

**The Effect of Electroless
Nickel Coatings on the
Galvanic Corrosion of
Other Metals**

THE EFFECT OF ELECTROLESS NICKEL COATINGS
ON THE
GALVANIC CORROSION OF OTHER METALS

ABSTRACT

While galvanic corrosion is possible between electroless nickel and other metals, in most environments it is not a problem. This paper discusses the factors which effect galvanic corrosion -- potential, couple size and resistance-- and describes when accelerated attack may be expected. The results of tests to better define the effect of different environments on the galvanic corrosion between electroless nickel and other metals is also presented, along with a description of the galvanic couples which occur at pores in metallic coatings.

INTRODUCTION

One of the most common questions about barrier coatings is: What is their effect on the galvanic corrosion of other metals? When an electroless nickel coated valve is installed in a steel pipeline, does the valve increase the corrosion of the pipe? Or, what happens to a steel part if its electroless nickel coating has a pore or crack through it?

This paper will attempt to answer some of these questions. Its objective is to describe galvanic corrosion and some of the factors -- environment, couple size and polarization -- which effect it. The results of tests to establish the galvanic relationship of electroless nickel to other metals in different environments is also presented, along with a description of the galvanic effects which occur at pores in metallic coatings.

GALVANIC CORROSION

Galvanic corrosion results when two different metals in electrical contact are immersed in an electrolyte. The potential or voltage difference between the metals causes a current to flow, usually increasing corrosion of one or both metals. This is the same process as occurs in a simple battery.

GALVANIC CORROSION CELLS

In a galvanic corrosion cell or a battery, the more active metal (that with the more negative potential) becomes the anode, while the more passive becomes the cathode. As a result, the anode is forced to give up positive ions and its corrosion is increased. Usually, corrosion of the cathode is reduced or eliminated. Thus, total corrosion (C_t) equals the corrosion a metal would normally experience in an environment (C_n) plus that corrosion due to galvanic coupling (C_g), or:

$$C_t = C_n + C_g .$$

The galvanic component can either be positive or negative depending upon whether it is for the anode or cathode. In turn the galvanic component is a function only of the current flow (I), the area of the anode or cathode (A) and a constant based on Faraday's Law (F), or:

$$C_g = \frac{I}{F \cdot A} .$$

Since, by Ohm's Law, current is equal to the potential difference (ΔE) divided by the cell's or couple's resistance:

$$C_g = \frac{\Delta E}{F \cdot A \cdot R}, \text{ and}$$

$$C_t = C_n + \frac{\Delta E}{F \cdot A \cdot R} .$$

Thus, galvanic corrosion will occur only as long as the potential difference is large enough and the resistance is low enough to support it.

An example of galvanic corrosion is what occurs to steel and copper in seawater. In this environment, steel takes a potential of about -600mv and becomes the anode; copper's potential is about -240mv and thus is the cathode. If uncoupled, the corrosion rate of steel is 800 $\mu\text{m}/\text{y}$. However, if equal areas of these metals are connected in flowing seawater, the corrosion of steel will increase to 2400 $\mu\text{m}/\text{y}$, while that of copper will remain at only 50 $\mu\text{m}/\text{y}$. Thus for steel:

$$C_g = 2400 - 800 \mu\text{m}/\text{y}, \text{ or}$$

$$C_g = 1600 \mu\text{m}/\text{y}.$$

Thus in this test the galvanic component was twice the uncoupled corrosion.¹

POTENTIAL

The potential of a metal is a measure of the energy stored in it by the refining of its ore and is indicative of its tendency to corrode. Reactive metals -- like magnesium and aluminum -- require large amounts of energy to refine, have highly negative potentials, and tend toward high rates of corrosion. Noble metals -- like copper and gold -- are relatively easy to smelt, have more positive potentials, and tend to be free of corrosion. In simple terms, corrosion is due to the stored energy in a metal. Iron ore, for example, is an oxide with the same chemical composition as rust, Fe_2O_3 . When a piece of iron corrodes, forming rust, it is releasing the energy it acquired in the refining process.¹ This is in accordance to the First Law of Thermodynamics, which states that energy can be converted in form but cannot be created or destroyed.

Several factors influence the potential of metals. A metal will have different potentials in different solutions depending on such properties as conductivity, temperature, salt content, acidity, dissolved gases, metal ions, and organic matter. Potentials can sometimes be calculated as for EMF values, but in practice they are determined experimentally.

A metal's potential is measured in much the same way as pH measurements are taken -- the metal of interest is placed in the solution to be studied and is electrically connected to a standard reference electrode. A reference electrode is one which has a fixed potential, such as calomel or Ag/AgCl. The voltage relative to the reference electrode is then measured using a potentiometer or a high impedance voltmeter. The voltages obtained by these measurements are called open circuit potentials, because they are measured without the metal being galvanically connected to a second metal.

By arranging metals according to their potentials, from the most active (most negative) down to the most passive (most positive), a galvanic series is developed for the solution being tested. The potential differences shown by the galvanic series can then be used to judge whether galvanic attack will occur. In general the larger the potential difference between metals, the greater will be the amount of galvanic attack.

One rule of thumb used by corrosion engineers for galvanic corrosion is that usually a potential difference of about 300mv is required to initiate and sustain galvanic corrosion in a marine or outside environment.² This is what may be thought of as the activation voltage for this attack. At lower levels the amount of galvanic acceleration is usually small and is often ignored.

POLARIZATION

As current flows in a galvanic cell, the metal's potentials will change over time. This is due to the accumulation of corrosion products or surface films at the anode and cathode. As a result, the potential of the anode is shifted toward that of the cathode, while the potential of the cathode becomes more anodic. This shift in potential is called polarization.

If polarization of the anode is greater than that of the cathode, the cell is under anodic control. Conversely, cathodic control occurs if the cathode's polarization is greater than the anode's. Equal polarization results in mixed control.

The effect of polarization in a galvanic cell is to reduce the potential difference between the anode and cathode. In turn, current flow and corrosion are reduced. It is for this reason that the extent of corrosion experienced in a real environment is generally less than that predicted by the difference in open circuit potentials listed in a galvanic series.

AREA

The cathode to anode area ratio also has a strong effect on the intensity of galvanic corrosion. This is illustrated by the following equation:

$$C_t = C_n \times \left(1 + \frac{A_c}{A_a}\right).$$

Where C_t is the total corrosion resulting from galvanic coupling ($C_n + C_g$), C_n is the corrosion of the anode which would normally occur if it was not coupled to the cathode, and A_c and A_a are the areas of the cathode and anode. Thus, as the ratio of the cathode and anode areas increases, corrosion also increases.

