

# ELECTROLYZED WATER AND ITS CORROSIVENESS ON VARIOUS SURFACE MATERIALS COMMONLY FOUND IN FOOD PROCESSING FACILITIES

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## ABSTRACT

*ASTM A-36 medium carbon steel, 110 copper, 3003-H14 aluminum, polyvinylchloride (PVC) type 1 and 304 stainless steel coupons were immersed in electrolyzed (EO) water, chlorine water, modified EO water and deionized water for a period of 8 days, and the properties of these types of water, weights and surface roughness of the coupons were monitored. EO water significantly increased ( $P < 0.05$ ) the surface roughness of carbon steel, aluminum and copper with time; however, chlorine water, modified EO water and deionized water produced minimal changes on these materials. Regardless of the treatment water used, the surface roughness of stainless steel and PVC essentially remained the same. Carbon steel, copper, aluminum and stainless steel had a fair, good, good and outstanding corrosion resistance in EO water, respectively. Chlorine and modified EO water had a much less corrosive effect than EO water on all the materials tested.*

## INTRODUCTION

The use of sanitizers in the food industry is aimed at reducing microbial numbers to safe levels; however, these sanitizers may have other side effects such as corrosion of food contact surfaces because of their reactivity. Corrosion caused by the use of sanitizers is primarily because of chemical reactions of a sanitizer with the contact surface. This effect may be locally concentrated to form a pit or a crack, or may uniformly proceed over the entire exposed surface (Fontana 1986). The presence of pits and abrasions is known to reduce

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cleanability and inactivation of pathogens on food contact surfaces (Holah and Thorpe 1990; Frank and Chmielewski 2000). This is because the pits and cracks on the corroded food processing equipment surfaces allow food material and bacteria to accumulate and form biofilms, which in the end survive the sanitation process. These bacteria will eventually cause cross contamination of food during processing and may lead to spoilage or food-borne outbreaks, defeating the sanitation process and the use of that sanitizer in the first place. The selection and evaluation of the reactivity of sanitizers with respect to the equipment to which they will be applied is therefore very important, if not critical.

Electrolyzed (EO) water production and its use as a sanitizer have recently received a lot of attention. EO water is produced by passing a dilute salt solution through an electrolytic cell, within which the anode and cathode are separated by a diaphragm. By subjecting the cell to DC voltage, two types of water are produced. The electrolyzed acidic solution produced at the anode side, which has a strong oxidizing potential (oxidation–reduction potential [ORP]  $\sim 1100$  mV), a low pH ( $\sim 2.6$ ), contains hypochlorous acid (HOCl), and hence, has a strong bactericidal effect (Kim *et al.* 2000). The electrolyzed basic solution that is produced at the cathode side has a strong reducing potential (ORP  $\sim -800$  mV) and a high pH ( $\sim 11$ ). Recent research by Ezeike and Hung (2004) showed that the properties of EO water can be further controlled and optimized by monitoring the processing parameters. They reported that increasing the voltage and sodium chloride (NaCl) concentration resulted in a lower pH, higher ORP and residual chlorine of the acidic EO water, and increasing the electrolyte flow rate caused a reversal of these trends because of shorter residence time in the electrolytic cell. Several reports have demonstrated the bactericidal effect of EO water on pathogenic bacteria (Kim *et al.* 2000; Kiura *et al.* 2002) and *Listeria* biofilms (Kim *et al.* 2001). EO water also achieved significant reductions in *Campylobacter jejuni* on poultry (Park *et al.* 2002), *Escherichia coli* O157:H7 and *Listeria monocytogenes* on lettuce (Park *et al.* 2001), *Salmonella* on alfalfa seeds and sprouts (Kim *et al.* 2003) and *E. coli* O157:H7 and *L. monocytogenes* on kitchen cutting boards (Venkitanarayanan *et al.* 1999). The effect of pH, chlorine and mode of application on the chemical properties and bactericidal efficacy of EO water has also been investigated. Park *et al.* (2004) and Hsu *et al.* (2004) reported that increasing pH and spraying decreased the bactericidal efficacy of EO water; however, both reports indicated that with sufficient residual chlorine concentration, EO water can be applied by spraying and within a considerably wide pH range (2.6–7.0) to achieve complete inactivation of *E. coli* O157:H7 and *L. monocytogenes*. EO water has also been successfully applied as a foliar spray to control powdery mildew on gerbera daisies (Mueller *et al.* 2003) and on other bedding plants without serious phytotoxic effects (Buck *et al.* 2003).

The use of EO water as a sanitizer in food processing plants has been suggested because of its high antimicrobial activity, low cost and ease of production and use, among other advantages. Although EO water has demonstrated a strong bactericidal activity, the possibility of corrosion of equipment because of its low pH and residual chlorine content is a matter of concern because acids and aqueous forms of chlorine are known to be corrosive (Daufin *et al.* 1988a; Bohner and Bradley 1991; McCafferty 2003; Abd El Meguid and Abd El Latif 2004). Most metals corrode when they come in contact with water, acids, bases, salts, some chemicals and gaseous compounds like acid vapors, sulfur-containing gases and ammonia gas. Stainless steel (types 304 and 316, American Iron and Steel Institute, AISI, Washington, DC) is the most widely used material in the construction of food processing equipment, food contact surfaces and pipes in food processing plants (Bohner and Bradley 1991). These AISI 300 series stainless steel materials contain chromium and nickel, which make them resistant in many aqueous environments. Other materials such as aluminum, carbon steel, copper and polyvinylchloride (PVC) have also been used in the fabrication of certain parts of equipment or pipes in food processing plants.

