

PERFORMANCE OF ELECTROLESS NICKEL COATINGS IN FOOD PRODUCTS

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ABSTRACT

High phosphorus, electroless nickel coatings have excellent resistance to corrosion in most of the environments present in the food industries. The results of tests to characterize the performance of this coating to a broad range of foods and beverages and to compare its resistance to that of other common materials of construction are reported. Data is also presented on the dissolution of nickel into these environments. The oral toxicity of nickel compounds and how this may effect the use of the coating is also reviewed.

INTRODUCTION

Corrosion of food processing and handling equipment can be a serious problem. Most often corrosion results in a loss of cleaniness or hygiene, or in product contamination, rather than in equipment failure. With food and beverages, however, these effects of corrosion can be more serious and costly than actual equipment breakdown. Nickel and nickel alloys are often used to protect food handling equipment. Their resistance to these environments is excellent and they are easily cleaned and maintained. In addition any corrosion products absorbed by the food are generally considered to be non-toxic¹.

Similarly the use of high phosphorus, electroless nickel coatings has become more and more common. These deposits are alloys of nickel and 10½ percent phosphorus and are amorphous. Not only do they provide corrosion resistance equal to that of most nickel alloys, but coated equipment is far less expensive than is solid or nickel clad construction.

In addition electroless nickel coatings offer the added advantage of high hardness and abrasion resistance. As deposited, their microhardness is about 500 VHN_{100} and can be increased to 1000 to 1100 VHN_{100} by heat treatment. This ensures good resistance against erosion and provides protection against impingement and impact. The natural lubricity of electroless nickel makes it easy to clean and helps to prevent the build up of scale or food by-products. The coating also provides a pleasing, stainless steel like appearance.

Even with its advantages, there have been two restraints to the increased use of electroless nickel in the food industries. First, the performance of the coating in foods has not been well documented. Accordingly, designers have been hesitant to specify an unknown material for such critical services. Second, there has been some concern recently regarding the toxicity of nickel salts. This arose because the Environmental Protection Agency listed nickel compounds as potentially hazardous constituents in their waste management regulations².

This paper describes the results of studies to address both of these concerns. Corrosion tests were conducted to evaluate the performance of electroless nickel coatings in foods and beverages. The objective of these tests was to determine the loss rate of the coating and to establish the amount of nickel dissolved as a result of the exposure. A review was also made of the available literature on the toxicity of nickel compounds and how this might effect the use of nickel alloys in foods.

EXPERIMENTAL PROCEDURE

The investigation was begun because of the interest shown in electroless nickel by users of food processing equipment, and was initially limited to foods. Subsequently the study was expanded to include different types of alcoholic beverages, juices, food constituents, cleaners and disinfectant solutions. Later, a series of tests were conducted to compare the performance of electroless nickel coatings with other commonly used materials -- stainless steel, aluminum, nickel and zinc. <u>General.</u> The performance of electroless nickel and the other metals was determined by immersion corrosion tests generally in accordance with NACE Standard TM-01-69³. Standard packages of commercial foods and beverages, obtained from local retailers, were used for the test environments. These are listed in Table 1. These products were selected to provide a cross section of the environments which might be encountered during food processing. Reagent grade chemicals dissolved in deionized water were used for the tests of food constituents, cleaners and disinfectants. These are listed in Table 2.

Most tests were conducted under ambient temperature conditions. Tests with dairy products, eggs, lard and margarine, however, were refrigerated to avoid degradation of the food. In addition some elevated temperature tests were run with coffee, tea, soups, milk and grapefruit juice.

The electroless nickel specimens consisted of AISI 1018 steel coupons with a 75 μ m (3 mil) thick coating. The Elnic deposit was used for these tests. It contains 10 to 11 percent phosphorus and less than 0.05 percent impurities. The coating was tested in the non-heat treated condition, since a previous investigation had shown that hardening of electroless nickel significantly increased its corrosion⁴. The stainless steel, aluminum and nickel specimens for the comparative tests were sheared from These alloys were UNS S30400⁵, UNS A96101⁶, sheet stock. and UNS N022007 respectively. The stainless steel and nickel specimens were also tested in the non-heat treated condition. The 6061 aluminum, however, was tested in the T-6 temper. In order to simulate electrolytic zinc plating, the zinc specimens were sawed from a commercial zinc anode. Before testing the cut edges of the zinc were ground smooth with 240 grit paper. All the coupons were 10 cm^2 (1.5 in^2) in area.

