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 μm/y. However, if equal areas of these metals are connected in flowing seawater, the corrosion of steel will increase to 2400 μm/y, while that of copper will remain at only 50 μm/y. Thus for steel:

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

$$C_g = 1600 \ \mu m/y.$$

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 positivite 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:

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

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, HNO_3, 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 electroplated nickel was applied by Inco Research and Development Center in Sterling Forest and the electroless nickel was done in Elnic's laboratories. 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 CO_2 and H_2S 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 $CaCO_3$). 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 HNO_3. 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, $CaCl_2$, $MgCl_2$, $NaHCO_3$, $BaCl_2$, and Na_2SO_4 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 impedence was 10^{13} ohms and whose accuracy was ± 0.02 percent. Such a high impedence 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 cummarized 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 INCO[8], 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 resistence. 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 occured 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 300 mv 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 CO_2 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 H_2S 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. Evans[10] 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 insoluable. 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.

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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_2O_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

COMPONENT	ENVIRONMENT
Total Dissolved Solids (%)	3 1/2
Salt Composition (mg/L)	
NaCl	32,000
$CaCl_2$	1,900
$MgCl_2$	750
$NaHCO_3$	120
$BaCl_2$	65
Na_2SO_4	30
Specific Gravity	1.02
Temperature	20°C
Pressure	1 atm
Dissolved CO_2 (mg/l)	1,000
Dissolved H_2S (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 sprayed coating	- 154 - 161
Tin-silver solder	- 374 - 396	Tin Bronze	- 153 - 154
Antimony	- 334 - 337	304 stainless steel	- 116 - 118
Lead	- 333 - 342	Aluminum brass	- 93 - 99
Hardened electroless nickel plating	- 283 - 288	Duplex stainless steel	- 43 - 50
Silver plating	- 250 - 279	70-30 copper nickel	- 34 - 38
Baked electroless nickel plating	- 222 - 246	316 stainless steel	- 16 - 30
Hastelloy B	- 222 - 235	Monel 400	+ 12 - 19
Sulfamate nickel plating	- 212 - 224	Silver	+ 38 - 41
Hastelloy C-276	- 201 - 216	Inconel 600	+ 117 - 120
Electroless nickel plating	- 194 - 215	Incoloy 800	+ 120 - 168
Nickel	- 190 - 191	Titanium	+ 150 - 152
Hard Chrome plating	- 185 - 188	Tantalum	+ 152 - 157
Cartridge brass	- 181 - 184	Alloy 20Cb3	+ 197 - 207
Stellite flame sprayed coating	- 181 - 184	Platinum	+ 212 - 220
		Graphite	+ 222 - 223

