Examination of Modeling Assumptions for Impressed Current Cathodic Protection Systems

V. G. DeGiorgi, A. Kee, K. E. Lucas and E. D. Thomas

INTRODUCTION

The use of computational methods has become an accepted practice in many fields of study in recent years. A variety of computational methods have been applied to the analysis of cathodic protection systems. The use of computational methods, boundary elements in particular, is well documented. These methods have been used on a wide variety of structures ranging from offshore oil platforms to buried pipelines. Initial work that investigated the usefulness of boundary element methods for corrosion problems was completed by the late 1980s as summarized in review articles by Adey and Niku [1], Munn [2] and Garland et al [3]. While there have been significant advances in boundary element modeling applications, there are still areas in which computational modeling approach can be further developed and improved. Recent advances in modeling processes for shipboard impressed current cathodic protection (ICCP) systems have been summarized by DeGiorgi [4]. It is standard in shipboard ICCP system computational evaluations to assume a constant value of seawater resistivity, perfect paint and that damaged paint regions behave as bare metal. Protection that may be provided by reduced thickness paint or partial paint coverage is not taken into account. In this work pertinent analyses that have been performed are reviewed in order to determine what effects variations in these assumptions have on calculated results. It is the objective of this work to determine if the standard assumptions made for computational evaluation of shipboard ICCP systems are valid or if these assumptions are in themselves a source of error in the calculated results. The influence of these assumptions are quantified by comparison of calculated results. Boundary element methods and existing meshes of two ship hull geometries are used in the parametric studies presented here. It is not the purpose of the work presented here to predict actual system performance rather it is the purpose of the work presented to determine the validity of assumptions made in computational evaluation of ICCP systems. Therefore procedures were used in the computational approach that are appropriate for comparison of calculated results that may not accurately model ICCP system performance.

The changes of seawater composition on system performance are examined using a model of U S Navy cruiser ship hull. System parameters are held constant as the ship is moved from low to high resistance water. The cruiser geometry has been used in several parameter studies, including comparison of ship trail data and physical scale model experimental results [5]. Use of this geometry for the variable seawater constitutive response study may provide insight into further defining sources of variation in calculated, experimental and ship trail data.

The effects of finite paint resistivity and damaged paint assumptions on calculated system performance are examined for a U S Navy aircraft carrier. The aircraft carrier ship hull mesh allows for more detailed study of changes in paint conductivity with increasing damage to paint sections than
is provided by the cruiser hull mesh. Element size, regularity and number of elements required to define the percentage of surface area characterized as damaged paint are better suited for this study than those of the cruiser hull mesh. There are more elements of a smaller size, relative to the ship hull dimensions, that represent damage areas. The effects of finite paint resistivity studies examine the validity of two basic assumptions; use of perfect paint and use of bare metal for damaged paint.

The commercial boundary element program BEASY-CP[6] is used in this work. Post processing is performed on a PC, PATRAN [7] and PC based plotting packages. The information presented should not be unique to the programs used, especially information on establishing the boundary element problem parameters.

THEORETICAL BASIS FOR BOUNDARY ELEMENT MODELING

The governing differential equation for electrochemical corrosion for a structure surrounded by a bounded uniform electrolyte is:

\[ k \nabla^2 \Phi = 0 \]

where \( \Phi \) is the potential and \( 1/\kappa \) is the resistivity of the electrolyte. Boundary element models of shipboard ICCP systems can be designed to meet the applicability requirements of Laplace’s equation. The systems are surrounded by seawater. It is permissible to define the seawater surrounding a ship as a uniform electrolyte without polarization concentration gradients. The combination of system and seawater can be defined without electron sources or sinks, another applicability requirement for Laplace’s equation. System anodes, which may be considered as a source of electrons, are defined using boundary conditions. The boundary element problem is defined so that total current in equals the total current out of the domain defined by the ship hull, ICCP system and surrounding seawater. Electroneutrality of the region is the last requirement for Laplace’s applicability. Details on the formation of boundary elements and the solution procedure can be found in textbooks such as reference [8].