Some work has been done in the medical field on the possible corrosive effects of EO water on dialysis equipment and metallic restorations used in the oral cavity. Tanaka *et al.* (1999) reported no visible significant differences in type 316 stainless steel sheets when soaked in electrolyzed strong acid aqueous solution (ESAAS) or 0.1% sodium hypochlorite (NaOCl). They, however, reported that stainless steel couplers used in dialysis equipment showed heavy corrosion after soaking in 0.1% NaOCl, while no significant corrosion was evident in ESAAS. EO water holds a lot of promise as an effective sanitizer for the food industry. It is therefore important to investigate its effect on some commonly used materials to aid in its selection as an appropriate sanitizer. The objective of this study was to determine the corrosive effect of EO water on various materials used in the fabrication of food processing equipment.

## MATERIALS AND METHODS

### Cleaning of Specimen Used for the Study

The following test materials were used: 304 stainless steel, ASTM A-36 medium carbon steel, 3003-H14 aluminum, 110 copper and PVC type 1. Tests were conducted according to the American Society of Testing and Materials (ASTM) standard G1-90 (ASTM 1999a) (standard practice for preparing, cleaning and evaluating corrosion test specimens) and ASTM standard

G31–72 (ASTM 1999b) (standard practice for laboratory immersion corrosion testing of metals). The specimen of the test materials were cut into  $2.5 \times 5$  cm rectangular pieces referred to as *coupons* and cleaned by scrubbing with a mild nonbleach cleaner (Versa-Clean, Fisher Scientific Co., Pittsburgh, PA) using a soft nylon bristle brush. After thoroughly rinsing with deionized water, the coupons were dipped in acetone, air-dried and kept in a dessicator until they were used.

### **Water Used for Corrosion Testing**

Four types of water were used for the corrosion tests: EO water, deionized water, chlorine water and modified EO water. Fresh EO water was produced from a ROX-20TA EO water generator (Hoshizaki Electric Inc., Toyoake, Aichi, Japan) at a current setting of 14 A. Deionized water was collected from the deionized water faucet in the laboratory. Chlorine water (1.2%) was prepared from calcium hypochlorite ( $\text{Ca}(\text{OCl})_2$ ; Fisher Scientific Co., Fair Lawn, NJ) to match the total chlorine concentration of EO water. Modified EO water was produced from a laboratory EO water generator at a current setting of 12.3 A to produce EO water with a chlorine concentration similar to that of the regular EO water at a pH value around 6.

### **Measurement of the Properties of Water**

The pH and ORP of all the types of water were measured using a digital pH/ORP meter (Acumet model 15, Fisher Scientific Co., Fair Lawn, NJ), and the total chlorine concentration was determined by the iodometric method using a total chlorine test kit (Hach Co., Ames, IA).

### **Immersion Tests**

For each coupon, 600 mL ( $24 \text{ mL/cm}^2$  of specimen) of freshly prepared water at room temperature (22C) was poured into a 2-L glass jar. The coupon was placed on a glass cradle and immersed in the test solution, and the jar was tightly covered to prevent loss of chlorine through evaporation. Each day (after 22 h of immersion), the coupon was taken from the water, washed using the cleaning procedure described above and dried. The pH, ORP and chlorine concentrations of the water after immersion were also measured daily. The weight of the dried coupon was determined using an analytical balance (Voyager, Ohaus Co., Pine Brook, NJ). The surface roughness of each coupon was measured using an automatic surface tester (Hommel tester T1000, Hommel America Inc., New Britain, CT). During measurement, a stylus with a diamond tip attached to a pickup arm is traversed over the surface to be measured. The pickup arm is connected to two laminae and two coils in a

pickup housing, and each movement of the stylus tip following its traverse over a rough surface causes the inductance of the coils to vary. These changes are picked up and converted into a signal that is proportional to the displacement and then reported as the corresponding surface dimension figure. The following surface roughness parameters,  $R_a$  (average surface roughness),  $R_z$  (DIN) (average of five largest peak-to-valley heights within one cutoff length) and  $R_{max}$  (DIN) (the maximum peak-to-valley height within one cutoff length), were calculated based on the surface dimension figure. After these measurements, the dried coupons were reimmersed into freshly prepared EO water, deionized water, chlorine water and modified EO water. The procedure was repeated for 8 days.

### Annual Corrosion Rate Determination

The average weight lost over the period of immersion was calculated for each coupon, and these values were used in determining the annual corrosion rate (ACR), which is the measure of the relative corrosion resistance of the material to the test solution.

$$ACR = KW/A\rho T$$

where  $K$  is the constant for unit of conversion ( $8.76 \times 10^4$ ),  $W$  is the mass loss (g),  $A$  is the surface area of the specimen ( $\text{cm}^2$ ),  $\rho$  is the density of the specimen ( $\text{g}/\text{cm}^3$ ) and  $T$  is the total time of exposure (h).

## STATISTICAL ANALYSIS

Data were analyzed using the general linear model procedures (SAS 1995). The comparison of means was performed using the Duncan's multiple range tests.

## RESULTS AND DISCUSSION

### Change in Water Properties

The initial properties (pH, ORP and chlorine concentration) of all four types of treatment water are presented in Table 1. Changes in water properties are reported as the average of changes occurring daily over a period of 8 days.

TABLE 1.  
PROPERTIES OF WATER USED FOR CORROSION TESTING

| Water | Properties measured |           |                               |
|-------|---------------------|-----------|-------------------------------|
|       | pH                  | ORP (mV)  | Chlorine concentration (mg/L) |
| EO    | 2.42 ± 0.04         | 1077 ± 67 | 48.66 ± 1.06                  |
| DI    | 6.37 ± 0.56         | 584 ± 5   | 0                             |
| CLW   | 8.72 ± 0.56         | 656 ± 90  | 49.16 ± 0.16                  |
| MEO   | 6.12 ± 0.12         | 774 ± 3   | 50.39 ± 0.07                  |

ORP, oxidation–reduction potential; EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified EO water.

