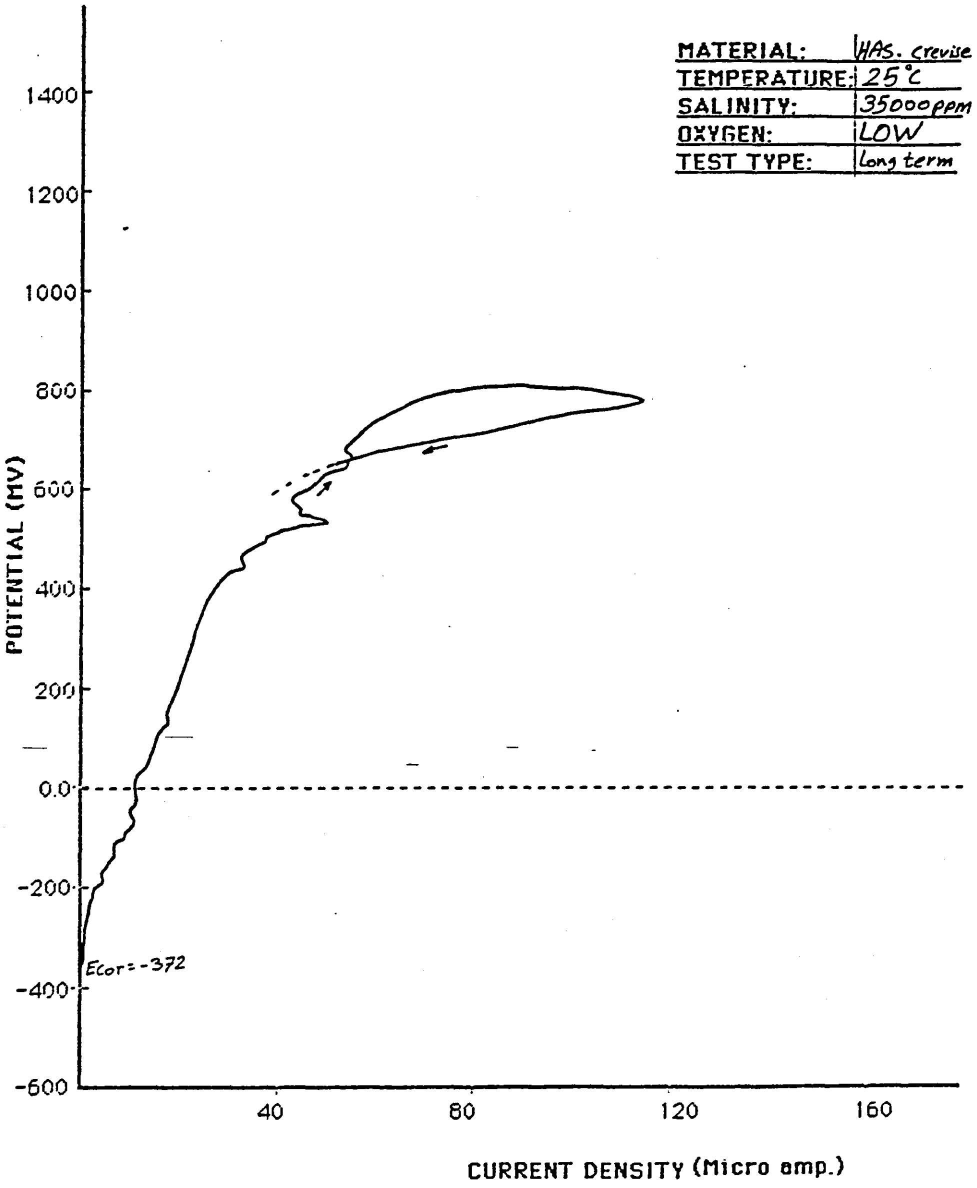

MATERIAL: T
TEMPERATURE: 25 °C
SALINITY: 35000 ppm
OXYGEN: LOW
TEST TYPE: Long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
E_{Corr} = -250
40
80
120
160
CURRENT DENSITY (Micro amp.)



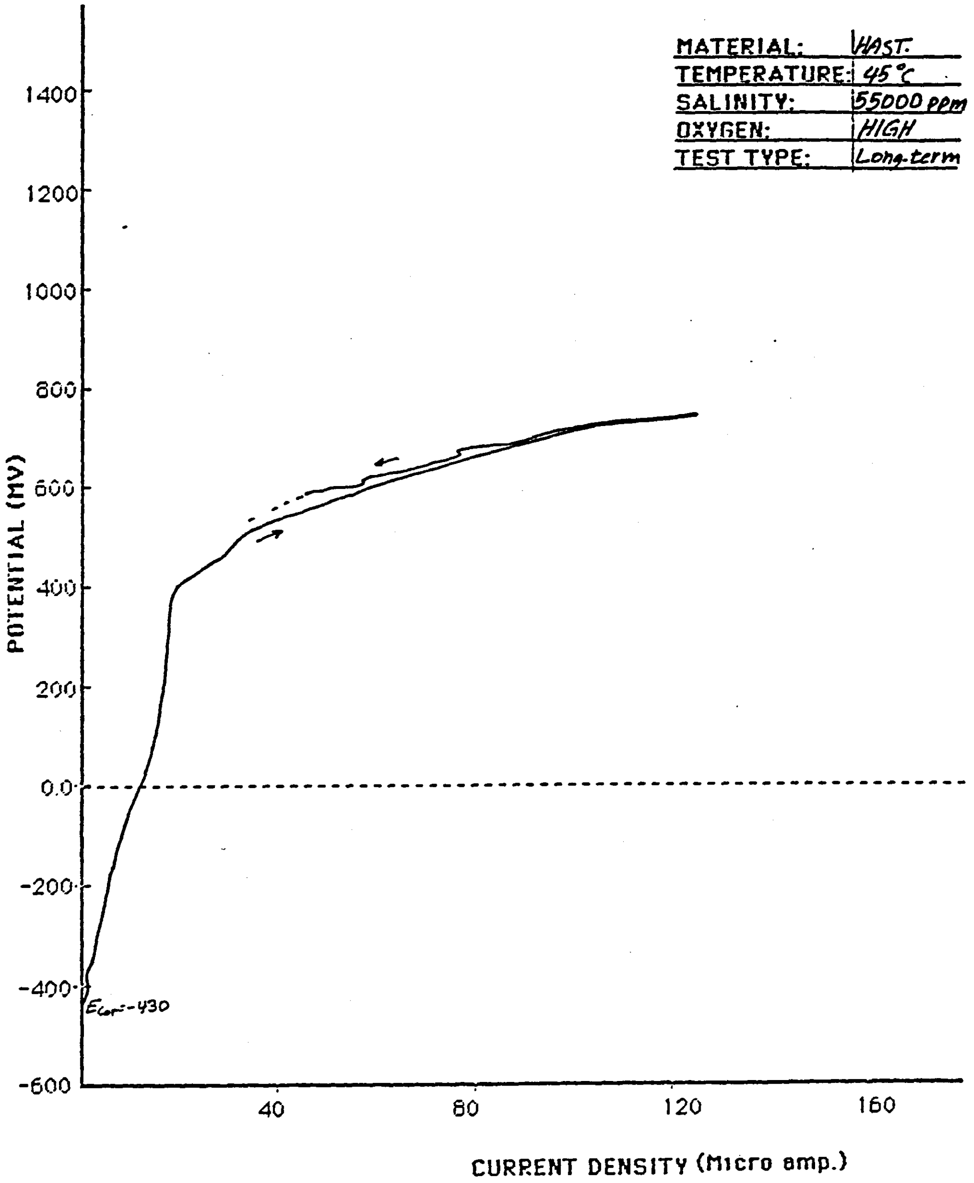
MATERIAL:	T
TEMPERATURE:	45°C
SALINITY:	35000 ppm
OXYGEN:	HIGH
TEST TYPE:	Long-term

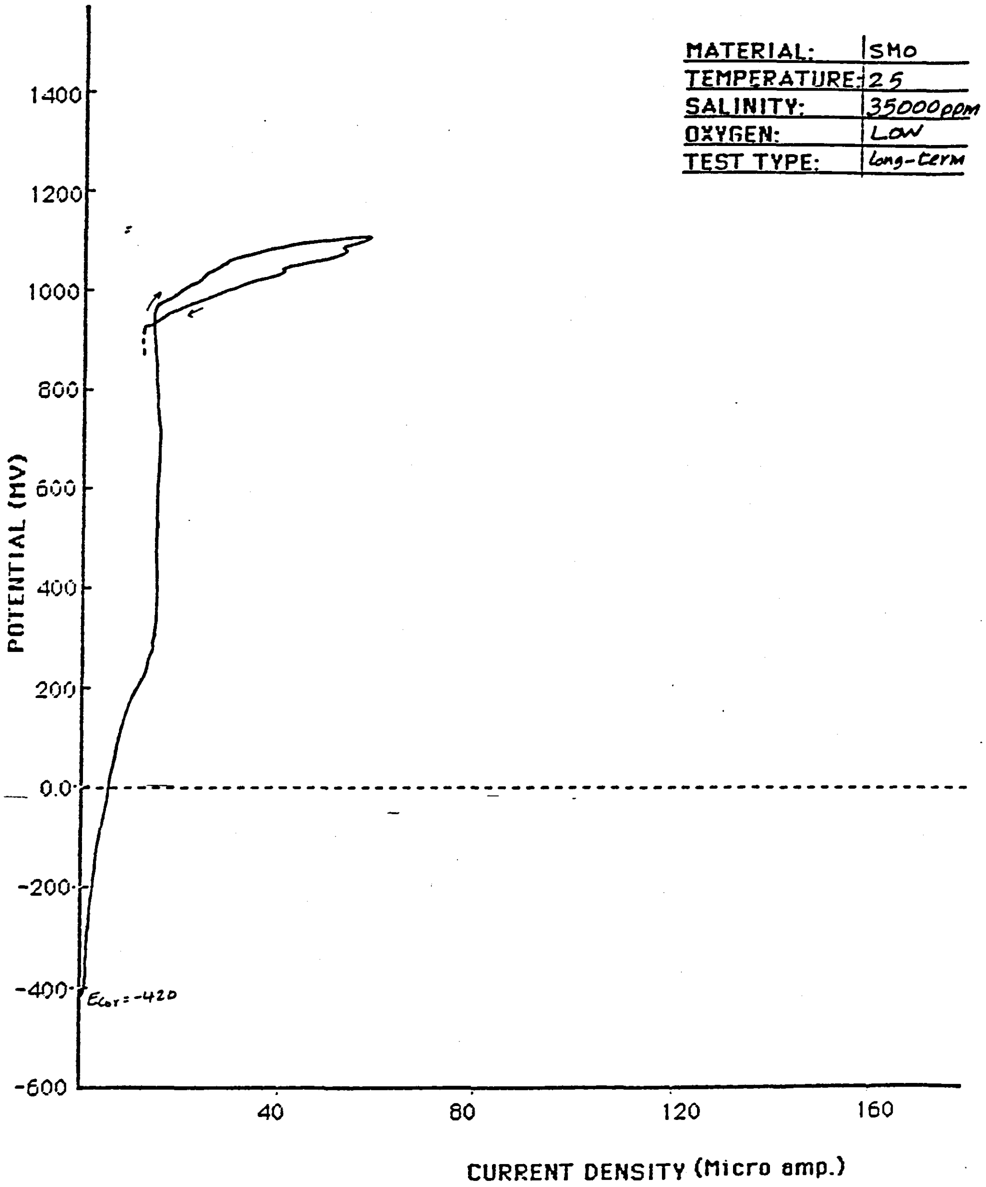


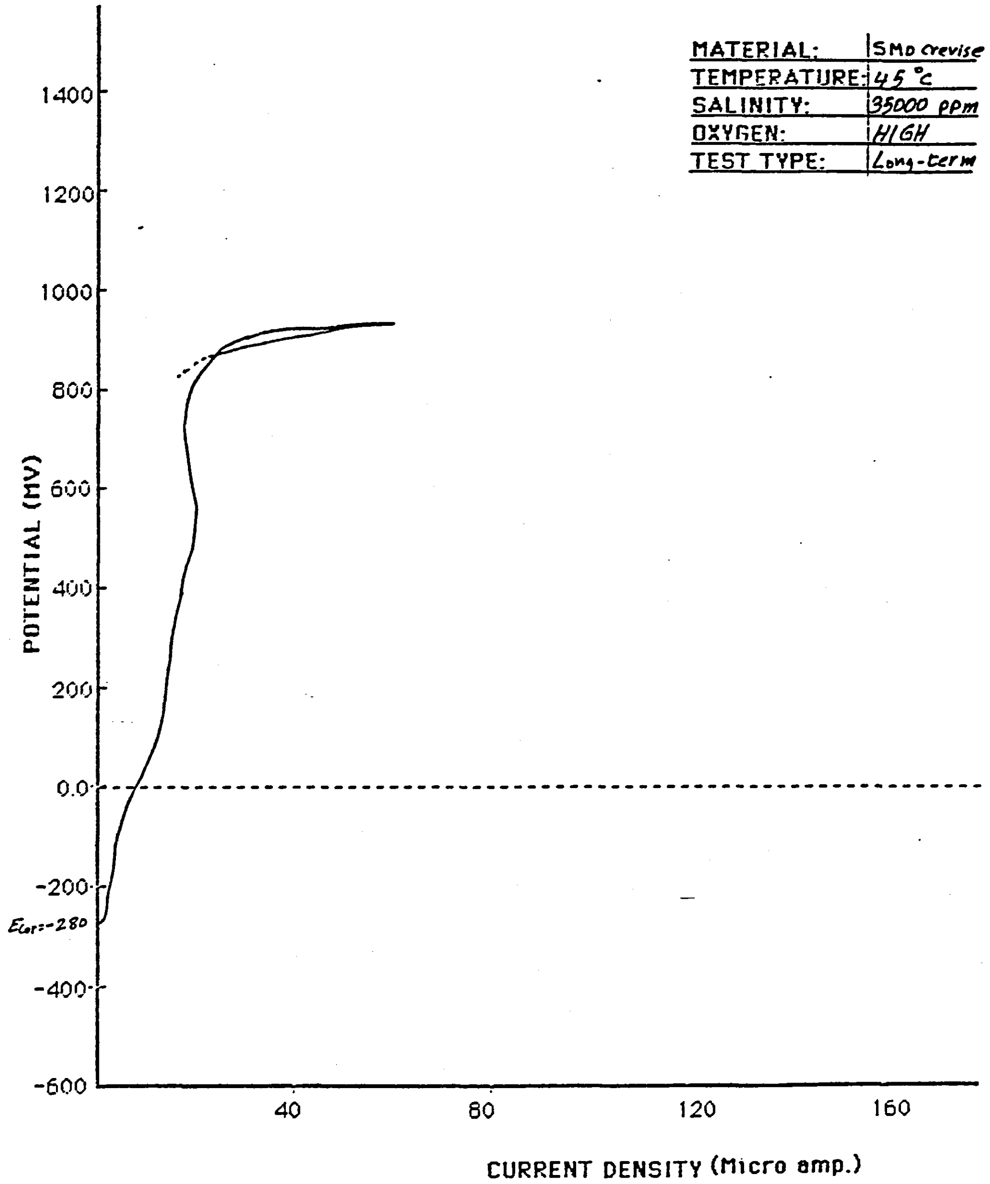
MATERIAL: T
TEMPERATURE: 45°C
SALINITY: 55000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term



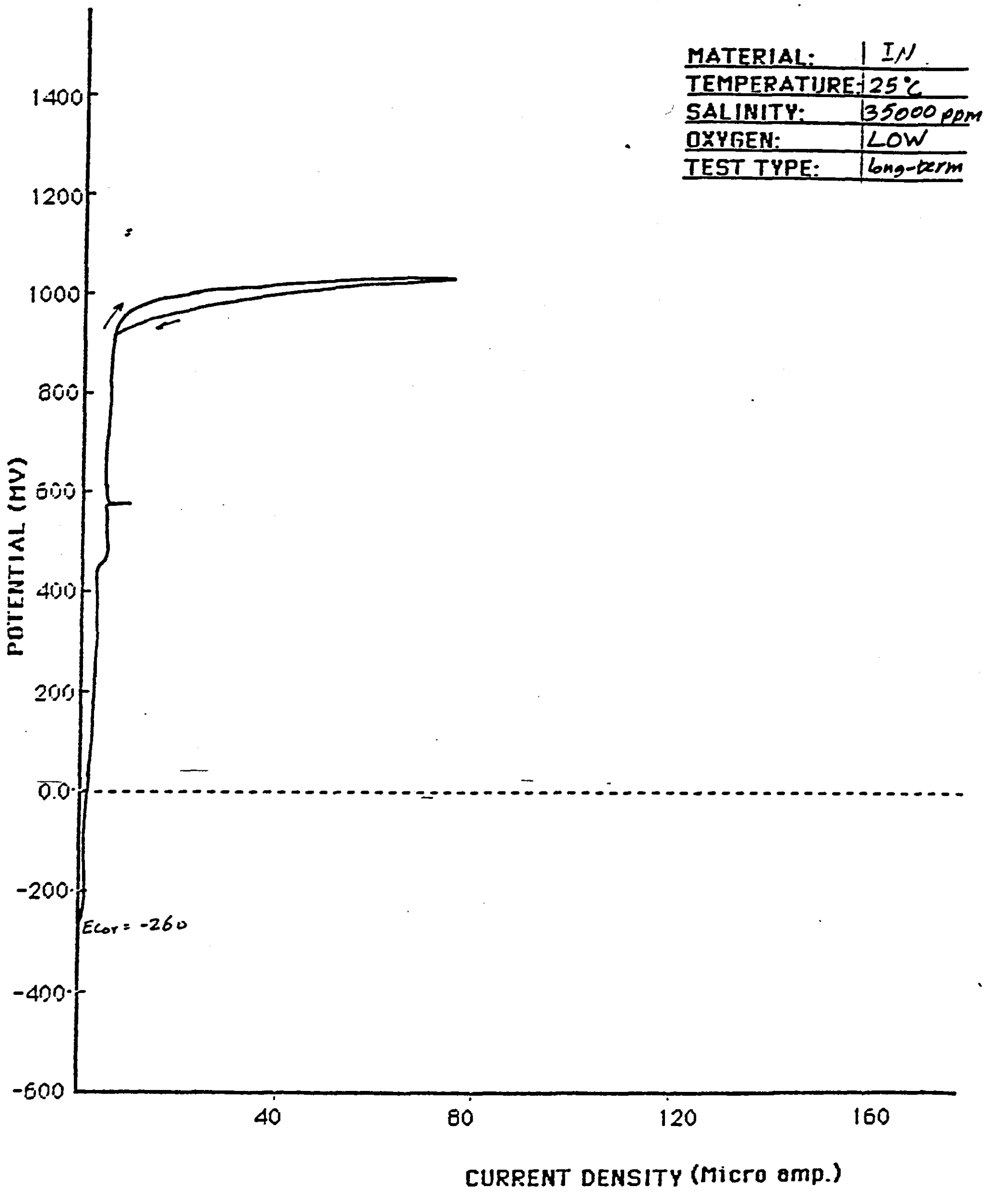
MATERIAL:	HAS. crevise
TEMPERATURE:	25°C
SALINITY:	35000ppm
OXYGEN:	LOW
TEST TYPE:	Long term

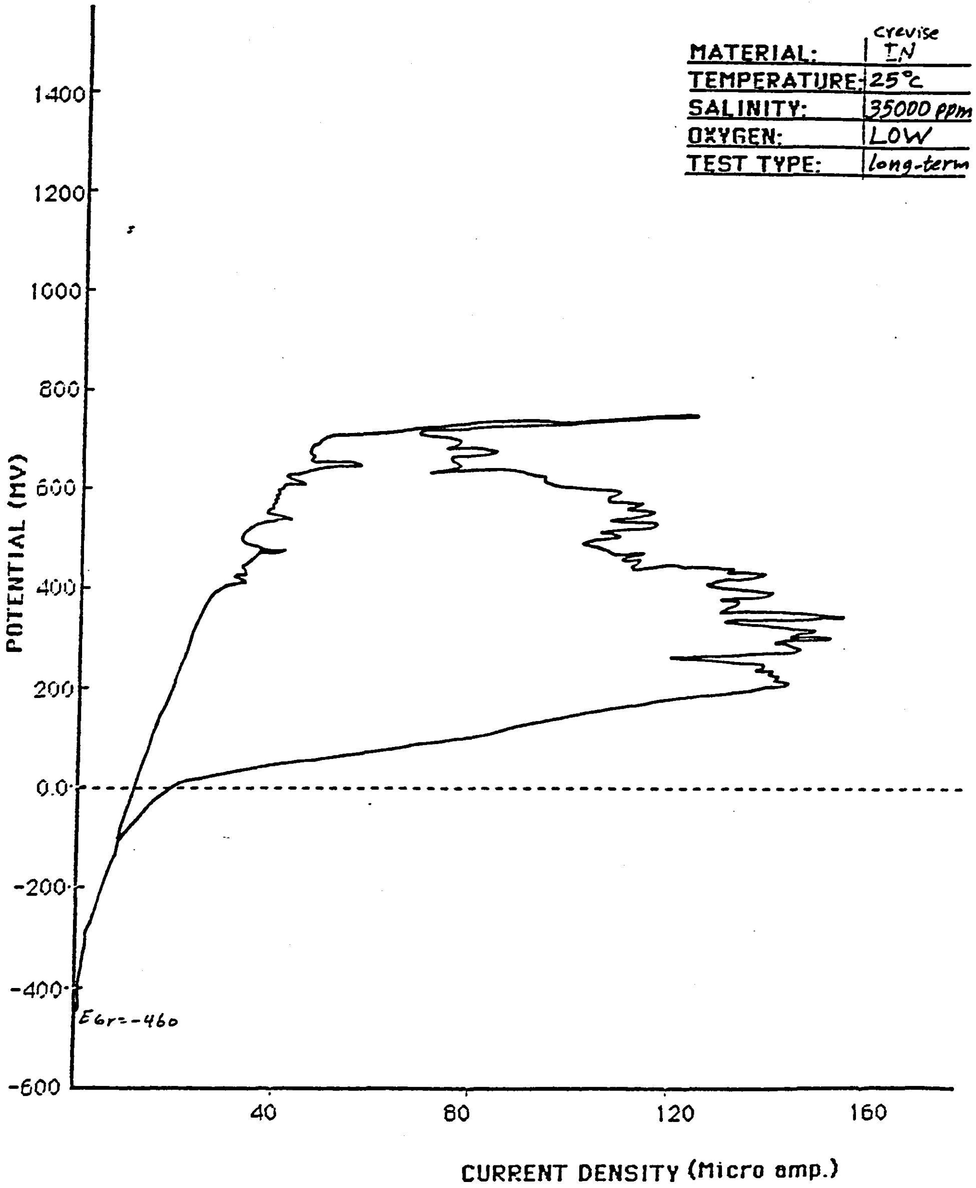

MATERIAL: HAST.
TEMPERATURE: 45°C
SALINITY: 55000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
E_{corr} - 430
40
80
120
160
CURRENT DENSITY (Micro amp.)

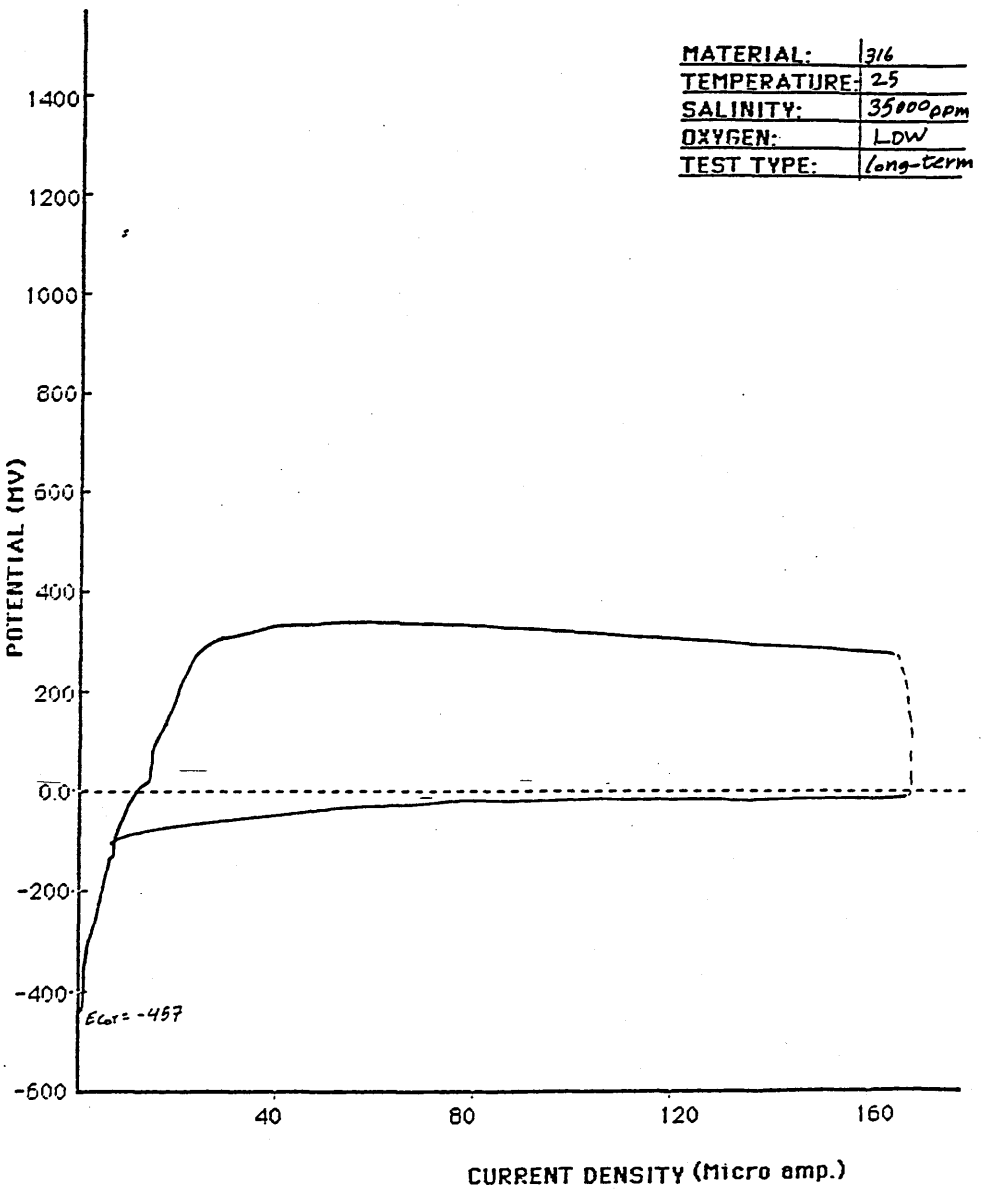

MATERIAL: SMo
TEMPERATURE: 25
SALINITY: 35000ppm
OXYGEN: LOW
TEST TYPE: Long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
E_{cor}=-420
40
80
120
160
CURRENT DENSITY (Micro amp.)

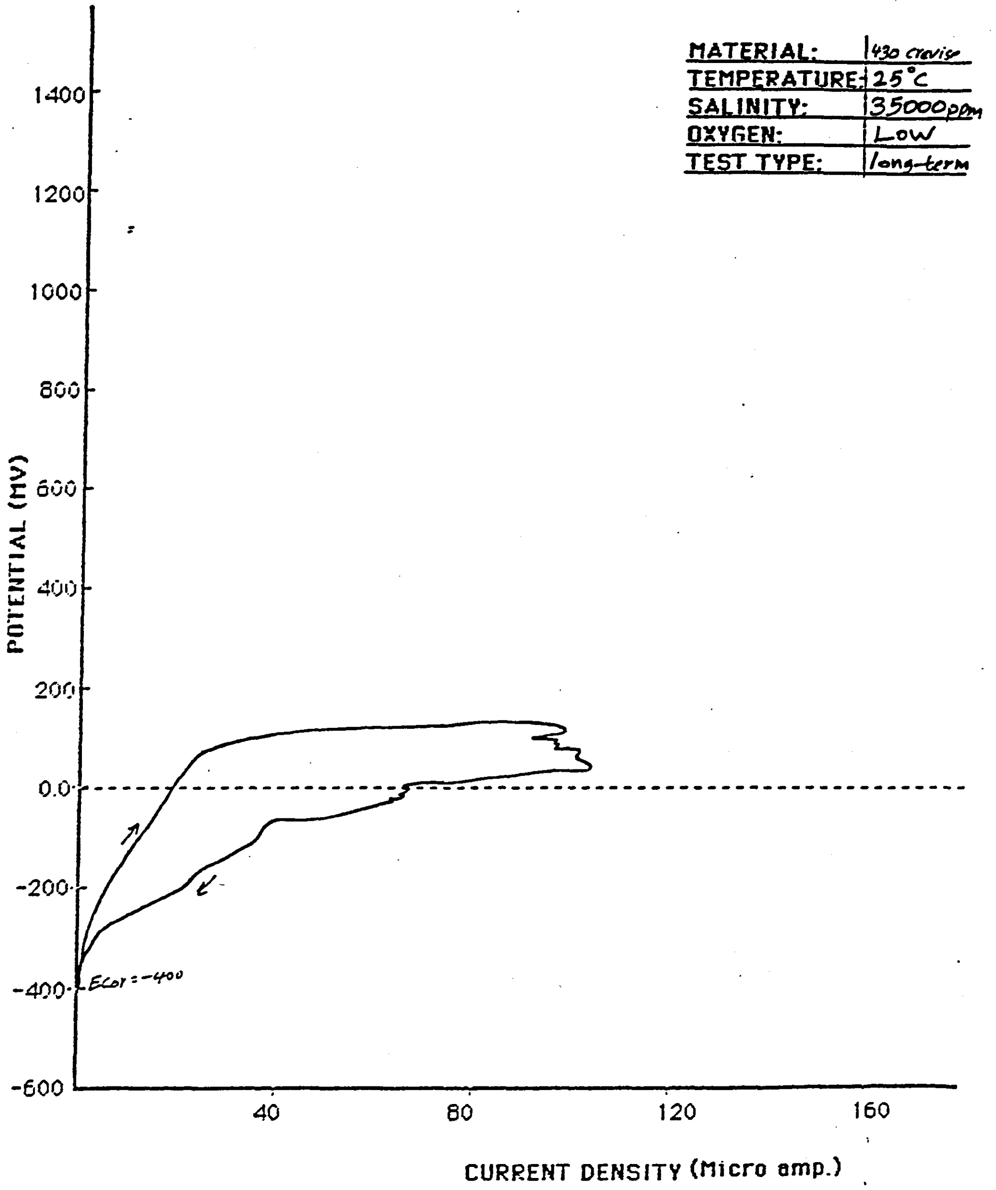


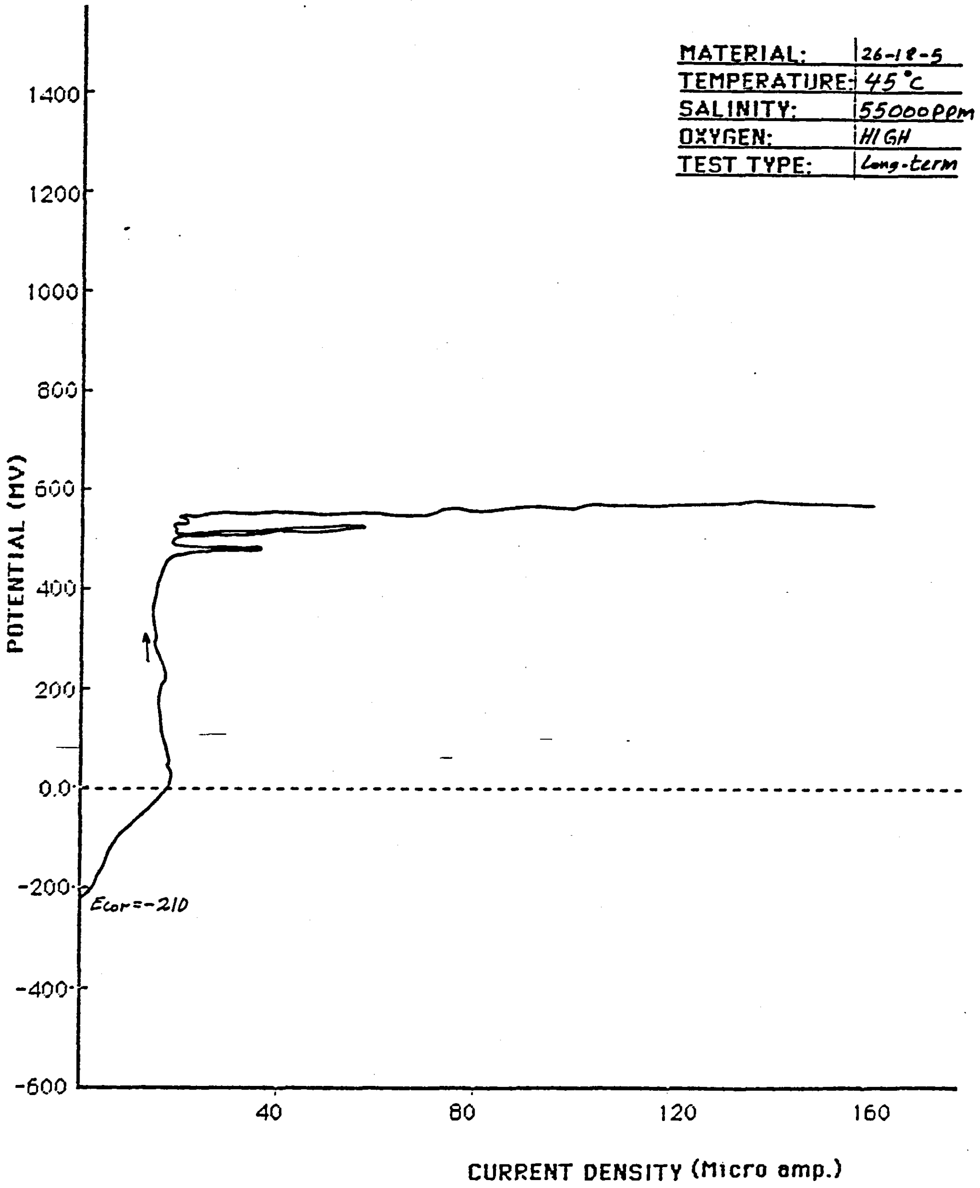
MATERIAL: SMo crevise
TEMPERATURE: 45 °c
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term

