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BEHAVIOR OF CANDIDATE CANISTER MATERIALS IN DEEP OCEAN ENVIRONMENTS

W. H. Smyrl, L. L. Stephenson, J. W. Braithwaite

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INTRODUCTION

The disposal of radioactive wastes has become a major area of concern in recent years. The projected increase in the number of nuclear reactors with the consequent increase in radioactive waste has spurred a need for the development of a technology for the handling and disposal of the waste. This waste disposal method must meet several requirements, the most important of which is that containment must be secure for thousands of years. This requirement has narrowed the search for possible disposal sites to geologically stable areas of the world where the natural properties of the site would serve as a major barrier to the dispersal of radioactivity into the biosphere.

One such site which has been identified as deserving further study is the sediments and bedrock beneath the deep ocean floor in the North Pacific Ocean. The merits of the site are: 1) it is an area which has not been geologically active for millions of years; 2) it is an area with small to moderate ocean currents to transport released radioactivity to the adjoining biosphere; 3) this part of the ocean has a low density of life forms which could be affected by released waste; 4) there are only small quantities of minerals which could potentially attract mining activities; and 5) the area is remote enough to discourage tampering by people with mischievous or harmful intentions.

Metallic canisters would be used for the emplacement of waste in this repository. These canisters would serve as shipping containers and possibly as an additional primary barrier to dispersal of the waste at the burial site. The lifetime of an implaced canister will depend on several factors, the most important of which are: 1) the nature of the waste form and its

compatibility with the canisters; 2) the compatibility of the canister with the external environment, and 3) the mechanical integrity of the canister under the pressure stress of the deep ocean. The expected lifetime will determine whether such a canister will be useful only as a shipping container, or, in addition, as a primary dispersal barrier. For the canister to act as a dispersion barrier, a lifetime of approximately 1000 years at temperature for a 1 cm wall is needed.

This paper describes preliminary results of tests undertaken to evaluate the compatibility of candidate canister materials with the external environments of ocean water and sediments. The compatibility of these materials with the radioactive waste form is expected to be studied at a later time.

The useful lifetime of a metal in a marine environment is limited by its rate of corrosion. Rates of uniform corrosive marine attack have been documented for a large number of systems, even though the basic corrosion processes which occur are not always well understood. Many materials, attractive because of their low initial cost and high availability, were precluded from further consideration because of unacceptably high corrosion rates. Specifically, the corrosion data Fink and Boyd [1] and Uhlig [2] collected on a wide range of materials in marine environments allowed steels, aluminum alloys, and copper alloys to be eliminated as possible canister materials. Their data showed aluminum alloys, copper alloys, and steels, including stainless steels, have corrosion rates which are too high by a factor of 10 to 100 to give the proposed 1000 year life for a 1 cm thick wall. These same sources [1,2] also list the types of nonuniform, or localized, attack which have been observed for specific materials. Rates of penetration due to localized corrosion (e.g., pitting, crevice corrosion) are not well documented, but are always faster than uniform dissolution rates. This led to the decision to reject candidate materials which show susceptibility to localized attack because of the uncertainty in the rates of penetration. Some iron alloys, stainless steels, high strength aluminum alloys,

and copper alloys, in addition to having excessively high corrosion rates, are also susceptible to localized corrosion. Some types of nonuniform attack could lead to localized stress concentration which could cause premature mechanical wall failure. Where no information was available on nonuniform attack of a material, another criterion was used. This criterion was based on the sensitivity of the electrochemical behavior of a material to the dissolved oxygen concentration in solution. That is, if a material is sensitive to the oxygen concentration, localized corrosion may be initiated by local differences in oxygen concentration. The nonuniform concentration causes a nonuniform potential distribution to be set up on the surface such that the oxygen starved region (e.g., under biological growth or beneath sediments) is driven to dissolve faster by the surrounding cathodic region (oxygen rich). Associated pH changes subsequently accelerate the dissolution process. For example, this corrosion mechanism causes nonuniform attack of steel anchor chains partially buried in sediments. Candidate materials which are susceptible to stress corrosion cracking, corrosion fatigue, and hydrogen embrittlement were also rejected.

Applying the above criteria to corrosion data obtained from a preliminary literature survey allowed materials from the titanium, zirconium, and nickel base alloys to be selected for the first series of experiments.