### Change in pH

Slight changes in the pH of the water were recorded. The pH of EO water and chlorine water increased during immersion (Fig. 1). The change in pH of these two types of water were, however, not significant ( $P < 0.05$ ). The pH of deionized and modified EO water, which were close to neutrality, decreased during immersion (Fig. 1). There was a significant ( $P < 0.05$ ) interaction between the type of material and water. The magnitude of pH change in deionized water and modified EO water was, therefore, dependent on the type of material immersed in the water. The changes in pH of modified EO water were not significant for all the test materials except carbon steel which had an average decrease in pH of 2.7 per day (Fig. 1).

### Change in Oxidation–Reduction Potential

The ORP of chlorine water and modified EO water increased during immersion (Fig. 2). The change in ORP of modified EO water was higher than that of chlorine water; however, the magnitude of change was highly dependent on the type of material immersed in the water. The ORP of EO and deionized water decreased during immersion, and the immersion of carbon steel in EO water produced the highest loss in ORP (Fig. 2). The change in ORP observed for EO water was, however, not significantly different ( $P < 0.05$ ) from the change in chlorine water except for the immersion of carbon steel.

### Chlorine Loss

The initial chlorine concentration of fresh EO, chlorine water and modified EO water was approximately 50 mg/L (Table 1). The chlorine content in the water decreased during the 22-h immersion; however, the magnitude of loss

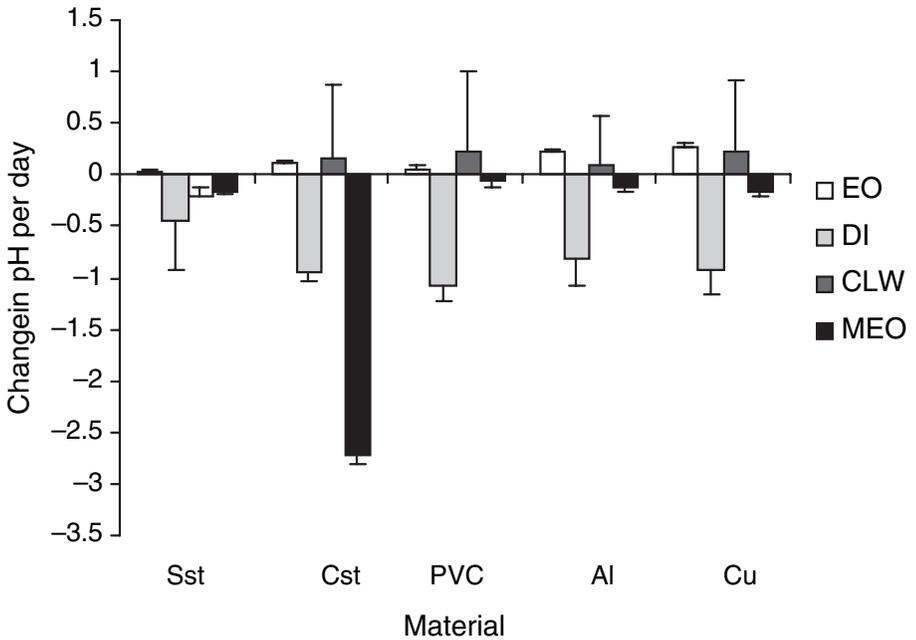


FIG. 1. CHANGE IN pH OF WATER DURING IMMERSION

Sst, 304 stainless steel; Cst, ASTM A-36 medium carbon steel; PVC, polyvinyl chloride type 1; Al, 3003-H14 aluminum; Cu, 110 copper. EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified electrolyzed water.

was dependent on the material tested. The most reactive type of water was EO water, which lost about 85% of the chlorine present per day during the immersion of carbon steel (Fig. 3). EO water also lost about 69% of its chlorine during testing with copper, followed by aluminum (49%), then stainless steel (24%) and PVC (23%). Chlorine water and modified EO water lost very little chlorine during testing with stainless steel (0.74 and 1.94 mg/L, respectively) and PVC (0.67 and 0.85 mg/L, respectively) (Fig. 3). When aluminum was immersed in chlorine water and modified EO water, chlorine water lost 3.4 mg/L daily and modified EO water lost only half as much (Fig. 3).

Len *et al.* (2002) reported a minimal change (< 3 mg/L) in chlorine concentration when EO water was stored in a closed container for 150 h. This suggests that the reduction in the residual chlorine concentration during the immersion of coupons, in this study, was largely because of a reaction between the coupons and the reactive chloride ions. The least resistant material in this study, carbon steel, lost about 50% less chlorine in modified EO water (22 mg/

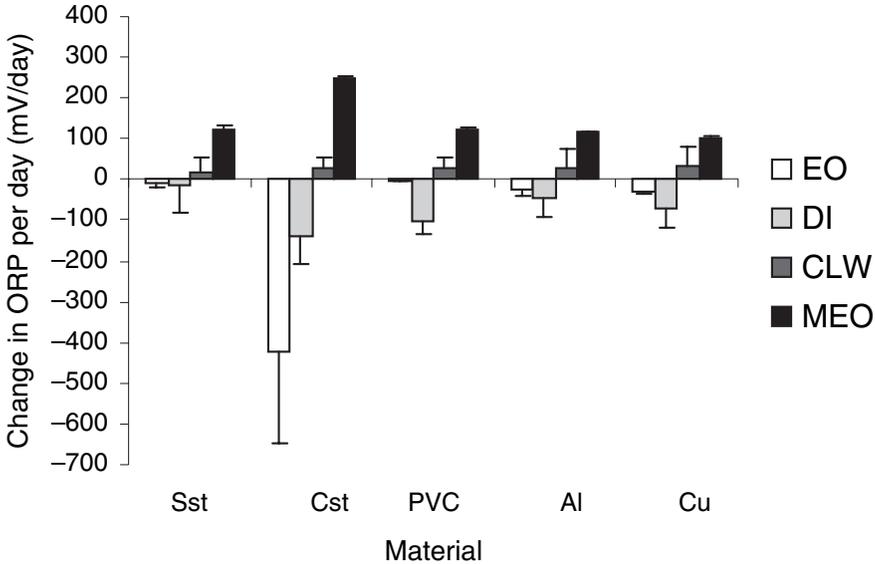


FIG. 2. CHANGE IN OXIDATION REDUCTION POTENTIAL (ORP) OF WATER DURING IMMERSION

Sst, 304 stainless steel; Cst, ASTM A-36 medium carbon steel; PVC, polyvinyl chloride type 1; Al, 3003-H14 aluminum; Cu, 110 Copper. EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified electrolyzed water.