Before immersion, the coupons were degreased, pickled, washed, and dried with acetone. The pickling solution used for the electroless nickel, stainless steel and nickel specimens was 50 percent (by volume) hydrochloric acid; that for the aluminum was 50 percent (by volume) nitric acid; and the zinc was cleaned in 10 percent (by weight) ammonium chloride. After testing, the specimens were scrubbed with a mild abrasive (when necessary) and cleaned in the same solutions used for pickling. They were then dried with acetone, weighed and examined for localized attack.

Corrosion of the coupons was determined by before and after meassurements of their weight. The metal dissolved by the test environment was determined by atomic absorption spectroscopy of the fluid. For non-homogeneous foods, like canned vegetables, a decanted sample of the associated juice was used for analysis.

Ambient Temperature and Refrigerated Tests. When the foods were obtained in resealable glass containers, these were used for the test vessel for the ambient temperature and refrigerated tests. Otherwise, the food and the specimen were placed into a screw top, 500 to 1000 ml (16 to 32 oz) capacity polyethylene bottle. The sample volume varied depending upon what was commercially available for each product and ranged from 200 to 1000 ml (7 to 32 oz). The typical sample size, however, was 500 ml (16 oz). The volume for each test is also shown in Tables 1 and 2. For the alcoholic beverages and some foods, a test volume of 240 ml (8 oz) was selected. This resulted in a solution volume to specimen area ratio less than the 40 ml/cm^2 (250 ml/in²) recommended by TM-01-69. Because of the low corrosion rates expected, however, this was judged to be sufficient.

For the ambient temperature tests, the bottles and jars were stored in a laboratory cabinet whose temperature was $22^{\circ}C^{\pm}$ $2^{\circ}C$ (72°F ± $4^{\circ}F$). For the refrigerated tests, the containers were placed in a 400 dm³ (14 ft³) capacity refrigerator whose temperature was maintained at $2^{\circ}C \pm 2^{\circ}C$ ($36^{\circ}F \pm 4^{\circ}F$). The period of the tests varied from 1250 hours for some of the refrigerated tests to 3900 hours for the tests with liquors. This is also shown in Table 1.

Elevated Temperature Tests. Tests with several foods and beverages were conducted at 60° and 95°C (140° and 200°F). For these pressure resistant, 200 ml (6 oz) capacity glass bottles were used. The bottles were sealed with neoprene gasketed, porcelain stoppers. These were maintained at $\pm \frac{1}{2}$ °C ($\pm 1^{\circ}$ F) by submerging them in an ethylene glycol bath. The period of these tests was 310 to 550 hours.

RESULTS

The results of the corrosion tests with electroless nickel in foods and beverages, and the nickel analysis of the environment, are shown in Table 1. To account for the varying test periods and volumes, dissolved nickel was normalized to a nickel dissolution rate per day of exposure for a standard 1 liter (32 oz) volume -- $\mu g/l/d$. This is also shown on Table 1. The results of tests in food constituents and additives, and in water, cleaners, and disinfectants are summarized in Table 2. With these tests the environment was not analysed for nickel.

No evidence of localized attack -- pitting, crevice corrosion, or corrosion cracking -- was observed with any of the electroless nickel tests. In some environments the coating developed a grey to gold discoloration due to the formation of a passivation film. This was most evident in environments containing sulfur compounds. Generally the corrosion of electroless nickel was low. The highest measured loss was 8.8 μ m/y (0.4 mpy). For most of the products tested, the measured nickel content was well below accepted oral toxicity limits for nickel salts (see Appendix A). Mold growth was apparent on the surface of a few food samples, and the canned potatoes, pineapple, and beets fermented during the tests. None of these changes, however, appeared to be associated with the coupon or to have any significant effect upon its loss. During the $95^{\circ}C$ ($200^{\circ}F$) tests, the tomato soup samples separated and developed a high gas pressure and a putrid odor. Accordingly this test was judged to be invalid and was ignored.