An example of this effect is the use of steel rivets to join copper plates. With this arrangement, the current per unit area flowing to the copper will be low, causing very little cathodic polarization. Thus the potential difference of the couple will stay close to its open circuit values. At the same time the current flow to the small area of steel will be high and its corrosion will be severe.

On the other hand, if copper rivets are used to join steel plates, the current per unit area on the copper cathodes will be high causing a large amount of polarization and greatly reducing the potential difference and overall current flow. Also, the current will be spread over a large area of steel greatly reducing its galvanic corrosion.

GALVANIC CORROSION TESTS

In order to establish the galvanic corrosion behavior of electroless nickel coatings in relationship to other common metals, a number of galvanic series were developed. Several different environments -- sea water, tap water, HCl, HNO₃, NaOH, and oil field brines -- were selected to try to provide a cross section of applications to which electroless nickel might be exposed. A secondary objective of these tests was to try to define how changes in environment may accelerate or deminish galvanic corrosion.

PROCEDURE

The galvanic series were developed by measuring the equilibrium open circuit potential of different metals in a given environment and then arranging them in order of their potential starting with the most active. In general this was done in accordance with ASTM Standard G-71.⁴ The conditions and equipment used for conducting these tests are described in the following paragraphs.

Metals. In total, 58 different metals and alloys were tested, including various aluminum and copper alloys, steels and stainless steels, high alloys, flame sprayed coatings, and both electroless and electrolytic deposits. The metals tested and their typical composition are listed in Table 1. Many of the specimens were standard, threaded, cylindrical electrodes, such as those commercially available for corrosion testing. Their dimensions ranged from 6 to 12mm diameter and 25 to 65mm long. These were mounted on commercial gasketed electrode holders.

This type of steel electrode was also used as the substrate for both electro-plated and electroless coatings. Except for the nickel platings, the coatings were applied in commercial plating shops.

The electroless nickel coatings were tested in three different conditions -- as deposited, baked for one hour at 190°C, and hardened for one hour at 400°C -- in order to determine whether heat treatment had any effect on galvanic performance.

Where desired alloys were not available as commercial electrochemical test specimens, electrodes were prepared by cutting a sample of the metal from sheet or rod, soldering a lead wire to it and then epoxying it into a glass tube holder. With both types of holders, all exposed surfaces of other metals, crevices and electrical connections were carefully masked to ensure that the potential measured was only that of the test specimen.

Prior to testing each of the metals was degreased, pickled, washed and carefully dried to ensure an active surface. The pickling solutions were generally those recommended by ASTM Standard G-1.⁵ A 50 percent hydrochloric acid solution was used for most metals; for aluminum alloys 50 percent nitric acid was used; for magnesium 50g/l of chromic acid was used; and the zinc was cleaned in a 10 percent ammonium chloride solution. After each exposure the specimens were examined for corrosion and cleaned in the same solutions used previously. No attempt was made to quantify the amount of corrosion experienced, although it was visually obvious that the more

active metals -- magnesium, zinc and aluminum -- were attacked by some of the acidic solutions. Normally the specimens were reused for subsequent tests until they began to experience significant corrosion. At this point they were replaced.

Environments. Eight different solutions were selected for tests. These were synthetic seawater, aerated and deaerated tap water, 0.1N hydrochloric acid, 0.1N nitric acid, 0.1N sodium hydroxide, and CO₂ and H₂S saturated oil field brines. Each test was conducted at ambient temperature (20-22°C) and under essentially stagnant conditions.

The synthetic seawater used for this test was prepared in accordance with ASTM Standard D-1141,⁶ and was made using reagent grade salts and deionized water with a resistivity of 5MΩ-cm. The solution was made up and maintained in a 110 liter glass aquarium and was constantly aerated by bubbling air through it. The seawater was found to have a resistivity of approximately 25Ω-cm. The flow of the solution past the electrodes resulted only from aeration and was estimated to be less than 0.5fps.

The remaining seven tests were all conducted in a 40 liter rectangular polyethylene tank which was fitted with fritted glass spargers to allow air or other gases to be bubbled through the test solution. The water used for both the aerated and deaerated tap water tests was Nashville city water containing 170ppm Total Dissolved Solids and 140mg/l hardness (as CaCO₃). It had a pH of 7.6 and a resistivity of 4,000Ω-cm. For the aerated test, air was constantly bubbled through the water in order to keep it saturated with oxygen. For the deaerated test, nitrogen was used to strip oxygen from the solution.

Three tests were also conducted in dilute chemical solutions - 0.1 N NaOH, 0.1 N HCl and 0.1 N HNO₃. Each of the solutions were made using deionized water and the appropriate amount of the reagent grade chemical. The pH of the three solutions was 13.2, 1.7, and 1.5 respectively. In order to keep the solutions uniformly mixed, they were mildly agitated with air.

The last two tests were conducted in synthetic oil field brines, one saturated with carbon dioxide gas and the other with hydrogen sulfide. The brines were mixtures of reagent grade NaCl, CaCl₂, MgCl₂, NaHCO₃, BaCl₂, and Na₂SO₄ in deionized water. The composition of this solution is listed in Table 2. It was based on typical analyses of oil field brines from the United States and Middle East and is the same as that used in previous immersion corrosion tests.⁷

Before testing the salt solutions were deaerated with nitrogen and then either saturated with reagent carbon dioxide or hydrogen sulfide gas at ambient temperature and pressure. The dissolved CO_2 and H_2S concentrations were estimated using Henry's Law to be approximately 1000 mg/l and 1600 mg/l respectively.

Measurement. The potential of the test electrodes was measured relative to a fused silver/silver chloride reference electrode, whose potential was measured to be 60mv to saturated calomel. This type of electrode was used to avoid the possibility of contamination of reference filling solutions by the various environments and because previous experience had shown it to be stable in both acid gas and salt solutions. The potential difference between the test specimens and the reference was measured using an electronic millivolt meter whose input impedance was 10^{13} ohms and whose accuracy was ± 0.02 percent. Such a high impedance meter was necessary in order to avoid polarizing the electrodes and changing their potential. The potential of the electrodes was measured two or three times daily until a steady state value was reached. The period required for this ranged from three days for hydrochloric acid to eleven days for deaerated tap water. After equilibrium was obtained, the last two or three readings were recorded as the electrode's open circuit potential.