L reduction per day) than in EO water (42 mg/L reduction per day), showing that EO water is more aggressive than modified EO water. With more resistant materials such as stainless steel, PVC, aluminum and copper, the percentage of chlorine lost during testing with modified EO water was less than 20% of what was lost in EO water (Fig. 3).

### Weight Loss

Weight loss determination is one of the most popular methods of estimating corrosion losses in metals. It is simple and direct, requiring no theoretical assumptions or approximations and applicable to all corrosive environments, irrespective of the type of corrosion occurring.

The average weight loss per day was determined from the weight measurements taken. With the exception of PVC, the coupons from all the other materials either maintained their original weight or decreased in weight after immersion. Irrespective of the type of water in which it was immersed, PVC had an increase in weight (Fig. 4). This was a result of the absorption of water into the coupons. Because PVC is porous to a very small extent, the amount

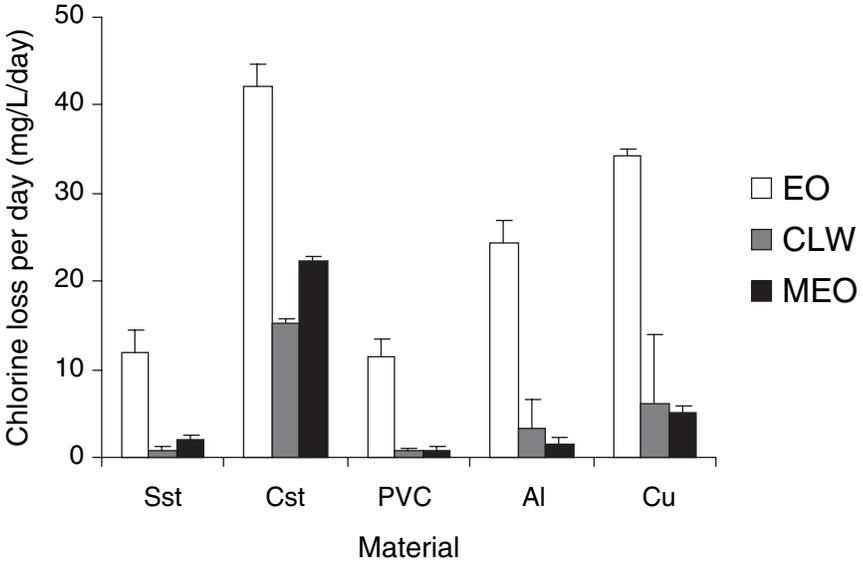


FIG. 3. CHLORINE LOST DURING IMMERSION

Sst, 304 stainless steel; Cst, ASTM A-36 medium carbon steel; PVC, polyvinyl chloride type 1; Al, 3003-H14 aluminum; Cu, 110 copper. EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified electrolyzed water.

of water absorbed was small with the maximum weight increase per day being 0.0015 g for PVC immersed in EO water. Tanaka *et al.* (1999) also reported that vinyl chloride ( $C_2H_3Cl$ ), polypropylene and viton rubber increased in weight when soaked in EO water for 5 weeks.

Carbon steel had the highest weight loss per day (0.04 g), followed by copper (0.03 g) during the immersion in EO water (Fig. 4). Aluminum was affected to a lesser extent and stainless steel was virtually not affected by the EO water. The extent of weight loss was dependent on the type of material as well as on the type of water in which it was immersed. Significant interactions ( $P < 0.05$ ) were found between the type of material and water. Stainless steel, aluminum, copper and carbon steel essentially maintained their original weights after the immersion tests in deionized water. Chlorine water did not affect stainless steel and aluminum; however, it caused weight losses in copper (0.001 g/day) and carbon steel (0.008 g/day). Modified EO water did not produce appreciable weight changes in stainless steel, aluminum and copper, but caused 0.018 g loss in weight per day in carbon steel (Fig. 4).

Depending on the type of water used in testing, each of the five materials behaved differently as a result of their completely different properties. Con-

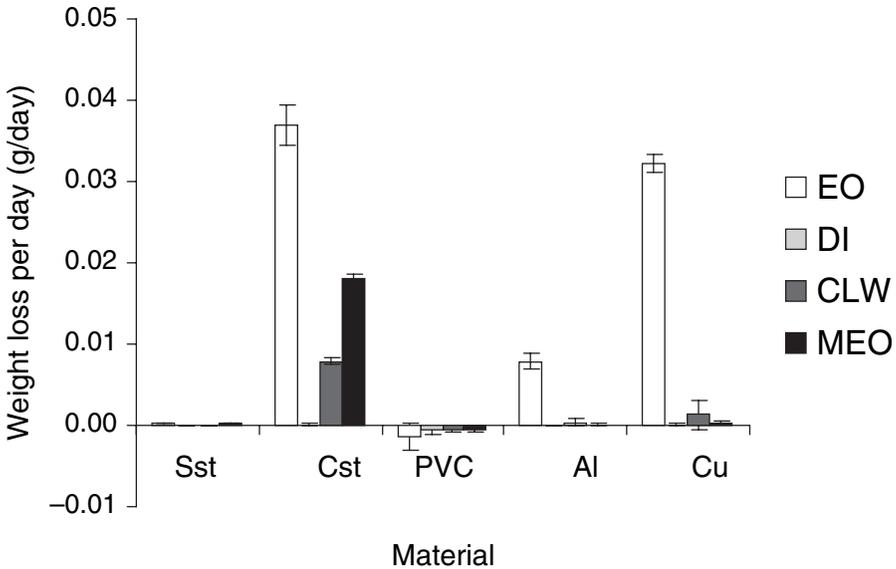


FIG. 4. WEIGHT LOSS IN COUPONS DURING IMMERSION

Sst, 304 stainless steel; Cst, ASTM A-36 medium carbon steel; PVC, polyvinyl chloride type 1; Al, 3003-H14 aluminum; Cu, 110 copper. EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified electrolyzed water.

