Polarization characteristics of geometrically confined spaces

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Abstract

With the advent and application of Impressed Current Cathodic Protection (ICCP) systems to confined spaces, the ability of an externally controlled ICCP system to effect sufficient cathodic protection to internal components is questionable. This paper seeks to evaluate the ability of ICCP systems to provide adequate corrosion control for confined and sensitive surfaces. Both a boundary element and a physical model were utilized to understand the effects of current distribution within a confined space, through a 1.27 mm gap. Initially, tests were performed to quantify polarization levels in a simplified parallel plate configuration. Then more complicated geometries and materials were modeled to effectively evaluate real world scenarios. Previous tests have determined that adequate cathodic polarization is achieved for simple and complex geometries at the increased driving voltages experienced with sacrificial anode systems. The results of this work provide evidence that adequate cathodic protection may be provided at controlling potentials more electropositive to conventional galvanic cathodic protection system.
Keywords: confined, gap, cathodic protection, corrosion, impressed current.

1 Introduction

Physical Scale Modeling (PSM) has been used extensively by the Naval Research Laboratory (NRL) to determine appropriate positioning and size of ICCP system components on Navy vessels [1]. Anode and controlling reference cell positions are determined by analysis of potential profiles collected from the hull, via an array of reference cells placed in numerous hull positions and geometrically confined areas which have historically proven to be problematic. In addition, an analysis of current outputs from individual anodes is taken into account to provide system stability and meet controller design tolerances. Normal cathodic protection set potentials on a vessel's ICCP system controller will be -0.80 to -0.85 V vs. Silver-Silver Chloride (Ag/AgCl) reference cell. Through PSM testing conducted on numerous ship designs, variations in the cathodic polarization level deviating from the set potential due to hull geometry, damage conditions or electrolyte conditions have been identified.

Possible areas of concern are those that are at risk of underprotection due to the configuration of the hull and its appendages; namely, the propellers, rudders, struts, bilge keels, and components within ballast tanks. Physical scale models have been able to accurately identify problematic areas and additionally allow for solutions to many of these problems. This is primarily due to the fact that both thermodynamic-based and kinetic electrochemical effects on the electrode are inherent to the technique and accounted for in the modeling process. On the other hand, numerical methods require continuously updated iterations as a function of electrode surface conditions in order to obtain an accurate result [2].

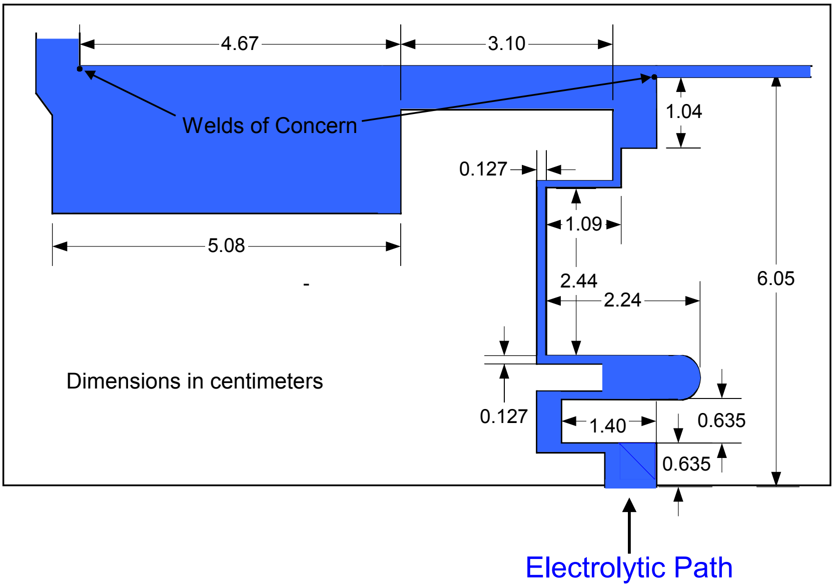


Figure 1: Cross-sectional depiction of the mating surface gap between concentric cylinders. Shaded region represents wetted portions.

In the current work, the level of protection of a confined and complex nickel aluminum bronze (NAB, UNS #95800) geometry that is enclosed in a ballast tank having an ICCP system was studied; a cross-sectional depiction of this geometry is shown in Figure 1. Adequate cathodic protection of these spaces is critical since they contain NAB welds which cannot be post-weld heat-treated; these welds are susceptible to stress corrosion cracking.