RESULTS

The results of the open circuit potential tests conducted are summarized in Tables 3 through 8. Each table represents a practical galvanic series for that environment. The metals are arranged in order of their potential beginning with the most active (negative) metal and proceeding progressively to the most passive (positive) metal. For example, in seawater the listing begins with magnesium and zinc and proceeds through aluminum, steel, nickel alloys, copper alloys, stainless steels, high alloys and titanium, until finally platinum and graphite are reached.

In general, the results of these tests were much as expected. The first galvanic series generated was that in synthetic seawater. This was done so that it could be compared to the classic series for natural seawater published by INCO⁶, and the suitability of the test method confirmed. This comparison showed a reasonable correlation between the two sets of results as shown in Figure 1. There were differences -- INCO's data showed aluminum and copper alloys to be more active and showed steel, nickel and stainless steel to be more passive -- but considering the higher oxygen content and velocity of INCO's seawater the agreement of the two series was judged to be good.

One surprising result was the increased passivity of electroless nickel. Previous test results had shown the potential of the coating to be between that of steel and the 400 stainless steels,⁹ while these results showed it to be more nearly equal to that of Type 304 stainless steel, a change of about 200mv. This shift, however, is thought to be due to differences in the phosphorus content of the two coatings.

The galvanic series for deaerated tap water was similar to that for seawater. While the ranking of some metals had changed and some minor shifts in potential had occurred, the ranking of most metals was the same. For example, the potential difference between electroless nickel and steel was 450mv in both seawater and deaerated tap water.

In aerated tap water the potential of most metals was shifted in a more positive direction by 100 or 200mv. This was most pronounced with metals like the aluminum alloys, which depend on surface oxide films for their corrosion resistance. The change in the potential of the aluminum alloys was most dramatic, varying from almost 1000mv in deaerated water to approximately 400mv in aerated water. It was the high resistivity and moderate hardness of the aerated tap water which caused the shifts in the potential from those measured in seawater. The removal of passivating oxygen from the deaerated solution offset this effect and made the metals more active.

The galvanic series in hydrochloric acid was surprisingly similar to that for seawater. Even in this reducing environment, most metals managed to maintain their passivity. Hard chrome and Type 316 stainless steel displayed typical active/passive behavior in this environment, as their potentials jumped back and forth between two states, 150 to 200mv apart. Electroless nickel became more active and established a potential only about 200mv less than that of steel.

Conversely, nitric acid caused a large shift in potential toward more positive values for all metals. Nitrates are highly oxidizing and tend to produce passive oxide films on metals. This was especially pronounced with stainless and aluminum alloys, but also occurred with nickel and copper alloys. In this test electroless nickel was found to be slightly more active than aluminum, but again was about 450mv more passive than steel.

The results of the galvanic series for sodium hydroxide were found to be far more compressed than those in previous environments. Only about 300mv separate the potential of platinum and cadmium. The only truly active metals in this environment were aluminum and tin alloys, lead and antimony. The potential of zinc, cadmium and magnesium all became

more passive due to the formation of insoluble metal hydroxide films. Generally, the passive metals tended to become more active, while the active metals became more passive, thus greatly reducing their potential differences.

The galvanic series in CO₂ saturated brine was also found to be similar to that for seawater, except that the potentials of copper and nickel alloys became more active. The potential of normally passive metals like the high alloys and platinum did not change significantly, nor did that of active metals like magnesium, zinc and aluminum. Electroless nickel also retained its passivity and was again 450 to 500mv more negative than steel or aluminum.

The addition of hydrogen sulfide to the oil field brine resulted in the formation of metal sulfide films on most metals and caused a great change in their potential. The presence of sulfide often times has a passivating effect on corrosion both because of the films it forms and because it produces a reducing environment. This is especially true for electroless nickel which has been shown to be completely free of corrosion in such solutions.⁷ Another result of sulfide film formation was to reduce the potential differences between metals. In these tests only 300mv separated aluminum and platinum; in seawater these metals were separated by almost 1 volt. Likewise, electroless nickel was found to be only 250mv more passive than steel.

Under some conditions the presence of sulfides can effectively eliminate potential differences between all but the most active metals. In Table 11, the results of tests conducted previously in the neutral overhead stream of a crude distillation unit are shown. This solution contained 2000 to 3000ppm of chloride and 2000 to 4000ppm of sulfide. In these tests zinc, 90-10 CuNi and aluminum were still relatively active. Steel, electroless nickel and all other metals, however, developed approximately the same level of potential.

DISCUSSION

These tests confirmed that the potential of a metal is largely a function of its environment. Such factors as salt content, conductivity, and dissolved gases all effect the metals' potential and can increase or decrease the effects of galvanic coupling.

These tests also showed electroless nickel to be far more passive than previously thought. As shown in Table 12, in most environments the potential of electroless nickel was about 400 to 600mv more positive than that of steel. The potential difference between electroless nickel and aluminum

was more erratic but usually was as high or higher than that of electroless nickel and steel. These differences are about twice what had been previously reported with lower phosphorus deposits.⁹ This is presumably due to the higher corrosion resistance and higher passivity of the 10½ percent phosphorus coating exposed in these tests.

As discussed previously, a 300mv potential difference is usually required to initiate and sustain galvanic corrosion. Thus, in seawater, tap water, nitric acid, and oil field brines galvanic corrosion of steel in contact with electroless nickel is possible. In hydrochloric acid and caustic, galvanic corrosion probably will not occur. With aluminum the situation is similar and only nitric acid and H₂S brine provide potential differences less than 300mv. Of course with stainless steel the condition is reversed and in many environments electroless nickel is the most active half of the couple. With stainless steel, electroless nickel is a sacrificial coating. Thus, if potential difference were the only factor, galvanic corrosion between electroless nickel and most other metals probably would be a serious problem.

EFFECT OF PORES

Metallic coatings are subject to a special form of galvanic corrosion, because the resistance of the galvanic couple is a function of the quality of the coating as well as the environment. Evans¹⁰ has shown that for the galvanic cell produced by a pore in a coating, the resistance of the cell (R) is a function of the coating thickness (t), the resistivity of the fluid in the pore (r), and the cross-sectional area of the pore (A):

$$R = \frac{t \cdot r}{A}$$

Substituting this into the previous equation for galvanic corrosion, and cancelling the two area terms, produces the following:

$$C_g = \frac{\Delta E}{F \cdot A \cdot R},$$

$$C_g = \frac{\Delta E \cdot A}{F \cdot A \cdot t \cdot r}, \text{ and}$$

$$C_g = \frac{\Delta E}{F \cdot t \cdot r}$$

Thus, galvanic corrosion becomes a function only of the potential difference between the metals, the resistivity of

the solution in the pore, and coating thickness. As either resistivity or thickness is increased, current flow and corrosion are reduced. Even if the potential difference is very high, if the coating thickness or the resistivity in the pore becomes large enough, corrosion will stop.