Considering the least resistant material, carbon steel, EO water was the most reactive among the four types of water used in testing. Modified EO water produced half as much weight loss in carbon steel as EO water. A similar trend was also observed with chlorine losses where the least resistant material, carbon steel, lost about 50% less chlorine in modified EO water than in EO water. From these results, modified EO water had 50% less corrosive effect than EO water. A highly significant correlation ( $r = 0.91$ ) was found between the concentration of chlorine lost and the average weight loss per day in this study, suggesting that the chloride ions were one of the primary causes of corrosion. However, although chlorine water and modified EO water had comparable amounts of chlorine as EO water, these two caused significantly less weight loss in all the tested materials, and hence, less corrosion than EO water. It is apparent, therefore, that the chloride ions were not the only cause of weight loss because of corrosion, that other properties of the EO water could be involved as well. Daufin *et al.* (1988a) stated that the corrosion of metallic materials in contact with aggressive media involves a whole range of factors, which may act singly or jointly. The higher loss in weight per day during the immersion in EO water can be attributed to a joint action of its low

pH and high oxidizing power (high ORP) enhancing the corrosive potential of the chloride ions. The presence of high concentrations of free hydrogen ions ( $H^+$ ), low pH in EO water could speed up the rate of release of electrons from the metal surface resulting in the higher weight loss observed.

### Annual Corrosion Rate

The ACR of all the tested materials, except PVC, was calculated using the total mass lost after 8 days of immersion in the test water. The ACR gives a measure of the resistance of the material to the environment in which it is tested. The higher the ACR, the less resistant the material is to that environment, and vice versa.

The highest ACR was produced when the materials were tested for their resistance to EO water. Carbon steel had the highest ACR (0.5730 mm/year) in EO water, followed by copper (0.4590 mm/year), aluminum (0.3438 mm/year) and stainless steel (0.0038 mm/year) (Table 2). The relative corrosion resistance rating was assigned based on the table developed by Fontana (1986) (Table 3). From this table, carbon steel, which had the highest ACR, was rated as having a fair corrosion resistance in EO water, while copper and aluminum were rated as having a good corrosion resistance in EO water (Tables 2 and 3).

Carbon steel also had a good resistance in chlorine and modified EO water, and its resistance to deionized water was rated as outstanding, showing the dependence of corrosion of materials on the type of environment it is in contact with. The corrosion resistance of carbon steel in modified EO water was 50% more than that in EO water, and copper and aluminum were even more resistant in modified EO water (Table 2). The ACR of aluminum was 74% higher in chlorine water than in modified EO water, and that of copper

TABLE 2.  
ACR OF MATERIALS USED IN THE CORROSION TESTS\*

| Material | Type of water   |                 |                 |                 |
|----------|-----------------|-----------------|-----------------|-----------------|
|          | EO              | DI              | CLW             | MEO             |
| Sst      | 0.0038 (0.0010) | 0.0000 (0.0008) | 0.0002 (0.0008) | 0.0048 (0.0003) |
| Cst      | 0.5730 (0.0393) | 0.0021 (0.0037) | 0.1223 (0.0063) | 0.2827 (0.0052) |
| Al       | 0.3438 (0.0398) | 0.0000 (0.0011) | 0.0169 (0.0191) | 0.0044 (0.0049) |
| Cu       | 0.4590 (0.0161) | 0.0015 (0.0010) | 0.0150 (0.0265) | 0.0053 (0.0027) |

\* Units for annual corrosion rate: mm/year; values in brackets are standard deviations. ACR, annual corrosion rate; Sst, 304 stainless steel; Cst, ASTM medium carbon steel; Al, 3003-H14 aluminum; Cu, 110 copper; EO, electrolyzed water; DI, deionized water; CLW, chlorine water; MEO, modified electrolyzed water.

TABLE 3.  
RELATIVE CORROSION RESISTANCE RANKINGS (Fontana 1986)\*

| Relative corrosion resistance | Annual corrosion rate (mm/year) |
|-------------------------------|---------------------------------|
| Outstanding                   | < 0.02                          |
| Excellent                     | 0.02–0.1                        |
| Good                          | 0.1–0.5                         |
| Fair                          | 0.5–1.0                         |
| Poor                          | 1–5.0                           |
| Unacceptable                  | 5.0+                            |

\* Based on typical ferrous- and nickel-based alloys.

was 65% higher in chlorine water than modified EO water, suggesting that chlorine water, which is commonly used as a sanitizer in the food industry, is also more corrosive to these materials than modified EO water. All four materials had an outstanding corrosion resistance in deionized water and except for carbon steel, the other three materials had an outstanding corrosion resistance in modified EO water.

Stainless steel, which is the most commonly used material in the fabrication of equipment in the food industry, had an outstanding corrosion resistance to all the types of water tested (Table 2). Similar results were obtained by Tanaka *et al.* (1999) who reported less than 0.01 mm/year loss in stainless steel (SUS316) dialysis couplers soaked in electrolyzed strong acid solution for 36 days.