The gap considered in this effort is essentially a non-linear mating joint between to concentric cylinders approximately 1.5 m in diameter, fabricated from NAB with a weld material at the deepest portion of this gap. Previous ballast tank systems on earlier vessels, having this same confined geometry, had been protected with a galvanic zinc system, and under these conditions, this space received adequate protection as evidenced by the presence of calcareous deposits. Given the latter, no effort had previously been made to empirically characterize or analytically measure the electrochemical potential profile interior to this "gap" or confined space. Since new construction vessels are outfitted with ICCP in these spaces, it was undetermined whether sufficient cathodic protection could be anticipated. The hypothesis was that the zinc sacrificial system, generally results in a driving voltage of approximately 0.8V whereas the ICCP system will result in a driving voltage of 0.6V and therefore may not have enough throwing power to deliver sufficient current to the deepest portions of the NAB gap. This hypothesis was tested with the criterion that sufficient cathodic polarization was delivered when the deepest portion of the gap, such that a potential of –0.65 V vs. Ag/AgCl was achieved.

2 Phase I experiments: parallel flat plate physical model

2.1 Materials and methods

Although the electrolyte, and therefore the current from the ICCP system anodes, travels an intricate path through this particular confined space, it was decided to linearize this complex path for ease of testing and to simulate a best-case scenario. If the current could not penetrate into the gap through a straight, non-shielded path, then it was unlikely that actual conditions would permit adequate protection. Based on early evaluation and analysis of the drawings and pictures of the confined space, the first approach was to simply reproduce a simulated gap. The gap was to have the same configuration and dimensions as the actual structure, thus producing the same relative surface areas, as well as, electrolyte ohmic pathway. To reduce the experiment to a two dimensional problem, the gap was linearized by constructing a dual flat plate assembly having a depth equivalent to the path length of the original gap and a length equal to the circumference of the 1.2 m diameter concentric cylinders. The resultant configuration is shown in Figure 2. The minimum gap width noted on the original mating surface was 1.27 mm, and this was used as the separation between the flat plates.

The complete test assembly for Phase I is shown in Figure 3. Overall, Phase I testing was comprised of two 0.38 by 0.19 m flat plates of Copper Nickel 70/30 (CuNi 70/30, UNS # C71500), which has a similar cathodic polarization response to NAB. The plates were arranged in parallel and separated by a 1.27 mm gap, as detailed above. All external surfaces were coated with a MIL-P-24441 polyamide epoxy and three sides of the assembly were sealed. As a result, the wetted components were all interior to the gap and only one longitudinal face (shown in inset of Figure 2) allowed for current flow. Ten Ag/AgCl reference electrodes were mounted interior to the gap at ten locations along the gap length and at three gap depths so that potentials could be monitored. With regard to depth-wise reference electrodes, these were positioned at the mouth of the gap (Gap), at the middle of the gap (Gap centerline) and at the deepest point in the gap (Gap rear). In order to cathodically polarize the internal gap, a potentiostat controlled by an external reference electrode with a set potential of -0.8V vs. Ag/AgCl was positioned 0.46 m from the gap mouth as shown in Figure 3. Furthermore, a steel cathode material with a total surface area of 0.09 m^2, external to the gap, was included in the circuit to simulate actual ICCP conditions shipboard.

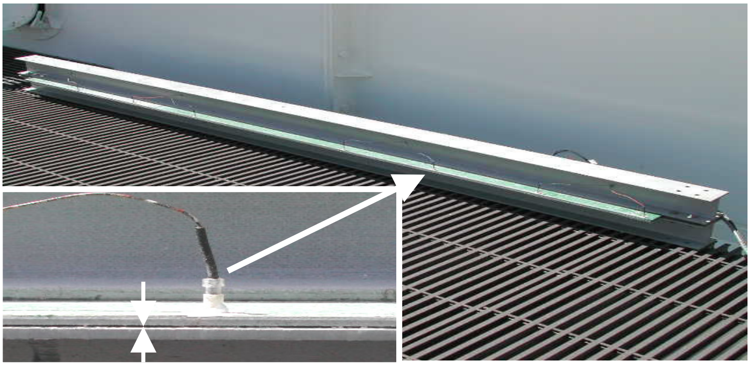


Figure 2: Pictorial of simulated gap flat plat assembly. Inset shows the mounted internal Ag/AgCl reference electrode and front face of internal 1.27mm gap.