In environments containing oxygen, like seawater or tap water, corrosion of steel produces iron oxide, which is very insoluble. As the oxide forms it fills the pore. This excludes water and oxygen and the pore's resistance begins to increase rapidly, reducing corrosion. Ultimately, when the pore is completely filled, its resistance becomes so high that corrosion stops. The corrosion products of steel in solutions containing CO_2 and H_2S are also insoluble and the same plugging action will occur. Accordingly, galvanic corrosion in pores should not normally be a severe problem in waters, brines, or caustic solutions.

CONCLUSION

While galvanic corrosion is possible between electroless nickel coatings and other engineering materials, in most common environments it has not been a problem. Electroless nickel coated valves have been used in steel pipelines for years with no evidence of accelerated attack of either material. Similarly, with most metals and in most environments, under-deposit corrosion through pores or damaged areas rapidly stops due to the formation of insoluble plugs of corrosion products.

TABLE 1
TEST SPECIMENS FOR GALVANIC
CORROSION TESTS

METAL	SPECIFICATIONS/COMPOSITION
Magnesium	ASTM B107 AZ31B - 3%Al, 1% Zn, 0.2% MN, Bal Mg
Antimony	99.8%+ Sb
Zinc	99.9%+ Zn
Zinc plating	Zinc plating on steel + chromate conversion coating - 99%+ Zn
Hard coat anodizing	Hard coat anodizing on aluminum (Al ₂ O ₃)
2024 Aluminum	ASTM B209 Alloy 2024 - 4.5% Cu, 0.6% Mn, 1.5% Mg, Bal Al
3003 Aluminum	ASTM B209 Alloy 3003 - 1.2% Mn, Bal Al
5052 Aluminum	ASTM B209 Alloy 5052 - 2.5% Mg, 0.25% Cr, Bal Al
6061 Aluminum	ASTM B209 Alloy 6061 - 0.6% Si, 0.25% Cu, 1.0% Mg, 0.25% Cr, Bal Al
7075 Aluminum	ASTM B209 Alloy 7075 - 5.6% Zn, 1.6% Cu, 2.5% Mg, 0.3% Cr, Bal Al
Cadmium plating	Cadmium plating on steel + chromate conversion coating - 99%+ Cd
Steel	AISI 1018 - 0.18% C, 0.75% Mn, Bal Fe
5Cr Steel	ASTM A335 Grade P5 - 5% Cr, 0.5% Mo, 0.45% Mn, 0.5% Si, 0.15% C, Bal Fe
Ni Resist	ASTM A436 Type 2 - 15.5% Ni, 2% Si, 1.25% Mn, 2% Cr, 3% C max, Bal Fe
Electroless Nickel	ELNIC Electroless Nickel - 10½% P, 89½% Ni plated on steel
EN - 375°	ELNIC Electroless Nickel on steel heat treated at 190°C for one hour

TABLE 1
TEST SPECIMENS FOR GALVANIC
CORROSION TESTS

METAL	SPECIFICATIONS/COMPOSITION
Aluminum brass	ASTM B111, CA687 - 77.5% Cu, 2% Al, 20.5% Zn
Red brass	ASTM B36, CA230 - 85% Cu, 15% Zn
Cartridge brass	ASTM B19, CA260 - 70% Cu, 30% Zn
Muntz metal	ASTM B111, CA280 - 61% Cu, 39% Zn
Naval brass	ASTM B21, CA464 - 60% Cu, 0.8% Sn, 39% Zn
Copper	ASTM B124, CA110 - 99.9%+ Cu
Tin	ASTM B339 - 99.8%+ Sn
Tin-silver solder	Solder wire - 90% Sn+ 10% Ag
Aluminum bronze	ASTM B124, CA614 - 7% Al, 2.5% Fe, Bal Cu
410SS	ASTM A240 Type 410 - 12% Cr, 0.15% C max, Bal Fe
Silicon bronze	ASTM B96 CA655 - 3% Si, Bal Cu
Admiralty brass	ASTM B171 CA443 - 71% Cu, 1% Sn, 28% Zn, 0.06% As
90-10 CuNi	ASTM B122 CA706 - 10% Ni, 1.25% Fe, 0.3% Mn, 88.5% Cu
EN-750°F	ELNIC Electroless Nickel on steel heat treated at 400°C for 1 hour
430SS	ASTM A420 Type 430 - 17% Cr, 0.12% C max, Bal Fe
Lead	ASTM B29 - 99.9%+ Pb
Colmonoy	Colmonoy #5 flame sprayed on steel - 11.5% Cr, 4.25% Fe, 3.75% Si, 2.5% B, 0.65% C, Bal Ni
Stellite	Stellite #6 flame sprayed on steel - 28% Cr, 1% C, 4% W, Bal Co

TABLE 1
TEST SPECIMENS FOR GALVANIC
CORROSION TESTS

METAL	SPECIFICATION/COMPOSITION
70-30 CuNi	ASTM B171 CA715 - 30% Ni, 0.5% Fe, 0.5% Mn, 69% Cu
Hard Chrome	Hard chrome over ELNIC Electroless Nickel on steel - 99%+ Cr
Duplex stainless steel	Sandvik 3Re60 - 18.5% Cr, 4.7% Ni, 2.7% Mo, 1.5% Mn, 1.65% Si, 0.03% C max, Bal Fe
Inconel 600	ASTM B168 - 15.8% Cr, 7.2% Fe, 0.2% Mn, 0.2% Si, 0.04% C, 0.10% Cu, Bal Ni
Duplex Nickel	Electro-deposited duplex nickel on steel - 99.9% Ni
Sulfamate Nickel	Electro-deposited sulfamate nickel on steel - 99.9% Ni
Watts Nickel	Electro-deposited Watts nickel on steel - 99.9% Ni
Nickel	ASTM B162 - 99.5% Ni, 0.25% Mn, 0.15% Fe, 0.06% C
Tin bronze	CDA 909 - 12½% Sn, 87½% Cu
Monel	ASTM B127 - 31½% Cu, 1.35% Fe, 0.9% Mn, 0.15% Si, 0.12% C, Bal Ni
Silver	ASTM B413 - 99.9%+ Ag
Silver plating	Silver plating on steel - 99%+ Ag
Rhodium plating	Rhodium plating over silver plating on brass - 99%+ Rh
304SS	ASTM A240 Type 304 - 18.5% Cr, 9.5% Ni, 0.08% C max, Bal Fe