The results of the comparative tests with stainless steel, aluminum, nickel and zinc are summarized in Table 3. These showed that stainless steel is the most resistant material to corrosion in food products. In the six environments tested, its corrosion rate was always less then 2 μ m/y (0.1 mpy). In most environments, the loss of aluminum and zinc was greater than that useable for processing equipment. The loss of electroless nickel was about five times that of stainless steel in coffee, spaghetti sauce and water. In vinegar, its loss was much higher than stainless steel, although still quite low. In milk and grapefruit juice, however, electroless nickel was found to be the most resistant material of construction.

DISCUSSION

Except for tests with coffee, lemonade, sauerkraut, spaghetti sauce, tea, vinegar and wine, the corrosion of electroless nickel was low and generally less than 2 µm/y (0.1 mpy). Small amounts of organic acids are present in all foods, as illustrated by Table 4⁸. Dilute solutions of these acids are known to cause moderate corrosion of electroless nickel⁹. This is also shown in Table 2. However, why some foods with high acid contents (lemon and grapefruit juice) produced relatively low corrosion, while high losses were experienced in others with lesser amounts of acid (coffee and lemonade) is not understood. Presumably this is due to the way in which the acids are complexed to the other components in the foods. More study, however, is needed before this can be confirmed.

No other correlation between corrosion and composition was apparent. Previous studies had shown the corrosion of electroless nickel to be related to pH and to be significantly increased at levels less than three⁹. With foods, however, this was not always true. While losses did tend to decline with increasing pH, this was not consistent. A corrosion rate of 8.8 μ m/y (0.4 mpy) was measured in 5.1 pH coffee, but in 2.3 pH cranberry juice losses were less than 1 μ m/y (0.04 mpy).

The comparative tests confirmed the excellent resistance of electroless nickel to foods and beverages and showed it to be superior to most materials of construction. The losses of aluminum and zinc were very high in most tests. This was not surprising considering the active character of these metals and the acidic nature of most foods. Their high corrosion rates, however, limit their use in many environments.

The corrosion of nickel was unexpectedly high, especially when compared to that of electroless nickel. In general, the loss of metallic nickel was 2 to 10 times that of the nickel-phosphorus coating. The corrosion rate of the nickel specimens, however, agreed well with that published previously for similar environments.^{1,10}

The improved corrosion resistance of electroless nickel over metallic nickel is probably due to the amorphous nature of coating. Amorphous materials generally have better resistance to attack than equivalent polycrystalline alloys, because of the glassy films which form on and passivate their surfaces. Also materials containing a high concentration of metalloids (such as high phosphorus, electroless nickel) tend to form more passive, and thus more protective, surface films. Metalloid atoms promote the formation of glass like surface films, and appear to allow thicker and higher density films to form ^{11,12}.

The comparative tests also confirmed that stainless steel is the most universally resistant material to corrosion in food environments. Its corrosion rate in all six tests was less than 2 μ m/y (0.1 mpy). Thus, where maximum assurance against attack is required, stainless steel should probably be specified. Where cost or abrasion resistance is a concern, however, the use of electroless nickel coatings should be considered. In these tests, the coating's loss was similar to that of stainless steel, and in two cases was even lower. Electroless nickel is also very resistant to pitting and crevice corrosion, which in some foods can be a problem with stainless steel.

In general, the dissolved metal content of the test solutions followed the corrosion measured with the coupons. High loss rates produced high levels of dissolved metal, and low rates produced little or no dissolution. As shown in Figure 1, there was good agreement between the normalized nickel dissolution rate and the corrosion rate of the electroless nickel coupons. The nickel content in most of the products was well below accepted oral toxicity limits for nickel salts (see Appendix A).