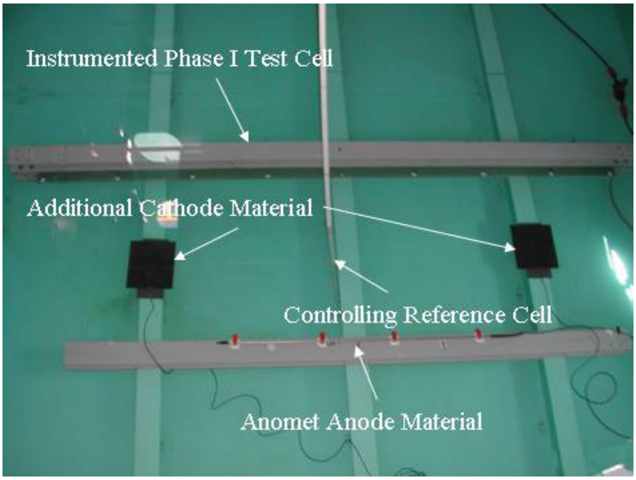
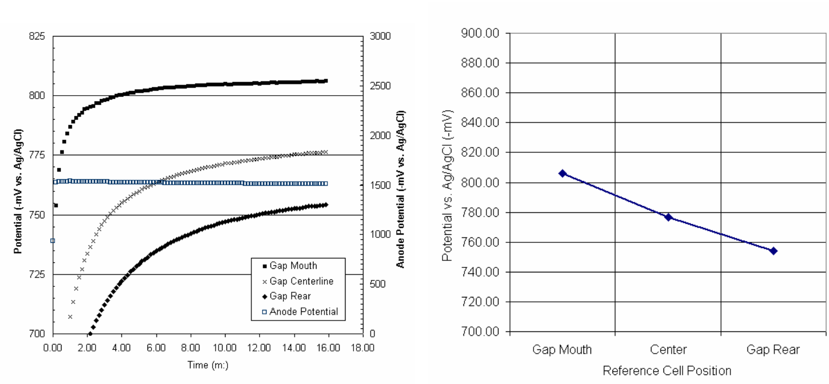


Figure 3: Pictorial of the test apparatus for Phase I testing.

2.2 Results

Internal gap potentials as a function of time are shown in Figure 4a. Anode potential was stable at approximately -1.5V vs. Ag/AgCl which is approximately half of the maximum design potential of this anode material. With regard to all potentials interior to the gap, potentials reached equilibrium after approximately 16 minutes of polarization. Note that the gap mouth (Gap) potential stabilized much sooner (6 minutes), than those deeper in the gap. This is clearly related to the increased resistance to current flow introduced by the narrow gap and subsequent formation of calcareous deposits. The potential subsequent to 16 minutes of testing for each location, depth wise, are plotted in Figure 4b. While these results indicate a depth wise differential in cathodic potential of 0.05 V, using the criterion established earlier, it was apparent that for this simplified linearized simulated gap, adequate polarization potentials were achieved at 0.19 m of penetration into the gap. This result indicated that testing of more complex geometries was warranted.



(a) (b)

Figure 4: Phase I testing results – (a) Gap potentials as a function of time and (b) Gap potential as a function depth.

3 Phase II experiments: physical model of complex gap geometry

3.1 Materials and methods

While Phase I tests did meet the -0.65 V vs. Ag/AgCl criterion, they also indicated a potential attenuation into the gap. Therefore, further potential attenuation was anticipated with the introduction of more complex gap geometry as considered in the Phase II testing. Given that the mating surface gap being considered was cylindrical and therefore symmetrical, a full scale, radial cross sectional, physical model was fabricated, as shown in Figure 5a. This test cell was then epoxy mounted with two 0.64 cm thick pieces of clear PVC as seen in Figure 5b. The model was instrumented with five Ag/AgCl reference cells in order to obtain the potential drop that would be seen upon penetration into this confined space. The complete configuration included, as before, a potentiostat and impressed current anode with an external controlling reference electrode.

The other major departure from the Phase I approach was that galvanostatic control was utilized instead of potentiostatic. From previous physical modeling of this ballast tank space [3], it was determined that the current density on these components was routinely between 75-140 mA/m^2 for all test situations. This was further validated since the design criterion used for that study required current densities of 108-161 mA/m^2 for a static condition. Given this realistic information, it was now possible to scale the current output from the galvanostat to these empirically derived current densities.