Corrosion was attributed to a reaction between the metals and the chloride ions in the water, and a high correlation ( $r = 0.95$ ) was found between the ACR and the concentration of chlorine lost daily to confirm this relation. Fontana (1986) reported that both hydrogen and chloride ions stimulate the dissolution of metals and alloys, and a similar observation was made from the results of this study. The presence of a higher concentration of  $H^+$  (low pH) in EO water seemed to facilitate the reaction of the chloride ions, resulting in higher corrosion rates in EO water than in chlorine water and modified EO water. From electrochemical considerations, it is also known that the presence of oxidizing agents greatly enhances the corrosiveness of chloride ions (Daufin *et al.* 1988b). The corrosion of carbon steel, aluminum and copper in EO water was therefore caused by the joint action of the low pH (high concentration of  $H^+$ ), the high ORP and chloride ions. It is important to note that the extent of reactivity of each type of water is dependent on the type of material in contact with it and this will also directly influence the extent of corrosion of that material. In essence, although some materials will corrode in some types of water, e.g., carbon steel in EO water, others will not.

## Appearance of Materials After Testing

The immersion of carbon steel in EO water over time produced rust-colored products, from the reaction of the iron present in the carbon steel with chloride, oxygen and water. Modified EO water also caused some minor rusting during the immersion of carbon steel; however, it was not as corrosive to carbon steel as EO water (Table 2). Rust formation is believed to be the result of a series of complex processes that begin with the oxidation of iron to ferrous ( $\text{Fe}^{2+}$ ) ions and then to ferric ( $\text{Fe}^{3+}$ ) ions. The electrons provided from the EO water (because of the strong oxidation potential) may reduce oxygen that would in turn combine with  $\text{Fe}^{3+}$  ions to form ferric oxides such as iron(III) hydroxide ( $\text{Fe}(\text{OH})_3$ ), iron oxide ( $\text{Fe}_3\text{O}_4$ ) and ferric oxide ( $\text{Fe}_2\text{O}_3$ ). Ferric oxides when hydrated in water form rust ( $\text{Fe}_2\text{O}_3 \cdot x\text{H}_2\text{O}$ ). At the end of the immersion period (8 days), deionized water and chlorine water did not change the color of carbon steel. Modified EO water and EO water, however, caused bleaching of its dark-gray color with the extent of bleaching being higher in EO water than in modified EO water.

During the testing of stainless steel with modified EO water and chlorine water, a small amount of yellow rust was observed on the cut and exposed edge of the coupon. This tainting, although very small, was not observed with EO water. Stainless steel relies on the stable chromium oxide film to provide corrosion resistance. The rust observed on the cut edge is evidence of some amount of corrosion because of the destruction of the oxide film on that side of the coupon during cutting and exposing iron to the environment. Besides the evidence of some rusting on its exposed sides, stainless steel had an outstanding corrosion resistance to modified EO water (Table 2). All the types of water tested also did not alter the shiny appearance of the stainless steel coupons.

The appearance of PVC did not change after immersion, irrespective of the test water used. After immersion in deionized and modified EO water, the appearance of aluminum did not change. On the other hand, chlorine water changed the silvery luster of the aluminum coupons to a dull tarnished color, and EO water bleached the coupons white.

Deionized water did not change the shiny appearance or color of copper; however, chlorine water and modified EO water changed its appearance to a dull rusty red. Black rust streaks that started from the edge of the coupons and grew progressive over their surface with time, were observed on copper coupons immersed in chlorine water and modified EO water. The coupons immersed in chlorine water had more of these black rust streaks than the coupons immersed in modified EO water. EO water caused pitting on copper and also made its color pale.

Besides deionized water, modified EO water had the least effect on the tested materials. In the case of stainless steel, in so far as the surface is not broken resulting in the destruction of the protective oxide layer, no problems will be encountered and modified EO water can be safely used. Modified EO water also had no effect on the appearance of aluminum and PVC. However, the application of modified EO water in an environment containing copper or carbon steel may not be desirable.

### Surface Roughness

Corrosion causes changes in the surface properties of the metal as a result of the formation of pits, crevices or cracks, and these changes can be monitored to obtain additional information on the extent and type of corrosion.

In this study, the effect of the treatment water on the surface roughness of the coupons was highly dependent ( $P < 0.05$ ) on the type of material. The  $R_a$  profile of stainless steel and PVC remained about the same during the immersion regardless of the treatment water (Fig. 5A,C). EO water significantly increased ( $P < 0.05$ ) the  $R_a$  of carbon steel, aluminum and copper than the other types of water tested. Multiple comparison tests showed that deionized water, chlorine water and modified EO water had the same effect on the  $R_a$  of carbon steel, aluminum and copper (Fig. 5B,D,E). The increase in  $R_a$  of the carbon steel, aluminum and copper after being immersed in EO water can be attributed to the dissolution of these metals and the formation of pits as a result of corrosion.

$R_a$  measures the average of the surface roughness, and hence, it is not sensitive to individual peaks and valleys such as  $R_z$  and  $R_{max}$  (Mummery 1992).  $R_z$  is a measure of the average depth of pits formed on the materials as a result of corrosion during immersion in the treatment water, and  $R_{max}$  is a measure of the depth of the largest pit formed within the assessed profile of the coupons. Graphs showing the change in  $R_z$  and  $R_{max}$  of the materials with time followed the same trend as that of  $R_a$  with time (data not shown). The only difference was that for every material at any point in time,  $R_{max}$  was greater than  $R_z$  which was in turn greater than  $R_a$ . For example, the initial surface roughness measurement, i.e., day 0,  $R_a$  for stainless steel was  $0.307 \mu\text{m}$ , while  $R_z$  was  $2.455 \mu\text{m}$  and  $R_{max}$  was  $3.122 \mu\text{m}$ . These differences in magnitude are a result of what each parameter is measuring with  $R_{max}$  accounting for the largest pit, while  $R_z$  accounts for the average of the five largest pits. As a result of the similar trends, the graphs of  $R_z$  and  $R_{max}$  with time are not shown.