In seawater, at or near room temperature, titanium has a very low corrosion rate and is not susceptible to localized attack at $\text{pH} > 2$ [1,2,3,4,5,6]. Some alloys are susceptible to pitting corrosion at room temperature with an induced potential. At elevated temperatures, pure titanium and many of its alloys corrode faster, and are susceptible to localized attack [1,2,5,6,7,8]. However titanium alloyed with small amounts of palladium, or up to 2% Ni is very resistant to all corrosion processes up to 250°F [8]. Titanium has been used as heat exchanger material in desalination plants since 1965 with no deterioration at 110°C [8,9,10]. Under equivalent conditions, 304 stainless steel is pitted through the tube thickness in a few days. Some meager deep ocean corrosion data for titanium alloys are also available [11].

Zirconium has low corrosion rates in marine environments [1,2,3,4]. It has also been used successfully in water-cooled nuclear reactors as cladding material [12], but the water is highly purified in this application. Very little is known about the localized attack of zirconium, but it is more susceptible than titanium to pitting [12].

Of the nickel-based alloys, Hastelloy C has the lowest corrosion rates in marine environments [1,2]. In addition, it is not susceptible to localized corrosion at 25°C in seawater, although strongly acidic conditions can induce crevice corrosion. The uniform corrosion rates of Hastelloy C increases with temperature [13], as does the susceptibility to nonuniform attack (pitting). At high temperatures (up to 500°F), Hastelloy C has lower corrosion rates than does pure titanium, and is more resistant to localized attack [14]. This correlates with its lower sensitivity to dissolved oxygen [14]. Determination of corrosion rates under deep ocean conditions have been performed [11,15,16,17] and Hastelloy C appears to perform satisfactorily under these conditions. However, the conditions were not equivalent to those presently required for deep ocean disposal.

The results to be described here are corrosion rate (weight loss) data at several temperatures and at a pressure representative of the deep ocean, and electrochemical data from tests conducted under ambient laboratory conditions. The data are preliminary and serve to illustrate the performance of the experimental facilities as well as the behavior of the materials in an ocean environment.

EXPERIMENTAL

The materials which were chosen for study were the following:

- 1) Titanium (chemically pure)
- 2) Titanium-6-4 (6% Al, 4% V, 90% Ti)
- 3) Zirconium (chemically pure)
- 4) Zircaloy-2, Zr-2 (1.5% Sn, .12% Fe, .1% Cr, .05% Ni, 98.2% Zr)
- 5) Zircaloy-4, Zr-4 (1.5% Sn, 0.2% Fe, 0.1% Cr, 98.2% Zr)
- 6) Hastelloy C-276 (59% Ni, 17% Mo, 15% Cr, 5% Fe, 4% W)
- 7) Udimet 700 (4% Al, 4% Ti, 5% Mo, 15% Cr, 15% Co, 57% Ni)

These materials show generally superior corrosion behavior in shallow seawater as discussed above. Bottom ocean water from the North Pacific and sediments with supernatant seawater from the Atlantic were received and stored until needed in large polyethylene carboys.

A. Pressure Tests

The corrosion and stress corrosion behavior of the metals and alloys selected for these preliminary tests were determined under simulated deep ocean conditions. Pressure at the floor of the North Pacific ocean is a function of total depth, but is about 55 MN/m^2 (8000 psi). Therefore, this pressure was chosen as the working pressure for the tests described here. Tests were run at 4°C , the temperature of the deep ocean water, and at 25°C and 90°C to determine the effect of increased temperature which could occur due to the heat load of the radioactive waste. These temperatures were not chosen to reflect an expected temperature, because this information depends on the specific design of the canister and had not been provided.

Two pressure chambers (5 cm ID x 53 cm depth, WP = 207 MN/m^2 (30,000 psi) were used at each of the three temperatures. The chambers were constructed of 4340 steel.

Corrosion coupons were cut from the plates as received, in one inch squares of plate thickness. The upper and lower surfaces were ground flat and polished to a mirror finish. Specimen weights were determined immediately before immersion in the seawater or sediments to 0.1 mg accuracy.

Stress corrosion cracking specimens were machined, polished, scribed and wedge-loaded in a vise to a given crack opening displacement. The wedge material was the same as the specimen material in every case. Stress corrosion cracking susceptibility was determined in seawater only.

