The Effect of Biofouling on the Performance of Al–Zn–Hg Sacrificial Anodes

G.W. Swain* and J. Patrick-Maxwell**

ABSTRACT

Aluminum anodes operating in seawater environments may become biofouled. This paper presents results of field studies that measured the change in performance of Al–Zn–Hg sacrificial anodes with respect to cover by marine growths. Electrochemical data showed that encrusting growths on anode surfaces increased resistance values and reduced anode current output. Loss of anode performance was greater on nonworking than working anodes. Biofouled nonworking anodes were capable of providing cathodic protection (CP) when connected to a steel cathode but at current densities below theoretical values.

KEY WORDS: biofouling, cathodic protection, sacrificial anodes.

INTRODUCTION

Biofouling is often observed growing on sacrificial aluminum anodes and yet little is known about its effect on anode performance. The extent and nature of biofouling is determined by geographic location, season, and the rate at which the anode corrodes. It has been shown that marine fouling will grow more readily on aluminum anodes operating at zero or low current densities and therefore the operational mode of a cathodic protection system may be an important factor in determining the extent and effect of marine growths.

Corrosion prevention of submerged steel may be achieved by applying CP to bare or coated steel. Uncoated structures require maximum anode current output for the initiation of the cathodic reduction of corrosion. After which cathodic cover exists and other surface deposits, including biofouling, will dramatically reduce current demand by the steel. Current requirements, however, can be expected to increase during times of severe weather and after structure-cleaning programs. Coated structures have a low initial current demand that will increase as the coating deteriorates. In both situations, the anodes become vulnerable to biofouling when current demands are low. This is due to low corrosion rates of the anodes.

Until now there have been no data presented to provide information on the effect biological growth may have on anode performance. This paper presents results of field studies that measured change in the performance of both working and freely corroding Al–Zn–Hg sacrificial anodes with respect to cover by marine organisms.

EXPERIMENTAL PROCEDURES

The field studies were carried out at the Florida Institute of Technology seawater exposure site. This is located in the Indian River Lagoon on the east coast of Florida and is an area of high biofouling activity. The dominant fouling organisms present during the tests were sponges, algae, bryozoans, and barnacles. Temperature, salinity, and resistivity for the test period is shown in Figure 1. The exposure sequence ran from June 6 (Day 0) to Oct. 11, 1986 (Day 127).

The test anodes were cut from a fluo-green Al–Zn–Hg alloy. These were mounted in polyester resin and one face was left expanded to provide a working surface area 10 by 10 cm. Three anodes were connected to steel cathodes, representing working anodes, and three were left to corrode freely, representing non-working anodes. The cathodes were made from sheet carbon steel that was grit blasted to NACE ST [specification prior to exposure. Each cathode measured 44 by 92 cm and had a total exposed surface area of 0.8 m². The cathode area was chosen to be compatible with the anode area. Anode current output was calculated from the Lloyd's anode-plate resistance formula and projected seawater conductivity values for the test site. This gave a theoretical maximum cathodic protection current density for the steel of between 212 and 375 mA/m², depending on the seawater resistance.

The experimental set up is shown in Figure 2. The anodes and cathodes were connected to control and monitoring panels by electric cable. This enabled the test specimens to be monitored. During the exposure period, the following observations and measurements were made on the anodes:

1. Surface condition and biofouling (percent)
2. Cathodic protection current (mA)
3. Anode and steel potentials with both metals connected (mV Ag/AgCl)
4. Anode and steel potentials with both metals disconnected (mV Ag/AgCl)
5. Anodic polarization curves (mV vs log μA/cm²)

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THEORETICAL BACKGROUND

Current output from an anode is a function of the driving potential $\Delta E$ and the total circuit resistance $R$. By the application of Ohm's law:

$$I = \frac{\Delta E}{R} \quad (1)$$

$\Delta E$ is normally defined as the potential difference between the closed-circuit potential of the anode and the protected potential of the steel. $R$ is made up of $R_A$, the anode to electrolyte resistance, $R_C$, the cathode to electrolyte resistance and $R_M$, the metallic resistance between the anode and cathode. For calculating anode current output, $R_C$ and $R_M$ are usually omitted and $R_A$ is obtained by using one of a number of anode resistance formulae.