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

TABLE 4

GALVANIC SERIES IN AERATED TAP WATER

METAL	POTENTIAL
Magnesium	-1240 - 1249
Zinc and zinc plating	- 882 - 912
Mild steel	- 625 - 634
5CR Steel	- 470 - 490
Cadmium plating	- 460 - 488
Ni-Resist alloy cast iron	- 453 - 474
Antimony	- 333 - 339
Aluminum alloys	- 300 - 447
Lead	- 278 - 283
Tin	- 255 - 271
Hastelloy B	- 232 - 243
Tin-silver solder	- 214 - 227
Duplex nickel plating	- 152 - 200
Hard coat anodizing	- 120 - 130
Nickel	- 115 - 134
Baked electroless nickel plating	- 107 - 128
430 stainless steel	- 89 - 106
Rhodium plating	- 77 - 93
Stellite flame sprayed coating	- 42 - 62
Hardened electroless nickel plating	- 39 - 58
Hastelloy C-276	- 27 - 54
Naval brass	- 12 - 24
Colmonoy flame sprayed coating	- 10 - 31
Sulfamate nickel plating	+ 8 - 22
Electroless nickel plating	+ 15 - 30
Hard Chrome plating	+ 17 - 27
Duplex stainless steel	+ 25 - 37
410 stainless steel	+ 29 - 53
Cartridge brass	+ 35 - 47
Aluminum brass	+ 38 - 52
310 stainless steel	+ 41 - 45
Muntz metal	+ 43 - 54
Silicon bronze	+ 46 - 57
Silver plating	+ 49 - 80
Red brass	+ 54 - 70
Admiralty brass	+ 55 - 58
Watts nickel plating	+ 61 - 80
90-10 copper nickel	+ 70 - 77
Copper	+ 71 - 89
70-30 Copper nickel	+ 86 - 99
Tantalum	+ 96 - 103
Tin bronze	+ 100 - 117
316 stainless steel	+ 105 - 114
Incoloy 800	+ 105 - 115
Aluminum bronze	+ 106 - 119
Alloy 20Cb3	+ 114 - 122
304 stainless steel	+ 130 - 144
Monel 400	+ 140 - 150
Graphite	+ 142 - 160
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
		Alloy 20CB3	+ 13 - 34
Baked electroless nickel plating	- 289 - 311	Monel 400	+ 14 - 28
Tin-silver solder	- 284 - 288	Incoloy 800	+ 15 - 26
Hastelloy C-276	- 274 - 280	316 stainless steel	+ 21 - 30
		Inconel 600	+ 22 - 31
Hardened electroless nickel plating	- 254 - 281	Silicon bronze	+ 23 - 36
Duplex stainless steel	- 242 - 269	Titanium	+ 29 - 44
Sulfamate nickel plating	- 240 - 280	Admiralty brass	+ 37 - 47
Electroless nickel plating	- 237 - 269	Red Brass	+ 51 - 92
Rhodium plating	- 225 - 260	70-30 Copper nickel	+ 55 - 66
Silver plating	- 223 - 295	Copper	+ 56 - 83
		90-10 copper nickel	+ 72 - 93
Stellite flame sprayed coating	- 215 - 228	304 stainless steel	+ 85 - 115
310 stainless steel	- 197 - 222	Platinum	+ 108 - 134
		Silver	+ 198 - 211
Colmonoy flame sprayed coating	- 165 - 192		

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

TABLE 6

GALVANIC SERIES IN 0.1N HCl

METAL	POTENTIAL
Magnesium	-1435 - 1445
Zinc and zinc plating	- 925 - 943
Cadmium plating	- 712 - 724
Hard coat anodizing	- 605 - 631
Aluminum alloys	- 585 - 670
430 stainless steel	- 514 - 517
Mild steel	- 497 - 522
Tin	- 452 - 460
Tin-silver solder	- 447 - 456
Silver plating	- 438 - 457
Hardened electroless nickel plating	- 435 - 436
Lead	- 434 - 440
410 stainless steel	- 405 - 460
5Cr steel	- 401 - 443
Ni-Resist alloy cast iron	- 369 - 379
Baked electroless nickel plating	- 325 - 330
Electroless nickel plating	- 310 - 314
Duplex nickel plating	- 220 - 225
Duplex stainless steel	- 200 - 297
316 stainless steel (active state)	- 150 - 155
Naval brass	- 138 - 167
Stellite flame sprayed coating	- 117 - 166
Hard chrome plating (active state)	- 117 - 125
Watts nickel plating	- 110 - 213
Sulfamate nickel plating	- 95 - 140
Inconel 600	- 88 - 124

METAL	POTENTIAL
Colmonoy flame sprayed coating	- 83 - 114
Rhodium plating	- 76 - 82
Red brass	- 71 - 81
Muntz metal	- 67 - 78
Cartridge brass	- 66 - 77
Hastelloy B	- 65 - 84
Admiralty brass	- 65 - 78
Aluminum brass	- 65 - 76
Aluminum bronze	- 63 - 76
Copper	- 62 - 78
Monel 400	- 56 - 77
Nickel	- 52 - 110
Silicon bronze	- 49 - 65
Tin bronze	- 49 - 59
90-10 copper nickel	- 34 - 47
70-30 copper nickel	- 30 - 43
Antimony	- 3 - 40
316 stainless steel (passive state)	+ 25 - 30
Silver	+ 37 - 68
Hard chrome plating (passive state)	+ 45 - 50
Graphite	+ 105 - 152
Incoloy 800	+ 152 - 198
Hastelloy C-276	+ 177 - 204
304 stainless steel	+ 178 - 231
310 stainless steel	+ 180 - 208
Tantalum	+ 205 - 259
Alloy 20Cb3	+ 219 - 272
Platinum	+ 271 - 327
Titanium	+ 288 - 355