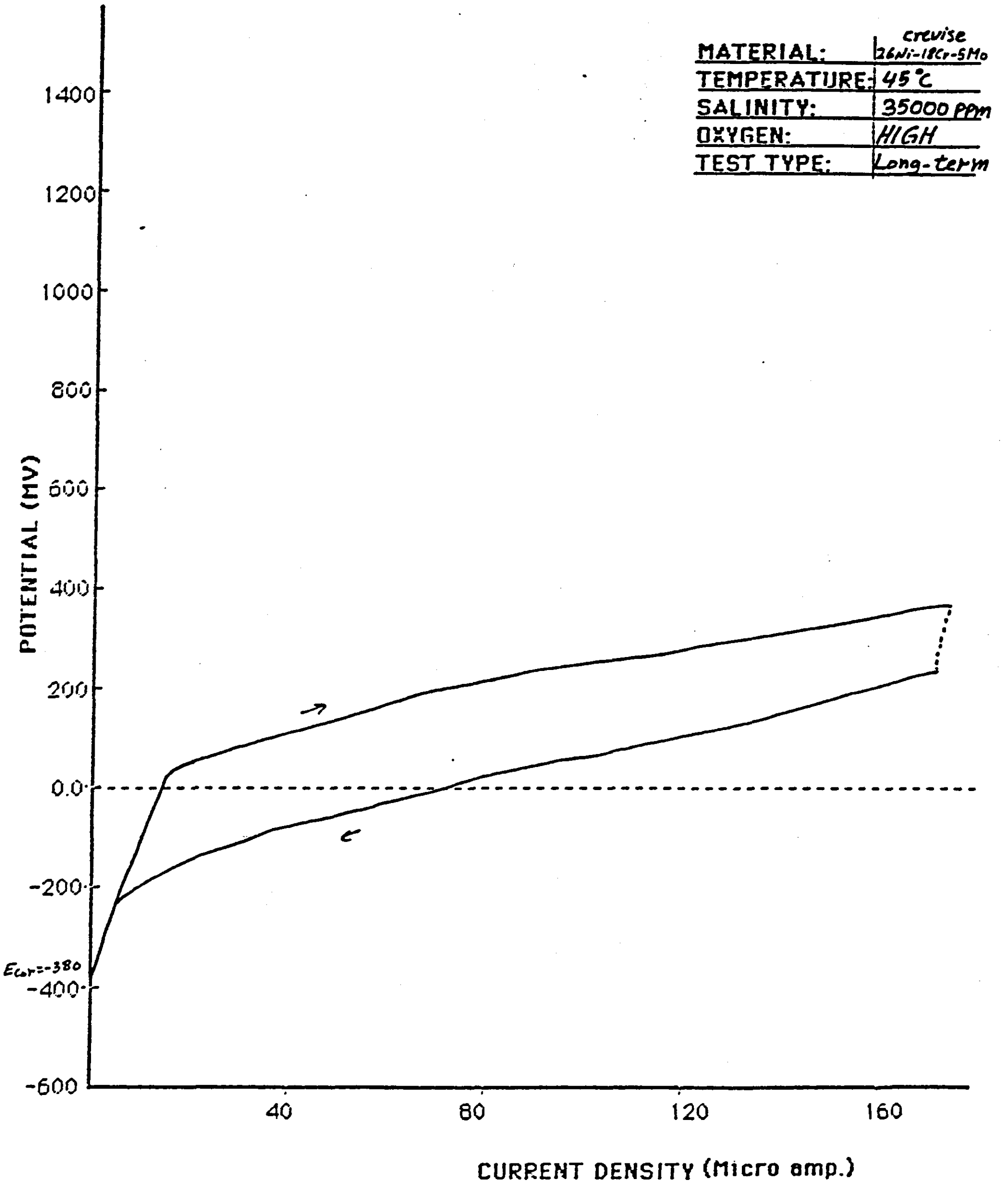

MATERIAL: I/N
TEMPERATURE: 25°C
SALINITY: 35000 ppm
OXYGEN: LOW
TEST TYPE: long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
Ecor = -260
40
80
120
160
CURRENT DENSITY (Micro amp.)

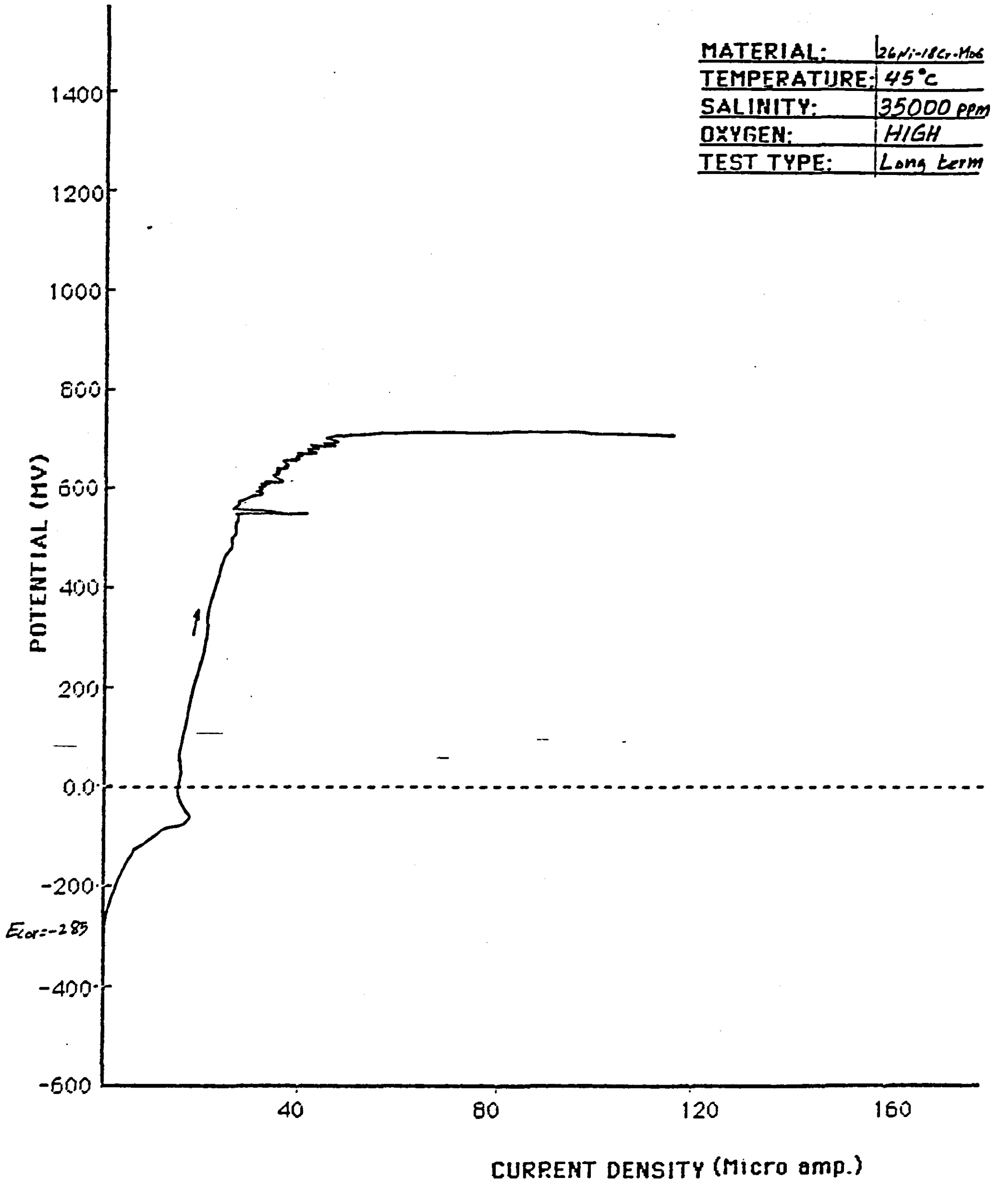

MATERIAL: crevise IN
TEMPERATURE: 25°c
SALINITY: 35000 ppm
OXYGEN: LOW
TEST TYPE: long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
E6r=-460
40
80
120
160
CURRENT DENSITY (Micro amp.)

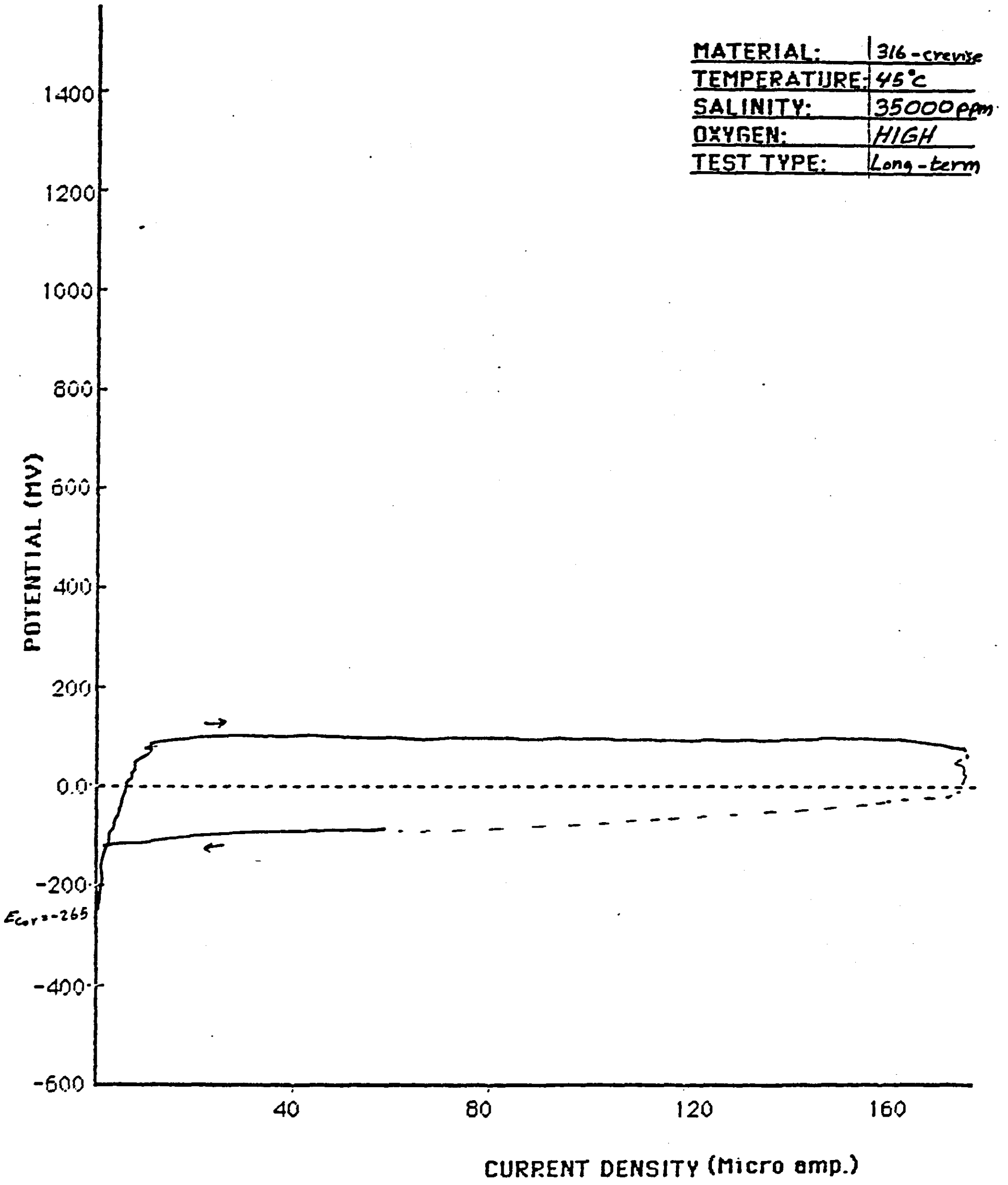

MATERIAL: 316
TEMPERATURE: 25
SALINITY: 35000 ppm
OXYGEN: LOW
TEST TYPE: long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
Ecor = -457
40
80
120
160
CURRENT DENSITY (Micro amp.)

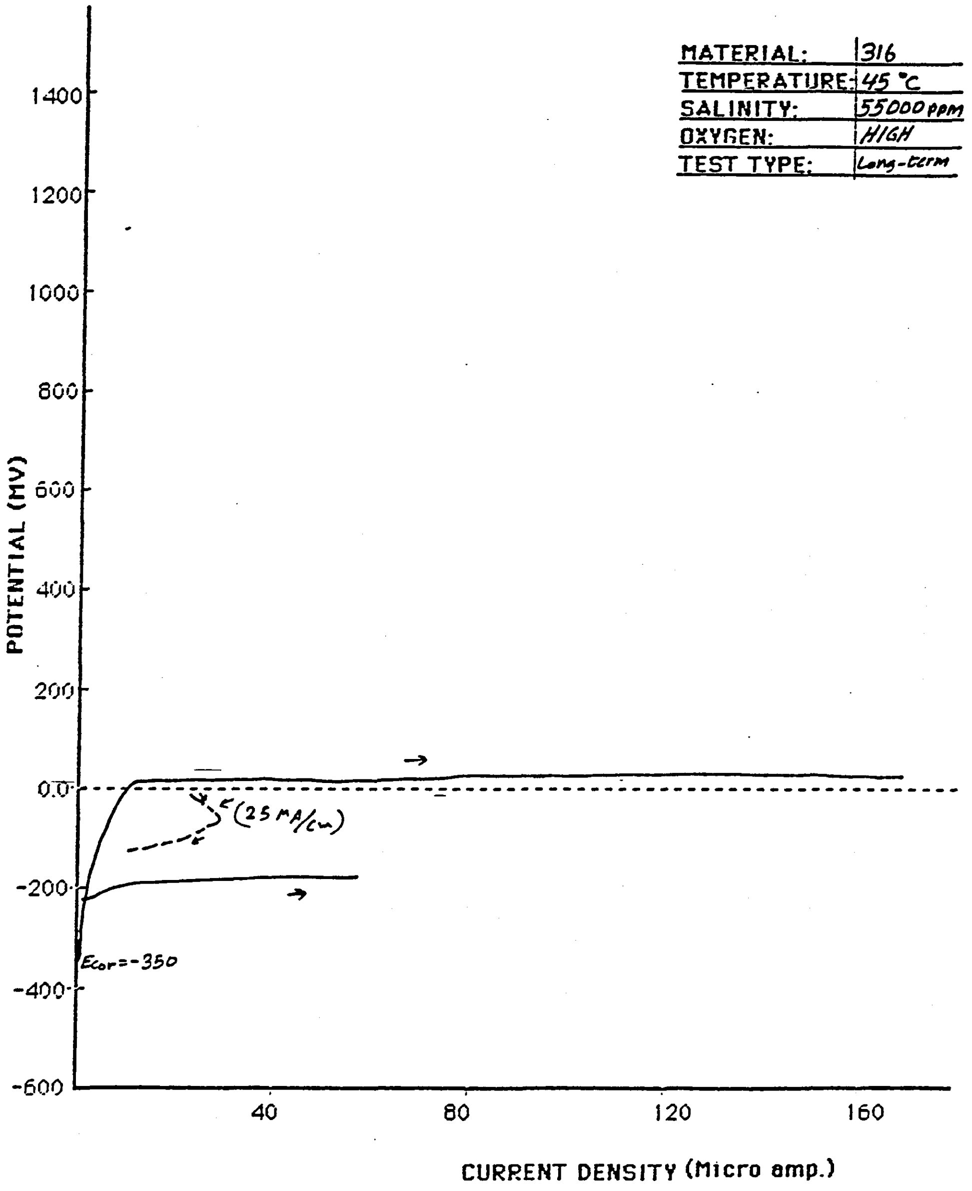

MATERIAL: 430 crevise
TEMPERATURE: 25°C
SALINITY: 35000ppm
OXYGEN: Low
TEST TYPE: long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecor = -400
40
80
120
160
CURRENT DENSITY (Micro amp.)

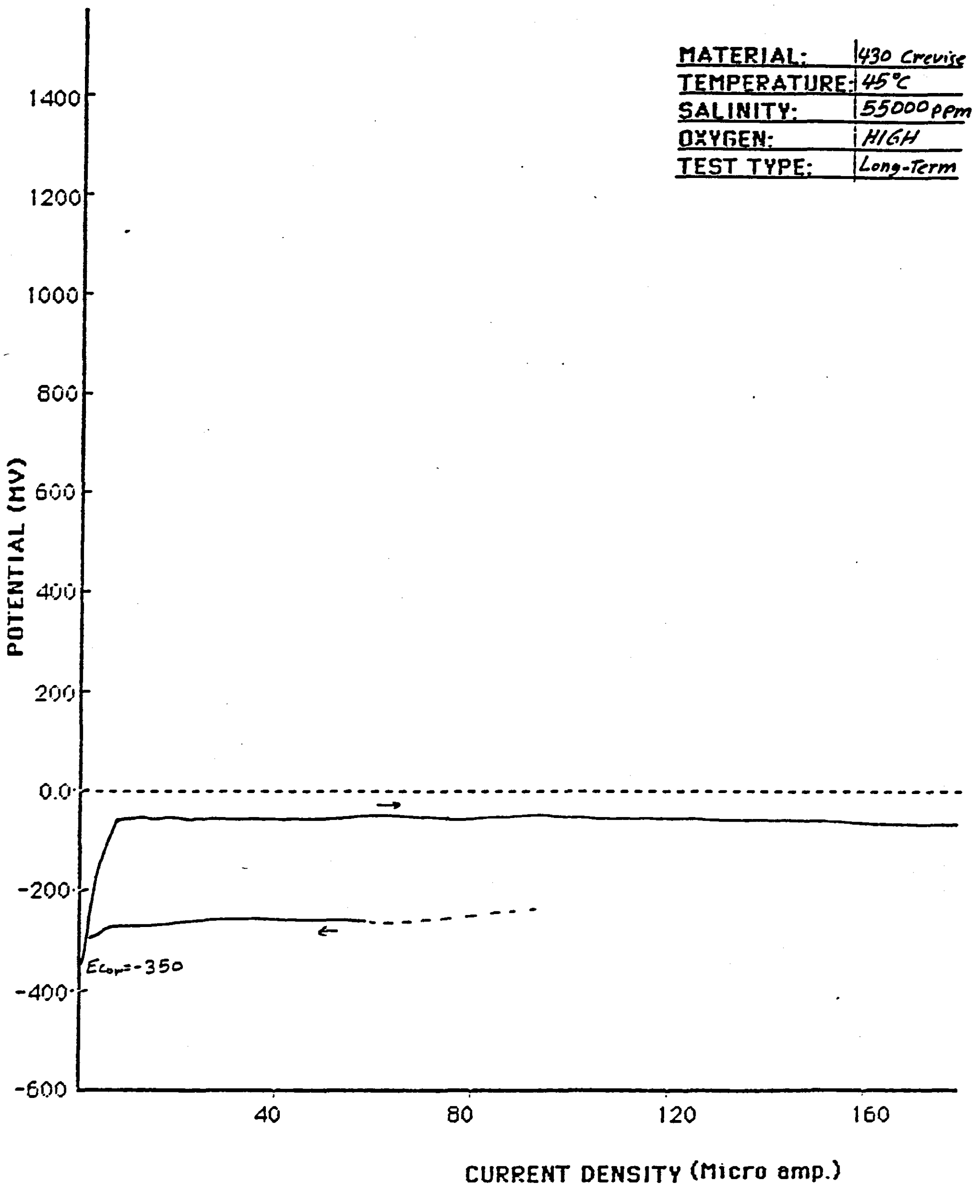

MATERIAL: 26-18-5
TEMPERATURE: 45 °C
SALINITY: 55000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecor=-210
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: crevise 26Ni-18Cr-5Mo
TEMPERATURE: 45°C
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
E_cor=-380
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)

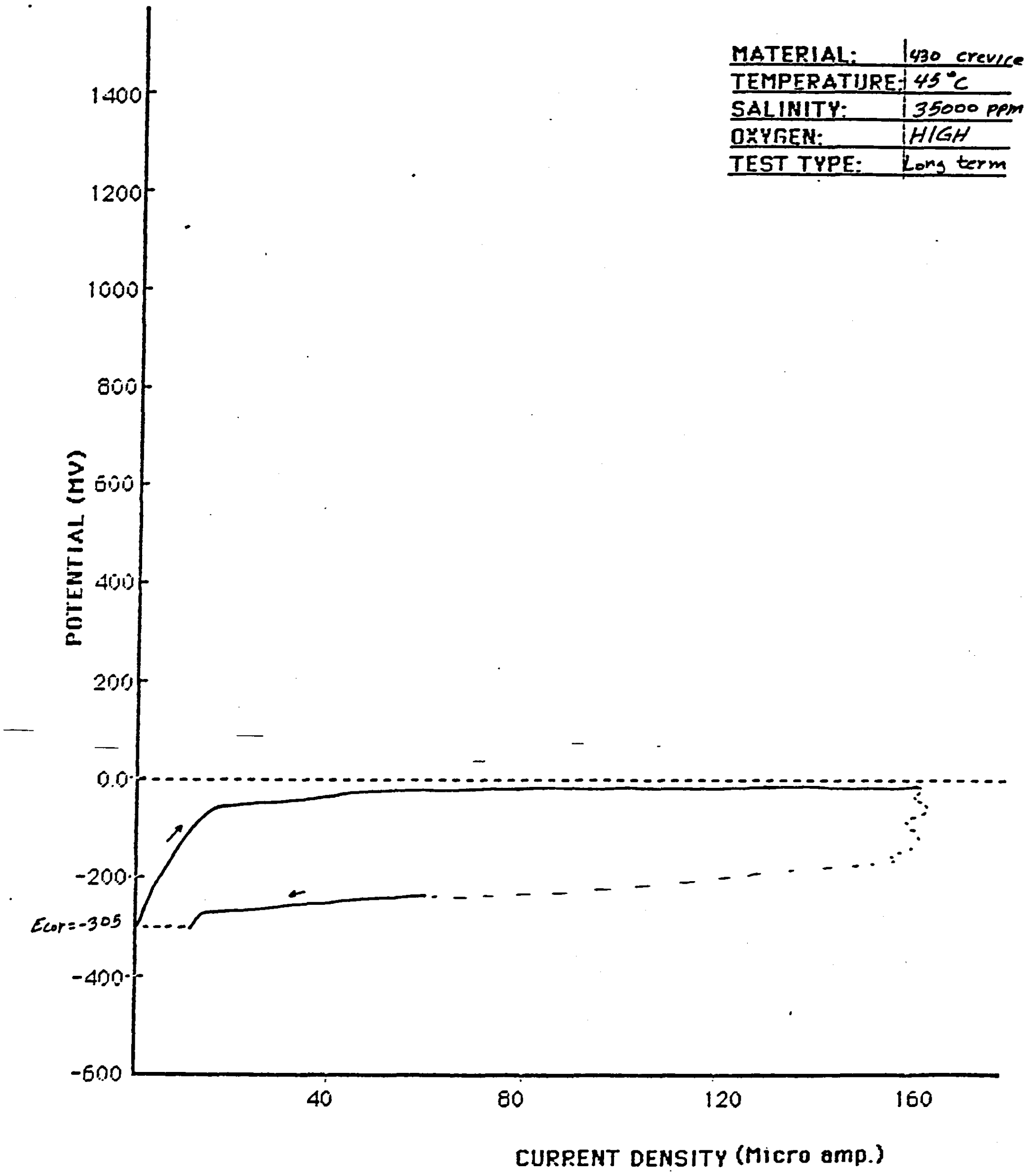

MATERIAL: 26Ni-18Cr-Mo6
TEMPERATURE: 45°c
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: Long term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
Ecor=-285
40
80
120
160
CURRENT DENSITY (Micro amp.)

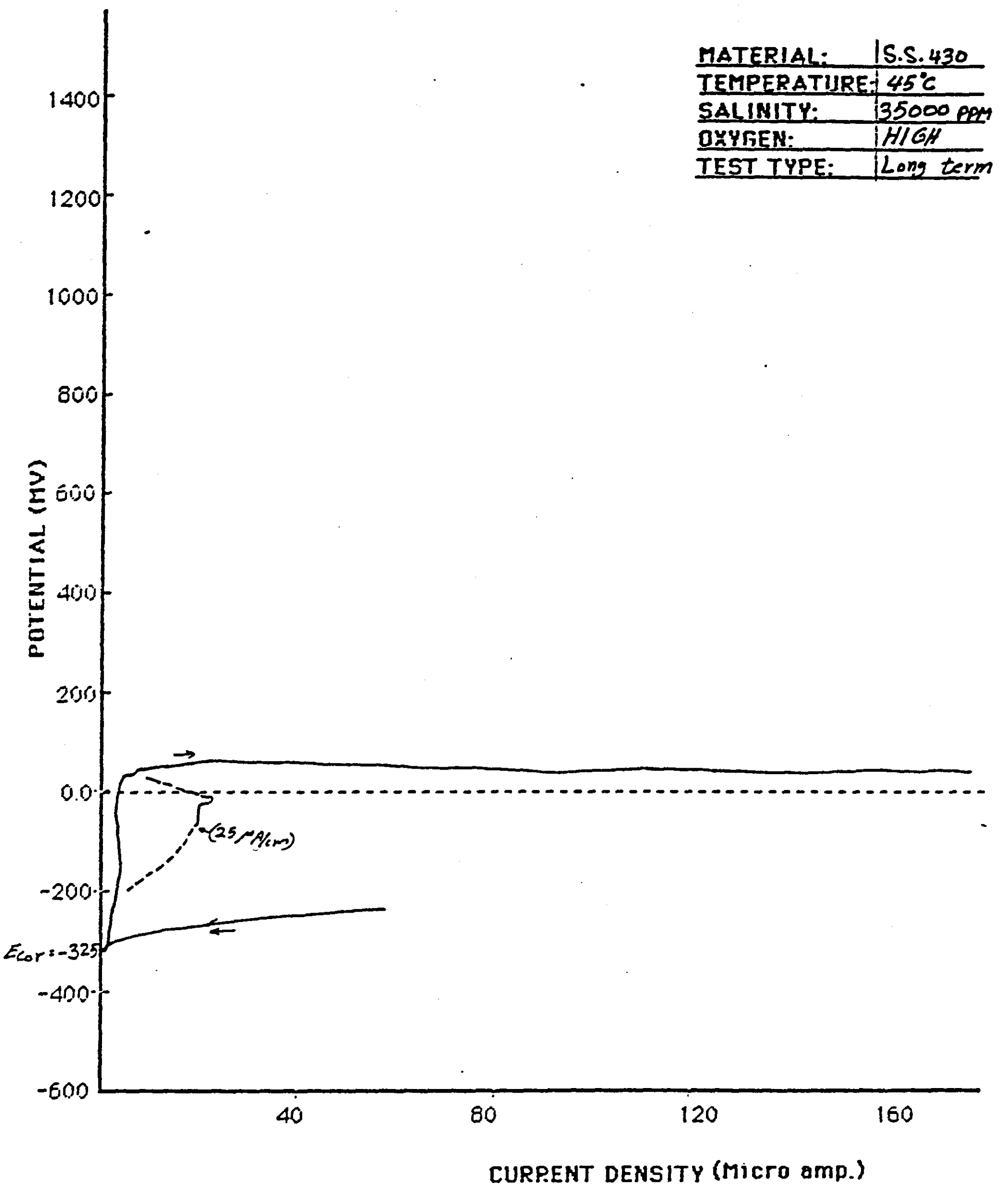

MATERIAL: 316-crevise
TEMPERATURE: 45°c
SALINITY: 35000ppm
OXYGEN: HIGH
TEST TYPE: Long-term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
E_{corr}=-265
-400
-600
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: 316
TEMPERATURE: 45 °C
SALINITY: 55000 ppm
OXYGEN: HIGH
TEST TYPE: Long-term
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
(25 mA/cm)
Ecor=-350
40
80
120
160
CURRENT DENSITY (Micro amp.)