The  $R_z$  and  $R_{max}$  of stainless steel and PVC also remained almost the same throughout the period of immersion in all four types of water, and statistical analysis showed that the treatment water did not significantly alter the  $R_z$  and

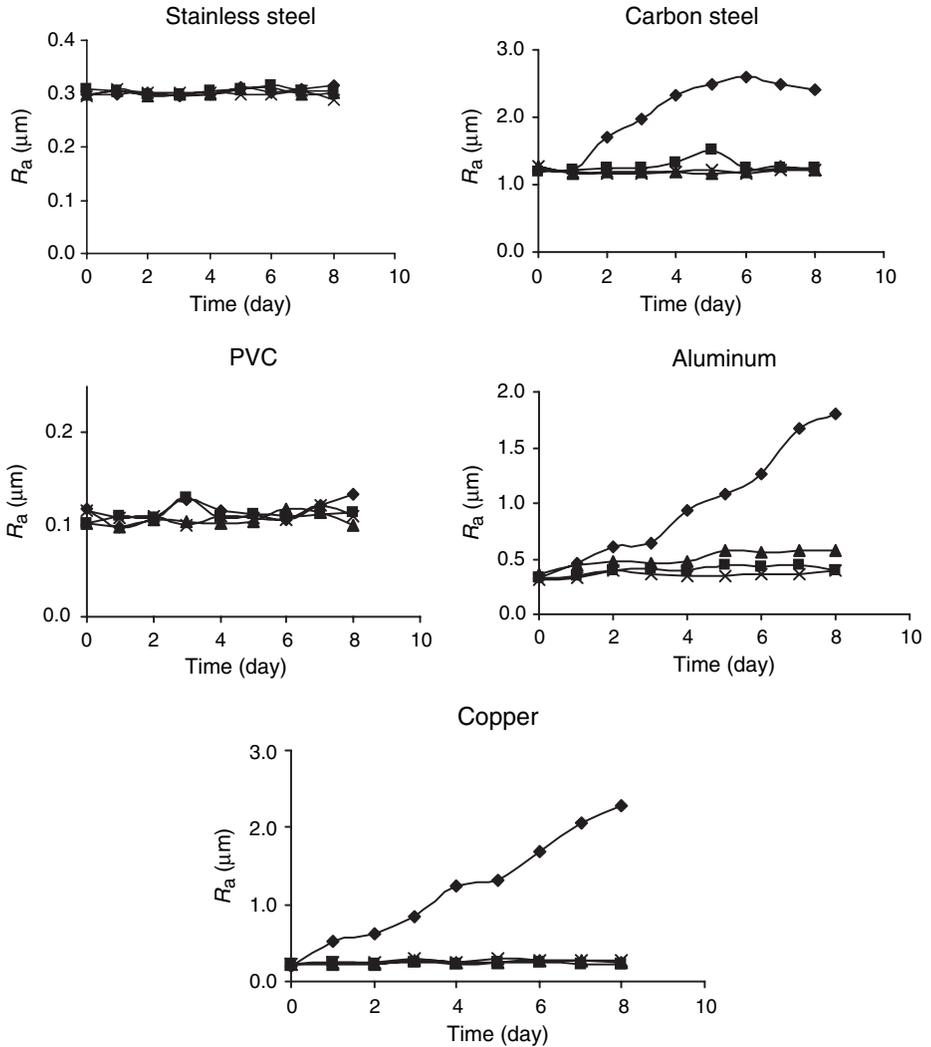


FIG. 5. CHANGE IN AVERAGE SURFACE ROUGHNESS OF COUPONS WITH TIME (◆) Electrolyzed water, (■) deionized water, (▲) chlorine water and (×) modified electrolyzed water.

$R_{\max}$  of these materials. This indicates that the treatment water did not affect the surface roughness of these materials.

The multiple comparison tests showed that the effect of deionized water, chlorine water and modified EO water on the  $R_z$  and the  $R_{\max}$  of carbon steel, aluminum and copper was the same, and changes occurring in the original

surface profile of these during immersion were minimal. As was observed with  $R_a$  measurements, EO water was the only test water that caused a significant increase ( $P < 0.05$ ) in  $R_z$  and  $R_{max}$  (evidence of pitting corrosion) on carbon steel, aluminum and copper. Significant changes in  $R_z$  and  $R_{max}$  of carbon steel were observed only after the second day of immersion; after the third day for copper and after the fourth day for aluminum. It was thought that the shorter the initiation period for pitting, the less resistant the material may be in that environment. This was confirmed by the annual corrosion rates of these materials in EO water (Table 2).

Because EO water contained about the same amount of residual chlorine as chlorine water and modified EO water, the aggressive nature of the EO water environment, causing significant changes in surface roughness, was attributed to a joint action of its low pH and high oxidizing power (high ORP) enhancing the corrosive potential of the chloride ions present.

## CONCLUSIONS

The results of this study showed that the corrosion of metals is dependent on the type of environment and the resistance of the material in question. Carbon steel was the least resistant of all the materials tested. Although carbon steel had a fair, good and good corrosion resistance in EO water, chlorine water and modified EO water, respectively, its use in such environments is not recommended. Stainless steel, which is the most commonly used material in food contact surface and equipment fabrication in the food industry, had an outstanding corrosion resistance to all the types of water tested. Because EO water did not have any adverse effect on stainless steel, it can still be safely used as a sanitizer to inactivate bacteria on food contact surfaces made from stainless steel in food processing plants. Among the four types of water tested, EO water was the most aggressive, causing uniform and pitting corrosion of carbon steel, copper and aluminum. When EO water was modified to a higher pH, it ceased to be as aggressive and in most cases only had the same effect as deionized water. These results demonstrate that EO water and modified EO water are promising sanitizers for the food industry.

## REFERENCES

- ABD EL MEGUID, E.A. and ABD EL LATIF, A.A. 2004. Electrochemical and SEM study of type 254 SMO stainless steel in chloride solutions. *Corros. Sci.* 46, 2431–2444.