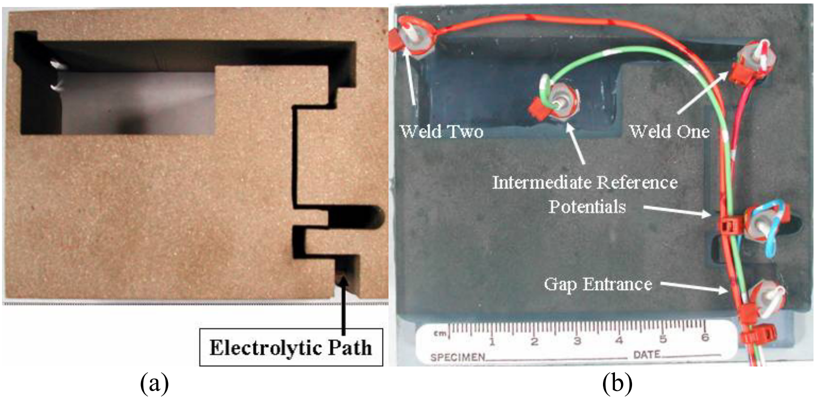


Figure 5: Cross-sectional view of (a) internal mating surface of gap physical model and (b) reference electrode instrumented physical model.

Two different scenarios were to be considered: 1) the instrumented gap test cell in addition to an external cathode and 2) the instrumented gap test cell by itself. The surface areas for the external cathode and gap test cell were 0.123 m^2 and 0.023 m^2, respectively.

Following the previous ballast tank physical scale model results [3], a current density of 108 mA/m^2 was used to calculate the current output for two scenarios and these currents were 16 mA and 2.5 mA, respectively. However, during testing, it was evident that with the external cathode, 16 mA was insufficient to polarize the external cathodes to –0.80 V vs. Ag/AgCl in a reasonable amount of time, rapid polarization of components to set potential is ideal and this was not the case. When the test was initiated, the system came to steady state with the external cathode at -0.745V vs. Ag/AgCl. Therefore, the current was increased until the potential of the external cathode reference cell reached -0.8V vs. Ag/AgCl, which was achieved with a current output of 19 mA. Notably, this current output corresponded to a current density of 130 mA/m^2, which is within the aforementioned design criteria.

3.2 Results

The cathode potentials measured as a function of position within the gap are given in Figure 6. As with the simplified linear gap in Phase I, potential was attenuated with increasing distance into the gap. Note, however, the drop in potential was considerably higher with a total differential of approximately 0.125V which was a 2.5 fold increase over the previous test. This would indicate that the cathodic polarization of the internal mating surface was more a function of gap geometry than of the electrolyte resistance. Despite this attenuation, sufficient cathodic protection was achieved based on the original criterion of a minimum potential of -0.65V vs. Ag/AgCl. Since the weld location deepest in the gap had a potential electronegative to the design criterion, there was little risk of stress corrosion cracking at this location.

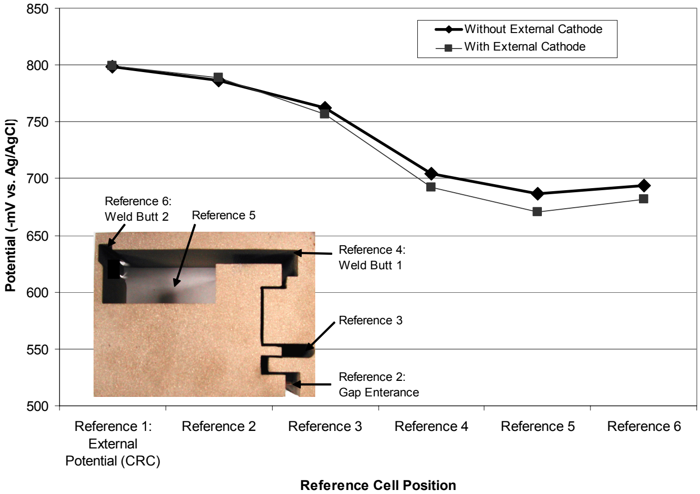
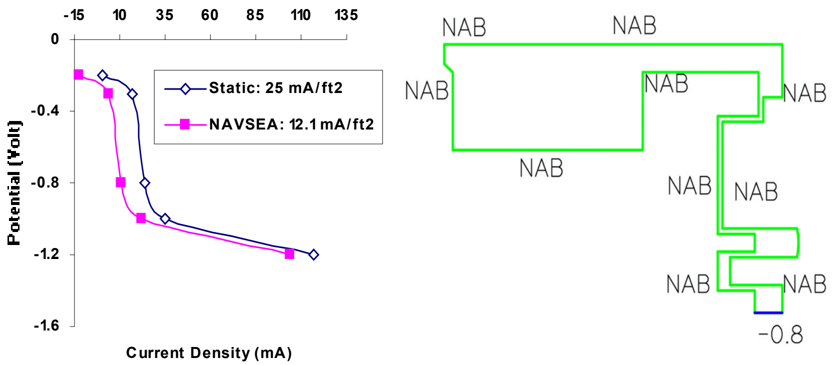


Figure 6: Cathodic potentials as a function of reference cell position of the gap model.