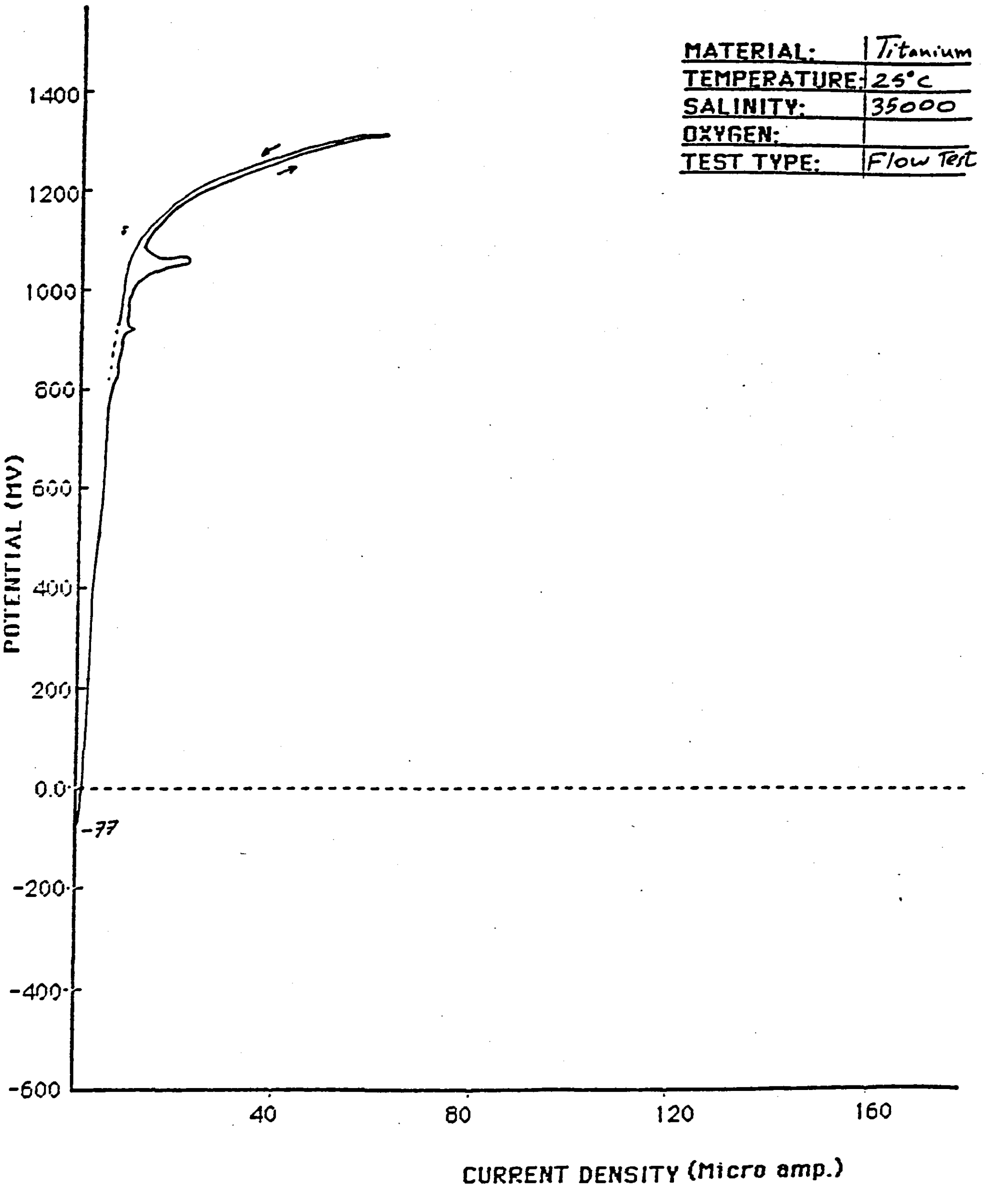


MATERIAL: 430 Crevise
TEMPERATURE: 45°C
SALINITY: 55000 ppm
OXYGEN: HIGH
TEST TYPE: Long-Term

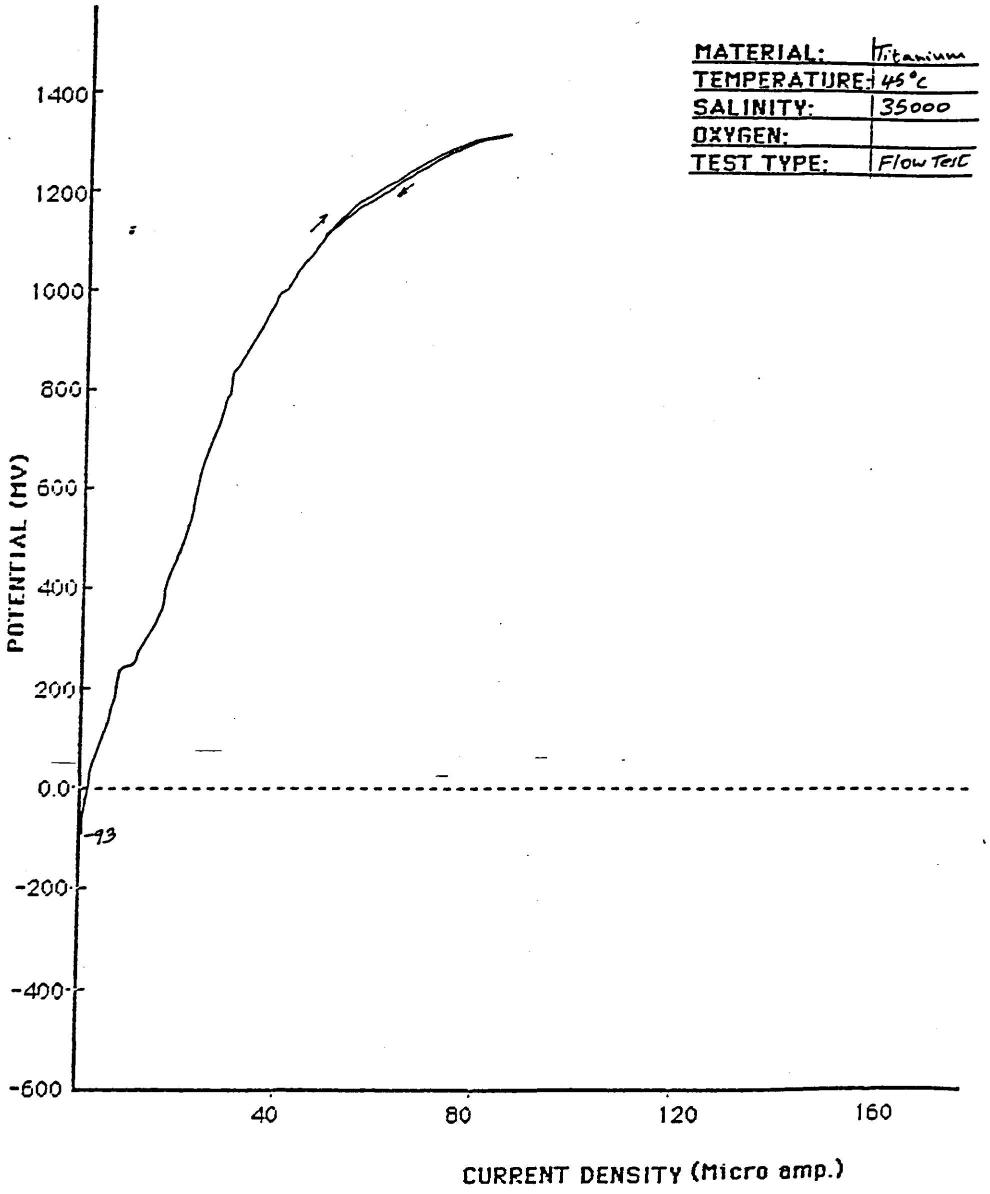

MATERIAL: 430 crevice
TEMPERATURE: 45 °C
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: Long term
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
Ecor=-305
-400
-600
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: S.S. 430
TEMPERATURE: 45°c
SALINITY: 35000 ppm
OXYGEN: HIGH
TEST TYPE: Long term
1400
1200
1000
800
600
400
200
0.0
-200
Ecor = -325
-400
-600
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)
(25 μA/cm)

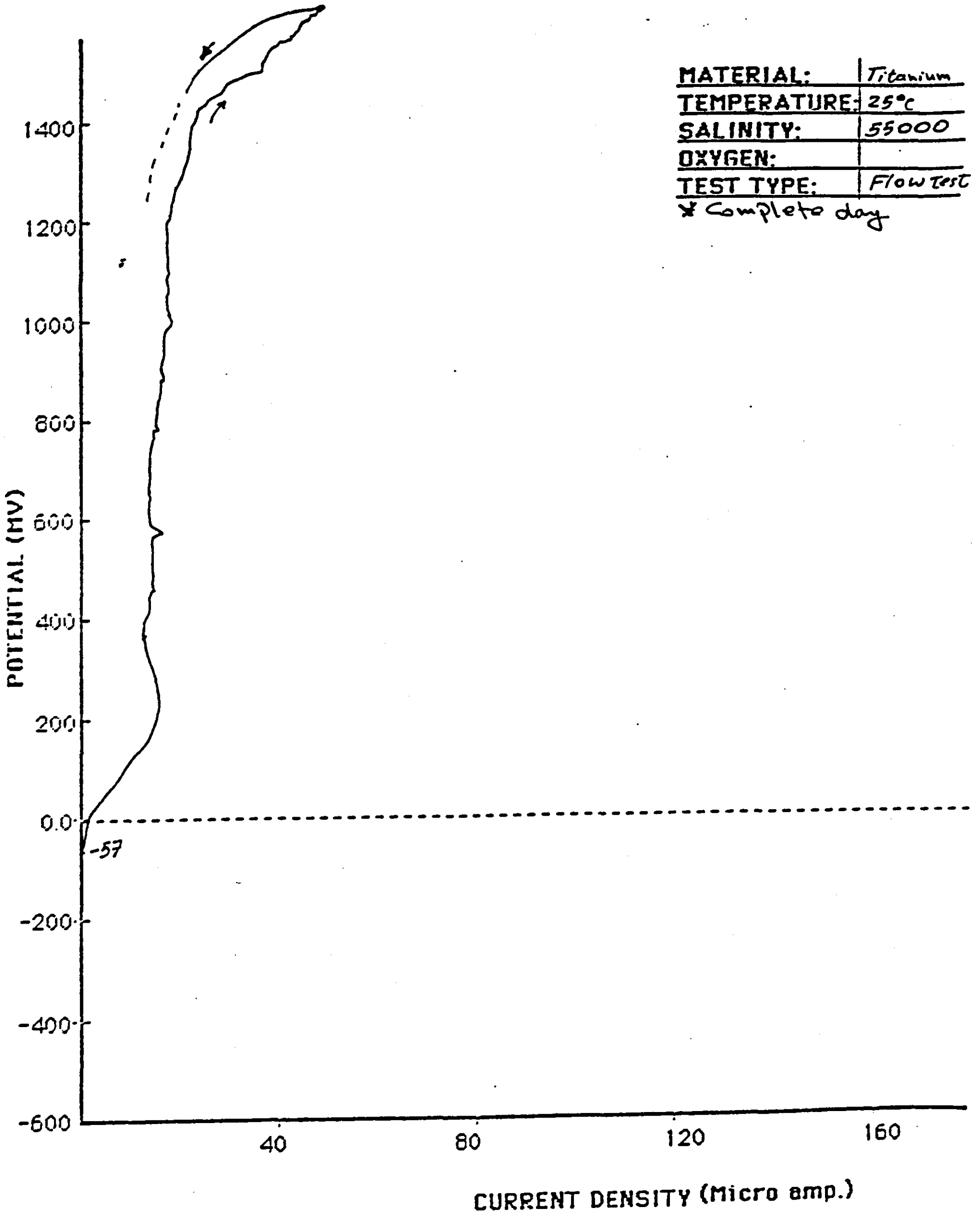
Flow Effect Test Rresults



MATERIAL:	Titanium
TEMPERATURE:	25°c
SALINITY:	35000
OXYGEN:	
TEST TYPE:	Flow Test

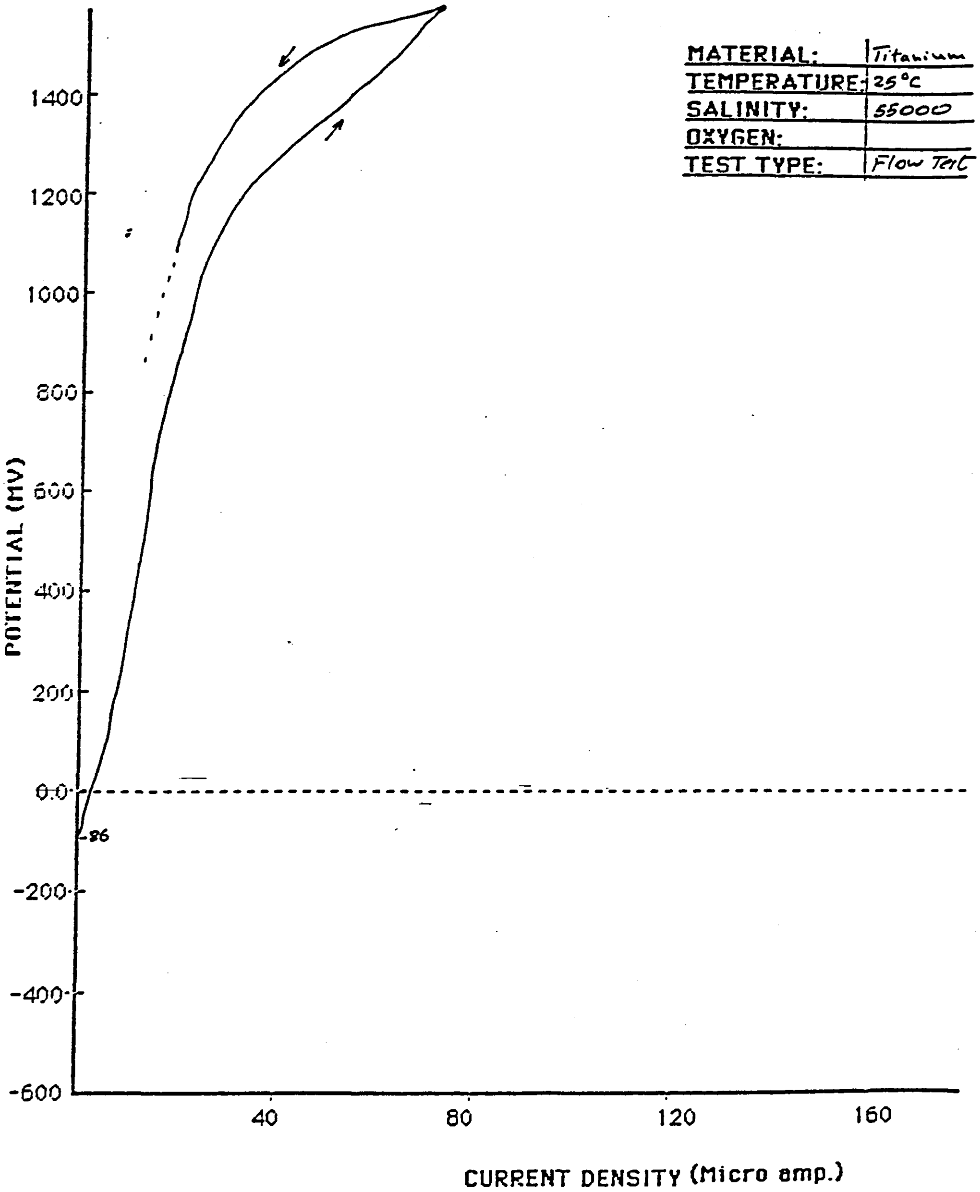


MATERIAL:	Titanium
TEMPERATURE:	45°c
SALINITY:	35000
OXYGEN:	
TEST TYPE:	Flow Test

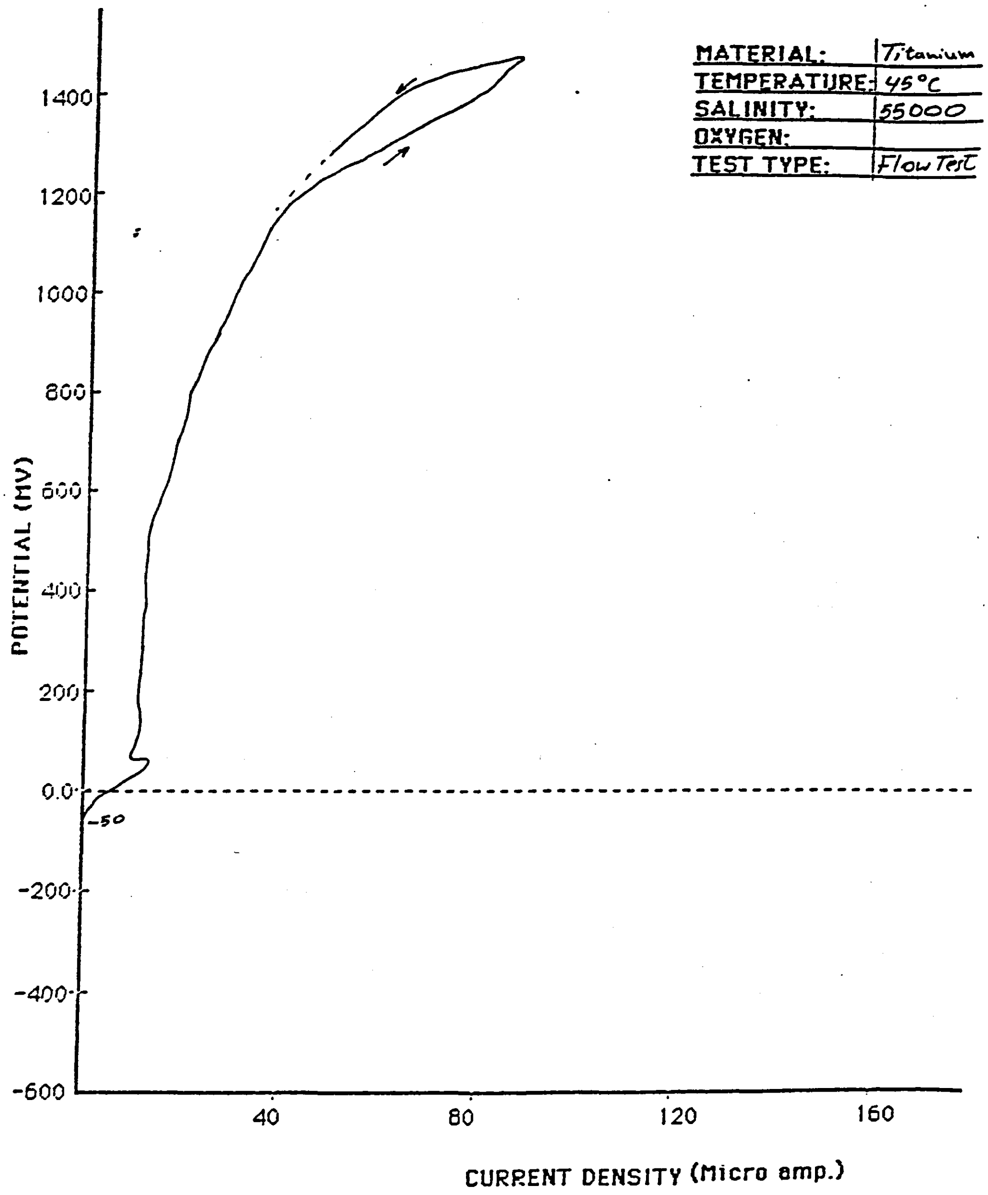


MATERIAL:	Titanium
TEMPERATURE:	25°c
SALINITY:	55000
OXYGEN:	
TEST TYPE:	Flow test

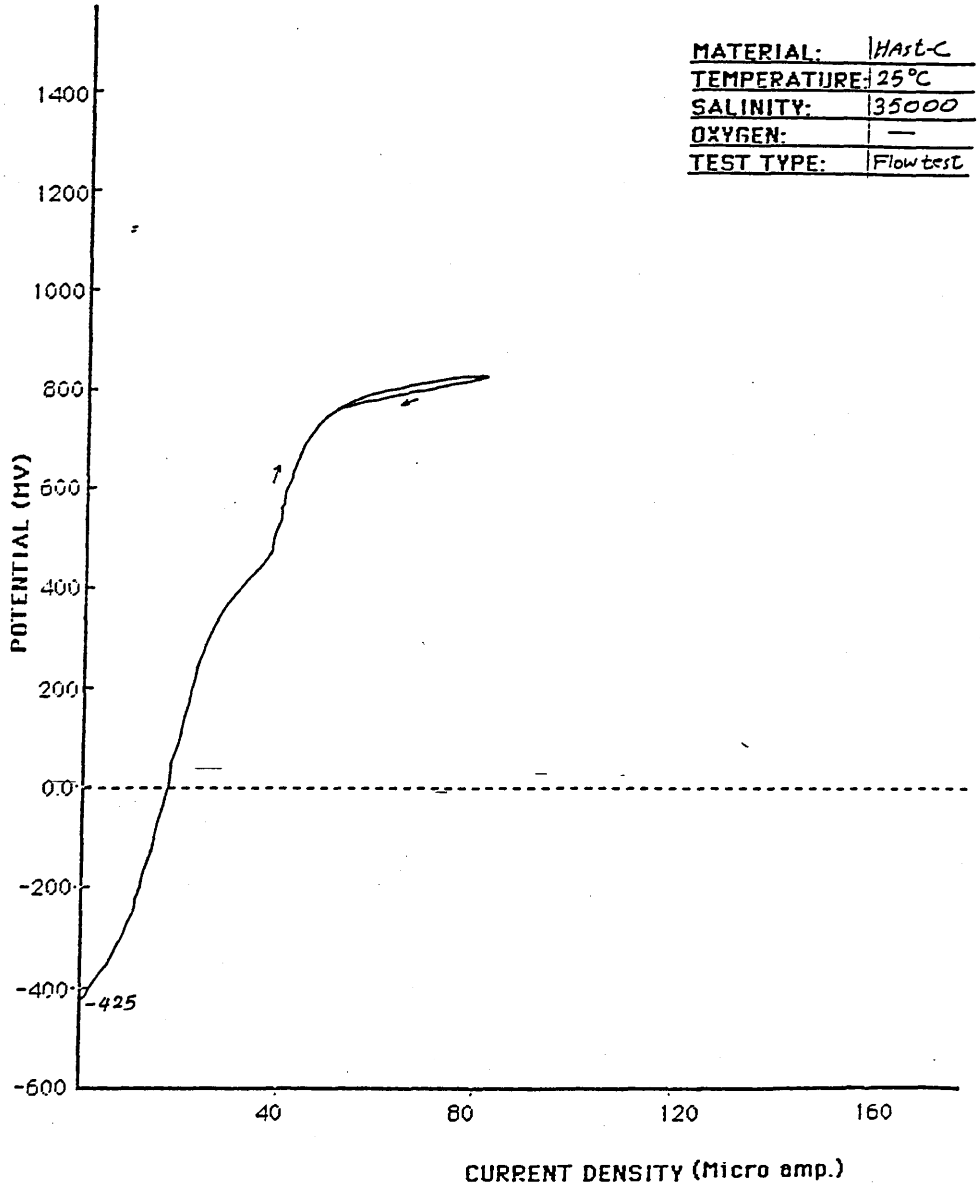
* Completo day



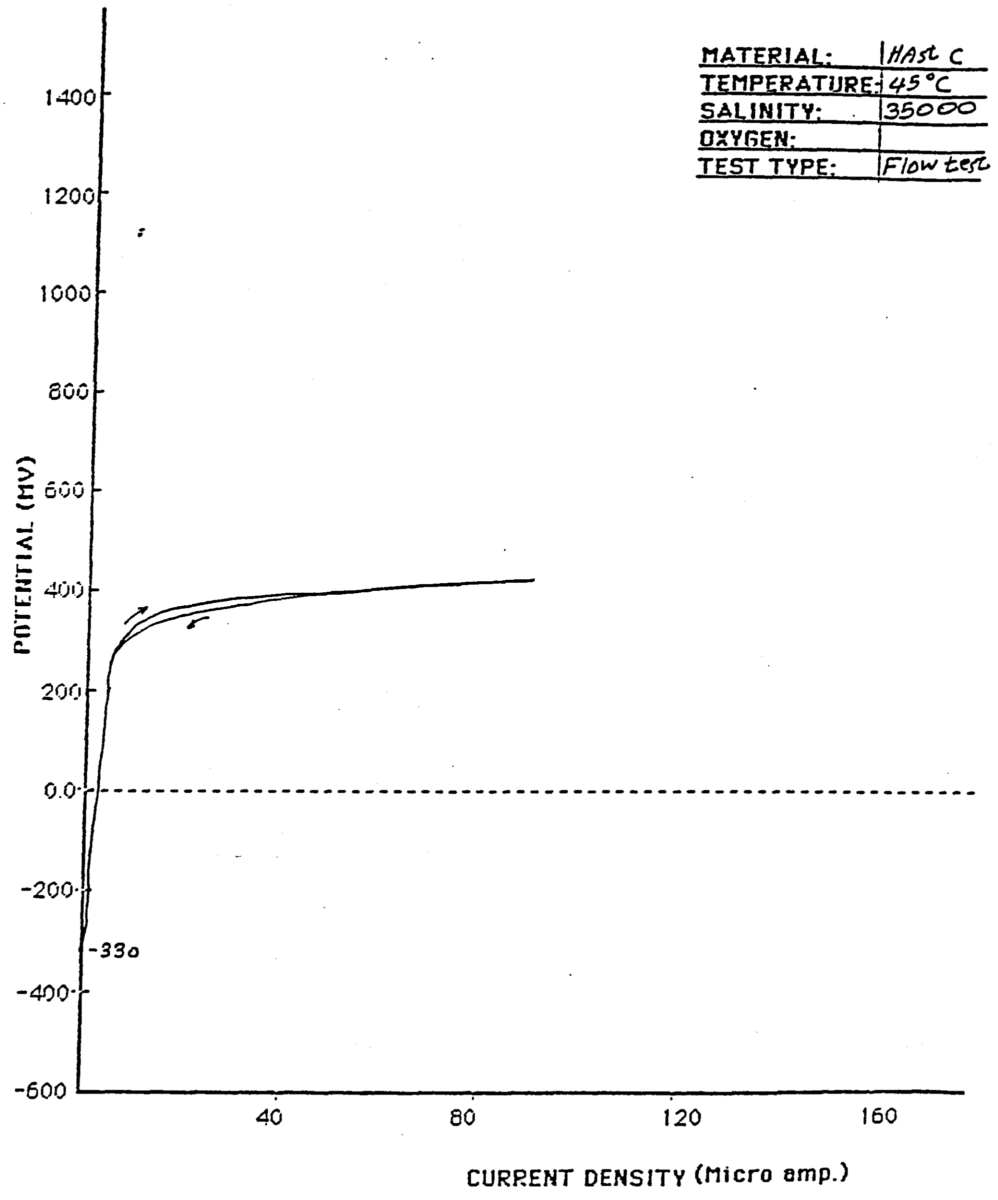
MATERIAL:	Titanium
TEMPERATURE:	25°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	Flow Test



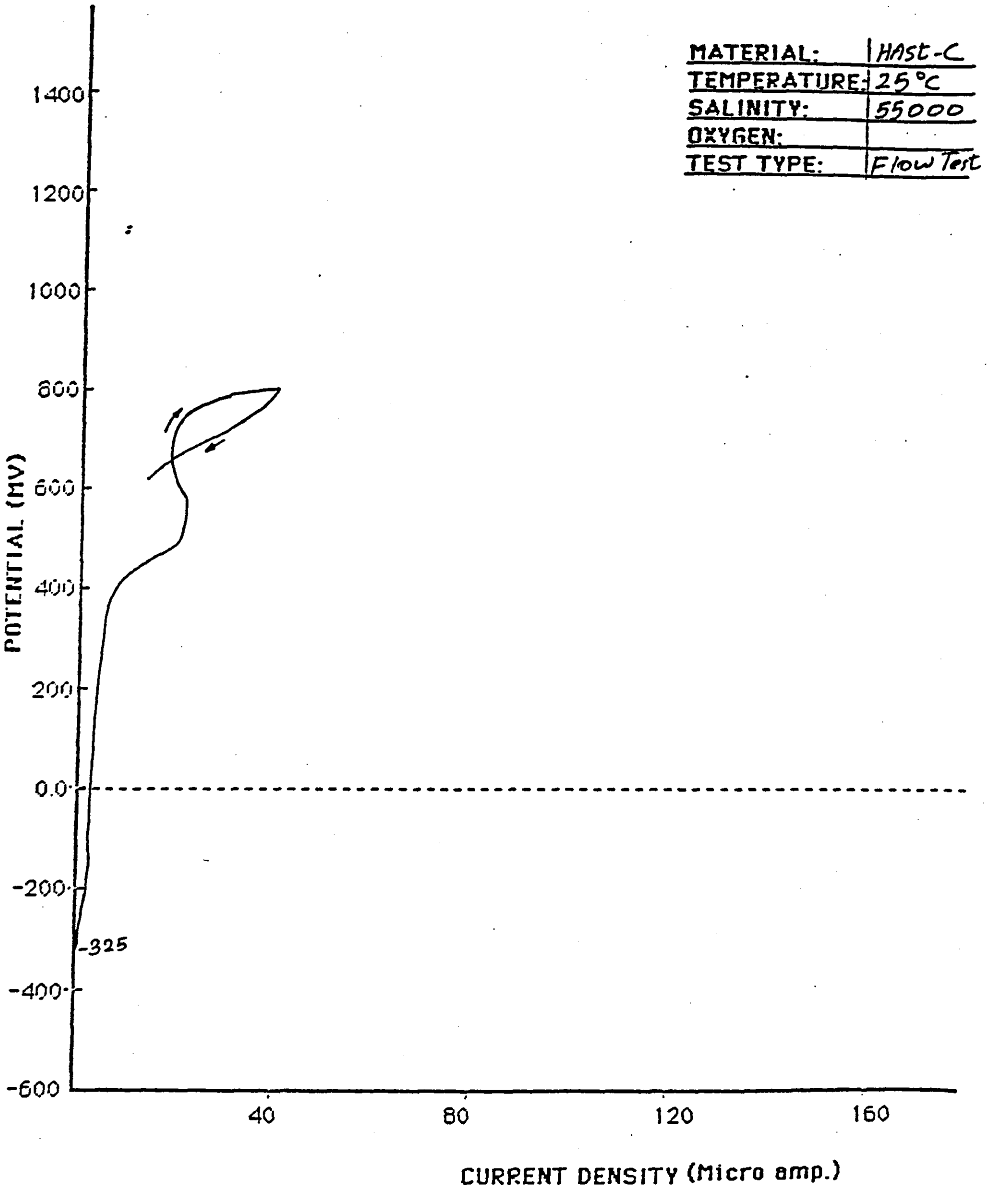
MATERIAL:	Titanium
TEMPERATURE:	45°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	Flow Test