Individual corrosion coupons were placed in plastic bags along with seawater or sediments (with a small amount of supernatant seawater), and the bag was sealed with a heat press. A small quantity of lab air was always trapped in the bag as well. The sealed bag was placed in a plastic bottle with other specimens of the same material.

Stress corrosion specimens were placed in the bottle with no bag, and the bottle was completely filled with seawater and the lid was screwed on.

The bottles containing the specimens were loaded into the appropriate pressure chamber. The pressure chamber assemblies were placed in controlled temperature cabinets and attached to a high pressure line. The chambers and lines were filled with hydraulic fluid and the system was pressurized to the desired 8000 psi. After thermal equilibrium was attained, the pressure was again adjusted to 8000 psi. The pressure was monitored frequently and maintained. No pressure rise was ever detected during the nine month tests.

B. Ambient Tests

Tests were performed under ambient laboratory conditions to determine the electrochemical behavior of the materials to supplement the corrosion tests. These preliminary tests consisted of stationary electrode polarization curves (i.e., current-voltage curves) of the materials in the seawater and seawater-sediment slurries to establish general corrosion behavior. Rotating disk studies were also performed to determine the sensitivity of the materials to dissolved oxygen in the seawater.

Individual electrode specimens for the stationary electrode polarization tests were machined to 0.6 cm diameter cylinders of plate thickness. A hole was tapped in one end of the cylinder to accommodate a threaded copper rod. The two were screwed together and potted in epoxy so that the joint between the dissimilar metals was covered. The bottom end was then ground back to expose the embedded disk of material. Additionally, the end was polished just before each polarization test was run. These tests were run without stirring, except as noted.

The rotating disk tests were used to determine oxygen sensitivity as will be discussed below. These tests were conducted in seawater saturated with room air and in deaerated seawater. Seawater was deaerated by purging ultra-pure argon through the seawater for a minimum of a few hours. All residual oxygen contained in the ultra-pure argon was removed before purging by passing the argon through a solution containing 15% pyrogallol and 25% NaOH [18]. This

deaeration procedure was done in the same container the rotating disk test was performed in. This container was designed with a minimum of non gas-tight external connections and a positive argon pressure was maintained above the solution at all times. The rotating disks were constructed as shown in Figure 1. The bottom surface of the specimen was polished just prior to use. The motor control and support frame for the rotating disk assembly were constructed as described previously [19].

RESULTS AND DISCUSSION

The results to be presented here are preliminary and should not be used for extrapolating to long times, although all the materials did show excellent corrosion resistance over the nine month test duration.

A. Pressure Tests

The measured weight loss of the individual samples is recorded in Tables I, II and III for the three different corrosion temperatures used, respectively. The weight loss in all cases is small, and titanium and Hastelloy C show the smallest weight loss. Some specimens had a weight gain, presumably due to the accumulation of corrosion products, but this has not been investigated. For those specimens with a weight loss, the loss was converted to the equivalent corrosion rate which is reported in the last column. The corrosion was uniform over the surface as discussed below. These data should not be extrapolated to thousands of years, but as a preliminary indication all the materials would be expected to show a long life in seawater environments and are worthy of continued attention. No susceptibility to stress corrosion cracking was observed for any of the materials tested (crack velocity was less than 2×10^{-9} cm/sec).

No pitting corrosion or nonuniform attack was observed on any of the specimens. Photographs taken before and after the test revealed virtually identical surface appearance. Only the zirconium alloys had any change, which was a uniform darkening of the polished surface. The scratches from the original polishing could be seen with a low power microscope (50X), but no other imperfections such

as pits were revealed. These observations are consistent with the very low weight losses measured on the specimens. They also strongly support a uniform corrosion mechanism of all specimens.

Scanning electron microscope investigation of specimen surfaces after corrosion testing revealed no evidence of localized attack. A typical example of scanning electron microscope pictures of untested and tested specimen surfaces are shown in Figure 2. Comparison of these pictures show that no pits were formed during testing. This behavior is consistent with the polarization results to be described below. However, even if pits had been revealed on this scale, there is no guarantee that the pits would grow to macroscopic size. It is known that pits must grow to some critical size (which depends on pH, Cl^- or Br^- or I^- concentration, pit density and convective conditions) before pit stability is achieved.