4 Boundary element modeling

It was decided that a mathematical or computational analysis of the enclosed space might provide additional insight into the phonological aspects of corrosion protection as observed in both the real structure and the physical scale model. Both finite element and boundary element computational techniques have been successfully applied to electrochemical processes. Because of the success of BE application to shipboard ICCP system analysis it was determined that initial analysis would be performed using BE techniques. The confined space was modeled using the commercial boundary element code BEASY [1]. The geometry modeled was identical to that used in the PSM testing.

The confined space surfaces were assigned NAB material properties derived from a NAVSEA defined polarization curve. The potential-current density polarization response was shifted to match observed experimental results. The shape of the experimentally determined curve is maintained. However, the curve is shifted so that current density corresponds to that measured during PSM at the reference set point. The original laboratory method NAB polarization response and shifted polarization response are shown in Figure 7.



(a) (b)

Figure 7: (a) Polarization curve used for model boundary conditions (b) boundary model used to solve potential distribution.

The boundary conditions applied to the boundary element model are NAB polarization response applied to all but the section representing the gap entrance. The gap entrance is assigned a voltage value of –0.8 V vs. Ag/AgCl. The region internal to the confined space was assigned an electrolyte conductivity equivalent to that used in PSM.

The resulting potential map of the internal volume of the confined space is shown in Figure 8. As can be seen, the potential variation between the gap entrance and the enclosed region is much larger than that observed in either experimental procedure. Almost no current reaches the larger volume. The extreme difference in calculated and experimental results was unexpected and lead to a review of the basic assumptions of the BE technique.

BE techniques as applied to this problem assume steady state electrochemical corrosion governed by LaPlace's equation:

$$k\nabla^2\Phi = 0 \tag{1}$$

Where Φ is the electric potential and k is the conductivity of the electrolyte within a domain. There are three necessary conditions for the valid application of LaPlace's equation. There can be no gain or loss in electrical current in the system. There can be no sources or sinks within the defined domain. These conditions were met. The electrolyte must be of a uniform composition. It is felt that this is not the case in the confined space geometry. There are stagnant regions, flow is constrained and regions of the electrolyte volume are essentially isolated from other regions with little mixing between the volumes. Therefore it appears that the confined space geometry does not lend itself to LaPlace based BE techniques. While the LaPlace solution based BE technique may be a reasonable approximation for a ship in the open sea and in deep water it is not appropriate for the confined space geometry in this work. Based on this no further comparisons of results were made.

Figure 8: BEM result of potential distribution interior to the gap.

5 Summary

The results from the Phase I testing was utilized to determine if it was necessary to model the complexity of the gap in question. The parallel flat plate gap testing revealed that electrolytic resistance alone was insufficient to appreciably attenuate cathodic protection potentials below -0.65V vs. Ag/AgCl in a 0.19 m deep gap when an exterior cathode is controlled to -0.8V vs. Ag/AgCl.

As a result, subsequent testing was conducted (Phase II) which included both the effects of electrolytic resistance and surface geometry/shielding effects. The latter was accomplished through the use of a radial slice, physical model of the actual in-service mating surface assembly. Additionally, the experiment was operated in galvanostatic mode with current outputs delineated from previous half-scale physical scale modeling of this ballast tank space. The results of these instrumented gap test, demonstrated a potential drop of between 0.1 and 0.15 V can be expected upon complete penetration into the gap. Clearly, the geometry of the gap affected the potential attenuation than did the solution resistance. Despite the resultant attenuation, however, the NAB weld metal, internal to the gap assembly, remained electronegative to the protection potential of -0.65 V vs.

Ag/AgCl. Thus the physical model indicates that sufficient cathodic protection is available to prevent stress corrosion cracking of NAB weld metal and to protect the internal surfaces of the mating assembly.

While the application of BE techniques to the confined space was not successful it provided essential insight into the limitations of the computational method as it currently exists in commercially available codes. The confined space does not appear to meet one of the fundamental requirements for use of LaPlace's equation; specifically the electrolyte is not of uniform composition. There is a need for computational methods that are valid for volumes with extremely non-uniform electrolytes. This need will increase in the future as more ICCP systems are installed in confined spaces. It is hoped that future research will provide the computational tools needed by the design community.

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