TABLE 1
TEST SPECIMENS FOR GALVANIC
CORROSION TESTS

METAL	SPECIFICATION/COMPOSITION
316SS	ASTM A240 Type 316 - 17% Cr, 10% Ni, 2½% Mo, 0.08% C max, Bal Fe
Alloy 10	Carpenter 20 Cb3 - 29% Ni, 20% Cr, 2.5% Mo, 3.5% Cu, Bal Fe
Incoloy 800	ASTM B409 - 32% Ni, 20½% Cr, 46% Fe, 0.04% C, 0.4% Ti, 0.4% Al
310 SS	ASTM A240 Type 310 - 25% Cr, 20% Ni, 0.25% C max, Bal Fe
Titanium	ASTM B265 Type Ti50A - 99.9% Ti
Hastelloy B	ASTM B333 - 28% Mo, 5% Fe, 0.3% V, Bal Ni
Hastelloy C276	ASTM B575 Alloy N10276 - 15% Cr, 0.5% Fe, 16% Mo, 0.02% C, Bal Ni
Tantalum	ASTM B365 - 99.8%+ Ta
Graphite	99.9% Graphite
Platinum	99.9%+ Pt

TABLE 2
 CONDITIONS FOR GALVANIC CORROSION
 TESTS IN OIL FIELD BRINES

<u>COMPONENT</u>	<u>ENVIRONMENT</u>
Total Dissolved Solids (%)	3 1/2
Salt Composition (mg/L)	32,000
NaCl	1,900
CaCl ₂	750
MgCl ₂	120
NaHCO ₃	65
BaCl ₂	30
Na ₂ SO ₄	
Specific Gravity	1.02
Temperature	20°C
Pressure	1 atm
Dissolved CO ₂ (mg/l)	1,000
Dissolved H ₂ S (mg/l)	1,600

TABLE 3
GALVANIC SERIES IN SYNTHETIC SEAWATER

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1450 - 1470	Silicon bronze	- 178 - 182
Zinc and zinc plating	- 967 - 984	Aluminum bronze	- 174 - 183
Hard coat anodizing	- 690 - 696	Naval brass	- 172 - 178
Cadmium plating	- 683 - 684	90-10 copper nickel	- 171 - 175
Mild Steel	- 656 - 658	Duplex nickel plating	- 169 - 178
Aluminum alloys	- 640 - 674	Copper	- 169 - 171
5Cr steel	- 539 - 566	Muntz metal	- 168 - 186
Ni-Resist alloy cast iron	- 492 - 493	Red Brass	- 167 - 168
Tin	- 402 - 405	Admiralty brass	- 166 - 167
Watts nickel plating	- 394 - 418	Rhodium plating	- 159 - 166
430 stainless steel	- 391 - 396	310 stainless steel	- 158 - 163
410 stainless steel	- 380 - 387	Colmonoy flame	
Tin-silver solder	- 374 - 396	sprayed coating	- 154 - 161
Antimony	- 334 - 337	Tin Bronze	- 153 - 154
Lead	- 333 - 342	304 stainless steel	- 116 - 118
Hardened electroless		Aluminum brass	- 93 - 99
nickel plating	- 283 - 288	Duplex stainless steel	- 43 - 50
Silver plating	- 250 - 279	70-30 copper nickel	- 34 - 38
Baked electroless nickel		316 stainless steel	- 16 - 30
plating	- 222 - 246	Monel 400	+ 12 - 19
Hastelloy B	- 222 - 235	Silver	+ 38 - 41
Sulfamate nickel plating	- 212 - 224	Inconel 600	+ 117 - 120
Hastelloy C-276	- 201 - 216	Incoloy 800	+ 120 - 168
Electroless nickel plating	- 194 - 215	Titanium	+ 150 - 152
Nickel	- 190 - 191	Tantalum	+ 152 - 157
Hard Chrome plating	- 185 - 188	Alloy 20Cb3	+ 197 - 207
Cartridge brass	- 181 - 184	Platinum	+ 212 - 220
Stellite flame sprayed		Graphite	+ 222 - 223
coating	- 181 - 184		

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 4

GALVANIC SERIES IN AERATED TAP WATER

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1240 - 1249	Hard Chrome plating	+ 17 - 27
Zinc and zinc plating	- 882 - 912	Duplex stainless steel	+ 25 - 37
Mild steel	- 625 - 634	410 stainless steel	+ 29 - 53
5CR Steel	- 470 - 490	Cartridge brass	+ 35 - 47
Cadmium plating	- 460 - 488	Aluminum brass	+ 38 - 52
Ni-Resist alloy cast iron	- 453 - 474	310 stainless steel	+ 41 - 45
Antimony	- 333 - 339	Muntz metal	+ 43 - 54
Aluminum alloys	- 300 - 447	Silicon bronze	+ 46 - 57
Lead	- 278 - 283	Silver plating	+ 49 - 80
Tin	- 255 - 271	Red brass	+ 54 - 70
Hastelloy B	- 232 - 243	Admiralty brass	+ 55 - 58
Tin-silver solder	- 214 - 227	Watts nickel plating	+ 61 - 80
Duplex nickel plating	- 152 - 200	90-10 copper nickel	+ 70 - 77
Hard coat anodizing	- 120 - 130	Copper	+ 71 - 89
Nickel	- 115 - 134	70-30 Copper nickel	+ 86 - 99
Baked electroless nickel plating	- 107 - 128	Tantalum	+ 96 - 103
430 stainless steel	- 89 - 106	Tin bronze	+ 100 - 117
Rhodium plating	- 77 - 93	316 stainless steel	+ 105 - 114
Stellite flame sprayed coating	- 42 - 62	Incoloy 800	+ 105 - 115
Hardened electroless nickel plating	- 39 - 58	Aluminum bronze	+ 106 - 119
Hastelloy C-276	- 27 - 54	Alloy 20Cb3	+ 114 - 122
Naval brass	- 12 - 24	304 stainless steel	+ 130 - 144
Colmonoy flame sprayed coating	- 10 - 31	Monel 400	+ 140 - 150
Sulfamate nickel plating	+ 8 - 22	Graphite	+ 142 - 160
Electroless nickel plating	+ 15 - 30	Inconel 600	+ 162 - 189
		Platinum	+ 194 - 225
		Silver	+ 198 - 213
		Titanium	+ 201 - 209