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

TABLE 7

GALVANIC SERIES IN 0.1N HNO_3

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
Hard coat anodizing	-1410 - 1420
Aluminum alloys	-1225 - 1400
Tin	- 967 - 984
Tin-silver solder	- 965 - 978
Lead	- 672 - 686
Antimony	- 630 - 661
Duplex stainless steel (active state)	- 418 - 432
Zinc and zinc plating	- 362 - 372
Cadmium plating	- 245 - 280
Baked electroless nickel plating	- 239 - 253
Magnesium	- 225 - 252
Nickel	- 223 - 230
Duplex stainless steel (passive state)	- 214 - 296
Watts nickel plating	- 207 - 221
Hardened electroless nickel plating	- 196 - 279
5Cr steel	- 192 - 212
310 stainless steel	- 177 - 194
Colmonoy flame sprayed coating	- 177 - 193
Muntz metal	- 177 - 181
Hastelloy C-276	- 176 - 185
Cartridge brass	- 173 - 179
Stellite flame sprayed coating	- 171 - 185
Aluminum bronze	- 169 - 180
Sulfamate nickel plating	- 168 - 192
Hastelloy B	- 167 - 173
Aluminum brass	- 166 - 177
Electroless nickel plating	- 151 - 158
Ni-Resist alloy cast iron	- 150 - 178
Silver plating	- 146 - 169
410 stainless steel	- 144 - 149
Tin bronze	- 134 - 151
Duplex nickel plating	- 133 - 158
Mild steel	- 131 - 147
Rhodium plating	- 126 - 130
Admiralty brass	- 124 - 142
90-10 copper nickel	- 122 - 132
Naval brass	- 118 - 147
Graphite	- 114 - 118
Titanium	- 109 - 130
Tantalum	- 101 - 108
70-30 copper nickel	- 101 - 107
Silicon bronze	- 96 - 153
430 stainless steel	- 92 - 123
304 stainless steel	- 85 - 94
Incoloy 800	- 83 - 92
Monel 400	- 82 - 93
316 stainless steel	- 78 - 89
Hard chrome plating	- 75 - 90
Red brass	- 67 - 81
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 CO_2 SATURATED 3½% BRINE

METAL	POTENTIAL
Magnesium	-1450 - 1510
Zinc and zinc plating	- 990 - 1010
Cadmium plating	- 735 - 741
Aluminum alloys	- 701 - 808
Hard coat anodizing	- 684 - 692
Mild Steel	- 655 - 661
5Cr steel	- 622 - 626
Hardened electroless nickel plating	- 603 - 606
Tin	- 511 - 522
Sulfamate nickel plating	- 484 - 524
Lead	- 476 - 484
Ni-Resist alloy cast iron	- 460 - 472
430 stainless steel	- 456 - 475
Silver plating	- 448 - 465
Watts nickel plating	- 444 - 460
Tin-silver solder	- 440 - 480
Duplex stainless steel	- 428 - 432
410 stainless steel	- 427 - 433
Baked electroless nickel plating	- 381 - 398
Duplex nickel plating	- 374 - 382
Rhodium plating	- 349 - 351
Hard chrome plating	- 340 - 364
316 stainless steel (active state)	- 302 - 330
Hastelloy B	- 285 - 287
Stellite flame sprayed coating	- 280 - 291
Naval brass	- 278 - 279
Cartridge brass	- 266 - 274
Muntz metal	- 261 - 266
Nickel	- 261 - 285
310 stainless steel	- 258 - 285
Aluminum bronze	- 255 - 265
Admiralty brass	- 255 - 257
Aluminum brass	- 252 - 253
Red brass	- 249 - 251
Silicon bronze	- 249 - 254
Colmonoy flame sprayed coating	- 248 - 253
Monel 400	- 243 - 247
Antimony	- 237 - 257
Copper	- 233 - 240
90-10 copper nickel	- 232 - 233
70-30 copper nickel	- 228 - 229
Electroless nickel plating	- 215 - 233
Hastelloy C-276	- 206 - 219
Tin bronze	- 197 - 228
Silver	- 112 - 171
Inconel 600	+ 37 - 47
Tantalum	+ 99 - 175
Titanium	+ 190 - 207
Incoloy 800	+ 207 - 236
316 stainless steel (passive state)	+ 212 - 225
304 stainless steel	+ 213 - 221
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 H_2S 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 plating	- 380 - 409
Aluminum bronze	- 694 - 700	Colmonoy flame sprayed coating	- 367 - 384
Hard coat anodizing	- 676 - 682	Stellite flame sprayed coating	- 365 - 373
70-30 copper nickel	- 672 - 679	Cadmium plating	- 362 - 380
Tin bronze	- 662 - 669	Baked electroless nickel plating	- 362 - 373
90-10 copper nickel	- 647 - 668	Monel 400	- 357 - 362
Aluminum alloys	- 633 - 672	Inconel 600	- 353 - 359
Hard chrome plating	- 587 - 628	Titanium	- 352 - 362
Mild Steel	- 587 - 618	Alloy 20Cb3	- 352 - 358
Watts nickel plating	- 556 - 564	Graphite	- 349 - 358
410 stainless steel	- 555 - 568	Platinum	- 348 - 358
430 stainless steel	- 547 - 563	Incoloy 800	- 348 - 349
Sulfamate nickel plating	- 544 - 553	Cartridge brass	- 344 - 364
5Cr steel	- 540 - 573	Lead	- 341 - 356
Duplex nickel plating	- 538 - 558	Hardened electroless nickel plating	- 338 - 358
Silver	- 514 - 534	Muntz metal	- 336 - 356
Rhodium plating	- 504 - 526	Admiralty brass	- 335 - 357
Tin	- 483 - 514	Hastelloy B	- 335 - 354
Ni-Resist alloy cast iron	- 464 - 499	Aluminum brass	- 334 - 355
Duplex stainless steel	- 449 - 457		
Hastelloy C-276	- 441 - 464		
Tin-silver solder	- 436 - 455		
304 stainless steel	- 435 - 440		