For this study, the Lloyd's formula was used:

$$R_A = \frac{\rho}{2S} \quad (2)$$

where

$$R_A \quad = \quad \text{anode to seawater resistance (ohms)}$$

$$\rho \quad = \quad \text{seawater resistivity (ohm-cm)}$$

$$S \quad = \quad \text{mean of anode's exposed sides (cm)}$$

The experimental values are $\rho = 17$ to $30$ ohm-cm and $S = 10$ cm. Therefore $R_A = 0.85$ to $1.50$ ohms. At anode current output $I = \Delta E/R_A$ where

$$\Delta E = \text{polarized potential} - \text{anode potential}$$

$$= -0.60 - (-1.65) = 0.25 \text{ V}$$

$$R = 0.85 \text{ to } 1.50 \text{ ohms}$$

the theoretical anode current output is 0.17 to 0.29 amps.

RESULTS AND DISCUSSION

The results can best be discussed by first considering how biofouling affected $R_A$ and then relating this to operational performance. Results are only given for representative test samples due to the large quantity of data that were generated.10

Biofouling and Anode Resistance

The anode resistance was calculated from data generated by the anodic polarization curves (Figures 3 and 4). The polarization curves show anode current output versus increasing potential for different days during the exposure. The nonworking anodes showed a considerable increase in resistance during the tests and by Day 63, it was necessary to reach a potential of $-800$ mV before activation of the anode occurred. The working aluminum anodes had more consistent polarization curves, which suggests that they were less affected by the biofouling.

The anode resistance, $R_A$, was calculated by dividing the potential difference between the polarized and at rest potential ($-1050$ mV) of the anode by the anode current output at the potential nearest to $-800$ mV. This potential was chosen because it is the value used by the Lloyd's anode resistance formula and it enabled a direct comparison to be made between the theoretical and actual anode resistance. The assumption that anode resistance was the major factor affecting the polarization curve was confirmed from polarization data of clean anodes that closely matched theoretical predictions.
For clean anode surfaces, the resistance derived from the polarization curves closely matched those calculated from the Lloyd's formula (Table 1). However, as anode surfaces became encrusted by biofouling (primarily barnacles), they showed an increase in $R_a$ (Figures 5 and 6 and Table 1).

The greatest increase in $R_a$ was found for the nonworking anodes and is clearly related to barnacle biofouling. Figure 5 shows the relationship between barnacle fouling, $R_a$ calculated from polarization curves and $R_a$ calculated from Lloyd's formula. Theoretical $R_a$ values were about 1 ohm and yet as barnacles became established on the anode surface the measured resistance increased and was recorded at a maximum of 100 ohms on Day 77. This coincided with maximum cover by barnacles and would equate to a 100-fold loss in current output capability. Subsequent to Day 64 of the exposure period, there was a natural seasonal die back of the barnacle communities and this was accompanied by a decrease in anode resistance.

In contrast, the working aluminum anode exhibited a much lower increase in resistance, despite the fact that there was high barnacle settlement (Figure 6). A maximum of about a tenfold increase in $R_a$ was recorded. This could be related to barnacle cover that had reached 99% by Day 55. The fact that the barnacles did not totally occlude the anode surface could be seen from anode corrosion products that appeared between individual barnacles. This suggests that anode activity under the fouling organisms was sufficient to prevent total occlusion of the surface.