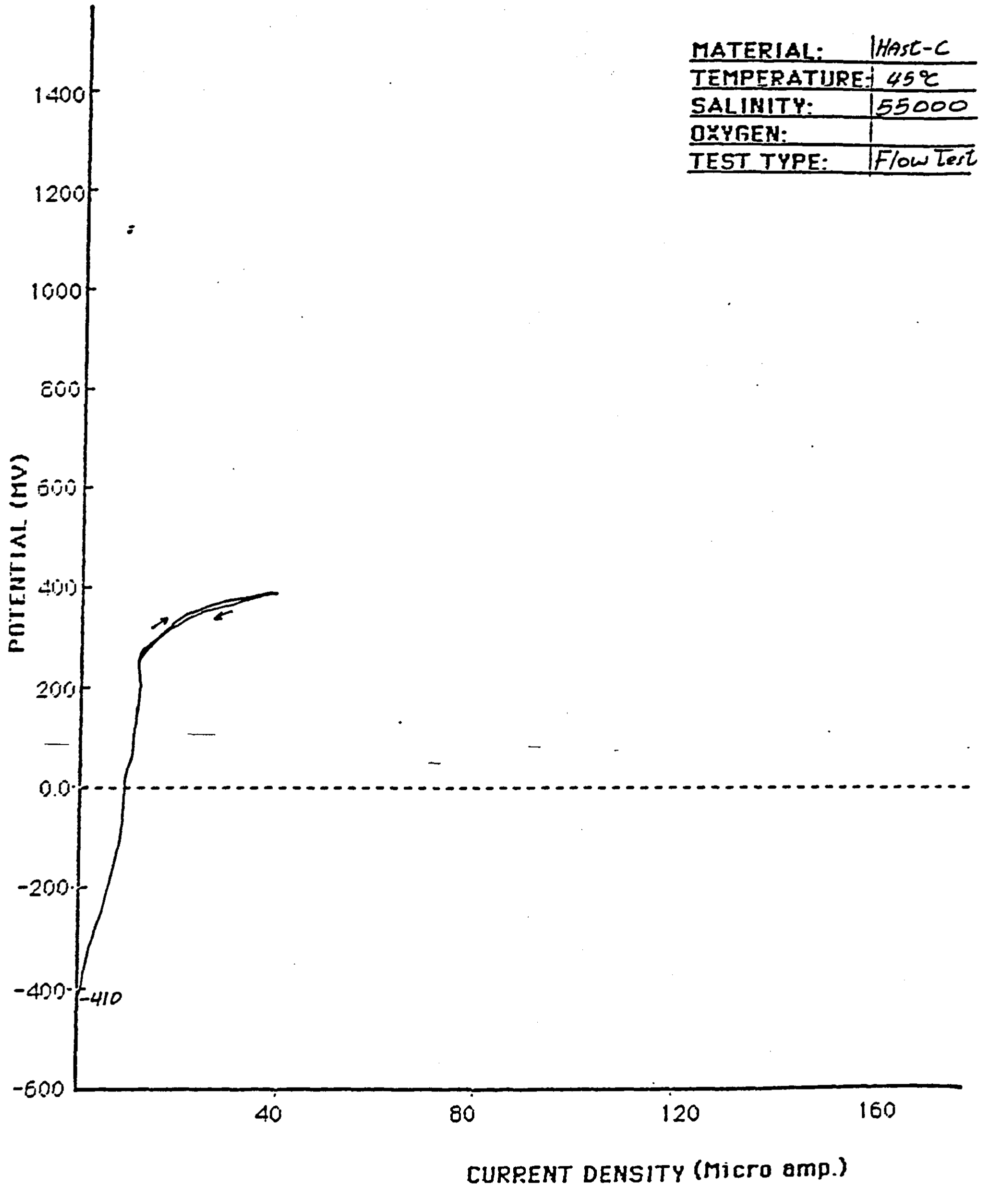


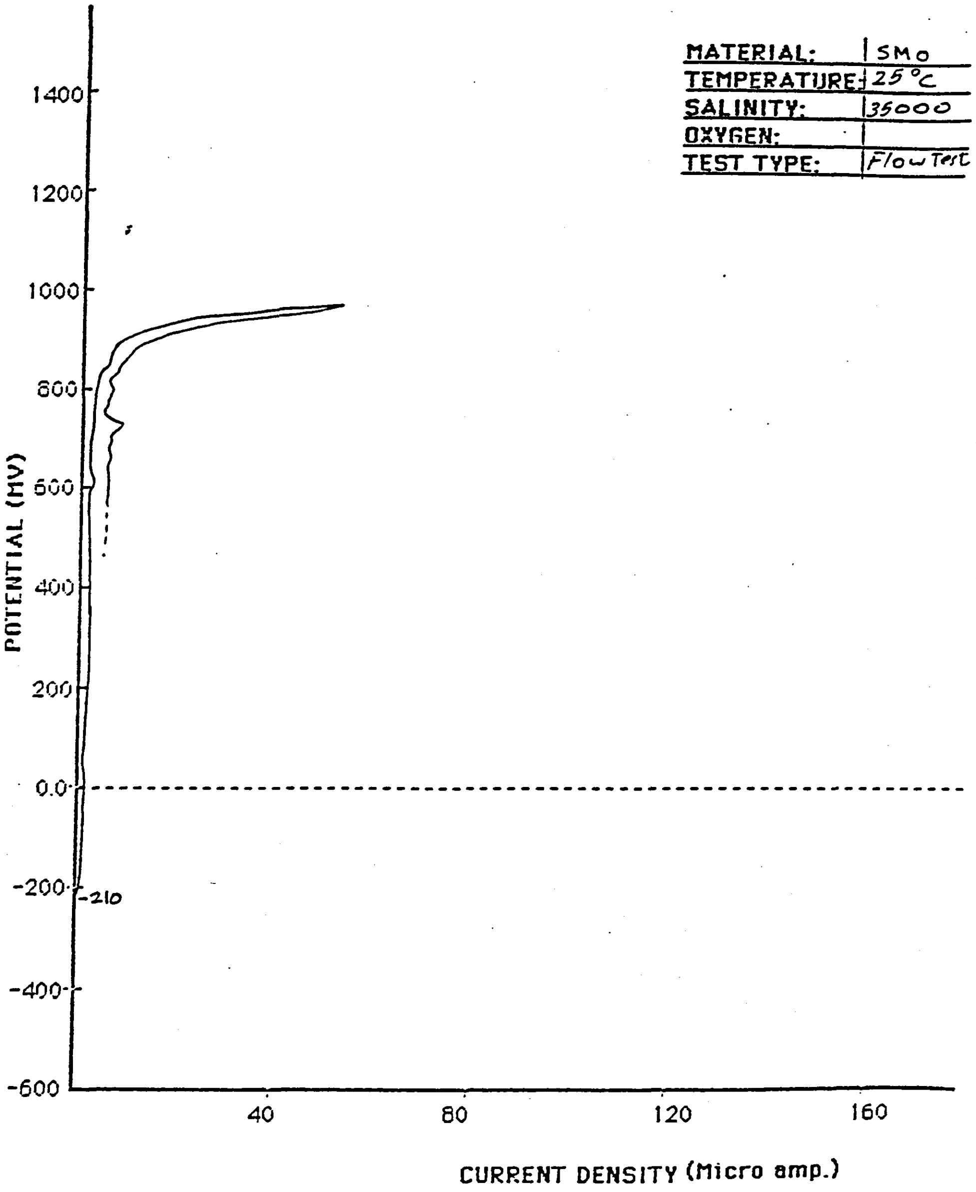
MATERIAL:	HAst-C
TEMPERATURE:	25°C
SALINITY:	35000
OXYGEN:	—
TEST TYPE:	Flow test

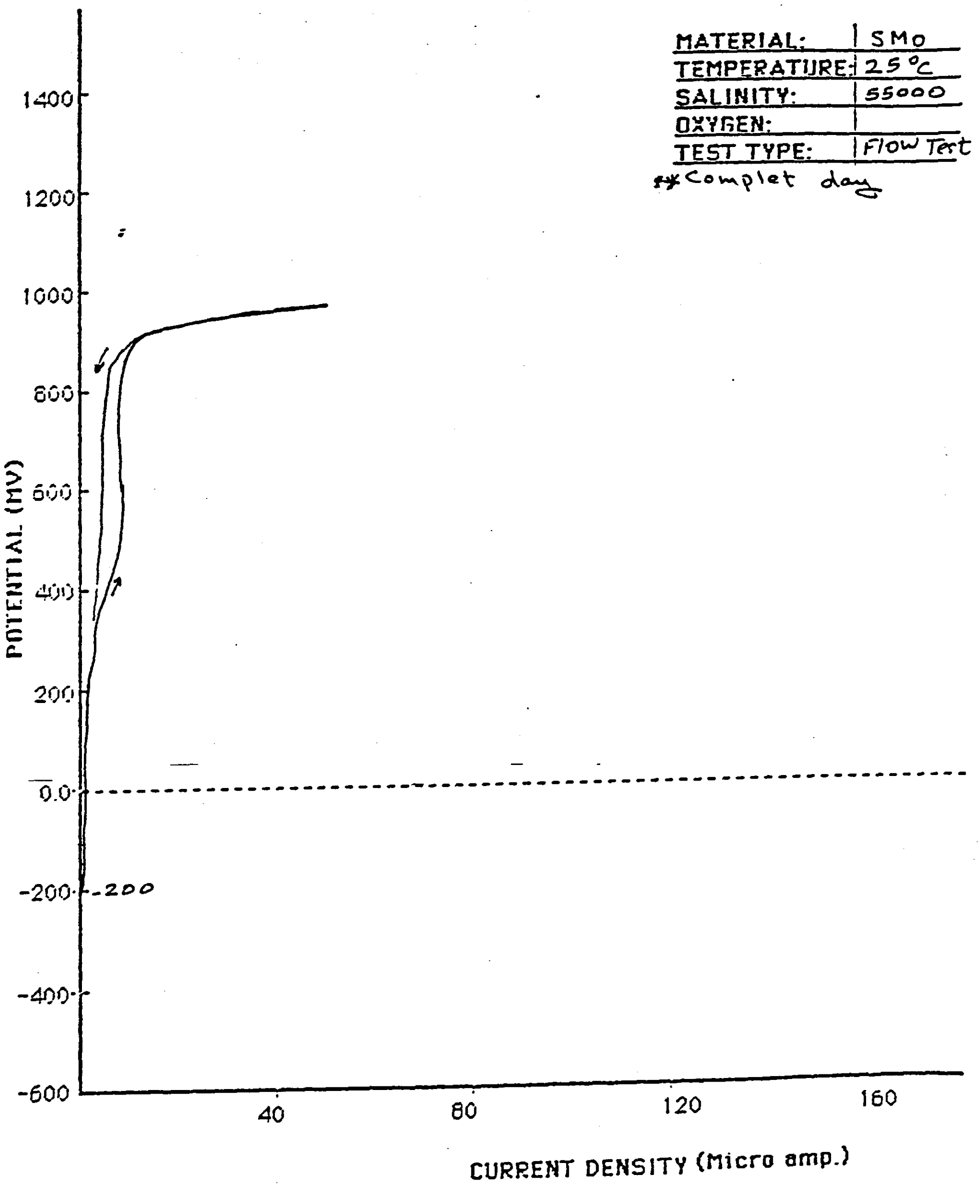


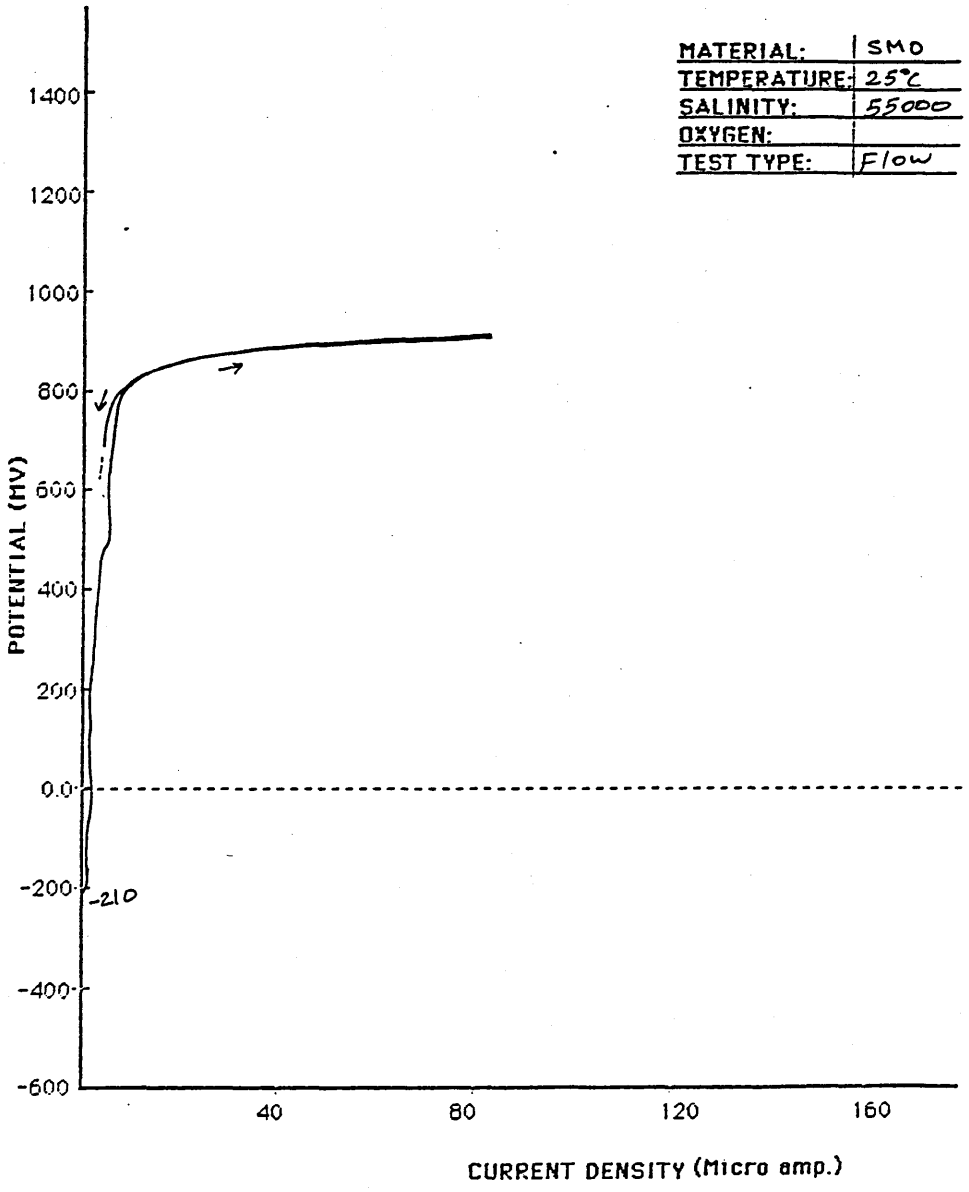
MATERIAL: Hast C
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: Flow test


MATERIAL: HAst-C
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-325
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)

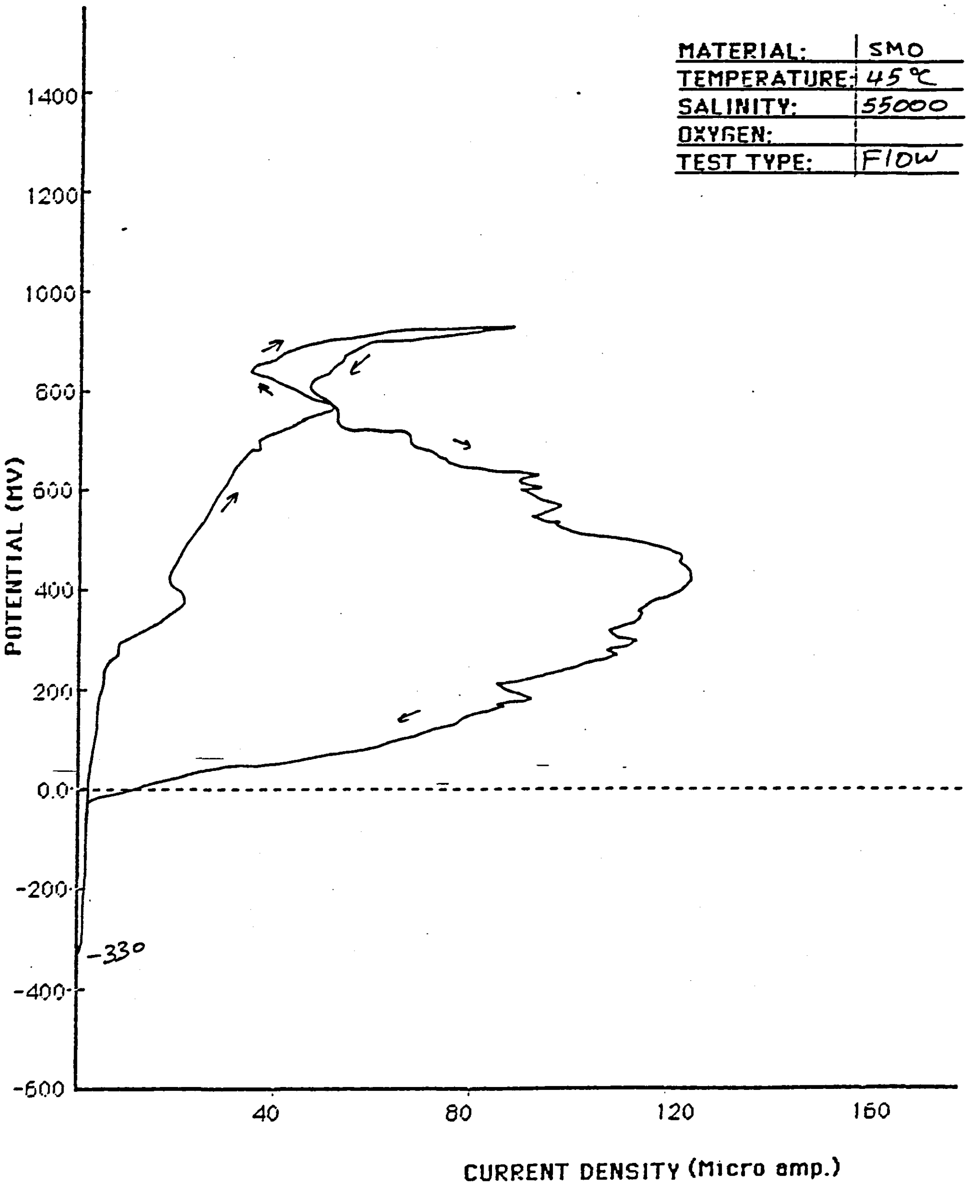

MATERIAL: Hast-C
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: Flow Test
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-410
40
80
120
160
CURRENT DENSITY (Micro amp.)

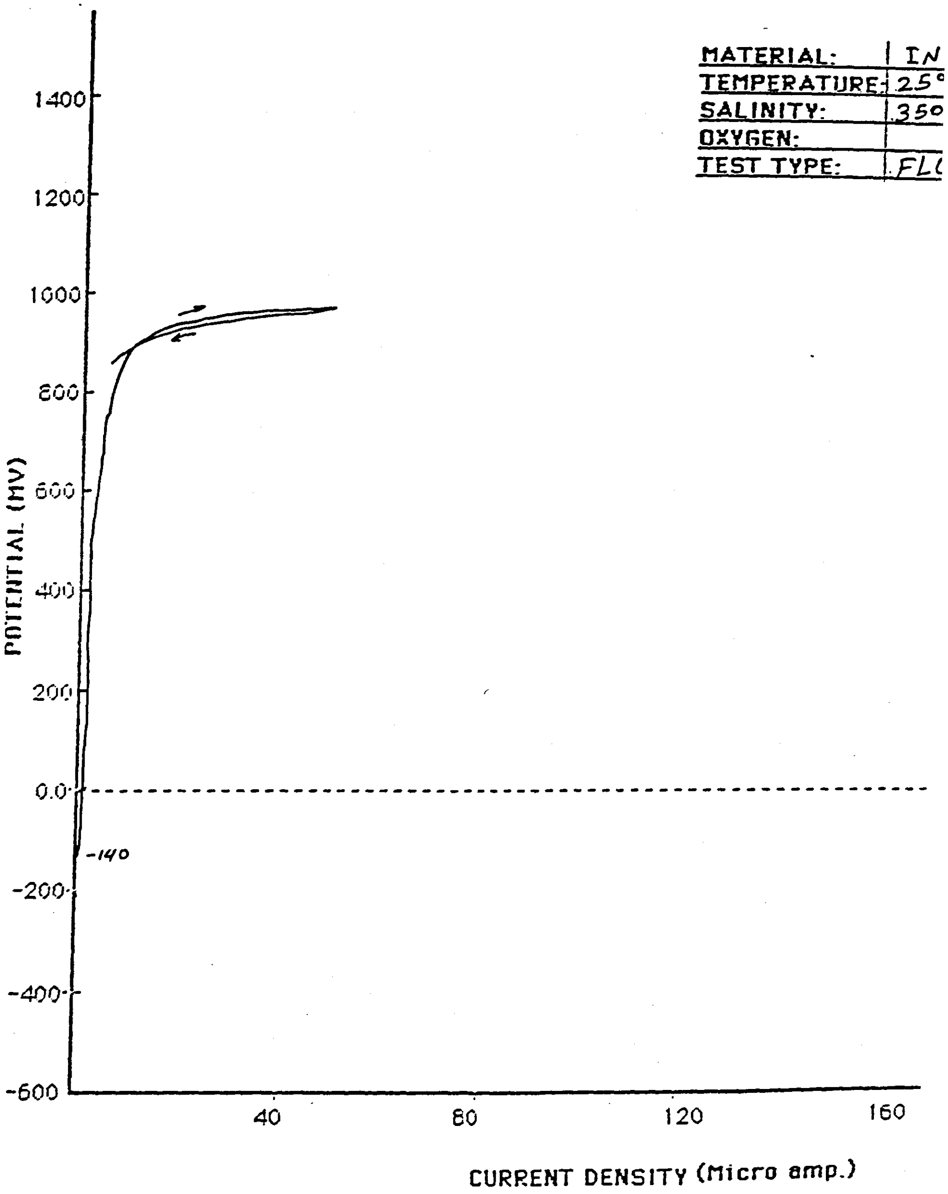

MATERIAL: SMo
TEMPERATURE: 25 °C
SALINITY: 35000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-210
-400
-600
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)


MATERIAL: SMo
TEMPERATURE: 25 °C
SALINITY: 55000
OXYGEN:
TEST TYPE: Flow Test
Complet day
1400
1200
1000
800
600
400
200
0.0
-200
-200
-400
-600
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)

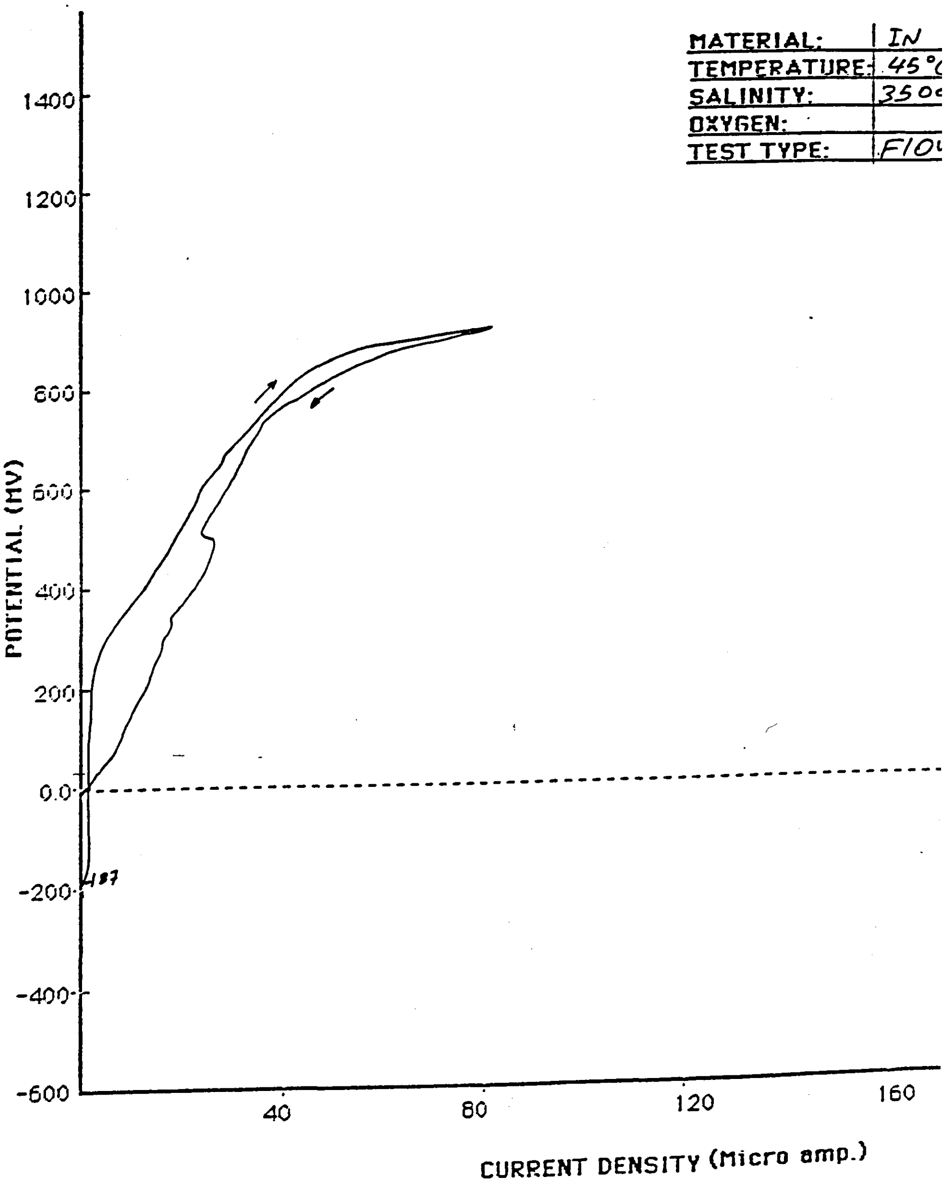


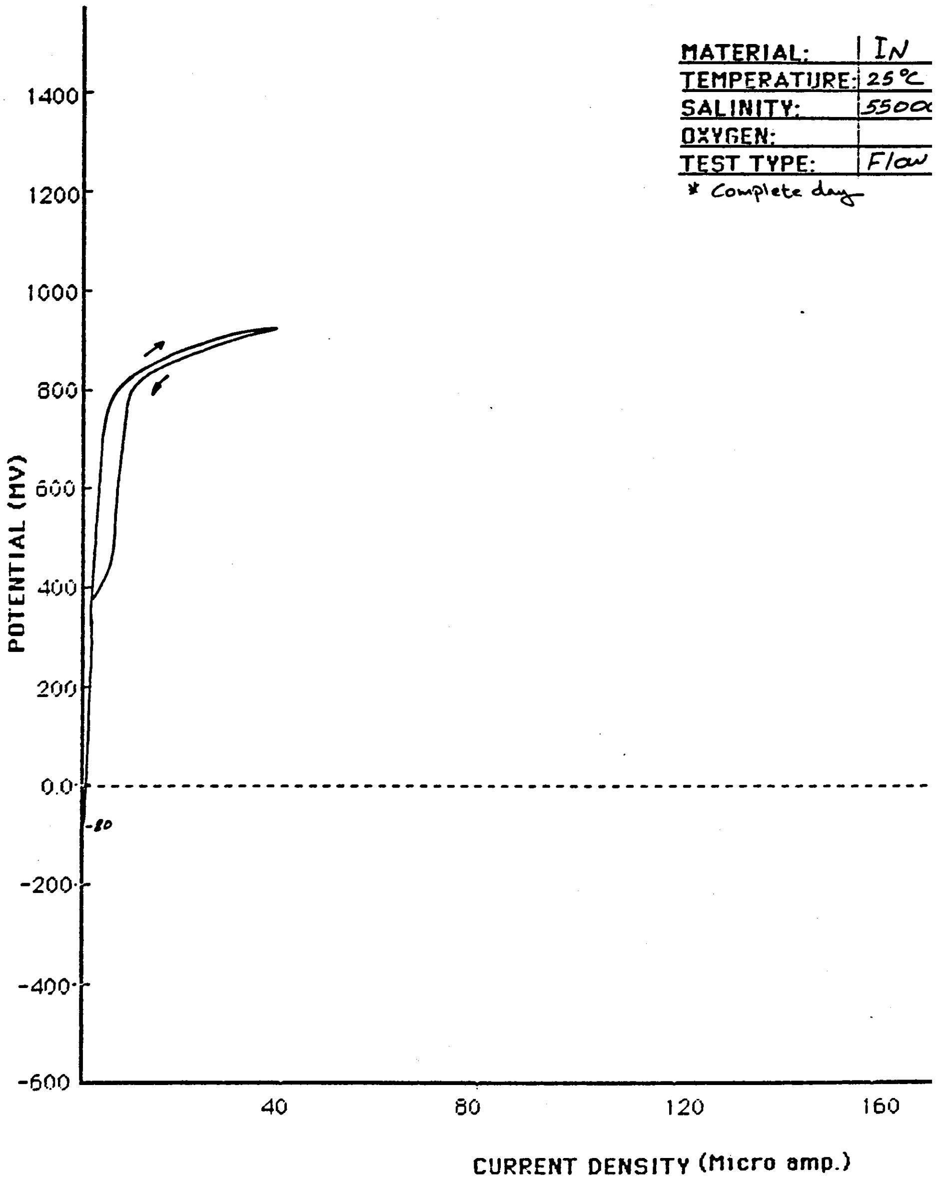
MATERIAL:	SMO
TEMPERATURE:	25°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	Flow


MATERIAL: SMO
TEMPERATURE: 45 °C
SALINITY: 55000
OXYGEN:
TEST TYPE: FlOW
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-330
40
80
120
160
CURRENT DENSITY (Micro amp.)



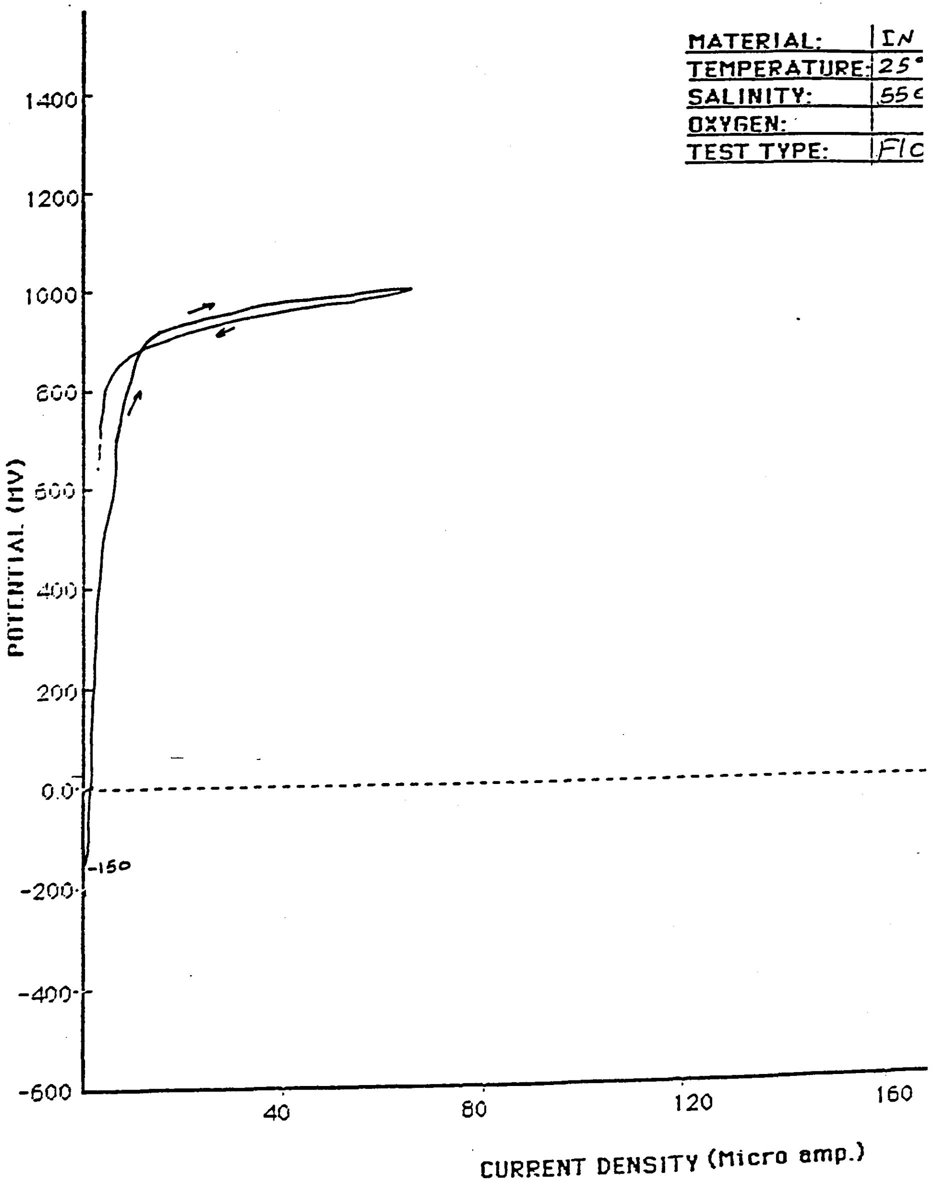
MATERIAL:	IN
TEMPERATURE:	25°
SALINITY:	350
OXYGEN:	
TEST TYPE:	FL


MATERIAL: IN
TEMPERATURE: 45°
SALINITY: 350
OXYGEN:
TEST TYPE: FlO
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
187
40
80
120
160
CURRENT DENSITY (Micro amp.)