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 5
GALVANIC SERIES IN DEAERATED TAP WATER

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1130 - 1200	430 stainless steel	- 161 - 178
Aluminum alloys	- 927 - 1000	410 stainless steel	- 120 - 127
Zinc and zinc plating	- 845 - 927	Watts nickel plating	- 81 - 132
Mild steel	- 692 - 716	Hard chrome plating	- 79 - 111
Cadmium plating	- 623 - 628	Cartridge brass	- 32 - 41
Ni-Resist alloy cast iron	- 516 - 533	Duplex nickel plating	- 22 - 47
Hard coat anodizing	- 486 - 499	Muntz metal	- 6 - 12
Antimony	- 478 - 483	Naval brass	- 5 - 17
5Cr steel	- 448 - 495	Aluminum bronze	+ 1 - 14
Lead	- 433 - 471	Tantalum	+ 2 - 11
Tin	- 403 - 415	Tin bronze	+ 4 - 25
Nickel	- 308 - 312	Graphite	+ 11 - 22
Hastelloy B	- 298 - 300	Aluminum brass	+ 13 - 21
Baked electroless nickel plating	- 289 - 311	Alloy 20CB3	+ 13 - 34
Tin-silver solder	- 284 - 288	Monel 400	+ 14 - 28
Hastelloy C-276	- 274 - 280	Incoloy 800	+ 15 - 26
Hardened electroless nickel plating	- 254 - 281	316 stainless steel	+ 21 - 30
Duplex stainless steel	- 242 - 269	Inconel 600	+ 22 - 31
Sulfamate nickel plating	- 240 - 280	Silicon bronze	+ 23 - 36
Electroless nickel plating	- 237 - 269	Titanium	+ 29 - 44
Rhodium plating	- 225 - 260	Admiralty brass	+ 37 - 47
Silver plating	- 223 - 295	Red Brass	+ 51 - 92
Stellite flame sprayed coating	- 215 - 228	70-30 Copper nickel	+ 55 - 66
310 stainless steel	- 197 - 222	Copper	+ 56 - 83
Colmonoy flame sprayed coating	- 165 - 192	90-10 copper nickel	+ 72 - 93
		304 stainless steel	+ 85 - 115
		Platinum	+ 108 - 134
		Silver	+ 198 - 211

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 6
GALVANIC SERIES IN 0.1N HCl

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1435 - 1445	Colmonoy flame sprayed	
Zinc and zinc plating	- 925 - 943	coating	- 83 - 114
Cadmium plating	- 712 - 724	Rhodium plating	- 76 - 82
Hard coat anodizing	- 605 - 631	Red brass	- 71 - 81
Aluminum alloys	- 585 - 670	Muntz metal	- 67 - 78
430 stainless steel	- 514 - 517	Cartridge brass	- 66 - 77
Mild steel	- 497 - 522	Hastelloy B	- 65 - 84
Tin	- 452 - 460	Admiralty brass	- 65 - 78
Tin-silver solder	- 447 - 456	Aluminum brass	- 65 - 76
Silver plating	- 438 - 457	Aluminum bronze	- 63 - 76
Hardened electroless		Copper	- 62 - 78
nickel plating	- 435 - 436	Monel 400	- 56 - 77
Lead	- 434 - 440	Nickel	- 52 - 110
410 stainless steel	- 405 - 460	Silicon bronze	- 49 - 65
5Cr steel	- 401 - 443	Tin bronze	- 49 - 59
Ni-Resist alloy cast iron	- 369 - 379	90-10 copper nickel	- 34 - 47
Baked electroless nickel		70-30 copper nickel	- 30 - 43
plating	- 325 - 330	Antimony	- 3 - 40
Electroless nickel plating	- 310 - 314	316 stainless steel	
Duplex nickel plating	- 220 - 225	(passive state)	+ 25 - 30
Duplex stainless steel	- 200 - 297	Silver	+ 37 - 68
316 stainless steel		Hard chrome plating	
(active state)	- 150 - 155	(passive state)	+ 45 - 50
Naval brass	- 138 - 167	Graphite	+ 105 - 152
Stellite flame sprayed		Incoloy 800	+ 152 - 198
coating	- 117 - 166	Hastelloy C-276	+ 177 - 204
Hard chrome plating		304 stainless steel	+ 178 - 231
(active state)	- 117 - 125	310 stainless steel	+ 180 - 208
Watts nickel plating	- 110 - 213	Tantalum	+ 205 - 259
Sulfamate nickel plating	- 95 - 140	Alloy 20Cb3	+ 219 - 272
Inconel 600	- 88 - 124	Platinum	+ 271 - 327
		Titanium	+ 288 - 355

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 7
GALVANIC SERIES IN 0.1N HNO₃

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1080 - 1090	Naval brass	+ 72 - 79
Cadmium plating	- 590 - 592	Silicon bronze	+ 74 - 82
Zinc and zinc plating	- 505 - 521	Muntz metal	+ 76 - 79
Mild steel	- 365 - 377	Red brass	+ 81 - 85
Lead	- 357 - 365	Cartridge brass	+ 84 - 87
5Cr steel	- 332 - 341	Aluminum brass	+ 88 - 93
Tin	- 239 - 248	90-10 copper nickel	+ 94 - 96
Ni-Resist alloy cast iron	- 236 - 243	Colmonoy flame sprayed coating	+ 95 - 98
Tin-silver solder	- 215 - 223	Nickel	+ 96 - 98
Duplex stainless steel	- 168 - 175	Monel 400	+ 100 - 106
Silver plating	- 137 - 171	70-30 copper nickel	+ 102 - 109
Hastelloy C-276	- 135 - 196	Stellite flame sprayed coating	+ 111 - 134
Hardened electroless nickel plating	- 98 - 113	310 stainless steel	+ 217 - 272
Aluminum alloys	- 75 - 133	Hard chrome plating	+ 335 - 340
Duplex nickel plating	- 25 - 55	410 stainless steel	+ 341 - 347
Rhodium plating	- 24 - 31	304 stainless steel	+ 392 - 416
Watts nickel plating	- 23 - 42	Silver	+ 395 - 399
Sulfamate nickel plating	+ 22 - 60	Graphite	+ 438 - 442
Antimony	+ 32 - 40	Inconel 600	+ 497 - 508
Copper	+ 44 - 51	430 stainless steel	+ 513 - 524
Baked electroless nickel plating	+ 46 - 73	Incoloy 800	+ 565 - 575
Hastelloy B	+ 51 - 56	Tantalum	+ 566 - 576
Electroless nickel plating	+ 57 - 73	Titanium	+ 569 - 580
Tin bronze	+ 67 - 74	Alloy 20Cb3	+ 574 - 589
Admiralty brass	+ 70 - 78	316 stainless steel	+ 576 - 586
Aluminum bronze	+ 72 - 76	Platinum	+ 671 - 675