A linear regression analysis of the data in Figure 1 gave a coefficient of determination (r^2) of $\bullet.82$ for the equation:

$$\mu g/1/d = 18.9 (\mu m/y) + 1.4.$$

While this correlation is not perfect, it does confirm that the amount of nickel built up in a food can be estimated directly from the coating's corrosion rate. The exceptions were non-homogeneous foods -- like beets and spaghetti sauce -- where the distribution of nickel through the product was not uniform.

CONCLUSION

These tests confirmed that electroless nickel coatings can be successfully used for food handling and processing equipment. In most environments, a 25 μ m (1 mil) thick electroless nickel coating should be adequate to provide long and reliable service. For more aggressive products, like coffee and vinegar, coating thickness of 75 μ m (3 mils) may be necessary to provide adequate life.

Similarly, the amount of nickel dissolved from the coating will be quite low in all but the most aggressive environments, and should not limit the coating's use for food processing equipment. Even in aggressive environments, nickel dissolution should not be serious for short term or intermittent exposures. In these environments, periods of weeks are usually needed to build up concentrations of nickel high enough to be of concern.

<u>APPENDIX A</u>

TOXICITY OF NICKEL COMPOUNDS

A toxic substance can enter the body through oral intake, inhalation, absorption through the skin, or injection into the bloodstream or tissue. The route of entry is usually as important in determining the toxicity of a substance as is the substance itself. Of the four, oral ingestion is often the least hazardous.

For a substance to be classified as orally toxic, it must cause damage to t ssue. This can be at molecular, cellular, tissue or organ levels. The major factors which determine the oral toxicity of a substance -- especially a metal -- are the extent to which it is absorbed from the gastrointestinal tract into the bloodstream, the rate and mechanism of its excretion from the body, and its accumulation in tissues. The amount and the form of the metal ingested are also important factors. Obviously, a cyanide compound is much more toxic than a carbonate compound.

For many metals, including nickel, the body controls the degree of absorption through homeostatic mechanisms. These mechanisms function (somewhat like osmosis) by limiting the intestinal absorption in much the same way that the absorption of essential trace elements is increased during low levels of dietary intake and decreased during high levels of intake.

After entering the bloodstream, the kidney and liver play a major role in eliminating excess metals from the body. Since metals cannot undergo metabolic degradation (as do organics) they must either be excreted or accumulated in tissues. The rate

and pathway of excretion varies greatly for different metals and to some extent determines their toxic hazard. For example, cadmium is believed to accumulate in the kidney over the entire lifetime of an individual, reaching valves of up to 50 mg per kg of body weight¹³.

Oral Toxicity. In the recent literature all authors agree that the intestinal absorption of nickel is low and its excretion is rapid. Nickel also has little tendency to accumulate in tissues^{13,14,15}.

Rats, mice, and monkeys fed large amounts of nickel (250 to $1000\mu g$ Ni/g diet) as soap, catalyst, and nickel carbonate for periods up to 16 months showed no change in general condition or growth¹⁴. Nickel chloride in the drinking water of rats at a concentration of 5 µg Ni/ml was found to be innocuous over their lifespan, while 55 µg Ni/ml was toxic over a four month period¹⁴. It was also found that high doses of nickel reduced the food consumption of test animals, apparently due to its unpalatability. As illustrated by Table 1A, in general the toxicity of nickel compounds is similar to that of other metallic compounds¹⁶. In fact, nickel sulfate is approved for use as a food additive and/or treatment for food-producing animals and is permitted in foods for humans¹⁶.

In other studies with animals, it was found that about 90 percent of the nickel ingested was eliminated in the feces, indicating that about 10 percent was absorbed. In order to overwhelm the homeostatic control mechanism for nickel, greater than 1000 μ g Ni/g diet (or 0.1 percent) is needed¹⁴.

The most common effect of contact exposure to nickel is an allergenic reaction. It has been estimated that approximately 10 percent of the population is hypersensitive to nickel, with exposure causing allergenic eczema (contact dermatitis or nickel itch).