In the current work the boundary element models consist of a mesh representing the ship hull and a surrounding box enclosing a large but finite volume of seawater. In all cases anodes are defined as elements with an assigned voltage value. Reference electrodes are data points on the ship hull where voltage values are calculated. In all cases the seawater is assigned a single value of resistivity.

In all analyses performed voltage levels at input anodes were defined and maintained at constant values. It is realized that this is not the standard procedure for operating shipboard ICCP systems. In previous work that dealt with system performance, anode values have been varied to obtain the target potential in a manner duplicating how ICCP systems operate [9-12]. However, the goal of this study is not to predict ICCP performance but rather to determine the sensitivity of the boundary element method with the models used for shipboard ICCP systems to variations in basic assumptions. It has been the experience of the authors and other researchers [13] that the boundary element approach is more robust in terms of potential than in terms of current density. Therefore it was felt that maintaining voltage levels while altering basic assumptions would lead to a better measure of the computational method’s sensitivity to such changes.

The values of anode strength for average seawater to maintain a target potential of -0.85 Volts Ag_AgCl at the reference cells were determined as part of the model validation analyses previously performed. These input anode voltage values are maintained for all values of seawater resistivity and paint polarization response. This process eliminates the feedback adjustment of the system from the model. Changes in calculated results to variations in assumptions are evaluated. The goal of the work
is to determine the sensitivity in calculated results for design conditions due to variations in assumptions rather than establish new operating parameters based on altered assumptions. The ICCP system is evaluated at steady-state conditions.

**AVERAGE SEAWATER CONDUCTIVITY**

The operating parameters and performance of ICCP systems are dependent on the resistivity of the surrounding water. It is expected that in extreme cases, such as entering brackish or fresh water environments, the operating parameters of an ICCP system would be adjusted.

Seawater is a solution of many different dissolved materials that is often defined by single parameter values. The composition of seawater varies with location, temperature and season. Two common measurement parameters are the resistivity and the chlorinity. These parameters provide different information but are related. For instance measured values of resistivity range from 333.3 Ohm-cm for a very high salt concentration represented by a chlorinity of 1 to 19.2 Ohm-cm for a chlorinity near that of average seawater [14]. In addition to being related to salt content, resistivity varies with temperature. Resistivity varies from 19.2 Ohm-cm for 25°C to 30.3 Ohm-cm for 5°C [9]. The range of resistivity chosen for this study is 16.5 to 24.8 Ohm-cm. This represents a 20% variation from an average seawater value of 19.8 Ohm-cm. Lower values represent more brackish and warmer waters. Higher values represent higher salinity content and cooler waters. This range represents moderate temperature and salt concentration variations. This range is of interest because it could represent the range experienced due to location, season, temperature or tidal variations.

**Cruiser Geometry and Computational Model**

The boundary element model of the cruiser and ICCP system used has been verified with experimental results for an average seawater resistivity [9-11]. The wetted surface of the ship hull is reproduced as a boundary element model. Symmetry of ship geometry and ICCP system allow for modeling of half of the hull as shown in Figure 1. Propellers are modeled as solid disks. The surface ship is enclosed in a large but finite seawater domain. The model consists of 1583 constant quadrilateral elements with quadratic geometric definitions. Materials definitions are assigned to each element in the model; a nickel-aluminum-bronze alloy (NAB) for the propellers, perfectly insulated material for the painted surfaces and steel for exposed metal representing paint damage. Experimentally obtained nonlinear polarization response curves for steel and NAB are used to define material behavior in the computational analysis. Minimum paint damage conditions define 3% of the wetted hull surface as exposed metal surfaces. Individual exposed areas are defined according to protocols based on observations of similar ships. The regions represented as bare metal in minimum damage conditions are the entire rudder, propeller and support block locations used in dry-dock. The ICCP system modeled is a 7 anode/2 power zone system that exists for a U S Navy cruiser. The anodes are spaced in pairs with a centerline anode in the propeller region. Pairs are spaced forward, mid-ship and aft. The forward and mid-ship pairs are attached to one power supply. Remaining anodes are attached to the second power supply. Power supplies are independent of each other.