**Biofouling and Anode Efficiency**

The results showed that large increases in anode resistance may be expected from barnacle fouling of nonworking anodes and some increase in resistance of working anodes. The question that remained was whether the anode would become reactivated if it were subjected to a galvanic couple over a prolonged period of time. To answer this, on Day 77 of the test, one of the nonworking
TABLE 1

<table>
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<tr>
<th>Day</th>
<th>Barnacle</th>
<th>%</th>
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<th>Anode Resistance</th>
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Nonworking anode connected to steel cathode on Day 77

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<th>Lloyd's</th>
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FIGURE 5. Cover by barnacles (percent), anode resistance calculated from the polarization curves (ohms), and anode resistance calculated from Lloyd's formula (ohms) for the non-working anode during the exposure period.

FIGURE 6. Cover by barnacles (percent), anode resistance calculated from the polarization curves (ohms), and anode resistance calculated from Lloyd's formula (ohms) for the working anode during the exposure period.

Anodes that had become heavily biofouled by barnacles was connected to a freshly prepared steel cathode. The polarization curves for this anode are shown in Figure 7 and the barnacle cover, R<sub>an</sub> calculated from polarization curves and R<sub>L</sub> calculated from Lloyd's formula are shown in Figure 8. At Day 77 there was 100% cover by barnacles and the anode resistance had reached 65 ohms. Within 24 hours of attachment to the cathode, the anode resistance had reduced to 4.48 ohms. At Day 93, there was a loss of barnacle cover that may have been associated with corrosion of the anode surface but was also probably part of a natural die back.

FIGURE 7. Anodic polarization curves for the nonworking anode that was connected to a steel cathode after 77-day exposure. Data are for Days 8, 42, 77, 78, 84, 93, 102, and 121 of the exposure period.

FIGURE 8. Cover by barnacles (percent), anode resistance calculated from the polarization curves (ohms), and anode resistance calculated from Lloyd's formula (ohms) for the nonworking anode that was connected to a steel cathode after 77-day exposure.
In addition to monitoring the changes in resistance, the anode to cathode current flow and polarization of the steel cathode were measured. The data are plotted in Figures 9 and 10 alongside values obtained for one of the working aluminum anodes starting at Day 0 of the test. Figure 9 shows that polarization of the steel took longer with the biofouled anode than with a clean anode. The reason for this becomes apparent when looking at the anode current output (Figure 10). It can be seen that the initial current flow between the fouled anode and steel cathode is low. Furthermore, current densities never reached the initial values observed for the working anode.

**SUMMARY**

Biofouling of aluminum anodes has been shown to increase $R_A$, which will reduce maximum current output to below that calculated from anode resistance formulae. Working anodes are less affected than nonworking anodes. This is because anodes operating at low or zero current densities will allow total cover by marine growth to occur. Anodes operating at higher current densities will maintain gaps in the fouling and prevent intimate adhesion by the fouling organisms. At high current densities, fouling will be totally prevented because of the continual breakdown of the anode surface.

The implications of these findings to operational procedures are important in situations where there may be an increase in current demand from anodes operating at zero or low current densities. It has been shown that anodes 100% covered by barnacles will reactivate but if at level below that calculated from anode resistance formulae. It is also possible that anode depletion patterns will be affected and the utilization factor reduced.

It must be emphasized that these results relate only to barnacle biofouling. Other hard calcareous growths such as corals and tube worms are more likely to cause an increase in resistance than the soft water types such as seaweeds and sea anemones.

Short-term field trials of aluminum anodes under severe fouling conditions have demonstrated that marine organisms can increase anode resistance. It may be incorrect to extend these results to different operational and biofouling environments and yet some clear conclusions may be made:

- Aluminum anodes are susceptible to biofouling.
- Biofouled aluminum anodes have increased $R_A$ and therefore they operate below the current output calculated from anode resistance formulae.
- Biofouling causes larger increases in $R_A$ of anodes operating at zero current.
- Biofouled aluminum anodes will become active when connected to a steel cathode. The level of activity will be below that of a clean anode.

**REFERENCES**