- ASTM. 1999a. *Standard G1-90: Standard Practice for Preparing, Cleaning and Evaluating Corrosion Test Specimens*, pp. 1–7, Annual book of ASTM standards. ASTM, West Conshohocken, PA.
- ASTM. 1999b. *Standard G31-72: Standard Practice for Laboratory Immersion Corrosion Testing of Metals*, pp. 1–8, Annual book of ASTM standards. ASTM, West Conshohocken, PA.
- BOHNER, H.F. and BRADLEY, R.L. 1991. Corrosivity of chlorine dioxide used as sanitizer in ultrafiltration systems. *J. Dairy Sci.* 74, 3348–3352.
- BUCK, J.W., VAN IERSEL, M.W., OETTING, R.D. and HUNG, Y.-C. 2003. Evaluation of acidic electrolyzed water for phytotoxic symptoms on foliage and flowers of bedding plants. *Crop Prot.* 22, 73–77.
- DAUFIN, G., PAGETTI, J., COWAN, C.T., WILDBRETT, G., OENEMA, S., FLUCKIGER, E., MORRISON, R. and WILES, P.G. 1988a. An introduction to the electrochemical principles of corrosion. *Bull. Int. Dairy Fed.* 236, 10–20.
- DAUFIN, G., PAGETTI, J., COWAN, C.T., WILDBRETT, G., OENEMA, S., FLUCKIGER, E., MORRISON, R. and WILES, P.G. 1988b. Corrosion by peracetic acid solutions. *Bull. Int. Dairy Fed.* 236, 3–9.
- EZEIKE, G.O.I. and HUNG, Y.-C. 2004. Acidic electrolyzed water properties as affected by processing parameters and their response surface models. *J. Food Process. Pres.* 28, 11–27.
- FONTANA, M.G. 1986. *Corrosion Engineering*, pp. 39–173, McGraw-Hill, New York.
- FRANK, J.F. and CHMIELEWSKI, R. 2000. Influence of surface finish on the cleanability of stainless steel. *J. Food Prot.* 64, 1178–1182.
- HOLAH, J.T. and THORPE, R.H. 1990. Cleanability in relation to bacterial retention on unused and abraded domestic sink materials. *J. Appl. Bacteriol.* 69, 599–608.
- HSU, S.-H., KIM, C., HUNG, Y.-C. and PRUSSIA, S.E. 2004. Effect of spraying on chemical properties and bactericidal efficacy of electrolyzed oxidizing water. *Int. J. Food Sci. Technol.* 39, 157–165.
- KIM, C., HUNG, Y.-C. and BRACKETT, R.E. 2000. Efficacy of electrolyzed oxidizing (EO) and chemically modified water on different types of food borne pathogens. *Int. J. Food Microbiol.* 61, 199–207.
- KIM, C., HUNG, Y.-C., BRACKETT, R.E. and FRANK, J.F. 2001. Inactivation of *Listeria monocytogenes* biofilms by electrolyzed oxidizing water. *J. Food Process. Pres.* 25, 91–100.
- KIM, C., HUNG, Y.-C., BRACKETT, R.E. and LIN, C.-S. 2003. Efficacy of electrolyzed oxidizing water in inactivating *Salmonella* on alfalfa seeds and sprouts. *J. Food Prot.* 66, 208–214.
- KIURA, H., SANO, K., MORIMATSU, S., NAKANO, T., MORITA, C., YAMAGUCHI, M., MAEDA, T. and KATSUOKA, Y. 2002. Bacteri-

- cidal activity of electrolyzed acid water from solution containing sodium chloride at low concentration, in comparison with that at high concentration. *J. Microbiol. Methods* 49, 285–293.
- LEN, S.-V., HUNG, Y.-C., CHUNG, D., ANDERSON, J.L., ERICKSON, M.C. and MORITA, K. 2002. Effects of storage conditions and pH on chlorine loss in electrolyzed oxidizing (EO) water. *J. Agric. Food Chem.* 50, 209–212.
- MCCAFFERTY, E. 2003. Sequence of steps in the pitting of aluminum by chloride ions. *Corros. Sci.* 45, 1421–1438.
- MUELLER, D.S., HUNG, Y.-C., OETTING, R.D., VAN IERSEL, M.W. and BUCK, J.W. 2003. Evaluation of electrolyzed oxidizing water for management of powdery mildew on gerbera daisy. *Plant Dis.* 87, 965–969.
- MUMMERY, L. 1992. *Surface Texture Analysis: The Handbook*, pp. 23–59, Hommelwerke GmbH, Schwenningen, Germany.
- PARK, H., HUNG, Y.-C. and BRACKETT, R.E. 2002. Antimicrobial effect of electrolyzed water for inactivating *Campylobacter jejuni* during poultry washing. *Int. J. Food Microbiol.* 72, 77–83.
- PARK, H., HUNG, Y.-C. and CHUNG, D. 2004. Effects of chlorine and pH on efficacy of electrolyzed water for inactivating *Escherichia coli* O157:H7 and *Listeria monocytogenes*. *Int. J. Food Microbiol.* 91, 13–18.
- PARK, C.-M., HUNG, Y.-C., DOYLE, M.P., EZEIKE, G.O.I. and KIM, C. 2001. Pathogen reduction and quality of lettuce treated with electrolyzed oxidizing and acidified chlorinated water. *J. Food Sci.* 66, 1368–1372.
- STATISTICAL ANALYSIS SYSTEM (SAS). 1995. *User's Guide*, Version 6. SAS Institute, Inc., Cary, NC.
- TANAKA, N., FUJISAWA, T., DAIMON, T., FUJIWARA, K., TANAKA, N., YAMAMOTO, M. and ABE, T. 1999. The effect of electrolyzed strong acid aqueous solution on hemodialysis equipment. *Artif. Organs* 23, 1055–1062.
- VENKITANARAYANAN, K.S., EZEIKE, G.O.I., HUNG, Y.-C. and DOYLE, M.P. 1999. Inactivation of *Escherichia coli* O157:H7 and *Listeria monocytogenes* on plastic cutting boards by electrolyzed oxidizing water. *J. Food Prot.* 62, 857–860.