**Analyses Description**

A parametric study was designed to determine the effects of seawater resistivity on system performance. The cruiser ICCP system was chosen for the analysis. The range 16.5 to 24.8 Ohm-cm was divided into 9 distinct values.
The polarization responses for steel and NAB used in the analysis were obtained for natural seawater. These are the material properties used for the validation analyses for the cruiser hull geometry. The same values of polarization response are used for all resistivity levels analyzed. This was considered acceptable because of the moderate nature of the range of resistivity studied.

Results

Results of interest in this study are the total current required to maintain the input voltage levels, the potential profile along a line at a depth of 3 m (10 ft) and the potential contours on the hull. Potential contours represent the effects of changing resistivity on overall system performance.

Potential profiles for a depth of 3 m (10 ft) below the waterline are shown in Figure 2. Ship length is reported in frames, a unit of linear measurement used for scaling purposes. This location corresponds to the depth of shipboard in situ reading locations. There is a shift to higher potential values for lower values of resistivity. The potential profiles bracket the physical scale model experimental results. The potential profiles do not indicate that there are differences in protection levels. Calculated potential contours, however, indicate significant changes in protection levels (Figure 3). Shifts in protection levels for a large portion of the hull occur so that examining potential along the hull at a single depth may lead to erroneous conclusions with respect to corrosion protection. Based on a comparison of Figures 2 and 3, it is easily seen that information not otherwise available can be obtained from the computational results.

Current required and current distributions are calculated as part of the boundary element solution. Table 1 shows the current to exposed steel areas. As one would expect current required to maintain anode voltage levels increases with decreasing resistivity.

<table>
<thead>
<tr>
<th>Resistivity (Ohm·cm)</th>
<th>Current</th>
<th>Current to Steel</th>
<th>% of Total Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.5</td>
<td>39.6</td>
<td>10.8</td>
<td>27.2</td>
</tr>
<tr>
<td>17.2</td>
<td>38.8</td>
<td>10.6</td>
<td>27.1</td>
</tr>
<tr>
<td>18.0</td>
<td>37.4</td>
<td>10.0</td>
<td>26.7</td>
</tr>
<tr>
<td>18.9</td>
<td>36.2</td>
<td>9.4</td>
<td>26.1</td>
</tr>
<tr>
<td>19.8</td>
<td>35.2</td>
<td>8.8</td>
<td>25.1</td>
</tr>
<tr>
<td>20.8</td>
<td>34.2</td>
<td>8.2</td>
<td>24.0</td>
</tr>
<tr>
<td>22.0</td>
<td>33.2</td>
<td>7.6</td>
<td>22.8</td>
</tr>
<tr>
<td>23.3</td>
<td>32.2</td>
<td>7.0</td>
<td>21.6</td>
</tr>
<tr>
<td>24.8</td>
<td>31.0</td>
<td>6.2</td>
<td>20.2</td>
</tr>
</tbody>
</table>

Table 1. Current distribution (Amps) for 3% damage static conditions.

The results of this parametric study were:

(1) Current requirement changes for moderate changes in seawater resistivity are moderate and follow expected trends.

(2) Moderate changes in seawater resistivity values can have significant effects on system performance as observed in calculated potential contours.
(3) Based on calculated results it has been seen that potential profiles alone are inadequate to capture the variations in protection from corrosion provided due to moderate changes in seawater resistivity.

(4) Limitations of system performance, while not observed from data corresponding to that obtainable from shipboard measurements, are clearly observed from computational results.

**PERFECT PAINT AND DAMAGED PAINT AS BARE METAL**

The second and third basic assumptions used in many shipboard ICCP system computational analyses are related assumptions. Painted surfaces are modeled as either perfect insulators or bare metal in the case of damaged paint. Use of these assumptions in previous analyses for the cruiser and aircraft carrier hulls allows for direct comparison to experimental studies [15]. In the test model painted areas were represented by fiberglass, a non-conducting material. Damaged paint areas were modeled by attachment of metal sections to the fiberglass model. The assumptions of perfect paint and bare metal for damaged paint are appropriate for direct comparison of computational and experimental results. In reality paint has a large but finite resistivity. This has been taken into account by techniques that use in situ measurements to define polarization response. This is frequently done in the case of offshore structures [3]. A similar approach for ships has been proposed in which the polarization response of the ship is an unknown to be determined by computational methods based on in situ voltage readings [16]. However, the majority of reported computational analyses of shipboard ICCP systems have not included finite resistivity of paint. The goal of the work performed was not to approximate the performance of actual paint systems but rather to determine the validity of the assumption of perfect insulation or nearly infinite resistance differences between bare metal and paint.