In studies of these hypersensitive people it was found that there was no significant difference in the nickel levels of plasma and urine of allergic and nonallergic subjects. It was also found that an oral dose of 5 mg Ni increased the nickel content of plasma and urine by about ten times during the 24 hours after ingestion, but that within 48 hours after ingestion, nickel concentrations returned to normal ranges¹⁷.

Daily Uptake of Nickel. In several studies the average daily uptake of nickel by humans from food and water has been estimated to be 300 to 600 μ g/day¹⁵. Table 2A shows typical nickel values in the serum , urine and feces of healthy adults. From this data it has been concluded that fecal excretion is the major route for the elimination of ingested nickel from the human body. Nickel that has been absorbed from the intestinal tract is excreted via urinary output. Since the absorption of nickel is very low, the mean excretion numbers shown in Table 2A probably correspond to the daily uptake as well¹⁸. In comparing the speed of excretion or clearance of a metal from the body the term biological half-time is often used. This simply means the amount of time needed for the initial concentration to be reduced by one half. For animals and humans the biological half-time of ingested nickel is 1 to 2 days^{13,15}.

An Essential Trace Element. As early as 1970, nickel was suggested as essential for nutrition in test animals¹⁷. In 1975 a nickel containing protein was discovered, confirming the necessity of dietary nickel. It was found that deprivation of nickel caused impaired intestinal absorption of iron in rats resulting in anemia. Long term tests over several generations on animals showed that nickel deficiency caused significant reductions in growth, performance, and red blood cell values, as well as anemia, and decreased the activity of liver enzymes necessary for metabolism¹⁷. In humans, a nickel rich metalloprotein has been isolated from serum as well as a glycoprotein with a strong binding capacity for nickel¹⁷.

Summary. Nickel salts have low toxicity when taken orally due to the body's homeostatic control mechanisms, which limit their absorption from the intestinal tract. Extremely high levels of dietary nickel are necessary to overcome these control mechanisms. The major route for elimination of ingested nickel is by fecal excretion which accounts for about 90 percent of that ingested. In addition, excretion of absorbed nickel is rapid via urinary output and accounts for almost all of the remaining 10 percent. The biological half-time of nickel is short, indicating that nickel does not tend to accumulate in tissues. Nickel toxicity in humans through oral intake occurs only in extreme and unusual circumstances.

TABLE 1A

TYPICAL ORAL TOXICITY VALUES FOR VARIOUS COMPOUNDS

COMPOUND	·	LD ₅₀ ,mg/kg (1)
Aluminum nitrate, Al(NO ₃) ₃		260
Calcium chloride, CaCl ₂		1000
Calcium nitrate, Ca(Ne ₃) ₂		3900
Copper nitrate, Cu(NO ₃) ₂		940
Magnesium chloride, MgCl ₂		2800
Mercurous acetate, $Hg(C_2H_3O_2)_2$		76
Nickel acetate, Ni(C ₂ H ₃ • ₂) ₂		350
Nickel nitrate, Ni(NO ₃) ₂		1688
Potassium acetate, $K(C_2H_3O_2)$		3200
Sodium acetate, $Na(C_2H_3O_2)$		3500
Sodium chloride, NaCl		3000
Sodium nitrate, NaNO3		220
Zinc acetate, $Zn(C_2H_3O_2)$		2500
Zinc nitrate, Zn(NO3)2		1200
Sodium chioride, NaCl Sodium nitrate, NaNO ₃ Zinc acetate, $Zn(C_2H_3O_2)$ Zinc nitrate, $Zn(NO_3)_2$		220 2500 1200

NOTE :

1) LD_{50} is the dose of the indicated compound, in mg of compound per kg of body weight, which was found to be lethal to 50 percent of the test population.