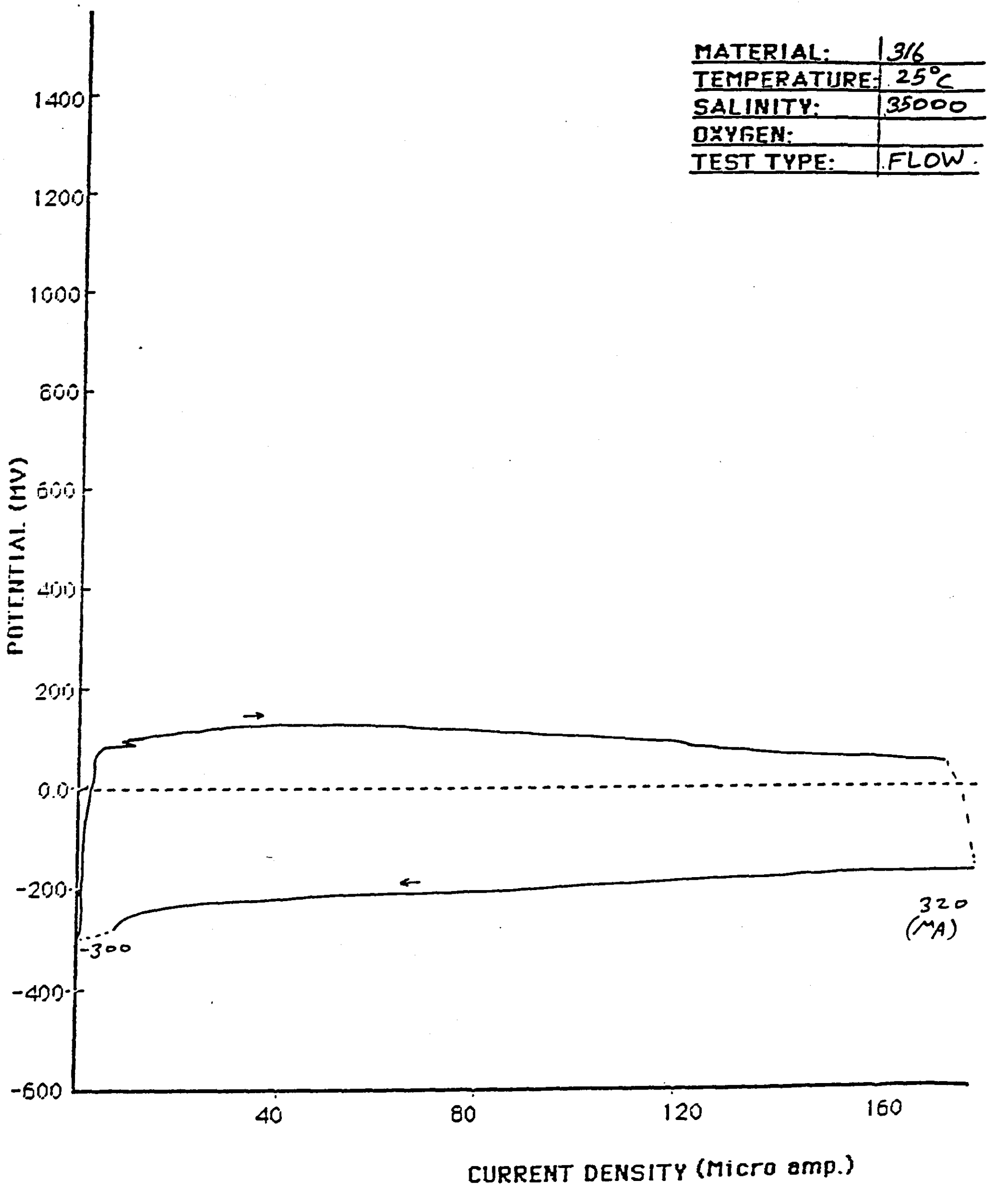


MATERIAL:	IN
TEMPERATURE:	25 °C
SALINITY:	5500c
OXYGEN:	
TEST TYPE:	Flow

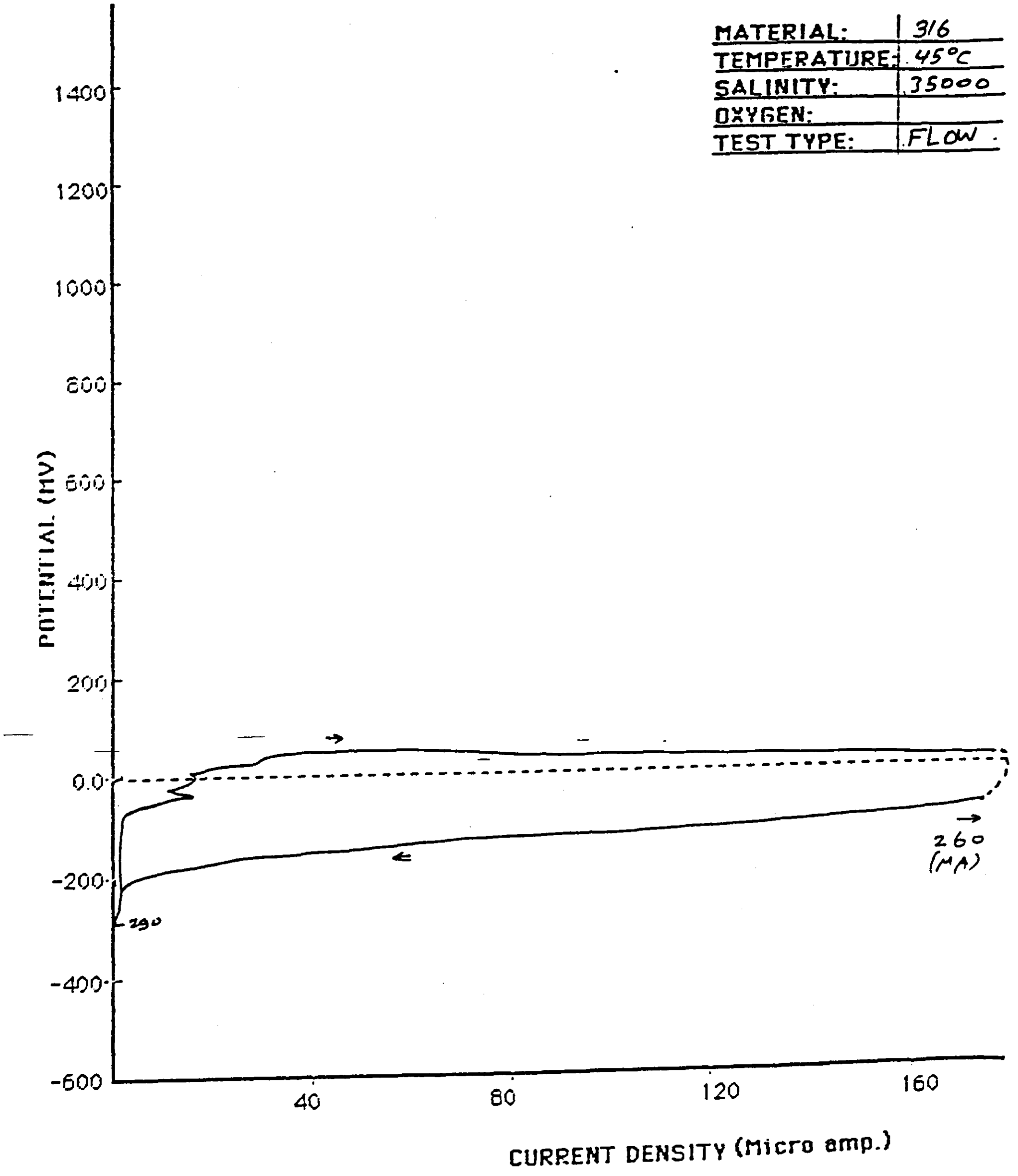
* Complete day

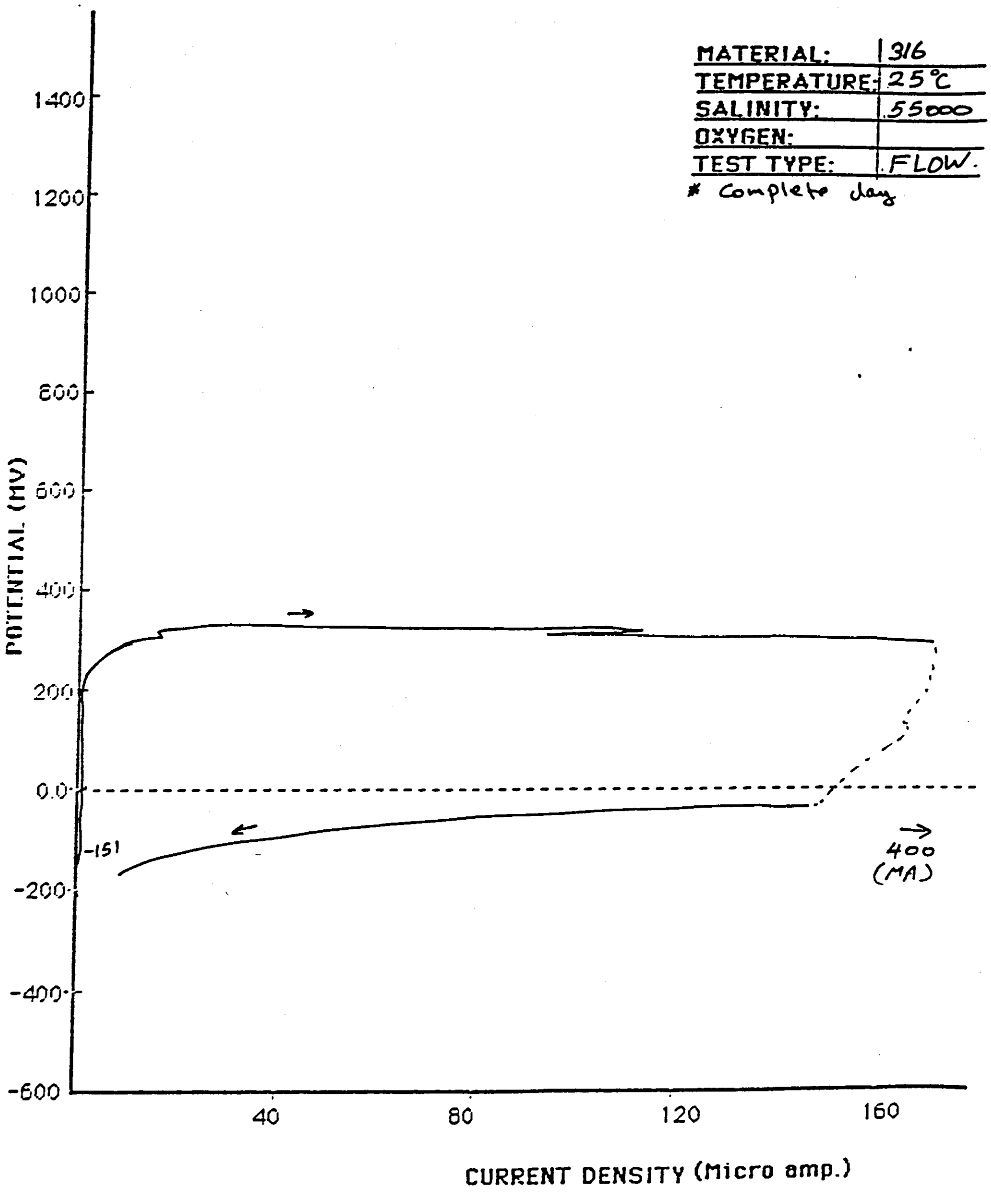


MATERIAL:	IN
TEMPERATURE:	25°
SALINITY:	.55
OXYGEN:	
TEST TYPE:	Flc



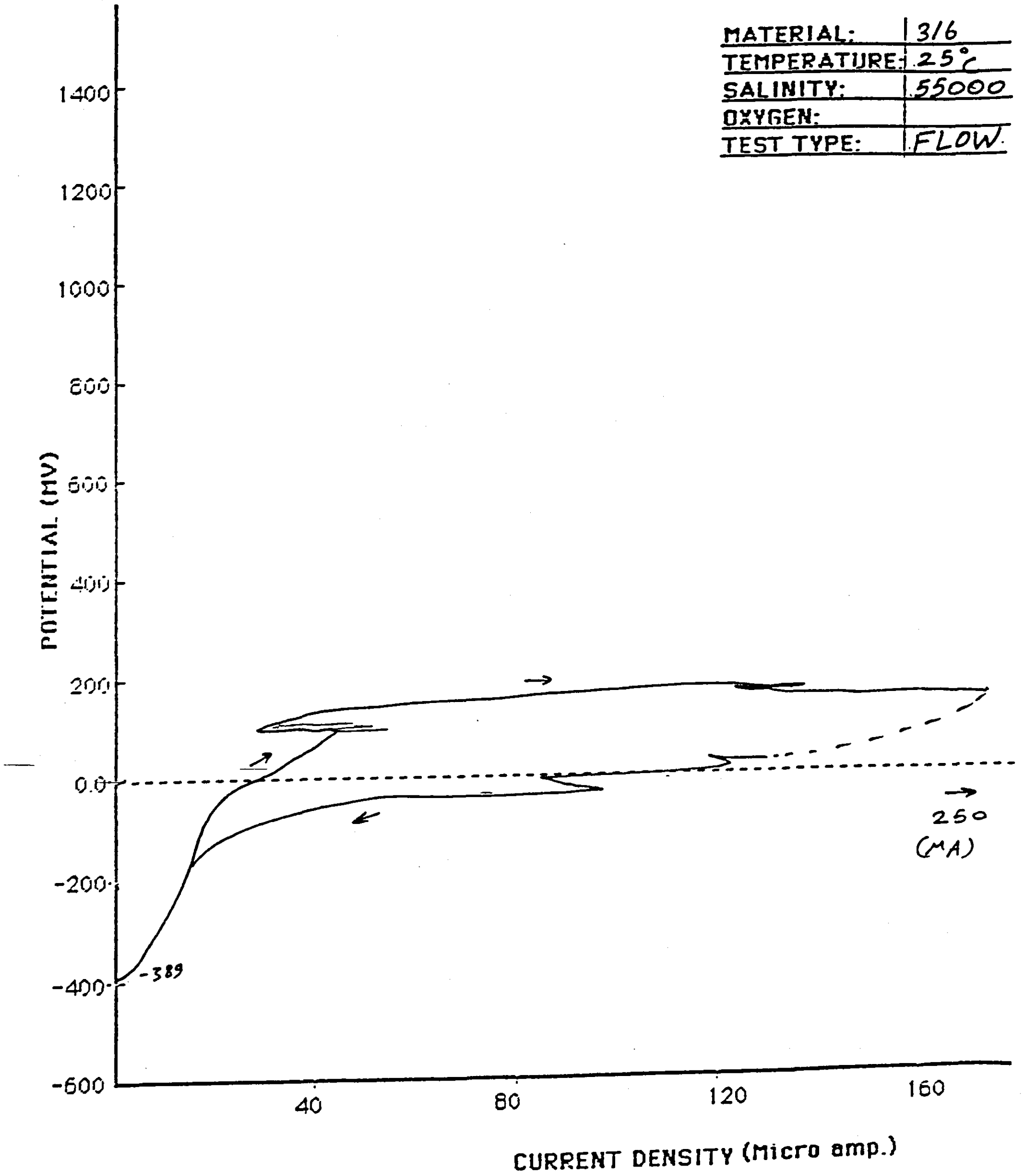
MATERIAL:	316
TEMPERATURE:	25°C
SALINITY:	35000
OXYGEN:	
TEST TYPE:	FLOW

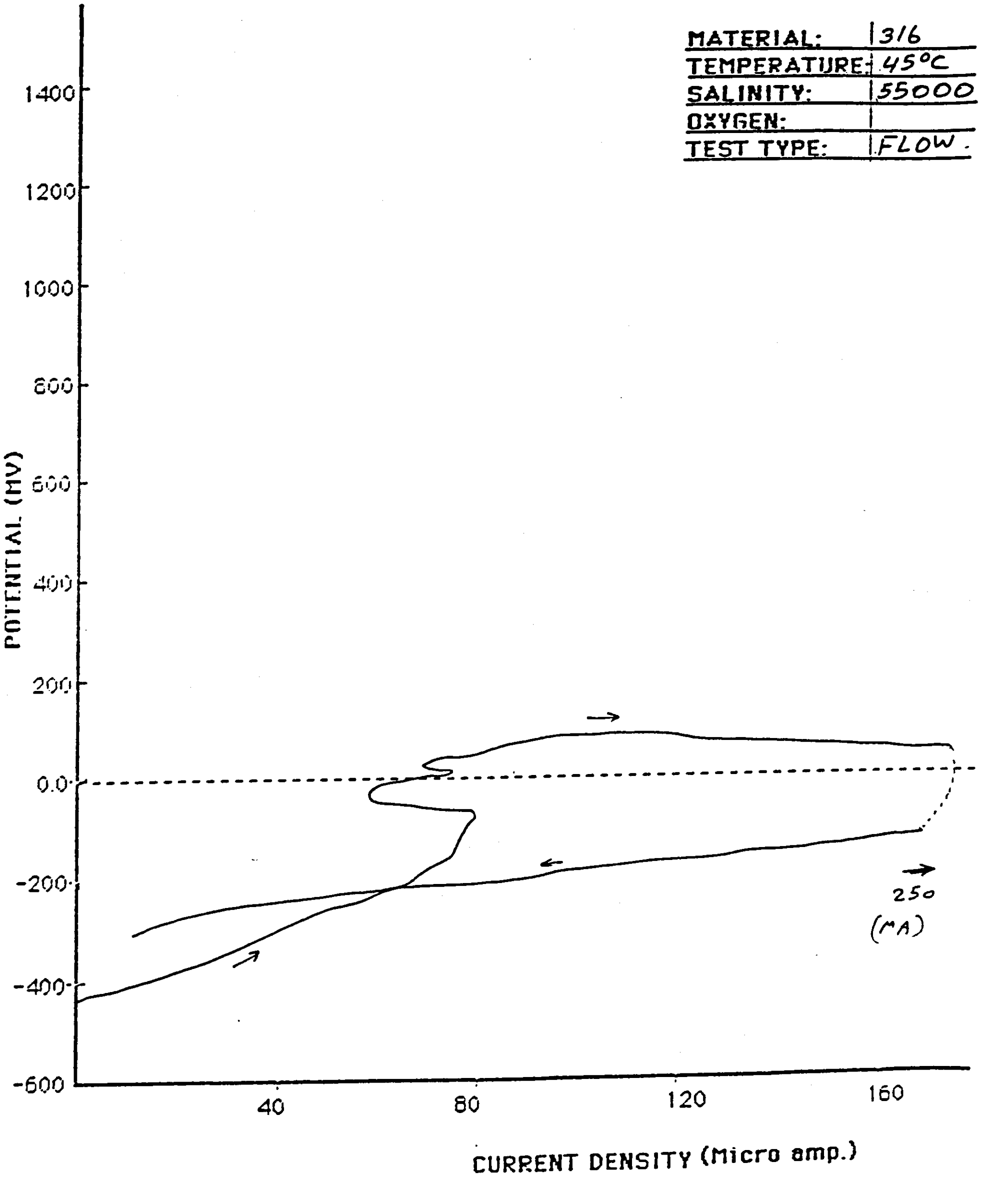

MATERIAL: 316
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: FLOW
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
40
80
120
160
CURRENT DENSITY (Micro amp.)
290
260
(μA)



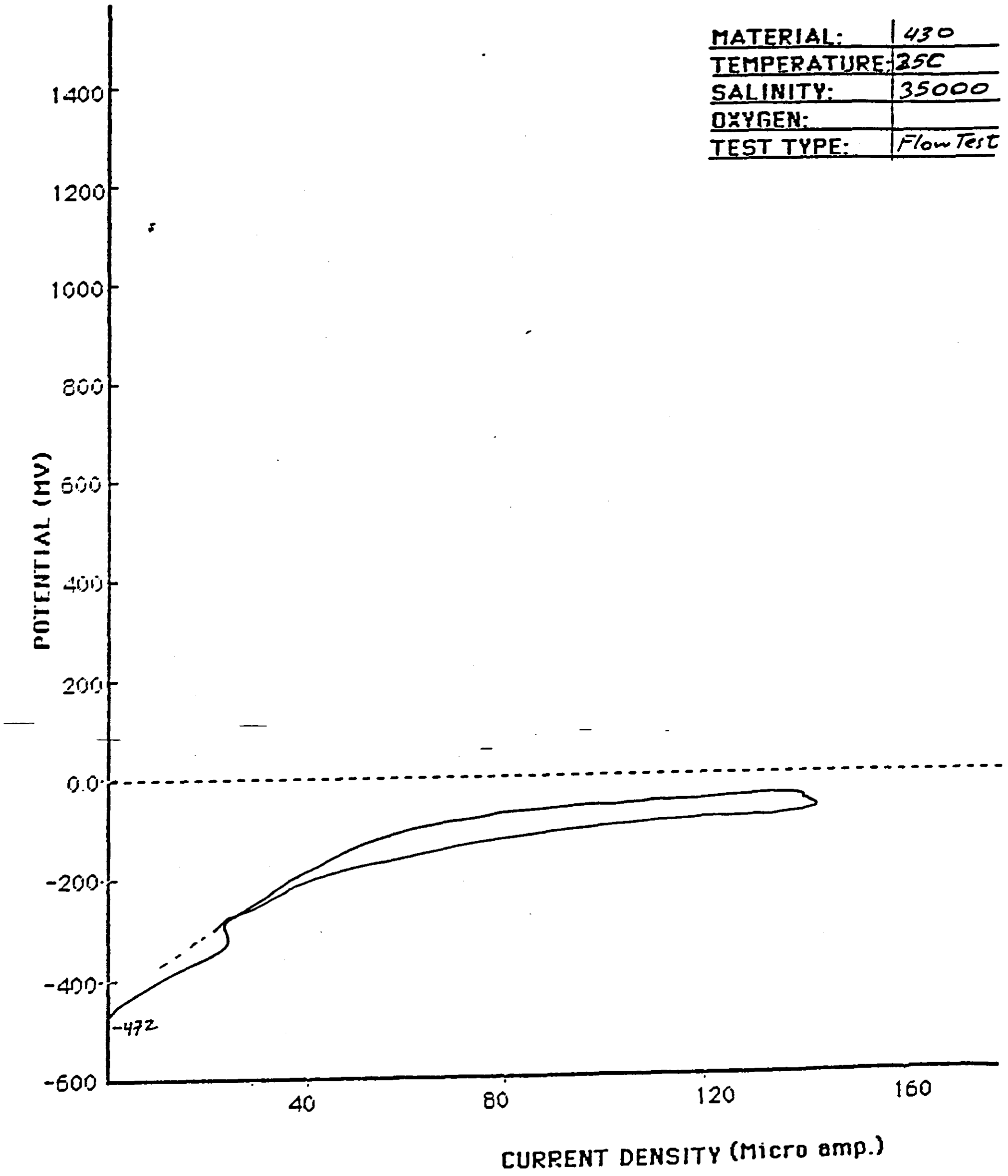
MATERIAL:	316
TEMPERATURE:	25°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	FLOW.

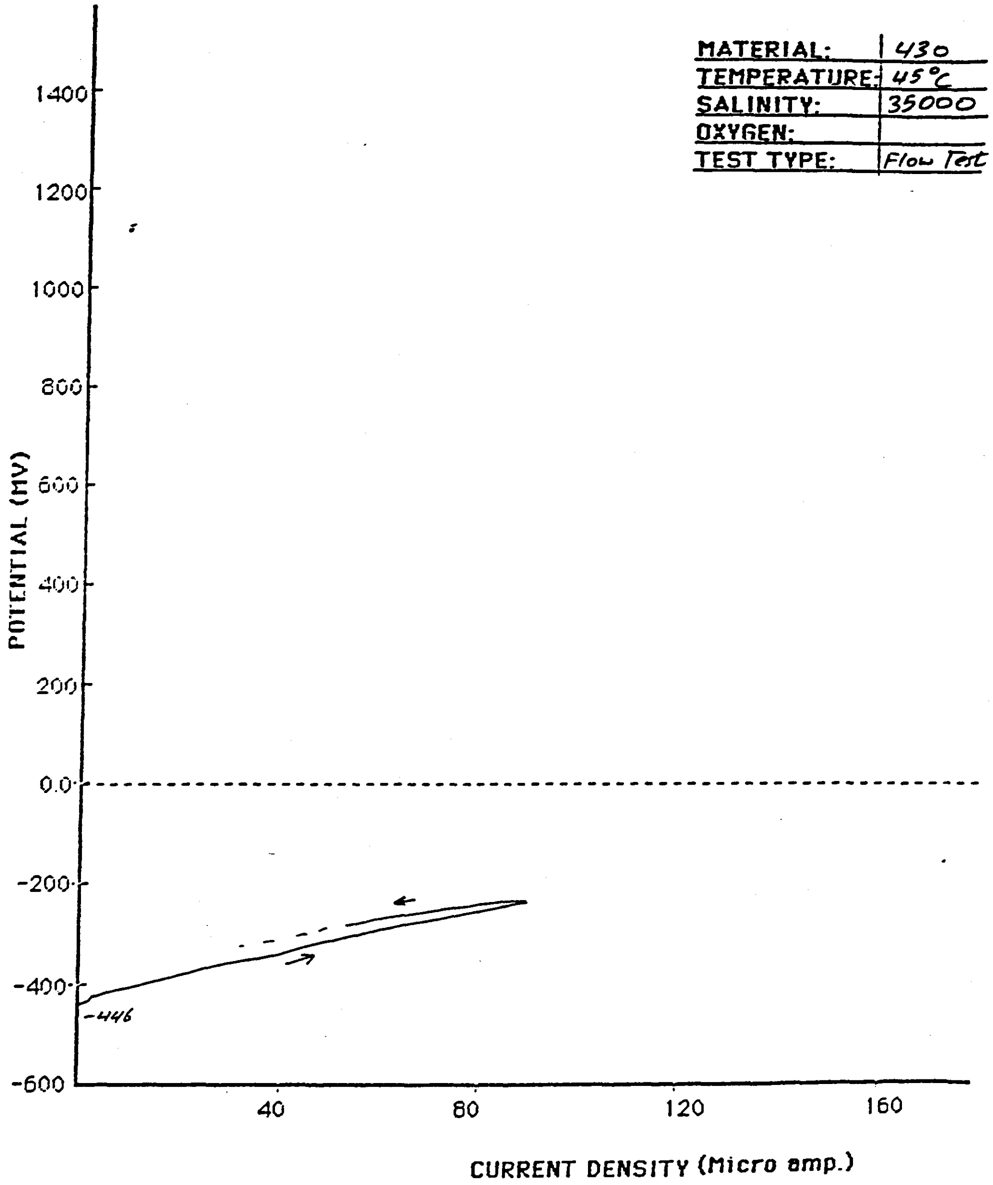
* Complete day

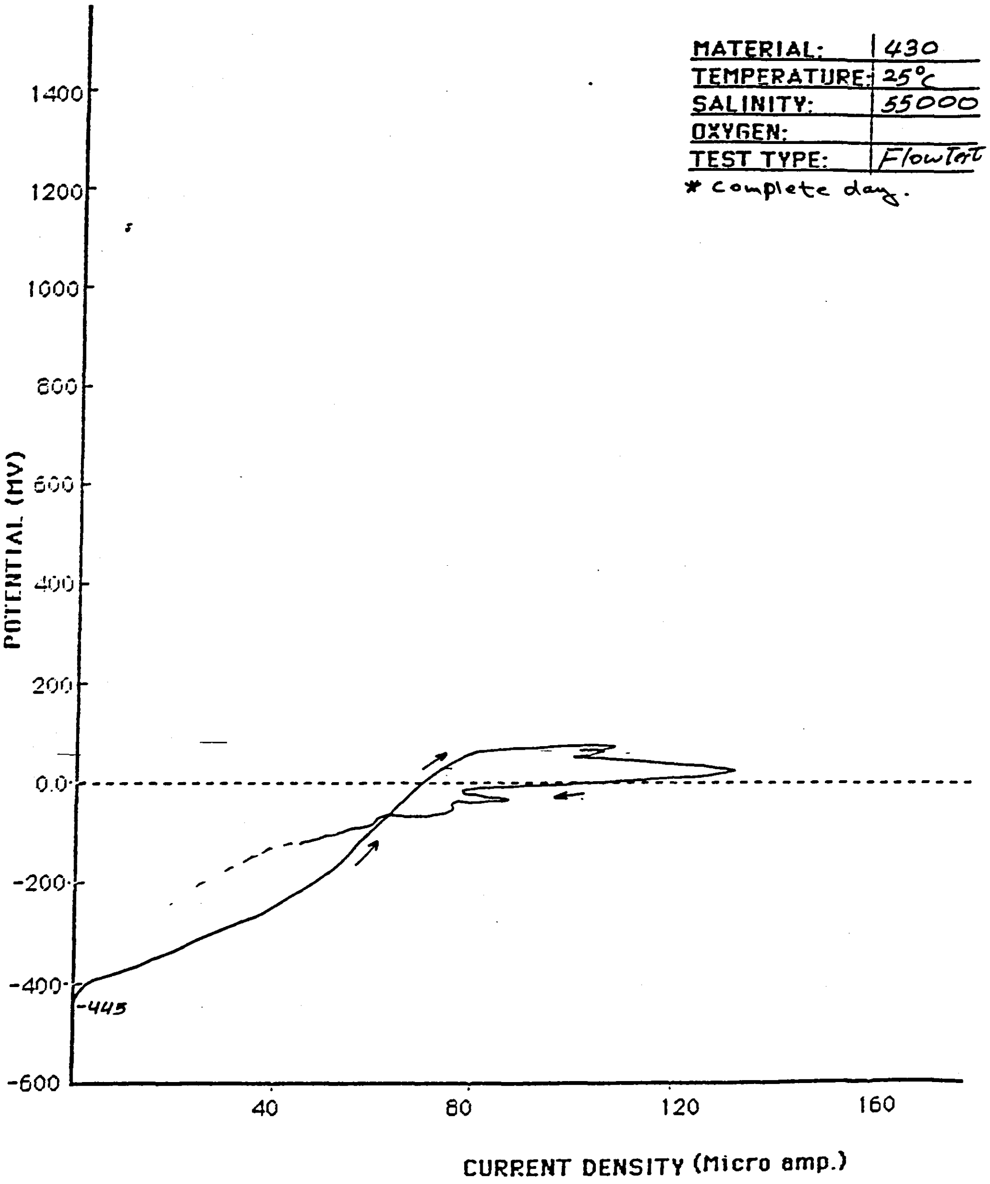

MATERIAL: 316
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: FLOW
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-389
250
(μA)
40
80
120
160
CURRENT DENSITY (Micro amp.)

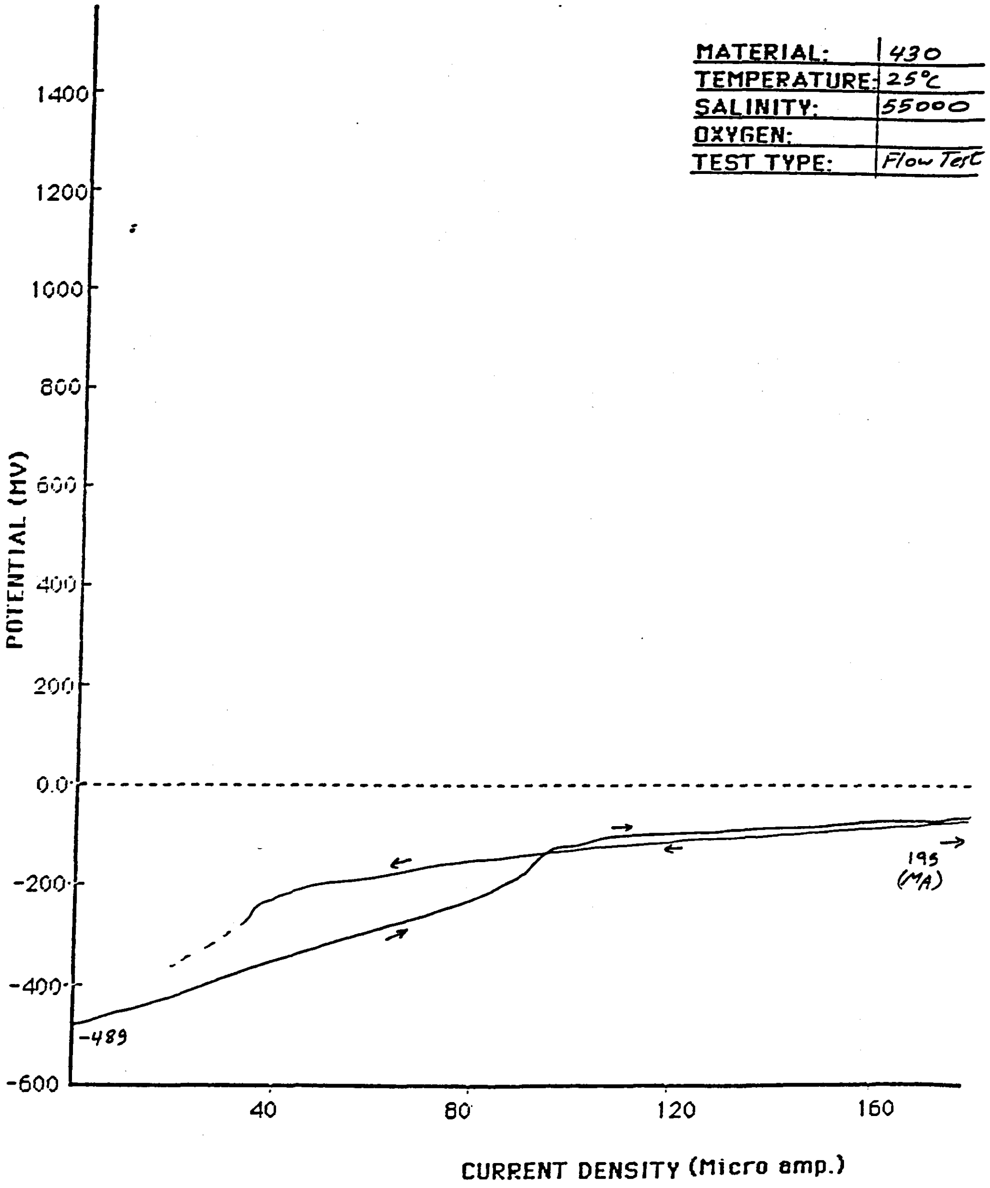


MATERIAL:	316
TEMPERATURE:	45°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	FLOW.