Use of infinite resistivity for paints is an assumption that simplifies the modeling process. With respect to computer modeling paints and passive coatings are similar. Passive coatings have been observed to reduce conductivity values by an order of magnitude or more [17]. Paints are engineered materials and are much more effective however paints vary in their effectiveness by several orders of magnitude [18]. This increases the difficulty in defining an appropriate range to consider for paint resistance. One source of data on painted surface current demand pertinent to this work is an experimental study used in the validation of computational methods by Hack and Janeczko [13]. As part of the study performed in [13] current data was obtained from 8 x 14 m (18 x 42 ft) barge for both uncoated and coated conditions. The coating applied was the standard U S Navy F-150/F-151 epoxy coating system with a standard F-120 copper-based antifoulant top coat. The presence of the coating reduced current demand on the hull from 4.2 Amps to 0.015 Amps. Defining polarization scaling factors as the ratio of current demand of the coated structure to current demand of bare steel, this coating system has a scaling factor of 0.0036. The range of scaling factors used are based on these results, perfect paint and damaged paint modeled as bare metal.

Natural films, paints and coatings reduce the current required to achieve predefined potential levels. This reduction in current demand is represented here as a shift in the polarization response curve. Scaling current density is one way to adjust polarization input data for the computational analysis to reflect the reduction in required current. While this does not address issues such as variations in test potential and general shape characteristics of the polarization curve, it does provide basic polarization data for the computational analysis. This approach may not be appropriate for predictive analyses. However it is appropriate to determine the sensitivity of computational results to variations in modeling assumptions of paint characteristics. Infinite and very large resistances have been used to model paint systems. The sensitivity of these assumptions in computational modeling
methods have not been examined in detail. The primary goal of this analysis is to determine this sensitivity.

**Aircraft Carrier Geometry and Computational Model**

The ship hull chosen for this study is a U.S. Navy aircraft carrier. The boundary element model for this ship hull has been previously validated by extensive comparison with experimental scale modeling results [12,19]. The aircraft carrier geometry chosen for the paint resistivity study is a much larger ship than the cruiser hull used in the seawater resistivity study. As in the cruiser geometry, symmetry conditions are used to define the ship hull geometry. Only 2 of the 4 propellers and 1 of 2 rudders are included in the model as shown in Figure 4. The boundary element mesh consists of 1884 elements. Each element is a 9 noded quadrilateral element with 8 side nodes and 1 center node. This is an element type that was not available when the cruiser model was created. The change in element allows for a more accurate modeling of the curved surface of the ship hull. The elements have quadratic geometry shape functions and linear representations of potential and flux density. Propellers are assigned NAB material properties. Painted and damaged paint areas are assigned separate material properties as defined below. The seawater is assigned a constant resistivity of 20 Ohm-cm. This value was chosen based on physical scale model testing conditions and is consistent with model validation analyses.

The ICCP system for the aircraft carrier hull consists of 3 independent power supplies that support 17 anodes. The forward power supply is attached to 4 anodes, 2 on either side of the ship. The mid-section power supply supports 8 anodes placed symmetrically along the hull. The rear power supply supports 4 symmetrically placed anodes and 1 centerline anode.

**Analysis Description**

Two parametric studies were completed to examine finite resistivity and system performance parameters. In the first study 15% paint damage in flowing seawater conditions were examined. This is the maximum paint damage design condition; 15% of the wetted hull surface is defined as paint damage. Paint damage is defined as finite areas of bare metal. In the same manner as for the minimum damage condition, areas and distribution of areas are defined to match the pattern of damaged used on the physical scale model.