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 8
GALVANIC SERIES IN 0.1N NaOH

METAL	POTENTIAL	METAL	POTENTIAL
Hard coat anodizing	-1410 - 1420	Electroless nickel	
Aluminum alloys	-1225 - 1400	plating	- 151 - 158
Tin	- 967 - 984	Ni-Resist alloy	
Tin-silver solder	- 965 - 978	cast iron	- 150 - 178
Lead	- 672 - 686	Silver plating	- 146 - 169
Antimony	- 630 - 661	410 stainless steel	- 144 - 149
Duplex stainless steel (active state)	- 418 - 432	Tin bronze	- 134 - 151
Zinc and zinc plating	- 362 - 372	Duplex nickel plating	- 133 - 158
Cadmium plating	- 245 - 280	Mild steel	- 131 - 147
Baked electroless nickel plating	- 239 - 253	Rhodium plating	- 126 - 130
Magnesium	- 225 - 252	Admiralty brass	- 124 - 142
Nickel	- 223 - 230	90-10 copper nickel	- 122 - 132
Duplex stainless steel (passive state)	- 214 - 296	Naval brass	- 118 - 147
Watts nickel plating	- 207 - 221	Graphite	- 114 - 118
Hardened electroless nickel plating	- 196 - 279	Titanium	- 109 - 130
5Cr steel	- 192 - 212	Tantalum	- 101 - 108
310 stainless steel	- 177 - 194	70-30 copper nickel	- 101 - 107
Colmonoy flame sprayed coating	- 177 - 193	Silicon bronze	- 96 - 153
Muntz metal	- 177 - 181	430 stainless steel	- 92 - 123
Hastelloy C-276	- 176 - 185	304 stainless steel	- 85 - 94
Cartridge brass	- 173 - 179	Incoloy 800	- 83 - 92
Stellite flame sprayed coating	- 171 - 185	Monel 400	- 82 - 93
Aluminum bronze	- 169 - 180	316 stainless steel	- 78 - 89
Sulfamate nickel plating	- 168 - 192	Hard chrome plating	- 75 - 90
Hastelloy B	- 167 - 173	Red brass	- 67 - 81
Aluminum brass	- 166 - 177	Alloy 20Cb3	- 67 - 81
		Inconel 600	- 60 - 75
		Copper	- 50 - 67
		Silver	- 31 - 43
		Platinum	+ 26 - 31

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 9
GALVANIC SERIES IN CO₂ SATURATED 3½% BRINE

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1450 - 1510	Cartridge brass	- 266 - 274
Zinc and zinc plating	- 990 - 1010	Muntz metal	- 261 - 266
Cadmium plating	- 735 - 741	Nickel	- 261 - 285
Aluminum alloys	- 701 - 808	310 stainless steel	- 258 - 285
Hard coat anodizing	- 684 - 692	Aluminum bronze	- 255 - 265
Mild Steel	- 655 - 661	Admiralty brass	- 255 - 257
5Cr steel	- 622 - 626	Aluminum brass	- 252 - 253
Hardened electroless nickel plating	- 603 - 606	Red brass	- 249 - 251
Tin	- 511 - 522	Silicon bronze	- 249 - 254
Sulfamate nickel plating	- 484 - 524	Colmonoy flame sprayed coating	- 248 - 253
Lead	- 476 - 484	Monel 400	- 243 - 247
Ni-Resist alloy cast iron	- 460 - 472	Antimony	- 237 - 257
430 stainless steel	- 456 - 475	Copper	- 233 - 240
Silver plating	- 448 - 465	90-10 copper nickel	- 232 - 233
Watts nickel plating	- 444 - 460	70-30 copper nickel	- 228 - 229
Tin-silver solder	- 440 - 480	Electroless nickel plating	- 215 - 233
Duplex stainless steel	- 428 - 432	Hastelloy C-276	- 206 - 219
410 stainless steel	- 427 - 433	Tin bronze	- 197 - 228
Baked electroless nickel plating	- 381 - 398	Silver	- 112 - 171
Duplex nickel plating	- 374 - 382	Inconel 600	+ 37 - 47
Rhodium plating	- 349 - 351	Tantalum	+ 99 - 175
Hard chrome plating	- 340 - 364	Titanium	+ 190 - 207
316 stainless steel (active state)	- 302 - 330	Incoloy 800	+ 207 - 236
Hastelloy B	- 285 - 287	316 stainless steel (passive state)	+ 212 - 225
Stellite flame sprayed coating	- 280 - 291	304 stainless steel	+ 213 - 221
Naval brass	- 278 - 279	Graphite	+ 213 - 279
		Alloy 20Cb3	+ 233 - 240
		Platinum	+ 234 - 256

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 10
GALVANIC SERIES IN H₂S SATURATED 3½% BRINE

METAL	POTENTIAL	METAL	POTENTIAL
Magnesium	-1385 - 1410	Antimony	- 427 - 435
Zinc and zinc plating	- 848 - 866	316 Stainless steel	- 425 - 436
Copper	- 736 - 758	Tantalum	- 409 - 414
Red Brass	- 716 - 723	Nickel	- 393 - 402
Silicon bronze	- 706 - 735	310 stainless steel	- 382 - 408
Naval brass	- 695 - 707	Electroless nickel	
Aluminum bronze	- 694 - 700	plating	- 380 - 409
Hard coat anodizing	- 676 - 682	Colmonoy flame sprayed	
70-30 copper nickel	- 672 - 679	coating	- 367 - 384
Tin bronze	- 662 - 669	Stellite flame sprayed	
90-10 copper nickel	- 647 - 668	coating	- 365 - 373
Aluminum alloys	- 633 - 672	Cadmium plating	- 362 - 380
Hard chrome plating	- 587 - 628	Baked electroless	
Mild Steel	- 587 - 618	nickel plating	- 362 - 373
Watts nickel plating	- 556 - 564	Monel 400	- 357 - 362
410 stainless steel	- 555 - 568	Inconel 600	- 353 - 359
430 stainless steel	- 547 - 563	Titanium	- 352 - 362
Sulfamate nickel plating	- 544 - 553	Alloy 20Cb3	- 352 - 358
5Cr steel	- 540 - 573	Graphite	- 349 - 358
Duplex nickel plating	- 538 - 558	Platinum	- 348 - 358
Silver	- 514 - 534	Incoloy 800	- 348 - 349
Rhodium plating	- 504 - 526	Cartridge brass	- 344 - 364
Tin	- 483 - 514	Lead	- 341 - 356
Ni-Resist alloy cast iron	- 464 - 499	Hardened electroless	
Duplex stainless steel	- 449 - 457	nickel plating	- 338 - 358
Hastelloy C-276	- 441 - 464	Muntz metal	- 336 - 356
Tin-silver solder	- 436 - 455	Admiralty brass	- 335 - 357
304 stainless steel	- 435 - 440	Hastelloy B	- 335 - 354
		Aluminum brass	- 334 - 355