TABLE 2A

NICKEL CONCENTRATIONS IN BODY FLUIDS

FLUID	·	TYPICAL CONCENTRATION
Blood		4.8 µg/l
Serum		2.6 µg/1
Urine		2.2 µg/1
		$(2.6 \mu g/day)$
Saliva		2.2 µg/l
Feces		14.2 µg/g (dry)
	•	(258 µg/day)
Sweat		52 µg/1
Hair	•	0.22 µg/g

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		TABLE 1			
PERFORMANCE	0F	ELECTROLESS NICKEL	ΙN	FOOD	PRODUCTS

ENVIRONMENT (1)	SOLUTION PH	TEST VOLUME,	TEST TEMPERATURE,	TEST PERIOD,	CORROSION RATE,	DISSOLVED NICKEL	DISSOLUTION RATE,
	· · · · · ·	141.1	<u> </u>	nours	<u>us/y</u>		<u>hā 11/0</u>
Apple juice	3.5	850	22	170	1.2	1.5	18
Beef stey (2 tests)	5.5	450	22	1150/1680	0.4	0.3	3
Beer (2 tests)	3.7	300	2	3560	0.2	1.5	3
Beets, sliced (2)	5.2	400	22	1680	1.8	1.1	6
Buttermilk (2 tests) Chicken broth (3 tests)	4.5	950	05	1250/1630	0.6	2 0	nil 19
Coca cola (2 tests)	2.2	300	2	3220	1.0	36	80
Coffee (2 tests)	5.1	950	22	1120/1730	8.8	18	220
Coffee (2 tests)	4.8	200	95	290	6.2	11	160
Carn syrun light (2 tests)	0.2 4 1	230	22	1150	0.2	2.0 nd	nil
Cottage cheese (2 tests)	4.9	300	2	1250/1630	0.4	1.4	8
Cranberry juice	2.3	950	22	1700	0.5	0.6	8
Dressing, 1000 Island	3.7	240	22	1730	1.0	1.8 nd	b nil
Gelatin, $7 g/l$ (2)	5.6	450	22	3140	0.1	nd	nil
Gin, English, 95 proof (2 tests)	7.5	240	22	3910	0.02	2.1	3
Grape juice	3.5	800	22	1700	1.8	2.6	29
Grapefruit juice (3 tests)	3.2	900	22	1/00	0.5 n11	0.0	8
Honey, light (2 tests)	3.3	15	22	1150	nil	nd	nil
Keol-Aid, tropical punch (3 tests)	2.7	950	22	1150/1700	2.2	1.9	34
Lard		560	2		nil	nd	nil 61
Lemen juice (2 tests) Lemonade (2 tests)	2.4	420/800	22	1150/1700	2.0	8.3	120
Margarine		200	2	1630	nil	nd	nil
Mayonnaise	3.7	470	22	1680	0.2	0.9	6
Milk (2 tests)	6.7	950	2 50	1250/1630	0.04	nd 0	n11 10
Molasses	4.1	350	22	1700	0.2	nd	nil
Mushreoms, button	6.2	150	22	1680	0.6	3.3	7
Mushroom soup (2 tests)	5.3	250/500	22	1150/1700	0.4	0.6	4
Olives, spanish Onional boiled	3.1 1.2	250	22	1700	0.3	1.2	10
Peaches. canned	3.5	400	22	1680	0.2	0.3	2
Peanut butter	4.7	4 50	22	1700	nil	0.1	1
Peas, canned	6.1	450	22	1700	0.2	0.3	2
Pineappie, canned (2) Pork and beans	3.0	350	22	1600	0.3	0.0	0
Potatoes, canned (2)	5.8	350	22	1680	1.9	9.0	45
Frune juice	3.8	1000	22	1700	1.0	0.1	1
Pudding, chocolate fudge		250	22	1680	nil	nd	nil
Sardines in sovbean eil	5.0	30 (011)	22	1690	0.2 pf1	6.2	9
Sauerkraut	3.5	250	22	1680	4.4	29	62
Sherry wine, 18% (2 tests)	3.6	250	22	1100/3910	8.0	73	200
Spagnetti sauce (4 tests) Tartar sauce	3.8	200	95	290	8.1	0.8	12
Tea, instant	2.9	750	22	1730	4.2	10	100
Tea, instant (4 tests)	2.6	200	95	310/550	9.0	7.6	84
Tequila, 40% (2 tests)	4.8	240	22	3910	0.4	9.4	14
Tomato juice (2 tests)	4.2	400	22	1320/1340	0.5	2.2	13
Tomato soup (2 tests)	4.2	250/500	22	1150/1700	0.3	1.1	6
Tomato soup (2 tests)	4.2	200	95	500	6.1 (3)	(3)	(3)
vo juice (j tests) Vegetable oil	4.2	/10	22	1320/1340	0.1	0.5	6
Vegetable aoum (2 testa)	5.4	479 250/500	22	1150/1700	n11 0.6	nd 14	n11 6
Vinegar (2 tests)	2.8	470	22	1130	14	13	140
Vodka, 80 proof	8.2	240	22	3910	nil	0.2	<1
wniskey, Bourbon, 90 proof Whiskey Canadian 87 proof	5.2	240	22	710	1.8	5.5	45
Whiskey, Scotch, 86 proof (2 tests)	5.3	240	22	3910	1.8	31	44
Wine, Burgundy	3.5	200	22	1150	3.4	26	100
Wine, Unenin blanc (2 tests)	3.3	2 0 0	22	1150	2.2	19	74