As in the seawater resistivity study, anode voltage values are maintained at a constant value. As previously noted this was considered appropriate because the goal of the analysis was to determine variations due to changes in basic assumptions rather than system performance predictions. Anode voltage input values were maintained at levels determined for the design condition based on paint defined as a perfect insulator. The painted surface area was assigned finite values of resistivity. Paint polarization is defined as a fraction of the current density value of steel polarization response; potential values are not scaled. Paint is defined as 0.1, 0.01, 0.001 and 0.0001 times the current density of steel were evaluated. In the second study paint damage was allowed to gradually increase from 3% to 15% surface area. This was done by defining the polarization response of the damage in excess of 3% surface area as 0.001, 0.01, 0.1, 0.2, 0.5 and 1.0 times that of steel. Each response value represents an analysis. Input voltages values were maintained for all analyses at levels required for adequate protection at 3% damage flowing seawater conditions.

The polarization responses for steel and NAB used are based on series of experiments using water with scaled conductivity used in the experimental evaluation of ICCP. The polarization response is obtained for conditions identical to physical scale modeling testing.
Results

Results of interest are the total current, the current associated with specific regions of paint damage and the potential contour along a line at a depth of 3 m (10 ft). Potential profiles were evaluated but are not presented here.

Total current calculated based on defined input anode voltages are given in Table 2 for variations in resistivity at 15% damage in flowing seawater. Current to specific areas are shown in Table 3. Areas of special interest are the exposed metal associated with propellers, damage areas on the propeller struts, docking blocks, waterline damage areas, bilge keel damage areas and damage areas on the rudder.

<table>
<thead>
<tr>
<th>Paint Resistivity:</th>
<th>Perfect</th>
<th>0.0001</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Results</td>
<td>Paint</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>1837.7</td>
<td>1707.2</td>
<td>1708.2</td>
<td>1710.2</td>
<td>1730.2</td>
<td>1855.3</td>
</tr>
</tbody>
</table>

*Average current in and current out of computational results

Table 2. Current total (Amps) for 15% damage in flowing seawater.

<table>
<thead>
<tr>
<th>Paint Polarization Scale Factor:</th>
<th>Perfect</th>
<th>0.0001</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area:</td>
<td>Paint</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel</td>
<td>Steel</td>
</tr>
<tr>
<td>Propellers</td>
<td>228.2</td>
<td>189.8</td>
<td>190.7</td>
<td>190.2</td>
<td>185.2</td>
</tr>
<tr>
<td>Docking Block</td>
<td>185.2</td>
<td>185.2</td>
<td>185.0</td>
<td>183.3</td>
<td>167.8</td>
</tr>
<tr>
<td>Waterline</td>
<td>229.8</td>
<td>206.8</td>
<td>206.6</td>
<td>205.5</td>
<td>205.5</td>
</tr>
<tr>
<td>Bilge Keel</td>
<td>290.8</td>
<td>174.4</td>
<td>174.4</td>
<td>169.7</td>
<td>167.9</td>
</tr>
<tr>
<td>Struts</td>
<td>104.4</td>
<td>85.8</td>
<td>85.8</td>
<td>85.2</td>
<td>81.2</td>
</tr>
<tr>
<td>Rudder</td>
<td>43.0</td>
<td>85.0</td>
<td>85.5</td>
<td>84.6</td>
<td>82.0</td>
</tr>
</tbody>
</table>

Table 3. Current total (Amps) for 15% damage in flowing seawater, selected damage areas.

Previous studies identified causes of variations between physical scale model experimental results and computational results as material interactions and film formation. Major differences between experimental and calculated results are in the region of the propellers. Variations in NAB and interactions between steel and NAB are primary factors in this region that are not addressed by previous or current analysis. It is interesting to note that there is a slight increase in the current of the propellers when polarization scaling factors of 0.001 and lower are used.