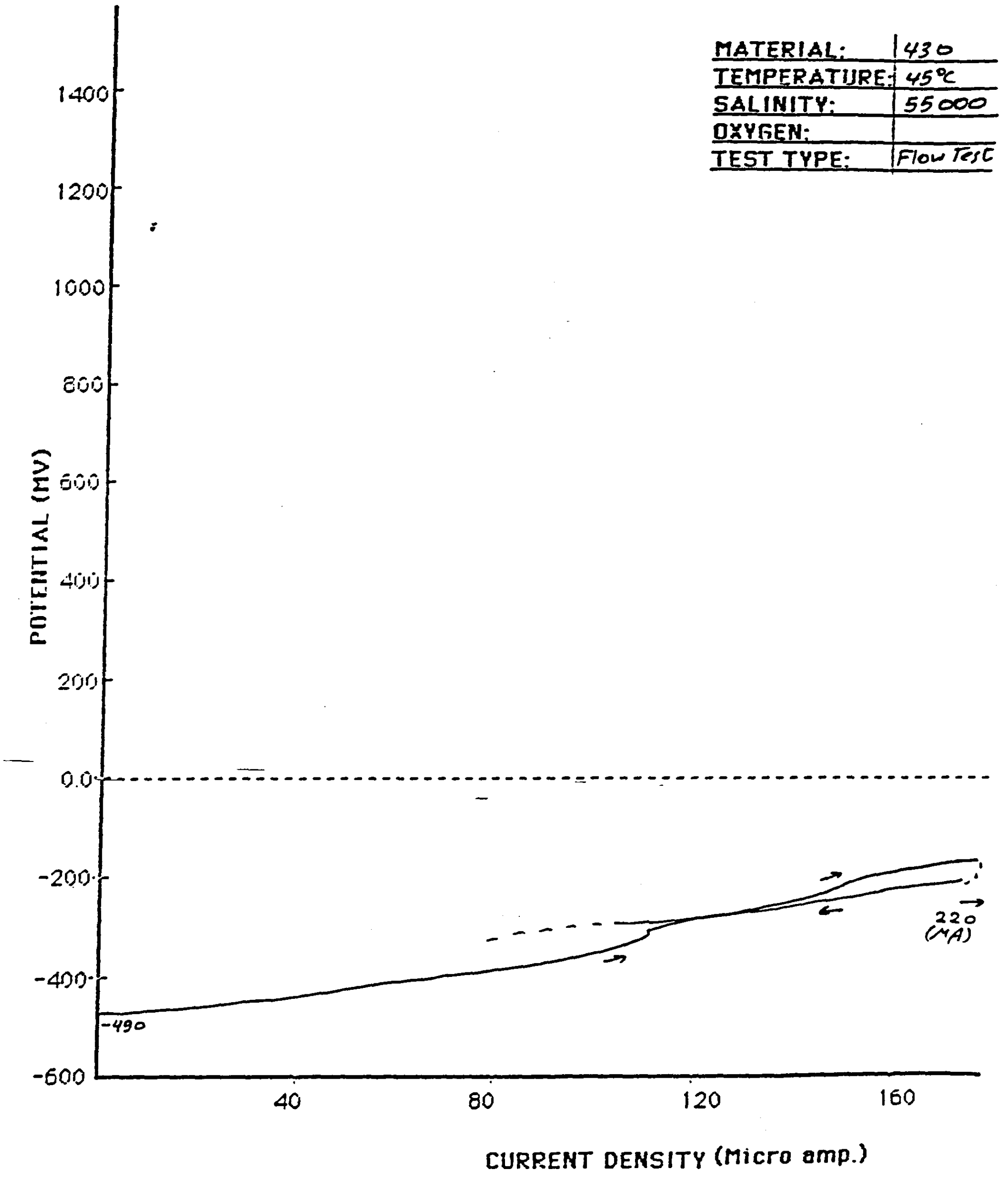

MATERIAL: 430
TEMPERATURE: 25C
SALINITY: 35000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-472
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: 430
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-446
40
80
120
160
CURRENT DENSITY (Micro amp.)

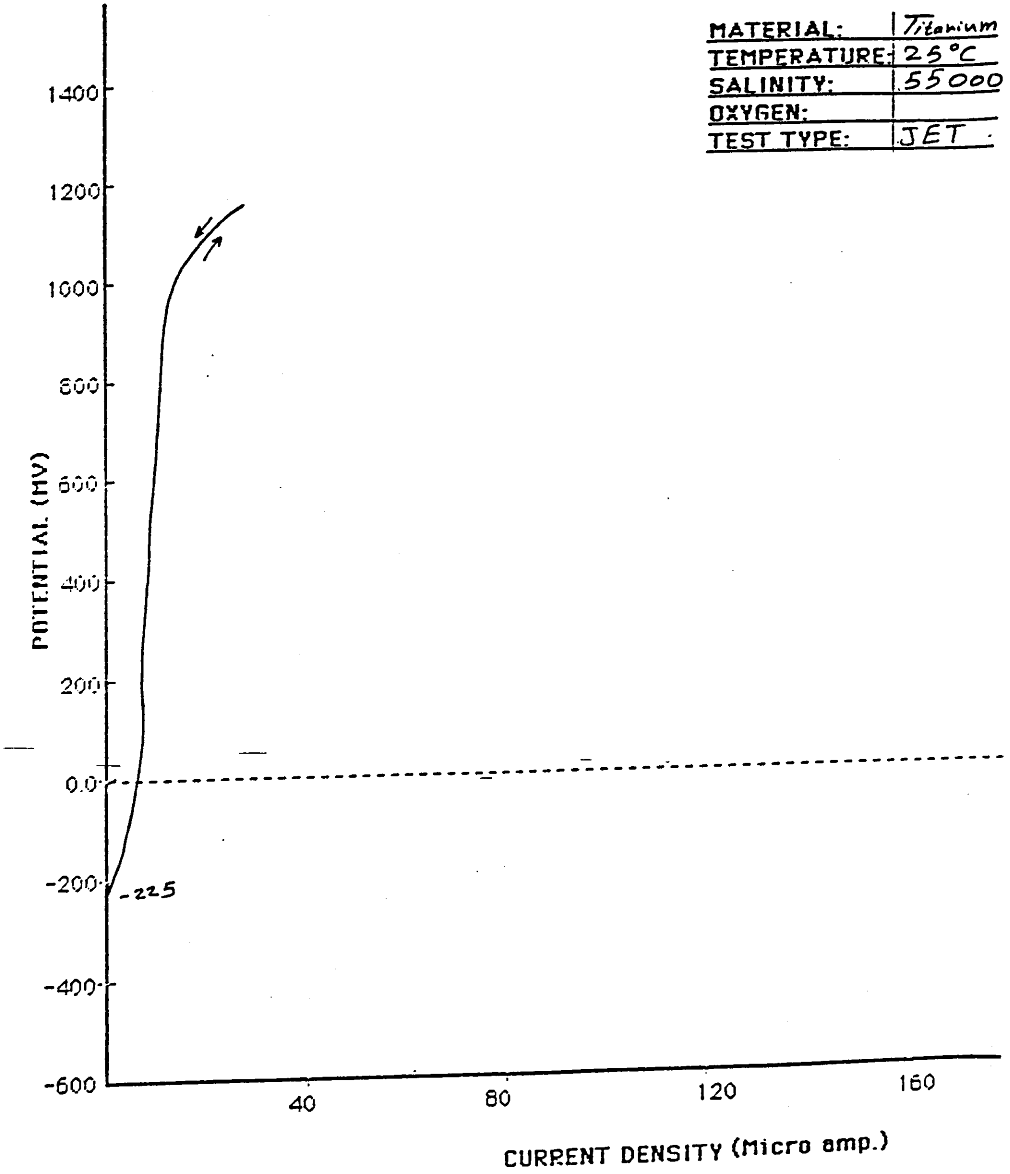

MATERIAL: 430
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: Flow Test
* complete day.
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-445
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)



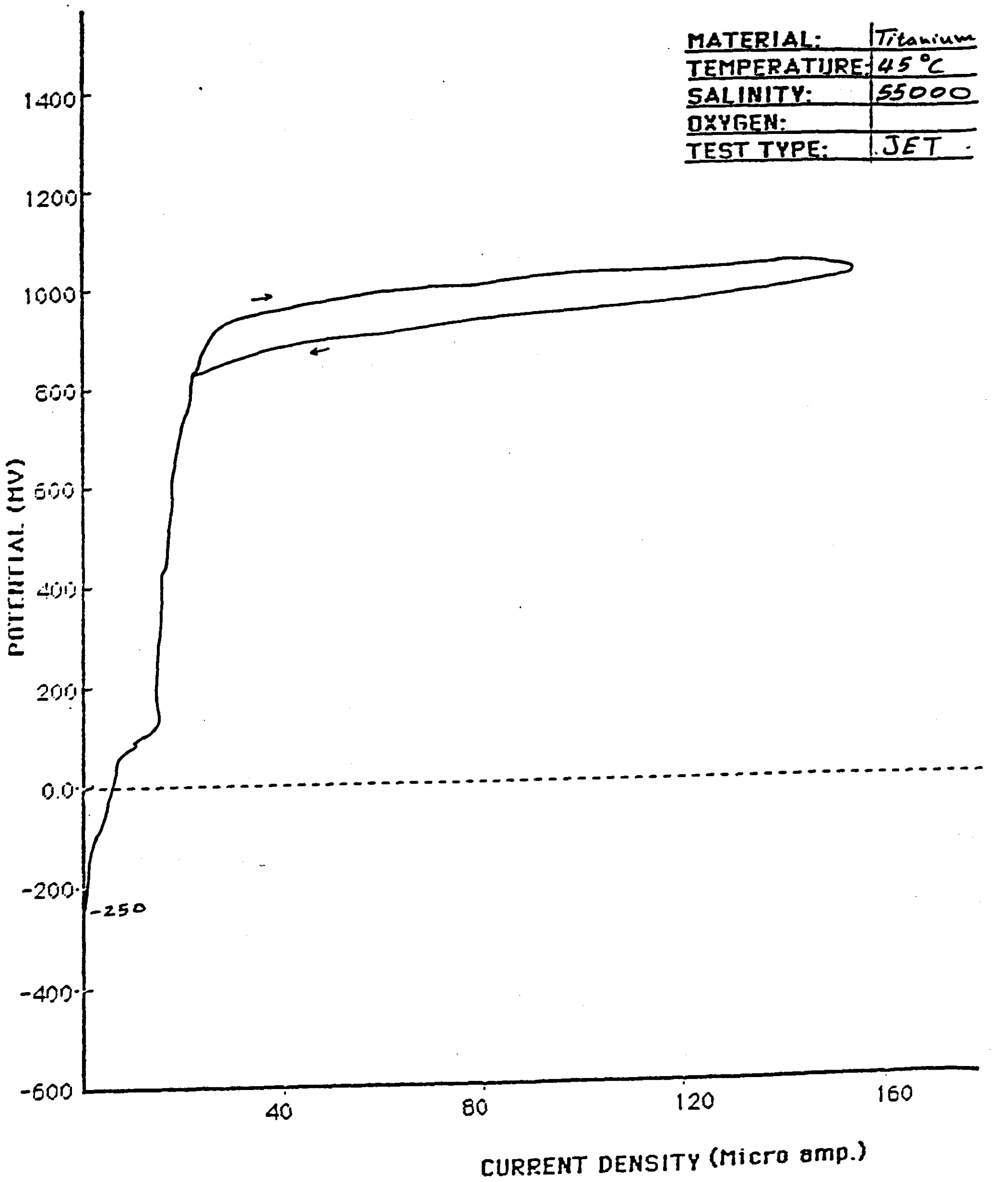
MATERIAL:	430
TEMPERATURE:	25°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	Flow Test


MATERIAL: 430
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: Flow Test
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-490
220 (μA)
40
80
120
160
CURRENT DENSITY (Micro amp.)

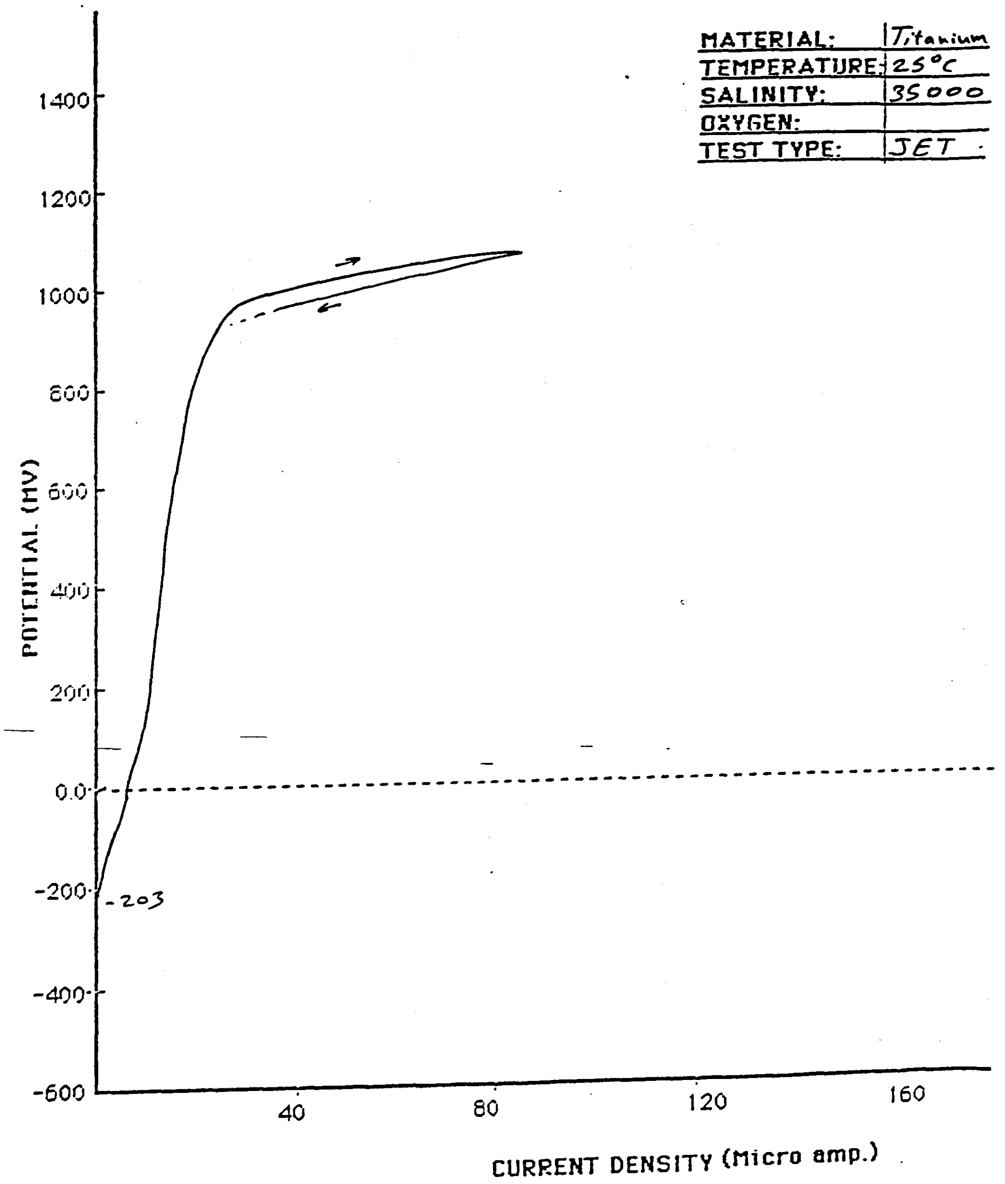
Jet Effect Test Rresults



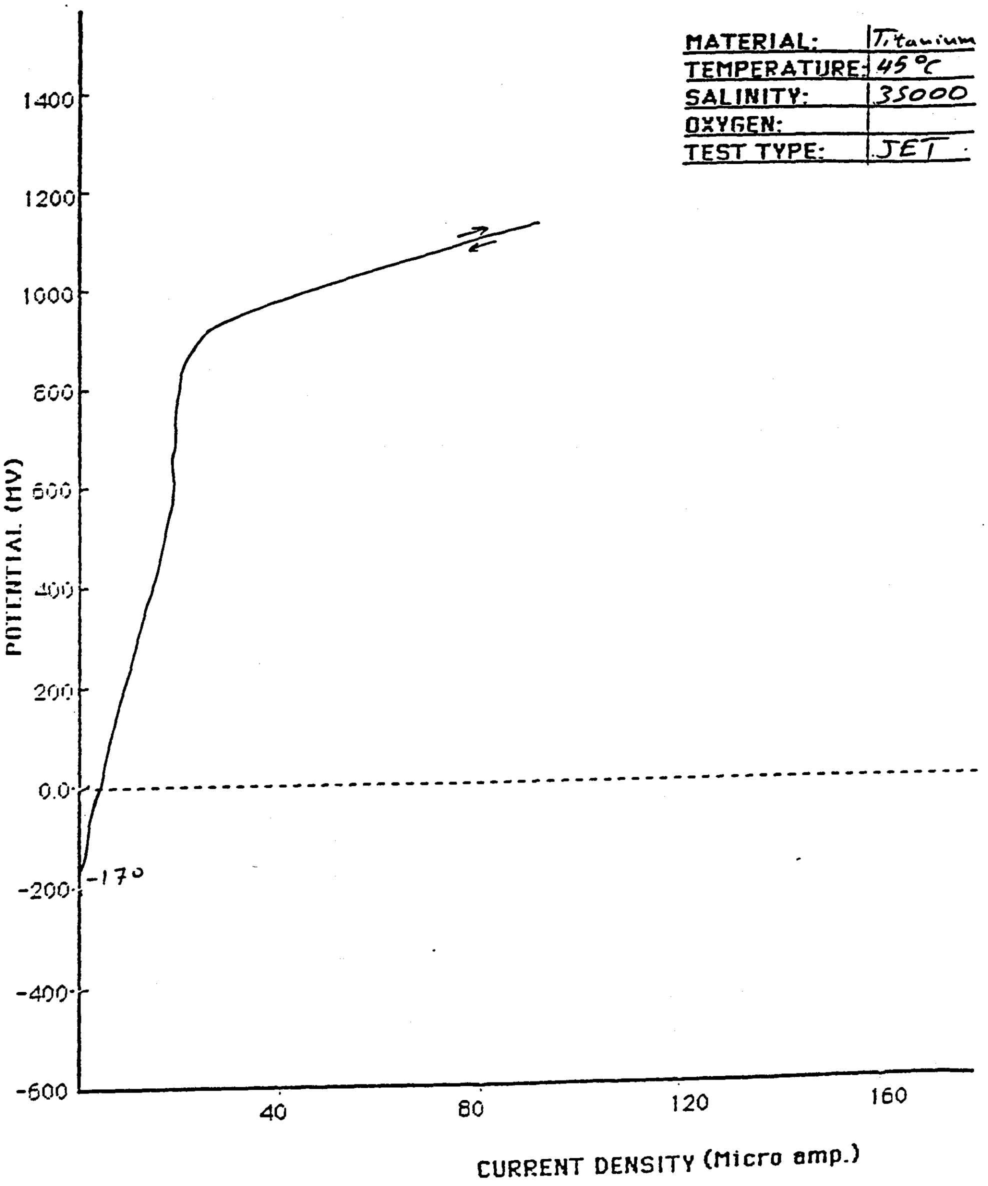
MATERIAL:	Titanium
TEMPERATURE:	25 °C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	JET

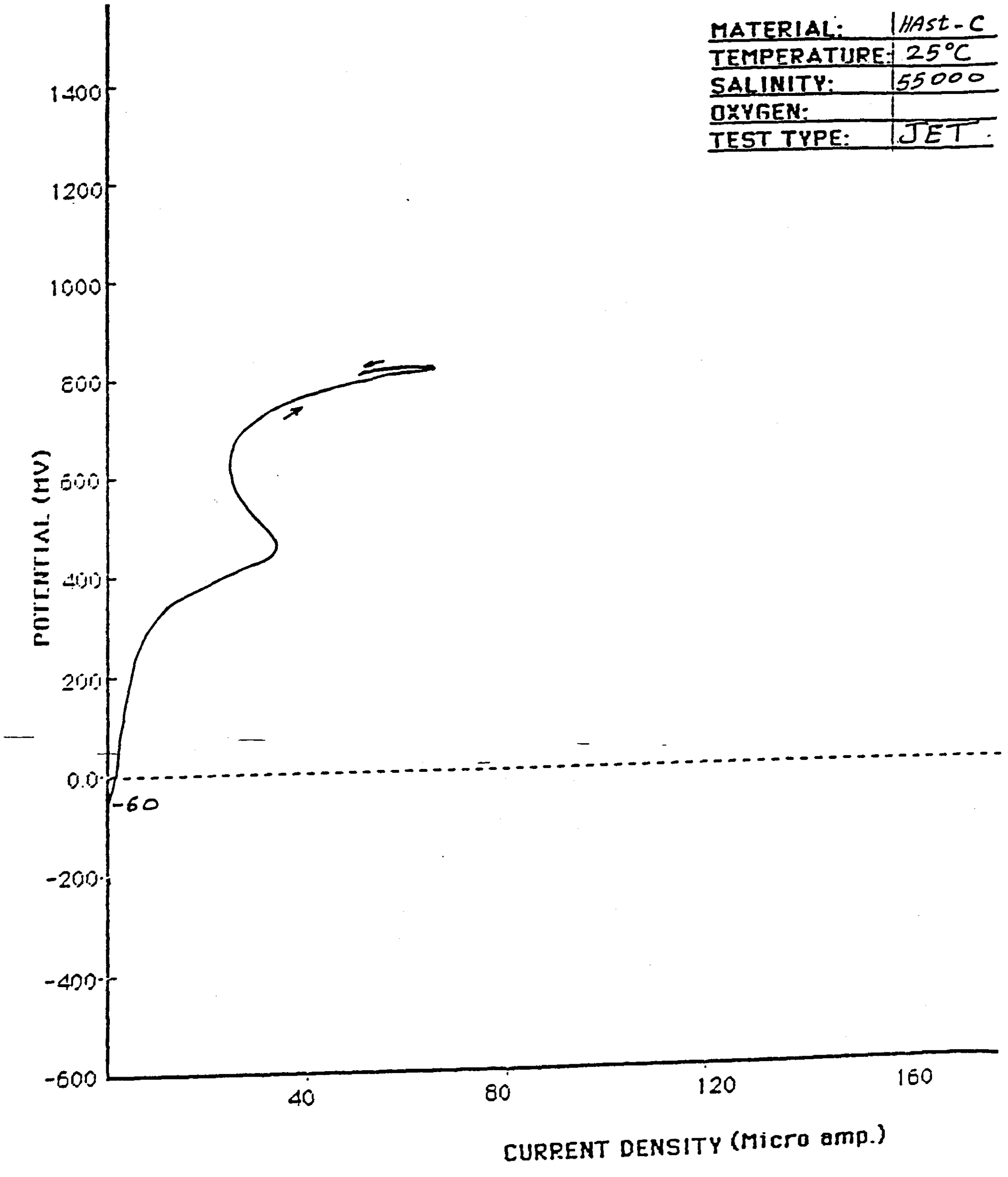


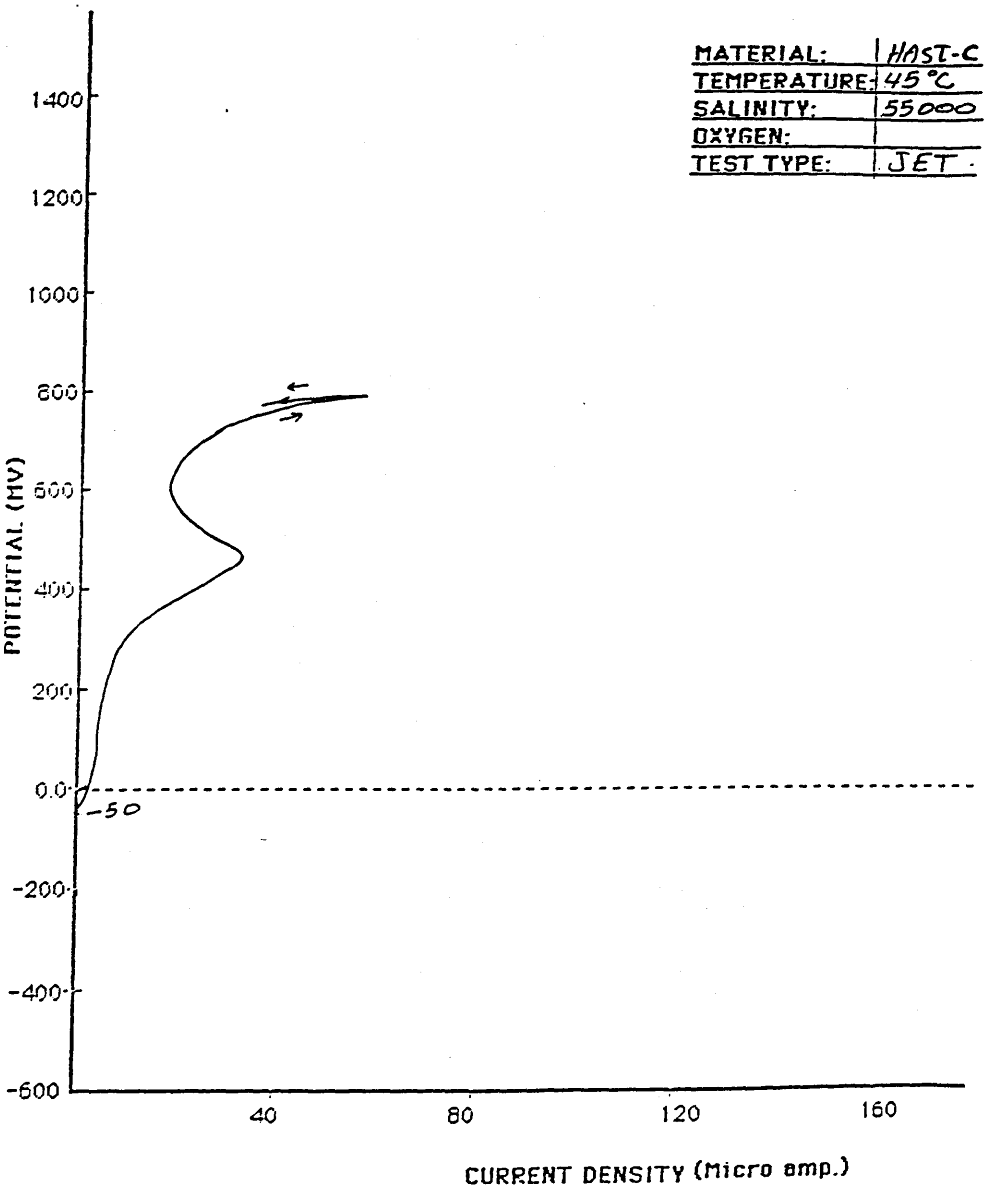
MATERIAL: Titanium
TEMPERATURE: 45 °C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET



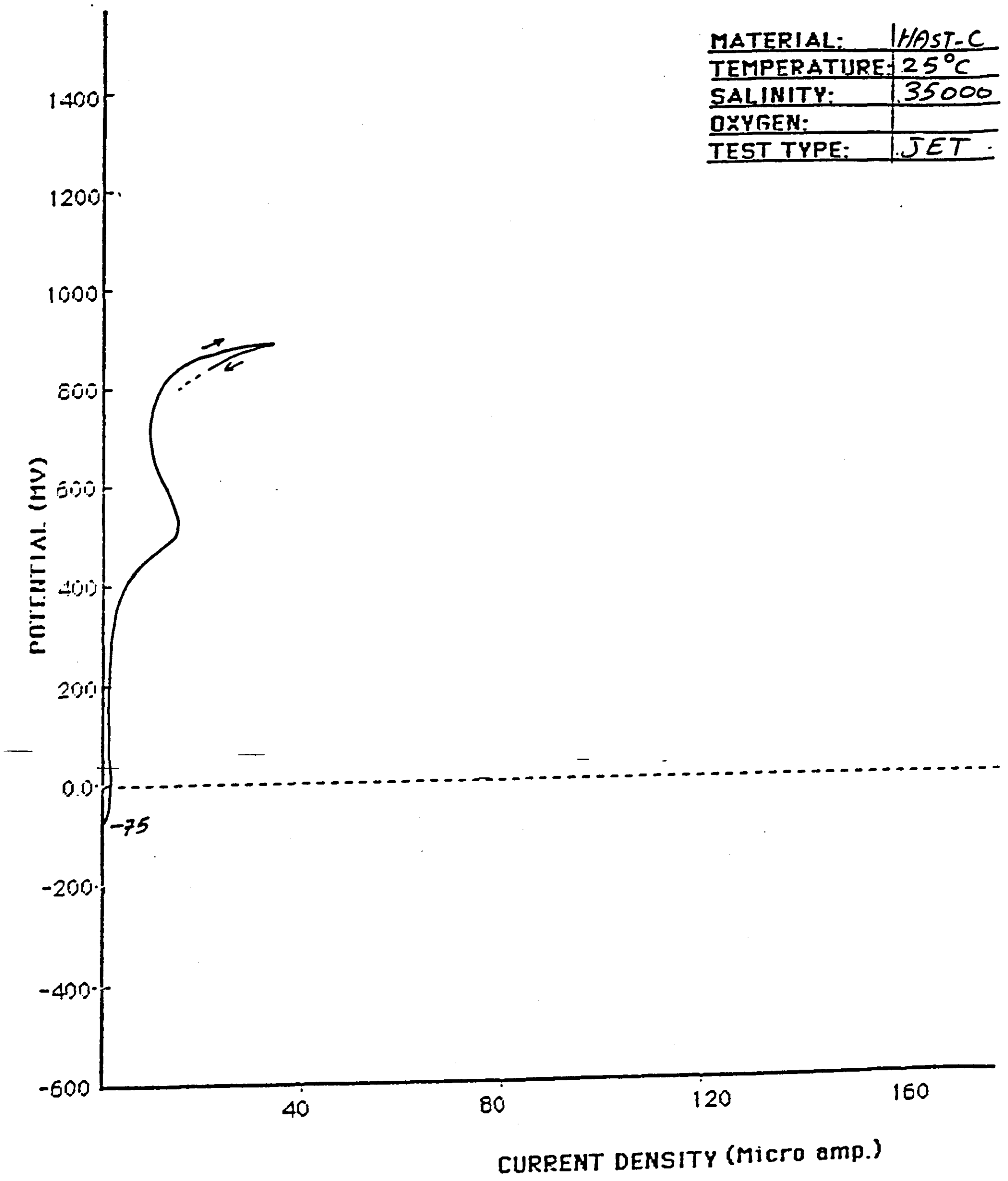
MATERIAL: Titanium
TEMPERATURE: 25°C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET


MATERIAL: Titanium
TEMPERATURE: 45 °C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-170
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)

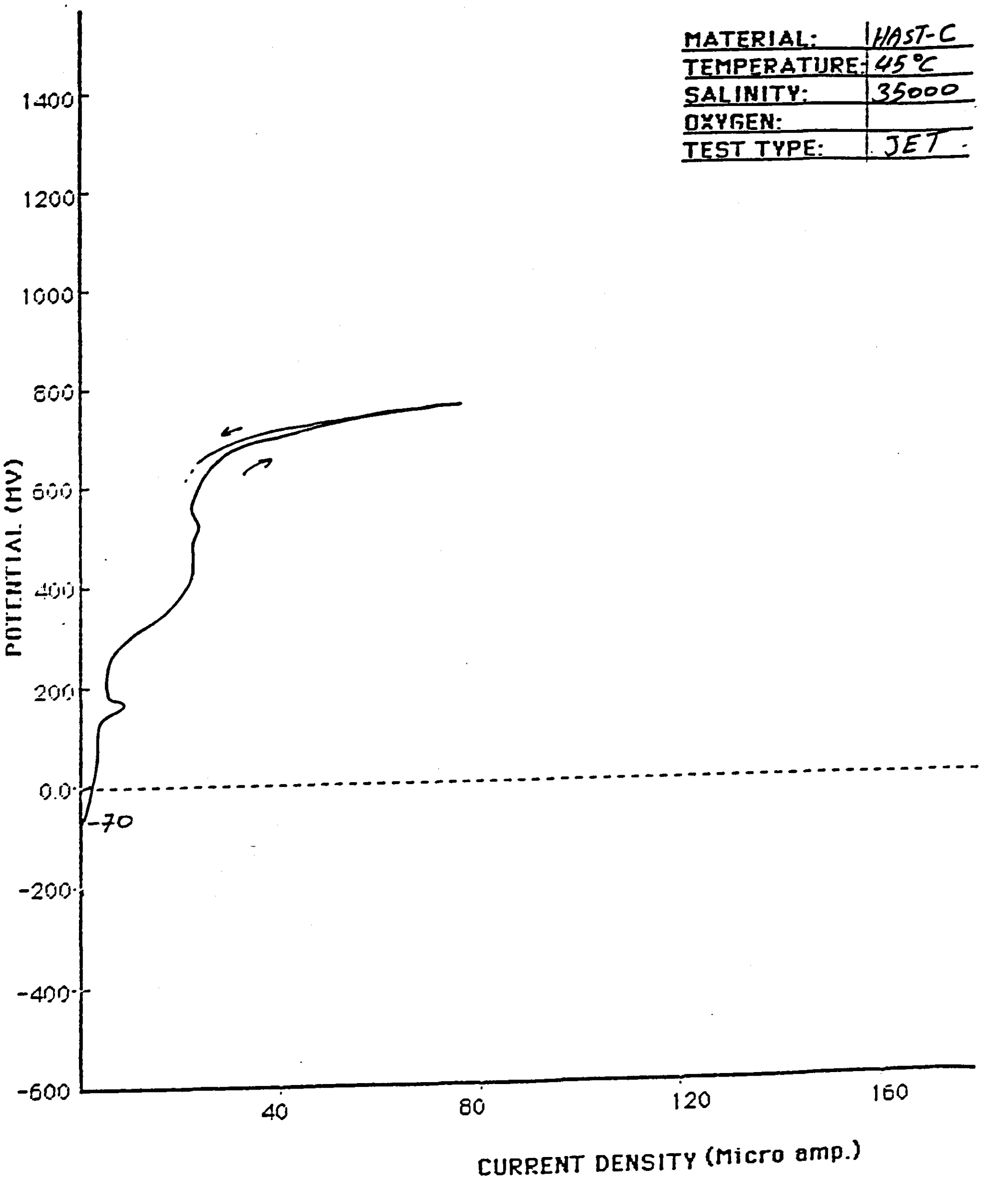

MATERIAL: HAst-C
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-60
40
80
120
160
CURRENT DENSITY (Micro amp.)