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 plating	-174 - 180
Aluminum brass	-180 - 242	Monel 400	-173 - 191
Red brass	-179 - 202	Incoloy 800	-173 - 186
Admiralty brass	-178 - 198	Inconel 600	-173 - 186
Mild steel	-177 - 210	Lead	-172 - 188
70-30 copper nickel	-176 - 228	Nickel	-172 - 183
Aluminum bronze	-175 - 200	Ni Resist alloy cast iron	-172 - 183
Naval brass	-175 - 193	Platinum	-171 - 185
Titanium	-174 - 191		

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

TABLE 12

POTENTIAL DIFFERENCES BETWEEN ELECTROLESS NICKEL AND OTHER METALS

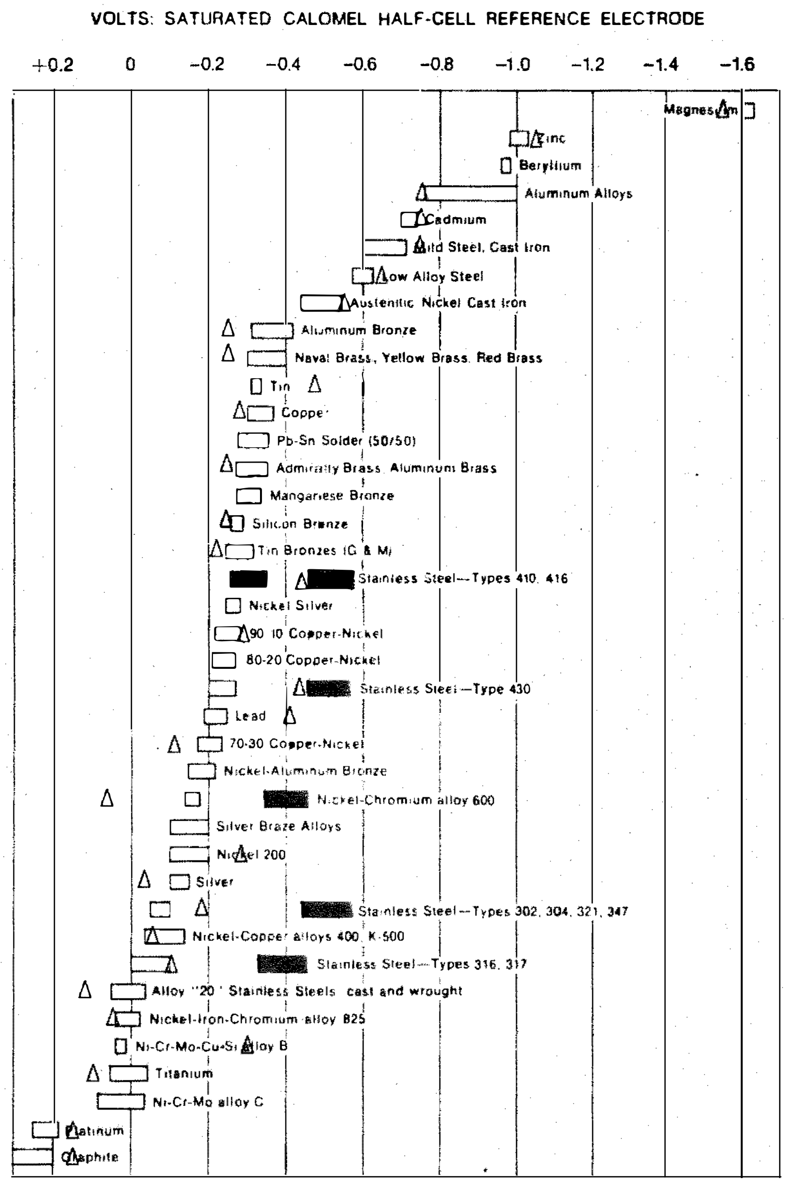
ENVIRONMENT	POTENTIAL DIFFERENCE, mv		
	ALUMINUM	MILD STEEL	304 STAINLESS STEEL
Seawater	450	450	(90)
Aerated tap water	400	650	(120)
Deaerated tap water	710	450	(350)
0.1N HCl	320	200	(520)
0.1N HNO_3	170	440	(340)
0.1N NaOH	1160	(20)	(60)
CO_2 brine	530	430	(440)
H_2S brine	260	380	40
CDU overhead	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