Only a single test was conducted at ambient temperature, unless otherwise noted.
 During these tests, the food developed some gas pressure and appeared to become fermented.
 During this test, the heated tomato soup samples separated and developed a high gas pressure and a putrid odor. The fluid was not tested for pH or nickel concentration.

TABLE 2 PERFORMANCE OF ELECTROLESS NICKEL IN FOOD ADDITIVES AND RELATED PRODUCTS

ENVIRONMENT	TEST VOLUME, ml	TEST PERIOD, hours	CORROSION RATE ym/y
Acacia, 17, 4.4 pH	500	8210	0.1
Acetic acid, 57 CH3COOH (2 tests)	500	2620	13.7
Alum, 57 Al2(SO4)3	4 50	1610	4.3
Ammonia, 28% NH4OH	500	3620	12.6
Ascorbic acid, 5% C6H8O6	500	4990	6.6
Brine, 40% CaCl2 (2 tests)	4 50	1200/3340	0.1
Brine, 26% NaCl (2 tests)	4 50	1340/3480	2.0
Carbonic acid, 5% C6H5OH	4 50	4890	4.3
Citric acid, 57 CiH807	500	2660	14.7
Detergent, liquid, 8 ml/1, 7.3 pH	500	8210	3.9
Dextrin, 17, 3.8 pH	500	8210	0.1
EDTA, tetra sodium, 0.2M	500	3840	13.1
Ethanol, 100% CH ₃ CH ₂ OH	500	6500	0.02
Lactic acid, 857 C3H6O3	500	1340	1.3
Malic acid, 107 C4H6O5	500	2660	16.7
Methanol, 100% CH3OH (2 tests)	500	10400	0.04
Phosphoric acid, 1% H3PO4 (2 tests)	4 50	2600/2620	12.6
Potassium chloride, 25% KCl (2 tests)	450	2300/3340	0.02
Potassium carbonate, 257 K ₂ CO ₃	450	2300	0.2
Salt, 5% NaCl, 6.2 pH	450	1200	0.5
Saltpeter, 47% NaNO3 (2 tests)	450	1840/3340	nil
Sausage casing solution 57 H2SO4 + 207 NaSO4	4 50	1460	11.8
Sodium bicarbonate, 27 NaHCO3, 8.5 pH	500	7070	3.6
Sodium hydroxide, 17 NaOH	500	5040	0.2
Sodium hypochlorite, 17 NaOCl, 11.3 pH	4 50	7690	nil
Sodium nitrite, 427 NaNO2, 8.8 pH	4 50	7730	4.3
Sodium phosphate, 467 NaH ₂ PO ₄	450	1840	2.8
Sodium potassium tartrate, 357 KNaC4H406, 9.5 pH	500	7070	9.5
Starch, 1%, 9.0 pH	500	7070	0.4
Water, deionized, 1Ma-cm (4 tests)	900	4540/5090	1.9
Water, tap, 8.0 pH (4 tests)	900	4540/5090	0.05
Water, tap (2 tests @ 95°C)	200	290	1.8
Water, sea, synthetic, 8.2 pH (2 tests)	500	1270	1.0
Water carbonated, 700 mg/1 CO ₂ , 3.9 pH (2 tests)	450	400	7.9