NOTE: All potentials are with respect to a fused AgCl electrode.

TABLE 11
 GALVANIC SERIES IN CRUDE DISTILLATION UNIT
 OVERHEAD WATER

METAL	POTENTIAL	METAL	POTENTIAL
Zinc	-556 - 606	304 stainless steel	-174 - 186
90-10 copper nickel	-439 - 491	316 stainless steel	-174 - 186
Aluminum	-231 - 275	Duplex stainless steel	-174 - 186
Silver	-200 - 217	410 stainless steel	-174 - 183
Tin bronze	-191 - 206	Electroless nickel	
Aluminum brass	-180 - 242	plating	-174 - 180
Red brass	-179 - 202	Monel 400	-173 - 191
Admiralty brass	-178 - 198	Incoloy 800	-173 - 186
Mild steel	-177 - 210	Inconel 600	-173 - 186
70-30 copper nickel	-176 - 228	Lead	-172 - 188
Aluminum bronze	-175 - 200	Nickel	-172 - 183
Naval brass	-175 - 193	Ni Resist alloy cast	
Titanium	-174 - 191	iron	-172 - 183
		Platinum	-171 - 185

NOTE: All potentials are with respect to a fused AgCl electrode.

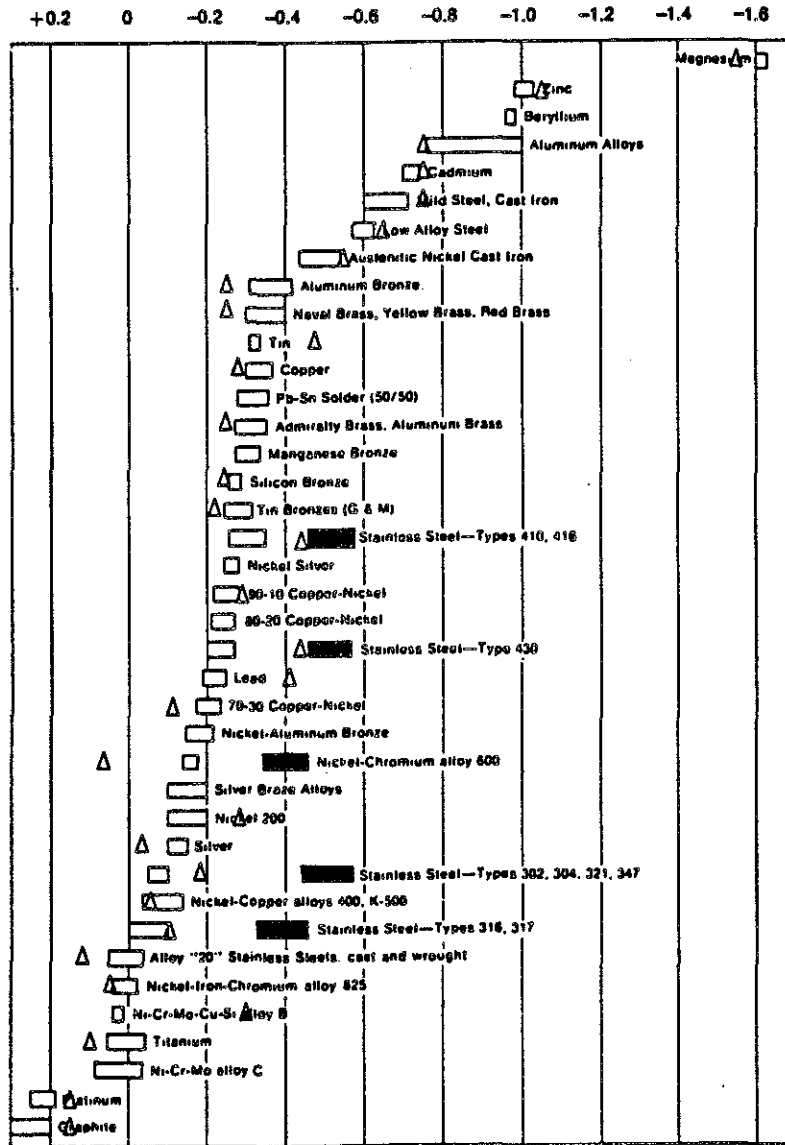
TABLE 12
 POTENTIAL DIFFERENCES BETWEEN
 ELECTROLESS NICKEL AND OTHER METALS

ENVIRONMENT	POTENTIAL DIFFERENCE, mv		
	ALUMINUM	MILD STEEL	304 STAINLESS STEEL
Seawater	450	450	(90)
Aerated tap water	400	650	(120)
Deaerated tap water	710	450	(350)
0.1N HCl	320	200	(520)
0.1N HNO ₃	170	440	(340)
0.1N NaOH	1160	(20)	(60)
CO ₂ brine	530	430	(440)
H ₂ S brine	260	380	40
CDU overhead	76	16	(1)

NOTE: Brackets () indicate that electroless nickel is more active than the second metal; otherwise electroless nickel is the more passive half of a couple.

FIGURE 1

GALVANIC SERIES
CORROSION POTENTIALS IN FLOWING SEAWATER
(8 TO 13 FT./SEC.) TEMP RANGE 50° - 80°F
VOLTS: SATURATED CALOMEL HALF-CELL REFERENCE ELECTRODE



Alloys are listed in the order of the potential they exhibit in flowing seawater. Certain alloys indicated by the symbol \blacksquare in low-velocity or poorly aerated water, and at shielded areas, may become active and exhibit a potential near -0.5 volts.

Δ indicates the potential data developed in synthetic seawater reported in Table 3