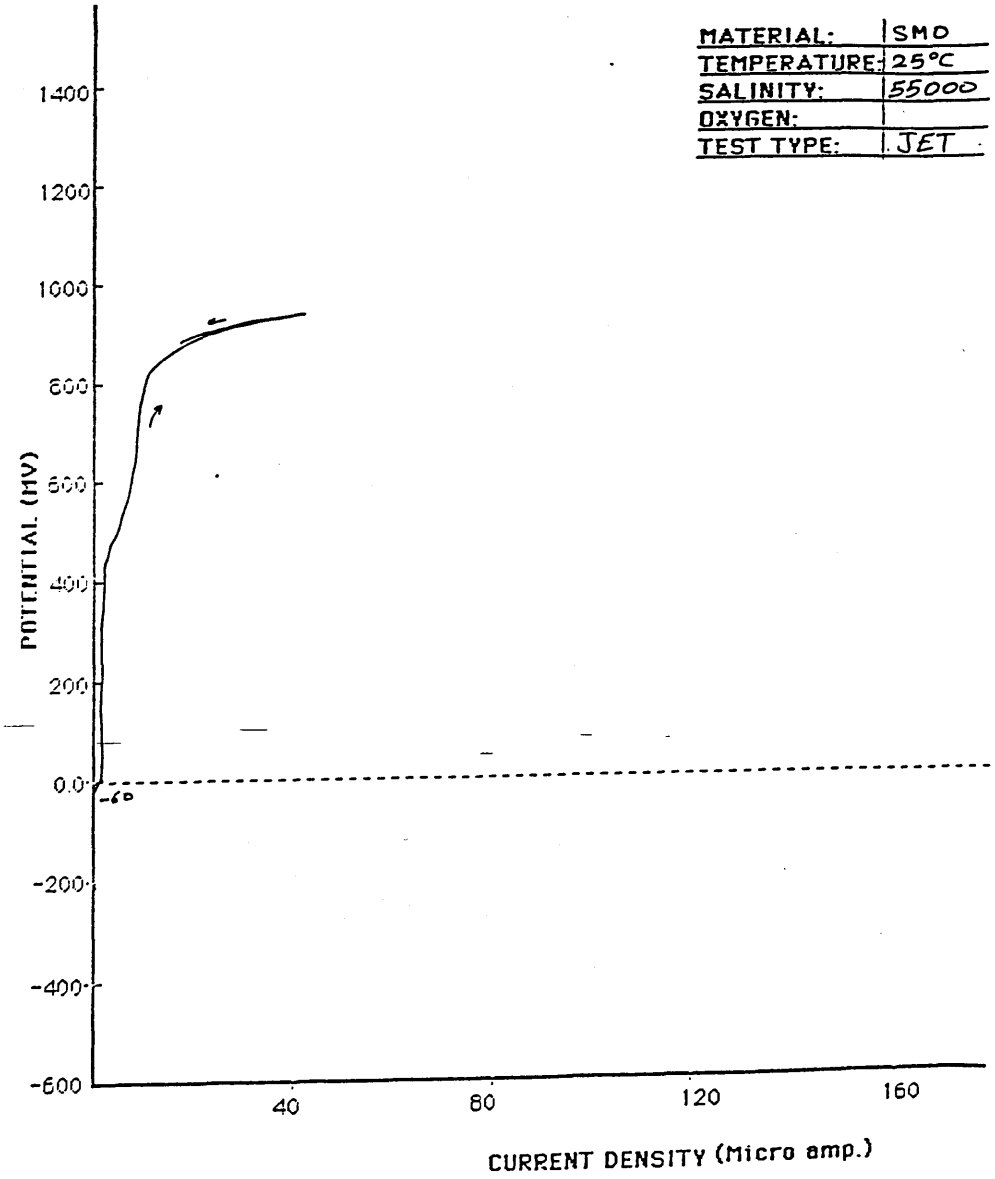
MATERIAL:	HAST-C
TEMPERATURE:	45 °C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	JET

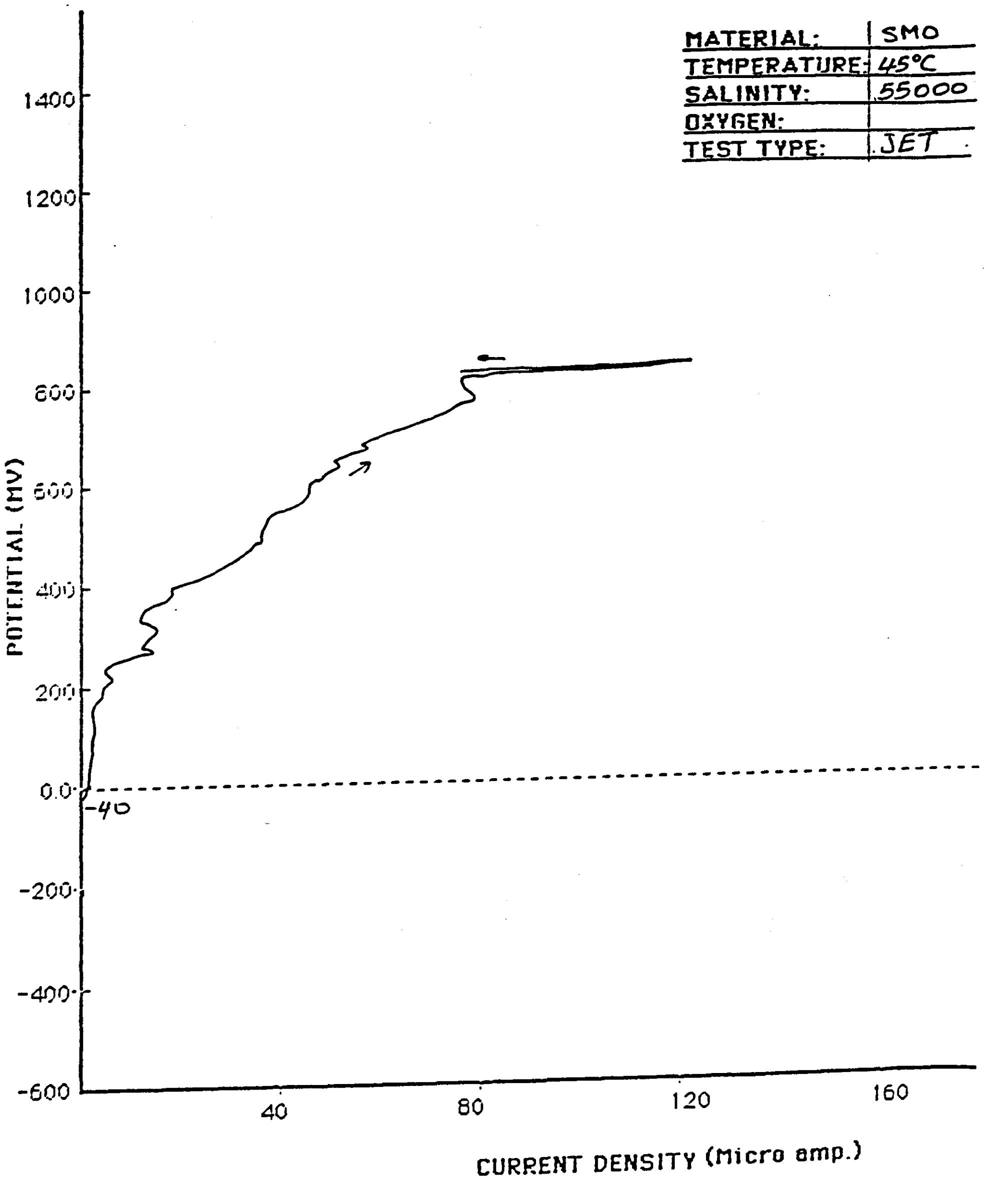


MATERIAL:	HAST-C
TEMPERATURE:	25°C
SALINITY:	35000
OXYGEN:	
TEST TYPE:	JET

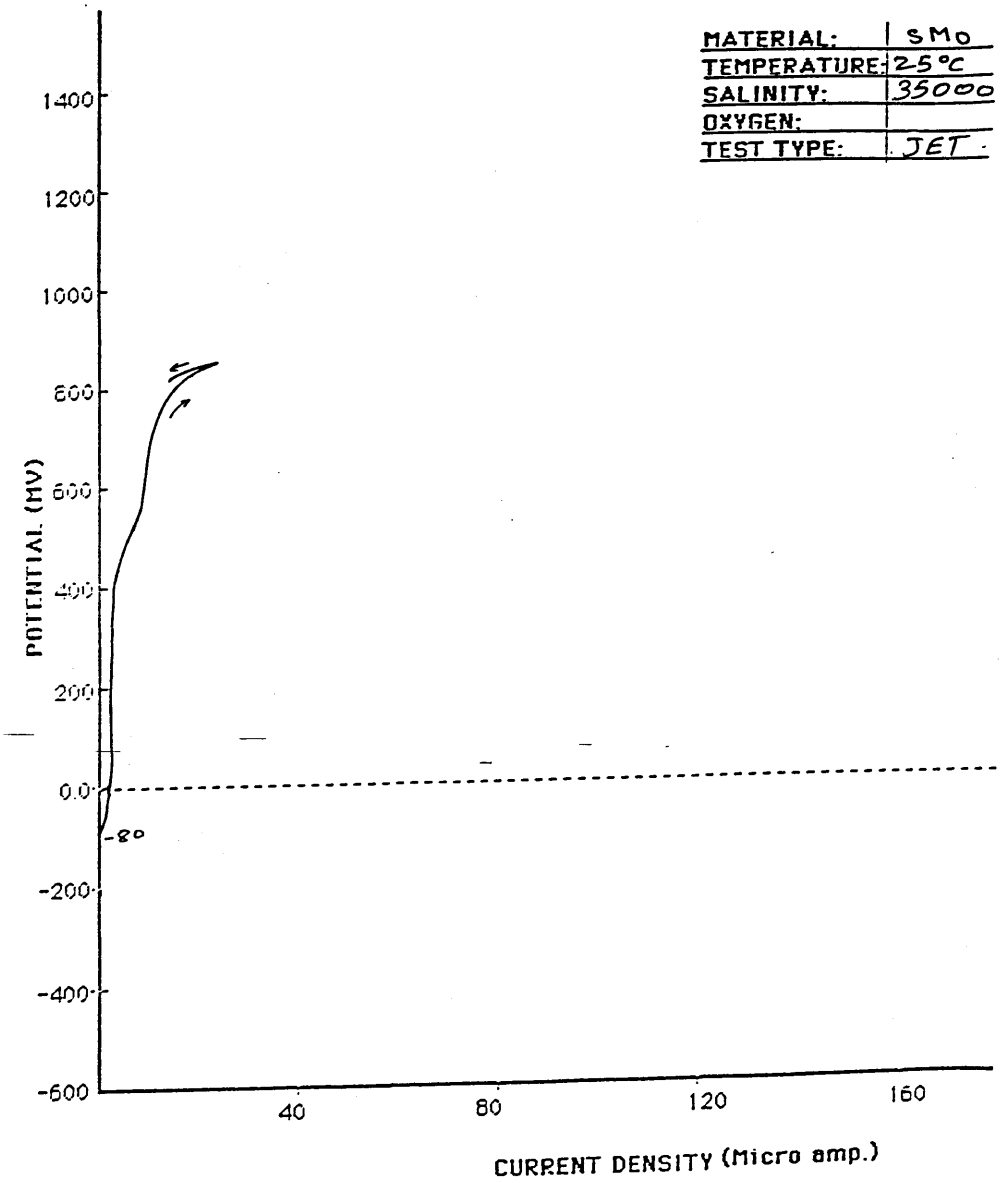


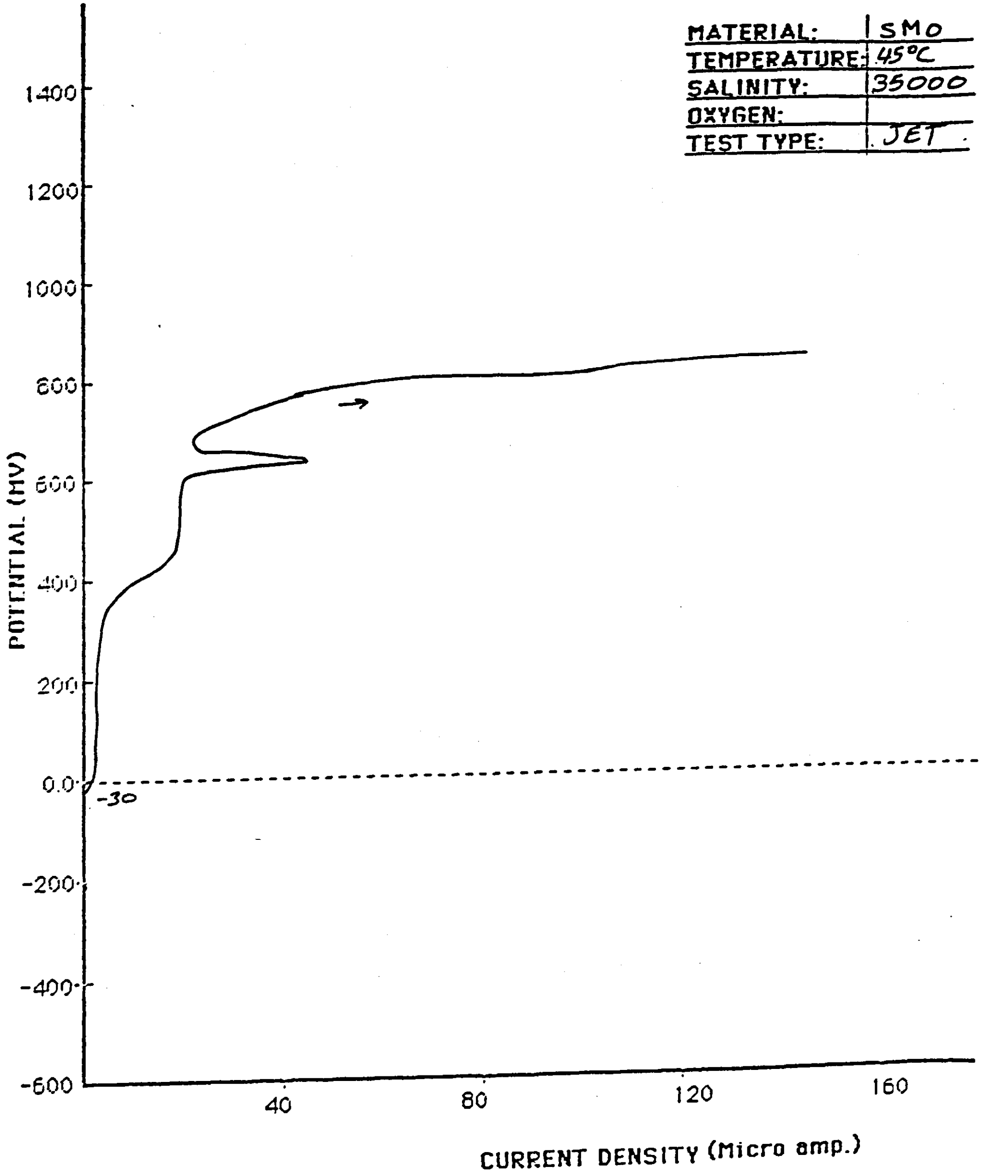
MATERIAL: HAST-C
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET

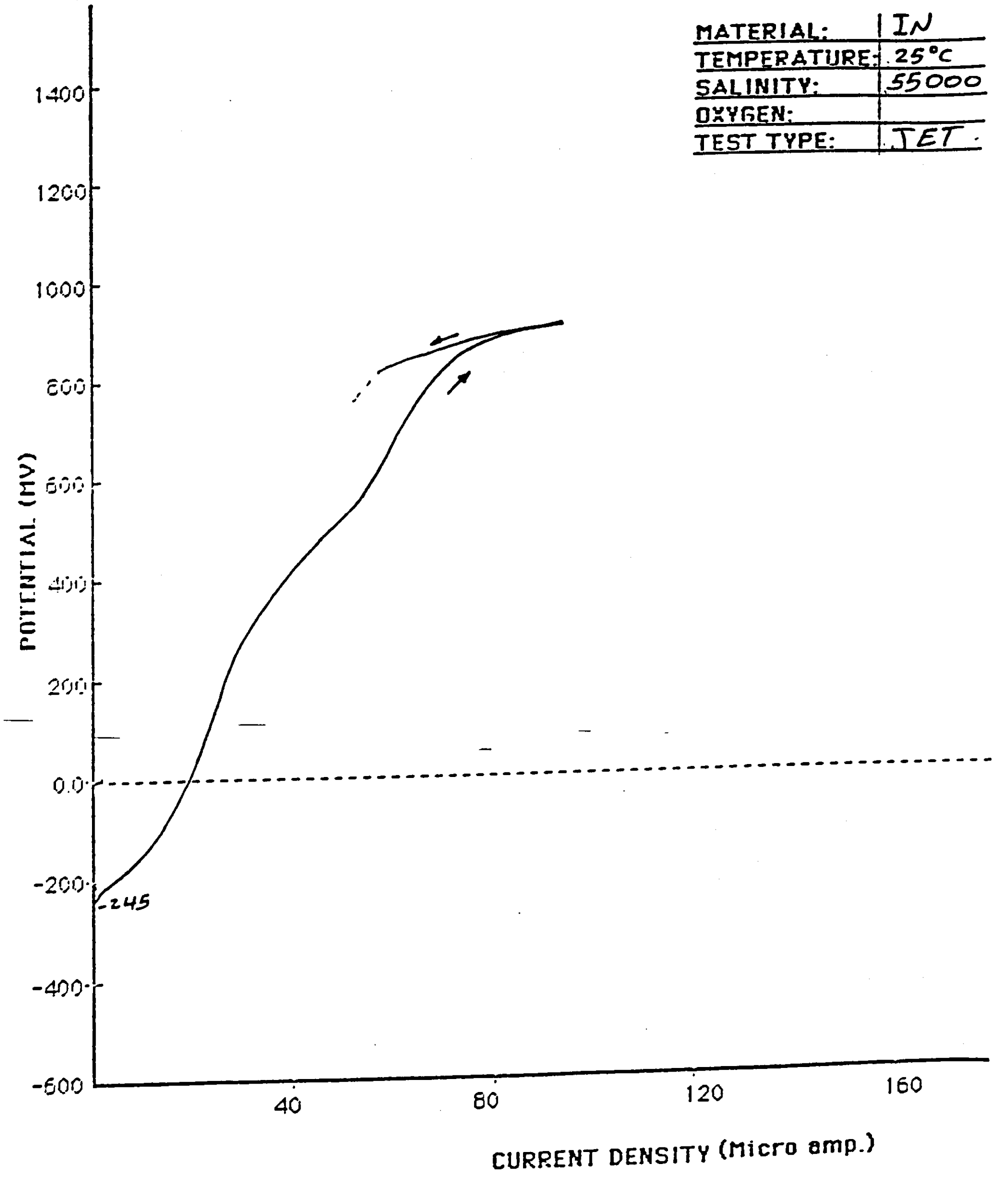

MATERIAL: SMO
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-60
40
80
120
160
CURRENT DENSITY (Micro amp.)

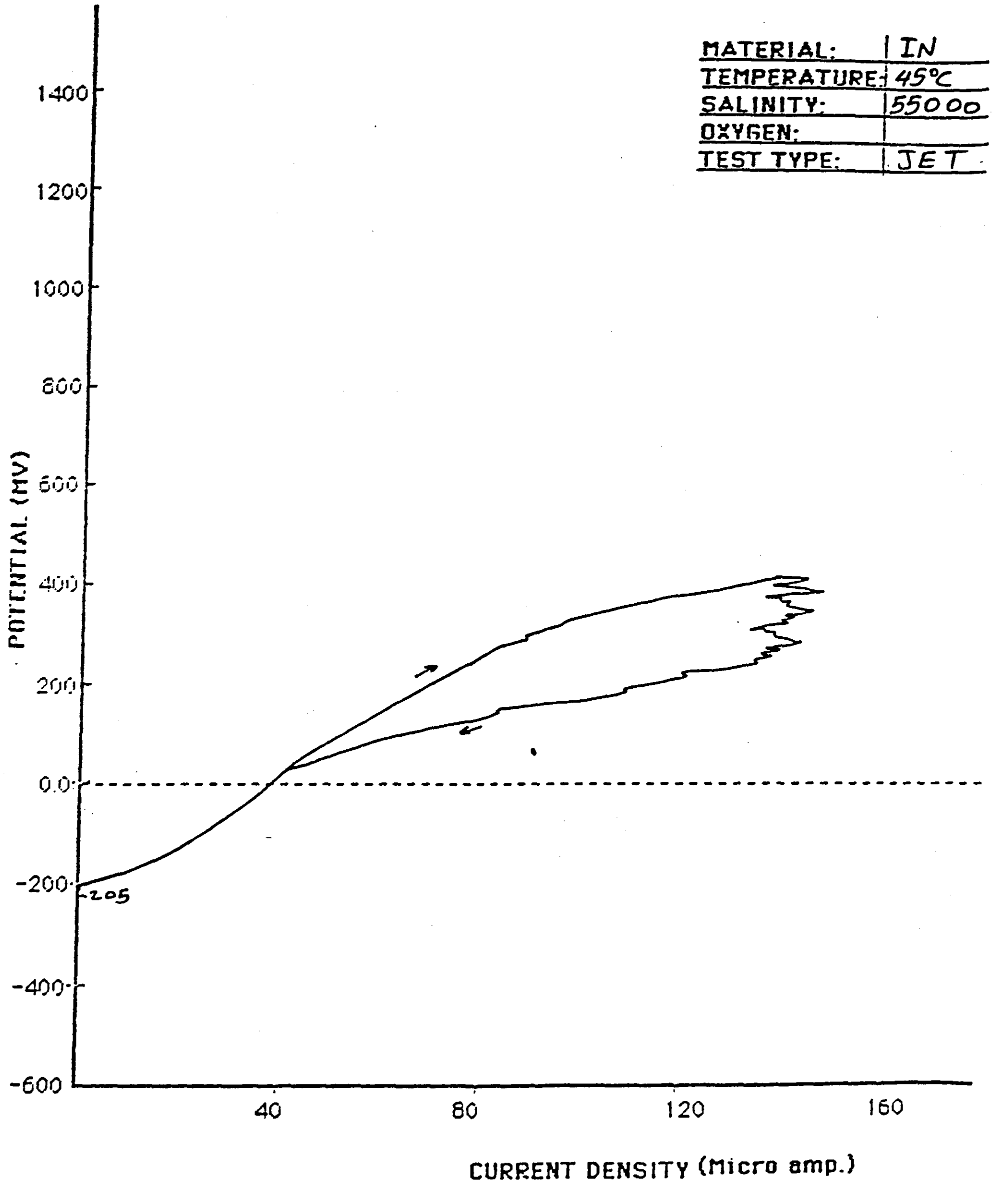


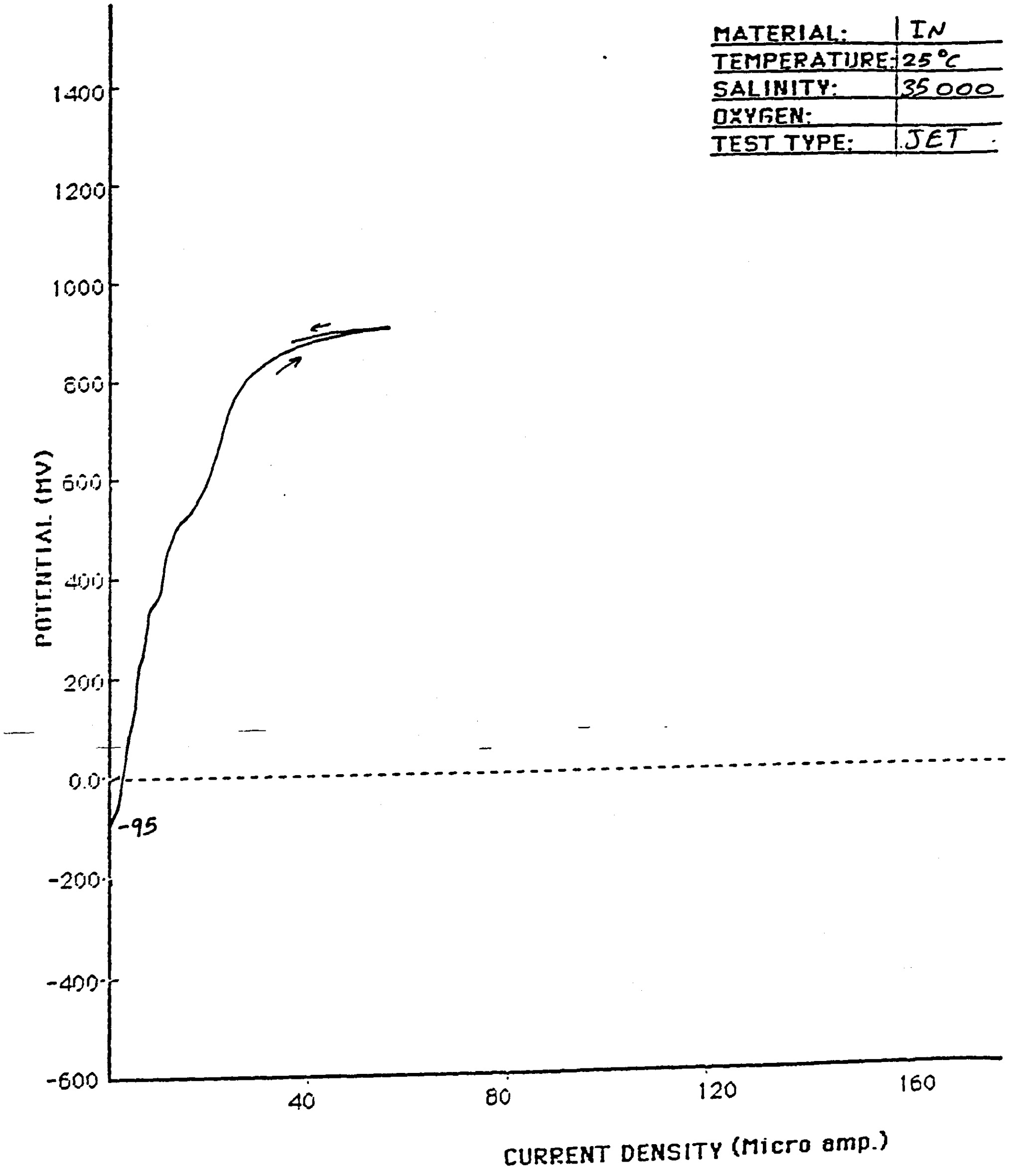
MATERIAL:	SMO
TEMPERATURE:	45°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	JET

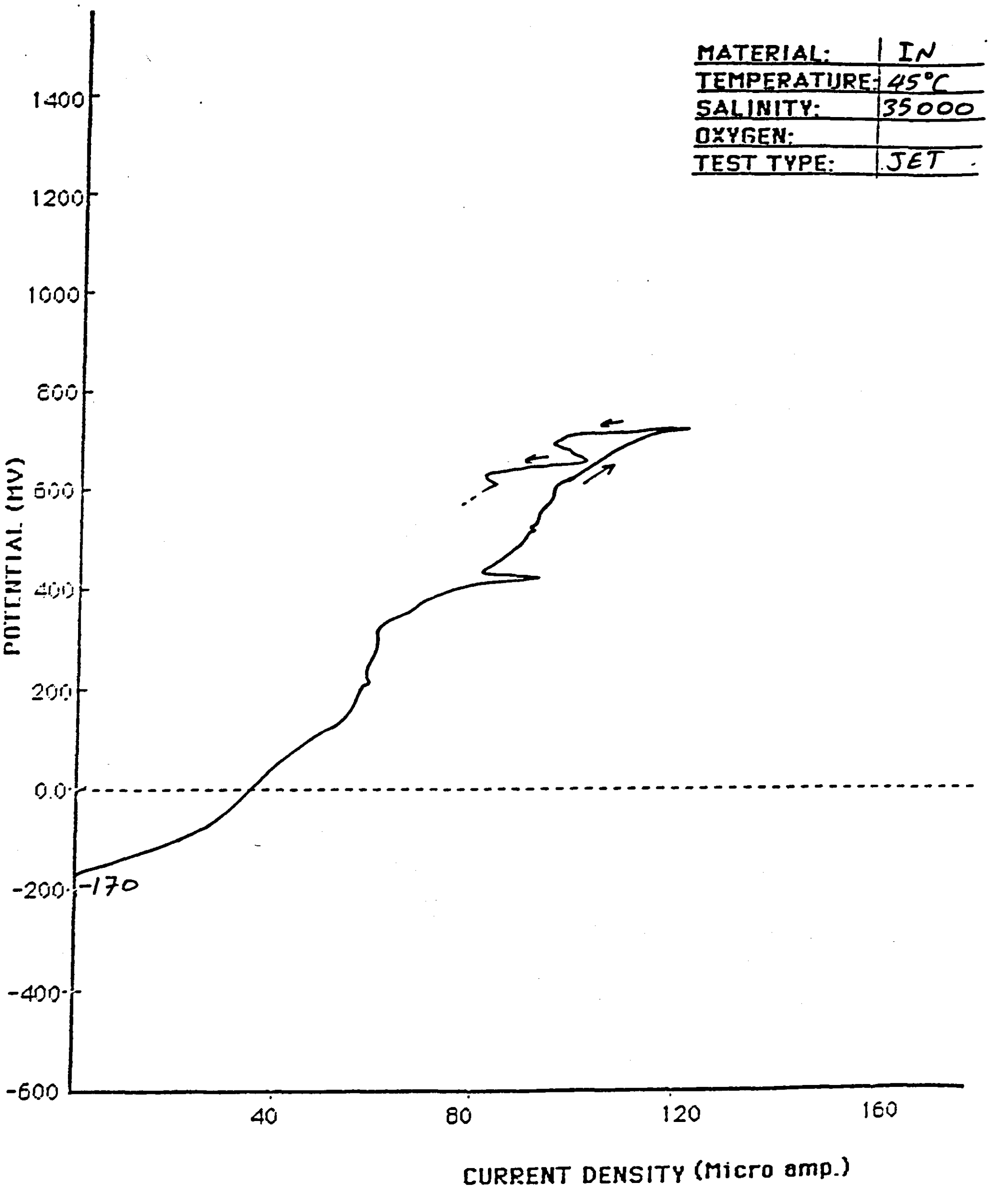

MATERIAL: SMo
TEMPERATURE: 25 °C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-80
-200
-400
-600
40
80
120
160
CURRENT DENSITY (Micro amp.)