(1) Only a single test was conducted at ambient temperature, unless otherwise noted. Solutions are of the listed compound dissolved in deionized water.

TABLE 3

COMPARISON OF COMMON MATERIALS OF CONSTRUCTION IN FOOD PRODUCTS

MATERIAL			ENVIRON	1ENT			
	Co	offee at 95°C	Spaghet	ti Sauce at 95 ⁰ C	Water at 95°C		
	Corrosion Rate,	Concentration, mg/l	Corrosion Rate,	Concentration,mg/l	Corrosion Rate,	Concentration,mg/1	
	µm./y	Ni Cr Al Zn	րա/ծ	Ni Cr Al 2n	µm./у	Ni Cr Al Zn	
Electroless Nickel	6.2	11	8.1	0.8	1.8	0.1	
UNS S30400 Stainless	1.2	0.1 ND	1.6	ND ND	0.4	ND ND	
UNS A96101 Aluminum	62	28 -	650	41 -	GAIN	1.2 -	
UNS NO2200 Nickel	17	29	29	3.0	8.9	0.2	
Zinc	130	100	1300	~ 200	31	0.1	
Test Volume,ml		200		200		200	
Test Period,hrs.		290		290		290	

MATERIAL			ENVIRONMENT	[
	V	/inegar at 22°C	Milk	at 60ºC	Grapefruit Juice at 60°C			
	Corrosion	Concentration,mg/1	Corrosian	Concentration,mg/1	Corrosion	Concentra	ation,mg/1	
	Rate,		Rate,		Rate,	P		
	µта/у	Ni Cr Al Zn	µm/y	Ni Cr Al Zn	um/y	Ni Cr	Al Zn	
Electroless Nickel	14	13	1.0	0.9	Nil	0.8 -		
UNS S30400 Stainless	0.1	0.8 ND	1.2	0.1 0.1	0.1	0.4 0.6		
UNS A96101 Aluminum	52	31 -	12	2.4 -	41		24 -	
UNS NO2200 Nickel	27	23	0.6	2.8	2.7	7.3 -		
Zinc	>8000	1000	160	100	2700		- 400	
Test V⊕lume,ml		500		200		200		
Test Period,hrs.		1130		430	· · · · · · · · · · · · · · · · · · ·	430		

TYPICAL ACID CONTENT OF SOME FOODS

FOOD	pH	ACID CONTENT, percent			
		<u>Citric Acid</u>	<u>Malic Acid</u>	<u>Other</u>	
Apples	3.6	nil	0.72	-	
Beets	5.0	0.11	nil	0.14 oxalic	
Corn	6.1	nil	nil	0.005 oxalic	
Cranberries	2.4	1.82	0.46	0.07 benzoic	
Grape juice	3.0	0.02	0.31	1.07 tartaric	
Grapefruit	3.0	1.33	0.08	•	
Lemon juice	2.3	6.08	0.29		
Milk	4.1	0.16		lactic	
Olives	6.0	0.02	0.17	en de la constante de la const En la constante de la constante	
Peaches	3.8	0.05	0.69	i de la companya de l	
Peas	5.8	0.11	0.08	- · · · ·	
Pineapple	3.4	0.84	0.12	0.006 oxalic	
Potatoes	5.7	0.51	nil	0.006 oxalic	
Теа	5.3	-	•	0.004 oxalic tannic	
Tomatoes	4.2	0.30	0.20	0.008 oxalic	
Vinegar	3.1			4.0 acetic	
Wines	3.3-3.6		-	tannic	



FIGURE 1

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.