B. Ambient Tests

Stationary electrode polarization curves for the Ti-6-4 and the Zr-4 specimens in seawater are shown in Figures 3 through 4, respectively. The stationary electrode polarization curves for the Hastelloy-C and commercial purity titanium specimens are similar to that for Ti-6-4 (Figure 3), while the Udimet-700, Zr and Zr-2 polarization curves are similar to the one for Zr-4 (Figure 4). Figures 3 and 4 are also typical for the respective specimens stationary electrode polarization curves measured in seawater and sediments, provided both the seawater and the slurry are agitated in the same way.

At negative potentials, the current is cathodic and is the result of hydrogen ion reduction on the working electrode. At positive potentials, the current is anodic and there is metal dissolution. At higher potentials (above 1.5V) oxygen is evolved, except on Ti and Ti-6-4. For these two titanium materials and especially commercial purity titanium, the potential must be increased to much higher values for oxygen evolution to occur. The polarization measurements were not continued to high positive potentials for titanium because it is unlikely that such potentials would be representative of service conditions of disposal canisters.

As shown in Figure 3, the current for the titanium alloys is

very low at intermediate potentials. This inert behavior, or "passivity," is caused by the formation of an insoluble oxide film on the surface. Similarly, the other materials studied also have very stable oxide films which cause the materials to support only small currents at potentials characteristic of service conditions--indicative of very low corrosion rates.

In Figure 4, it should be noted that there is a marked hysteresis in the polarization curve for Zr-4 at positive potentials. The positive-going part of the curve is lower than that for the return curve. This behavior is characteristic of metals which will undergo pitting corrosion. The appearance of a Zr-4 specimen which has been held at potentials in the hysteresis region is shown in Figure 5. Such localized attack would cause a canister wall to be breached or penetrated rapidly in these pitted areas. This behavior was observed for all the zirconium based materials.

The potential on the zirconium alloys used to produce the localized attack as shown in Figure 5, had to be adjusted artificially to the pitting susceptibility region. In order for such attack to occur in service, there must be a mechanism to produce such conditions. We do not propose such a mechanism here, but rather suggest that some caution be exercised in using these alloys. It should be noted that susceptibility to pitting corrosion is generally increased at higher temperatures, i.e., pitting occurs at lower potentials as the temperature is increased, and therefore might occur under higher temperature service conditions.

C. Electrochemical Reduction of Oxygen at Rotating Disk Electrodes

Polarization curves for stationary electrodes reveal behavior adequately for reactions controlled by surface kinetics. When diffusion of a species becomes the limiting factor, stationary electrodes are inadequate because the surface is generally not uniformly accessible to the diffusing species. To study such situations, the rotating disk electrode has been developed [19,20, 21,22]. It has well-defined hydrodynamics which enable the surface to be uniformly accessible to a species diffusing from solution. The electrochemical reduction of dissolved oxygen at an electrode may be studied with this electrode system. The information from such

studies can be used to predict the susceptibility of materials to nonuniform corrosion which may be initiated by differential aeration (i.e., different rates of supply of oxygen to different parts of a surface). Therefore, polarization measurements in the cathodic region (oxygen discharge and hydrogen reduction) have been made using rotating disk electrodes to evaluate this differential aeration susceptibility of the candidate materials.

The reduction of dissolved oxygen at a cathodic site may be expressed by the net reaction

Different metal and metal oxide surfaces catalyze the kinetics of oxygen reduction to different degrees. Some metals with oxide films are such poor catalysts for the oxygen reduction that there is hardly a detectable oxygen cathodic current at low voltages. Measurement of the cathodic current in neutral seawater with different quantities of oxygen, or at different rates of supply to the surface (caused by different rotation speeds), will reveal whether the oxygen reaction takes place at any appreciable rate at the metal surface. The measurements reported here were performed at disks rotating at different angular velocities in deaerated and air-saturated seawater. The data for the cathodic polarization on Ti-6-4 rotating disks in air-saturated seawater are shown in Figure 6. There is a distinct plateau at potentials of -1400 mV, and the plateau current is a function of rotation rate. The inverse of the plateau current is plotted in Figure 7 versus the square root of the inverse of the rotation rate. This functional dependence is that expected for the rotating disk electrode system [20]. Also the extrapolation of the line through the origin is an indication that the current is diffusion controlled. From the slope of the curve in Figure 7 and the Levich equation for the limiting diffusion current [20],

$$i = -0.62 nF D_{\text{O}_2}^{2/3} \nu^{-1/6} \omega^{1/2} C_{\text{O}_2} (\infty)$$

the value of the diffusion coefficient of oxygen in seawater was calculated to be $2.06 \times 10^{-5} \text{ cm}^2/\text{sec}$, very close to the literature values [23]. In the above equation