Alloys are listed in the order of the potential they exhibit in flowing seawater. Certain alloys indicated by the symbol ■ 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

Teri Arney is Senior Research Chemist at ELNIC where she is responsible for electroless plating bath formulation.

She joined ELNIC in 1979 after graduating from Middle Tennessee State University and has been involved in many different areas including quality control, technical service, corrosion research and product development.

She is a CEF and Past-President of the Middle Tennessee Chapter of AES.

Ron Duncan is Director of Research for ELNIC, and is also responsible for corrosion and metallurgical research.

Before joining ELNIC he spent 12 years in the petroleum industry in the USA, the Middle East, and Europe, where he was responsible for the solution of materials problems.

He is an Accredited Corrosion Specialist and a Professional Engineer, and has authored numerous papers on materials performance, corrosion and coatings. He is the principal author of the chapter on Electroless Nickel in the new Volume 5 of the Metals Handbook. He is active in the technical committees of NACE and ASTM.

Ronald N. Duncan

BIOGRAPHICAL SKETCH

In Memory of Ron Duncan

Ron Duncan served as Vice President of Palm International, Inc., where he led the company's technical and educational initiatives. Prior to joining Palm, he was Director of Research at Elnic, Inc., focusing on electroless nickel formulation and materials research.

Before entering the metal finishing industry, Ron spent 12 years in the oil sector with Exxon and Caltex Petroleum Corporations, tackling materials and corrosion challenges. His work took him across the globe—including the United States, Middle East, Europe, South America, and Africa—where he developed a reputation for his deep expertise and practical problem-solving.

Ron held a BE in Mechanical and Metallurgical Engineering from Vanderbilt University. He was a Registered Professional Engineer and a certified Corrosion Specialist through NACE. A leader in technical standards, he chaired NACE task groups T-1G-19 and T-6A-53, contributing to authoritative reports on electroless nickel and other metallic coatings. He also served on the AESF's Electroless Committee.

Throughout his distinguished career, Ron authored more than fifty technical papers on corrosion, coatings, and electroless nickel. His work appeared in Materials Performance, Plating and Surface Finishing, Metals Progress, Products Finishing, and Finishers Management, as well as in numerous industry conferences. He was the principal author of the electroless nickel chapter in Volume 5 of the Metals Handbook and was honored with the AESF Gold Medal in 1996 for the best paper published in Plating and Surface Finishing.

Ron also directed the Electroless Nickel School, a comprehensive four-day seminar presented by Palm, which educated professionals in all aspects of electroless nickel technology.

Ron Duncan passed away on December 15, 2006. He is deeply missed by his family, colleagues, and the broader surface finishing community. His legacy of innovation, mentorship, and integrity continues to inspire all who had the privilege of working with him.