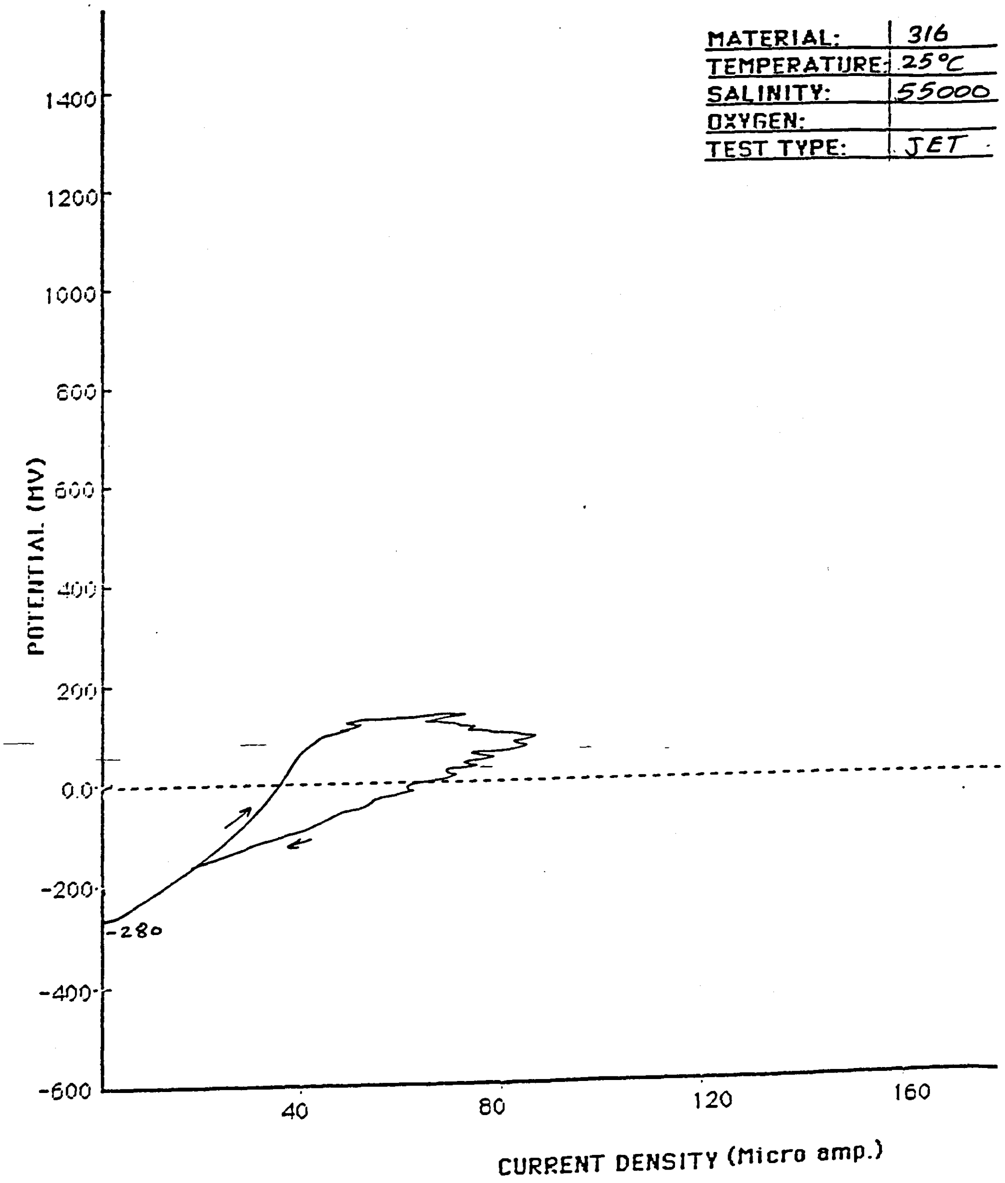

MATERIAL: SMo
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-30
-200
-400
-600
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: IN
TEMPERATURE: 25°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-245
-400
-600
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)

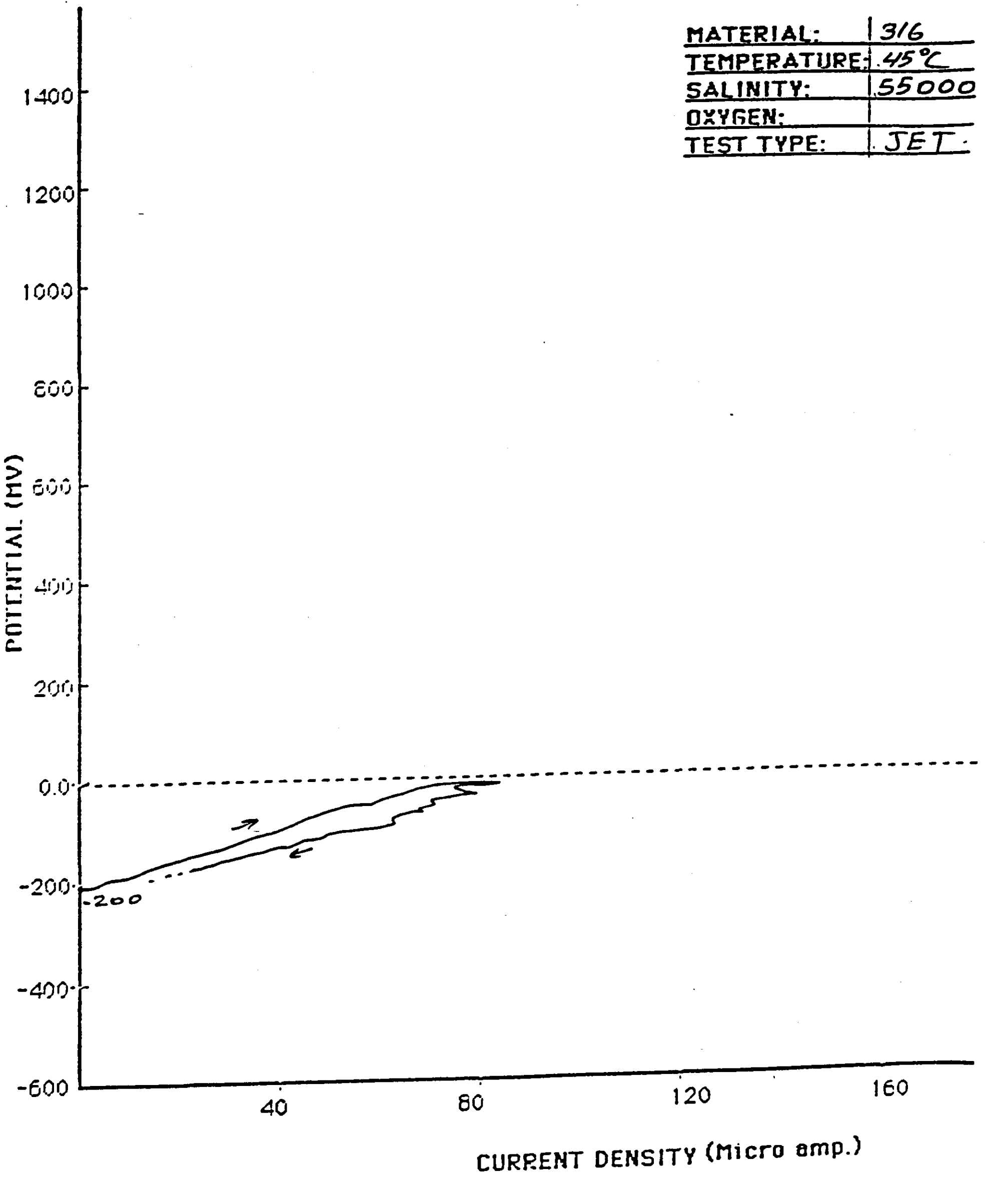

MATERIAL: IN
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-205
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)

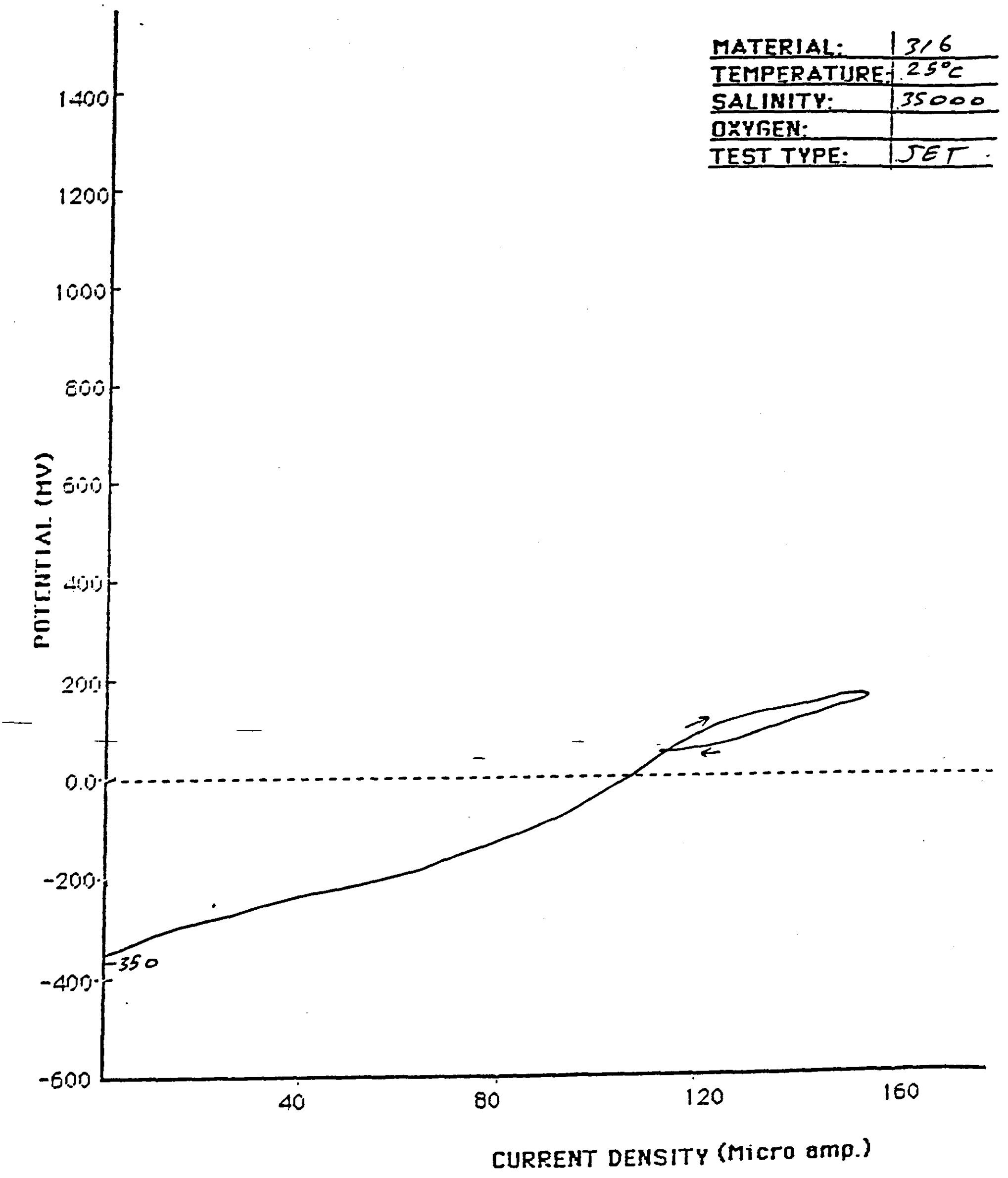

MATERIAL: IN
TEMPERATURE: 25 °C
SALINITY: 35 000
OXYGEN:
TEST TYPE: JET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-95
40
80
120
160
CURRENT DENSITY (Micro amp.)

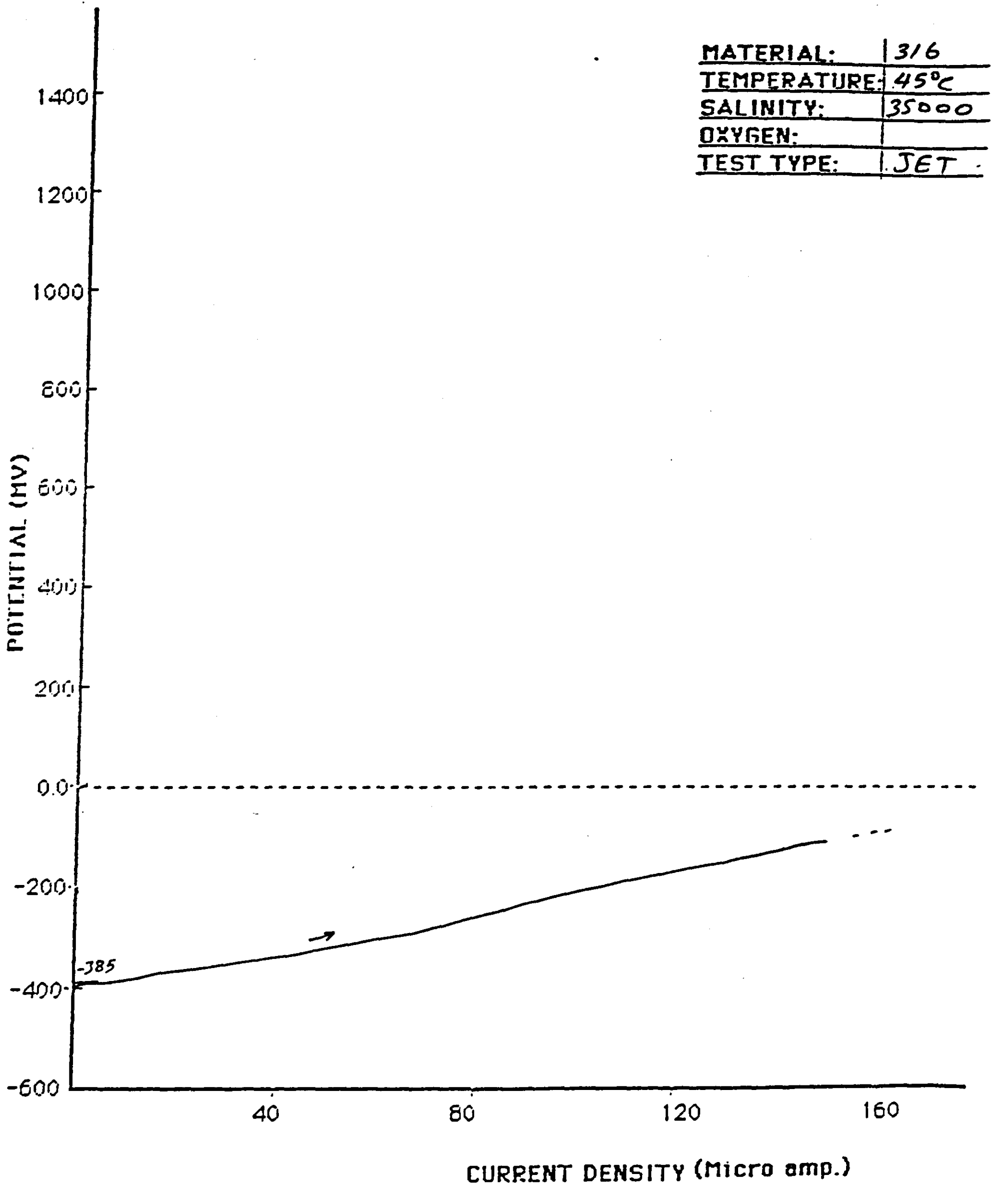

MATERIAL: IN
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-170
40
80
120
160
CURRENT DENSITY (Micro amp.)

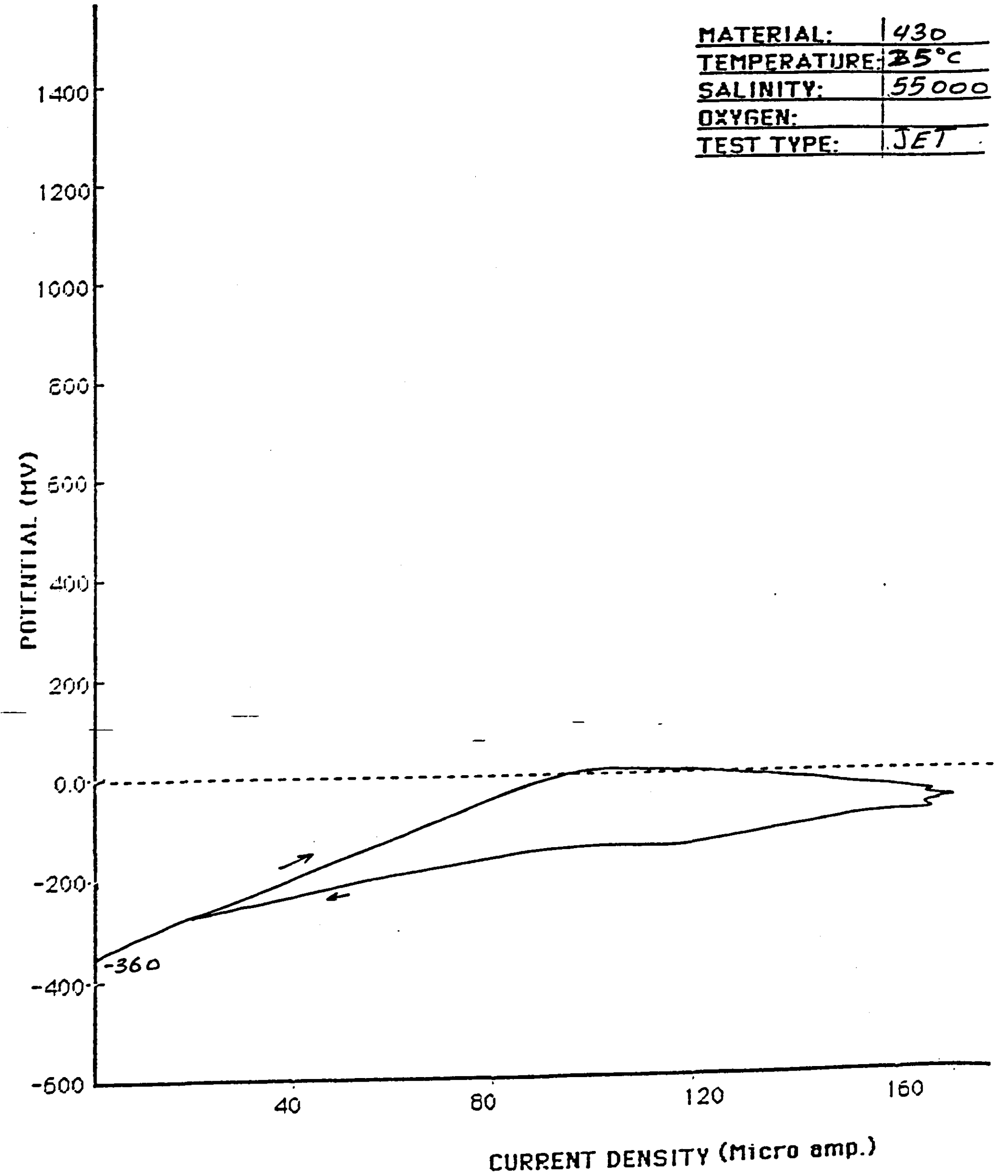


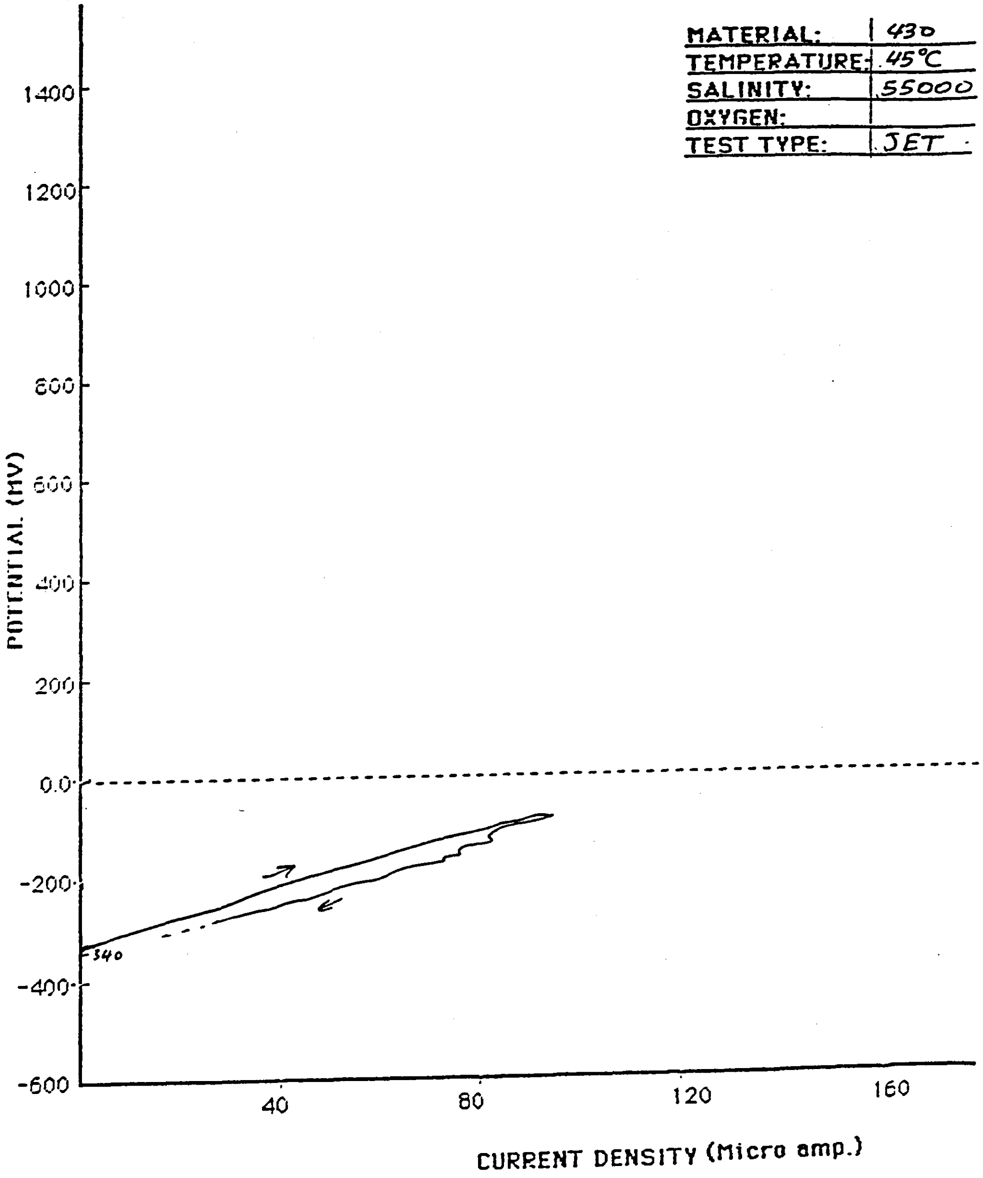
MATERIAL:	316
TEMPERATURE:	25°C
SALINITY:	55000
OXYGEN:	
TEST TYPE:	JET


MATERIAL: 316
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-200
40
80
120
160
POTENTIAL (MV)
CURRENT DENSITY (Micro amp.)

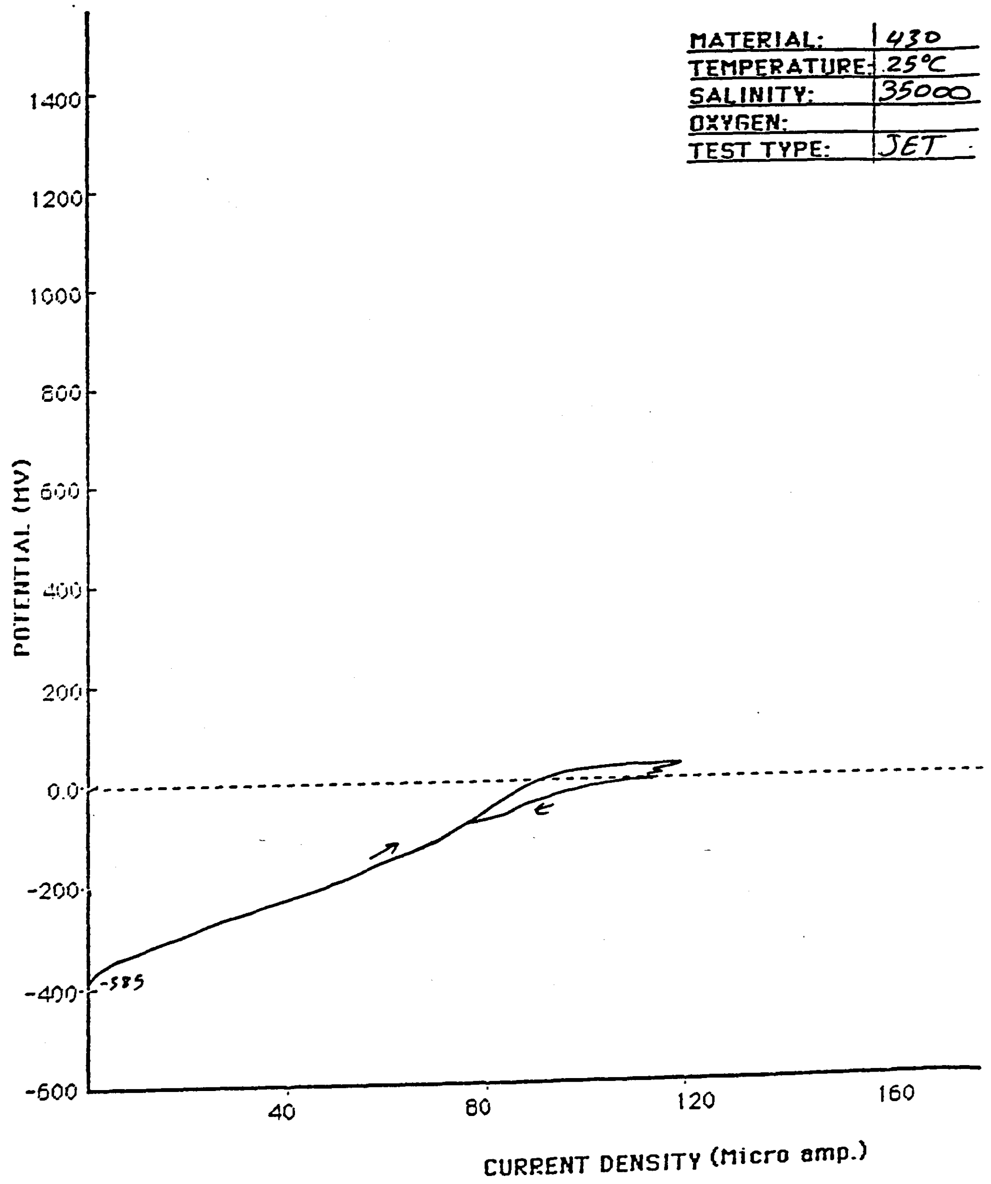

MATERIAL: 316
TEMPERATURE: 25°C
SALINITY: 35000
OXYGEN:
TEST TYPE: SET
POTENTIAL (MV)
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-350
40
80
120
160
CURRENT DENSITY (Micro amp.)


MATERIAL: 316
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-385
40
80
120
160
CURRENT DENSITY (Micro amp.)

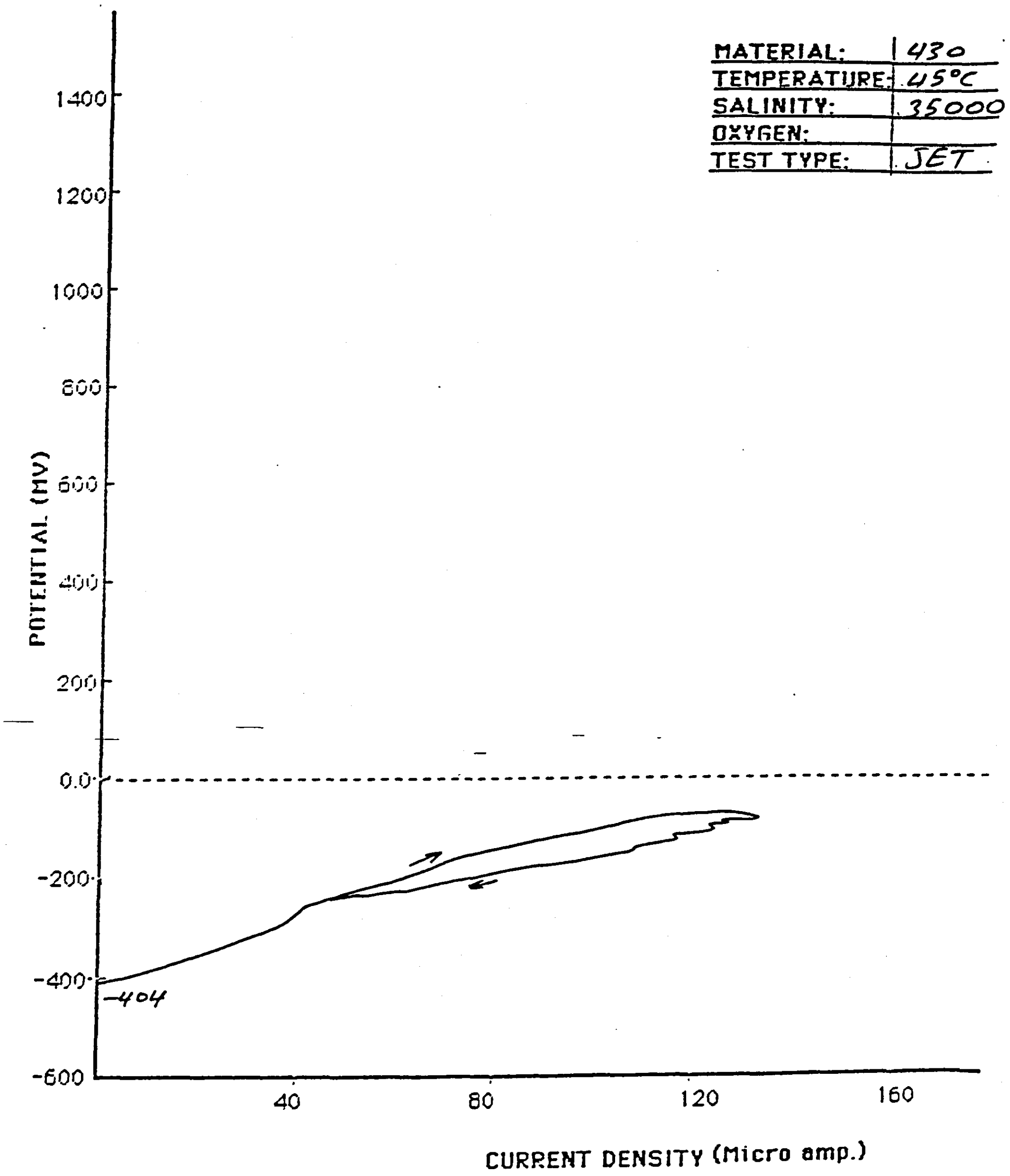

MATERIAL: 430
TEMPERATURE: 35°c
SALINITY: 55000
OXYGEN:
TEST TYPE: JET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
POTENTIAL (MV)
-360
40
80
120
160
CURRENT DENSITY (Micro amp.)



MATERIAL: 430
TEMPERATURE: 45°C
SALINITY: 55000
OXYGEN:
TEST TYPE: JET



MATERIAL:	430
TEMPERATURE:	25°C
SALINITY:	35000
OXYGEN:	
TEST TYPE:	JET


MATERIAL: 430
TEMPERATURE: 45°C
SALINITY: 35000
OXYGEN:
TEST TYPE: SET
1400
1200
1000
800
600
400
200
0.0
-200
-400
-600
-404
POTENTIAL (MV)
40
80
120
160
CURRENT DENSITY (Micro amp.)