- n is the number of electrons involved in the reduction action
- F is the Faraday constant
- D_{O_2} is the oxygen diffusion coefficient
- ω is the rotation rate
- ν is the kinematic viscosity of seawater
- C_{O_2} is the bulk concentration of dissolved oxygen

The fast increase in cathodic current at potentials less than -1600 mV is due to hydrogen ion reduction on the Ti-6-4 surface. The corresponding Ti-6-4 rotating disk electrode polarization curves in deaerated seawater are shown in Figure 8. The expected complete absence of any rotation speed effect and oxygen plateau should be noted.

The zirconium and nickel base materials did not show a similar oxygen sensitivity. The rotation rate and oxygen concentration did not influence the polarization curves for either Hastelloy-C or Zircaloy-4 as shown in Figures 9-12. These materials are therefore very poor oxygen reduction catalysts.

The polarization curves for the other nickel base alloy, Udimet-700, are shown in Figures 13 and 14. A very slight oxygen sensitivity is shown in these figures for Udimet-700 (e.g., one between Ti-6-4 and Hastelloy-C). This oxygen sensitivity is almost negligible, however, when compared to that for Ti-6-4.

The overall conclusion to be reached from these rotating disk studies is that, under ambient conditions, the zirconium and nickel base alloys should not be expected to be susceptible to differential aeration-related corrosion (e.g., crevice corrosion) whereas the titanium base alloys could be susceptible.

However, in order for a metal to be susceptible to differential aeration corrosion, the polarization curve in the deaerated solution must be related to that in the aerated solution as shown in either Figure 15a or 15b. Alkire, et al [24], have discussed aeration

effects for metals with polarization curves like the one shown in Figure 15a. The key property is that the reduction of oxygen takes place at potentials where the surface is in the passive region--potentials more positive than the active metal dissolution region. Therefore, if one part of the surface is exposed to oxygen-rich conditions, and another part to deaerated conditions, the deaerated surface will anodically dissolve while the other will support oxygen reduction. These two reactions will drive one another and current will flow in solution from one part of the surface to the other.

The condition that an anodic reaction takes place at a more negative potential with respect to oxygen reduction on the metal may also be fulfilled by the behavior shown in Figure 15b. This behavior is more usual than the behavior in Figure 15a. It is sufficient to say that the titanium base alloys do not exhibit either type of behavior. Thus, although they will support oxygen reduction currents, the titanium base materials will not be susceptible to differential aeration corrosion at ambient conditions. This is consistent with the literature reports. High temperatures are required, at one atmosphere pressure, to produce, for example, susceptibility to crevice corrosion [14]. The polarization behavior of titanium at such temperatures is similar to that in Figure 15a.

SUMMARY

Corrosion tests have been conducted under simulated deep ocean conditions for nine months. The experimental apparatus performed adequately, and the results indicated that longer term tests could be conducted. The materials chosen to test were base alloys of titanium, zirconium, and nickel. All materials tested showed corrosion rates that were very low even at the highest test temperature. Additionally, none of the materials showed susceptibility to either stress corrosion cracking or differential aeration corrosion. Ambient electrochemical tests confirmed the findings that none should be sensitive to differential oxygen effects. The zirconium alloys may be more susceptible to pitting corrosion than the others, although the pitting conditions are unlikely to be found in service, unless higher temperatures are encountered. All the alloys tested could give long life under deep ocean conditions and are candidates for more detailed corrosion studies.

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TABLE I

Corrosion Rate of Candidate Materials in Seawater
and Sediments at 4°C, 55 MN/m² (8000 psi)¹

Material	Weight Change (0.001 gm)	Corrosion rate (mm/yr.) x 10 ⁵
C. P. Titanium (area = 22.7 cm ²)	0 (S) ²	--
	+1 (M) ³	--
	0 (M)	--
Titanium 6-4 (area = 19.8 cm ²)	-5 (S)	8
	-1 (S)	1.5
	-4 (M)	6
	-7 (M)	11
Zircaloy-2 (area = 23.2 cm ²)	-2 (S)	1.8
	+1 (S)	--
	-2 (M)	1.8
	-2 (M)	1.8
	-6 (M)	5.3
Zircaloy-4 (area = 21.2 cm ²)	-3 (S)	3
	-4 (S)	3.9
	-3 (M)	3
	-3 (M)	3
Udimet-700 (area = 12.76 cm ²)	0 (S)	--
	+3 (S)	--
	0 (M)	--
	+2 (M)	--

Note 1. Nine month

2. S denotes in seawater

3. M denotes in seawater and sediments

TABLE II

Corrosion Rate of Candidate Materials in Seawater
and Sediments at 25°C, 55 MN/m² (8000 psi)^{1,2}

Material	Weight change (0.0001 gm)	Corrosion rate (mm/yr.) x 10 ⁵
C. P. Titanium	-1 (S) ³	1.3
	+1 (S)	--
	-1 (M) ⁴	1.3
Titanium 6-4	+1 (S)	--
	+2 (S)	--
	+1 (M)	--
Zircaloy-2	-6 (S)	5.3
	-3 (S)	2.7
	-3 (S)	2.7
	-4 (M)	3.5
	-3 (M)	2.7
Zircaloy-4	-7 (S)	6.8
	-2 (M)	1.9
	0 (M)	--
Udimet-700	-3 (S)	3.5
	+1 (S)	--
	-2 (M)	2.3
	-6 (M)	7

Note 1. Nine months test

2. Areas, notation same as Table I

3. S denotes in seawater

4. M denotes in seawater and sediments

TABLE III

Corrosion Rate of Candidate Materials in Seawater
and Sediments at 90°C, 55 MN/m² (8000 psi)^{1,2}

Material	Weight Change (0.0001 gm)	Corrosion Rate (mm/yr.) x 10 ⁵
C. P. Titanium	-6 (S) ³	7.8
	-5 (S)	6.5
	-7 (S)	9.1
Titanium 6-4	+3 (S)	--
	-5 (M) ⁴	8
	-7* (S)	11
	-10* (S)	15
Zircaloy-2	-19 (S)	17
	-8 (S)	7.1
	-9 (S)	8
	-9 (S)	8
	-7 (S)	6.2
Zircaloy-4	-5 (S)	4.8
	-9 (S)	8.7
	-12* (S)	12
	-7* (S)	6.8
Hastelloy C-276	-7 (S)	5.2
	-3 (S)	2
	+2 (M)	--
	-9 (S)	6.9
	-14* (S)	10
	-11* (S)	8.2

Note 1. Nine month test

2. Areas, notation same as Table I.

3. S denotes in seawater

4. M denotes in seawater and sediments

FIGURE 1. Cross section of a rotating disk electrode.

(A)

(B)

FIGURE 2. Scanning electron microscope photographs of Zircaloy-4 surfaces at 2000X, (A) freshly polished, (B) corroded for nine months.

FIGURE 3. Polarization curve of a stationary Ti-6-4 electrode in seawater.

FIGURE 4. Polarization curve of a stationary Zr-4 electrode in seawater.

FIGURE 5. Photograph of a pit in a corroded Zircaloy-4 surface at 100X. Photograph centered in pit bottom. Pit diameter = 0.015 inch.

FIGURE 6. Cathodic polarization curves for a rotating disk of Titanium-6-4 in aerated seawater.

FIGURE 7. Oxygen reduction current on a rotating disc electrode of Ti-6-4.

FIGURE 8. Cathodic polarization curves for a rotating disk of Ti-6-4 in deaerated seawater.

FIGURE 9. Cathodic polarization curves for a rotating disk of Hastelloy-C in aerated seawater.

FIGURE 10. Cathodic polarization curves for a rotating disk of Hastelloy-C in deaerated seawater.

FIGURE 11. Cathodic polarization curves for a rotating disk of Zircaloy-4 in aerated seawater.

FIGURE 12. Cathodic polarization curves for a rotating disk of Zircaloy-4 in deaerated seawater.

FIGURE 13. Cathodic polarization curves for a rotating disk of Udimet-700 in aerated seawater.

FIGURE 14. Cathodic polarization curves for a rotating disk of Udimet-700 in deaerated seawater.

FIGURE 15. (a) Polarization curves for an active-passive metal in solutions with oxygen and without oxygen.
 (b) Polarization curves of an active metal in solutions with oxygen and without oxygen.

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