The second study on paint resistivity examined the effects of using bare metal to represent damaged paint. In this case elements corresponding to 3% paint damage are assigned bare metal properties while elements corresponding to the difference in 15% and 3% damage cases are assigned a fractional value of steel polarization. Other surfaces are assigned paint properties, perfect paint in the baseline case and 0.0001 of steel in all other cases. Input anode voltage values are maintained at those required to maintain the target potential at reference cells for 3% paint damage conditions. A significant drop in potential levels is expected with increased paint polarization response for the additional areas of damage. A goal of this study was to determine the point where the paint polarization response of the additional damaged areas results in significant variances in the calculated
results. Major changes in current values do not occur until significant increase in paint polarization values. This indicates that continual deterioration of paint may not be a concern until a relatively low value of resistance is achieved. A more detailed analysis with material information on a specific paint may provide insight in extensions of useful service life basing retirement on cause rather than on time in service.

Potential profiles for a depth of 3 m (10 ft) are shown in Figure 5 for the paint damage study. The reduction in potential levels is due to the increased current demand caused by the transition from perfect paint to steel for 12% (15% total damage area minus 3% minimum damage area that is maintained at bare steel) of the surface area. The voltage input is held constant to that determined necessary for the 3% damage case. Therefore the reduced protection level is expected. What is important to note is that there is negligible change in the potential profile until significant paint polarization is reached.

Current totals calculated for increasing paint polarization response are shown in Table 4. Current totals for specific areas are shown in Table 5. Changes in current total are not significant until a paint polarization scale factor of 0.1. The large variation between experimental and calculated results has been attributed to polarization response definitions, material interaction affects and the observed presence of films on some surfaces in the experiments [17]. This variation would be consistent for all calculated results. The experimental results reported are for 3% paint damage conditions.

<table>
<thead>
<tr>
<th>Paint Polarization Scale Factor:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp. Results</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>314.7</td>
</tr>
</tbody>
</table>

*Average current in and current out of computational results

*Table 4. Current total (Amps), 3% - 15% damage transition, flowing seawater.*

<table>
<thead>
<tr>
<th>Area</th>
<th>Exp. Res.</th>
<th>Perf. Paint</th>
<th>0.001 Steel</th>
<th>0.01 Steel</th>
<th>0.1 Steel</th>
<th>0.2 Steel</th>
<th>0.5 Steel</th>
<th>1.0 Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propellers</td>
<td>204.1</td>
<td>118.9</td>
<td>123.8</td>
<td>120.0</td>
<td>99.9</td>
<td>95.0</td>
<td>80.1</td>
<td>88.4</td>
</tr>
<tr>
<td>Docking Block</td>
<td>110.6</td>
<td>71.7</td>
<td>63.8</td>
<td>59.3</td>
<td>34.5</td>
<td>27.2</td>
<td>20.5</td>
<td>14.9</td>
</tr>
<tr>
<td>Waterline</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
<td>3.8</td>
<td>15.6</td>
<td>17.6</td>
<td>21.9</td>
<td>22.8</td>
</tr>
<tr>
<td>Bilge Keel</td>
<td>0</td>
<td>0</td>
<td>0.2</td>
<td>1.6</td>
<td>13.4</td>
<td>20.8</td>
<td>34.1</td>
<td>47.4</td>
</tr>
<tr>
<td>Struts</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>1.2</td>
<td>6.8</td>
<td>8.2</td>
<td>9.4</td>
<td>9.8</td>
</tr>
<tr>
<td>Rudder</td>
<td>0</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
<td>6.6</td>
<td>8.4</td>
<td>9.8</td>
<td>10.4</td>
</tr>
</tbody>
</table>

*Table 5. Current total (Amps) 3% - 15% damage transition, flowing seawater. selected areas*

The results of the parametric studies on paint and damage resistivity are:

1. Changes in computational results due to incorporating realistic levels of paint resistance instead of perfect paint assumptions are minimal.

2. In the worse case, 15% damage in flowing seawater, variations in calculated results are within observed differences between computational and experimental results. These differences have been attributed to material characterization.
limitations rather than the use of infinite paint resistivity since the experimental results are derived from fiberglass models that exhibit perfect paint characteristics.

(3) Results support assumptions that for design purposes it is conservative to define painted surfaces as either perfect or non-existence (use of bare metal for damaged areas).

(4) Results indicate that computational model with specific paint properties could be used to determine useful life of paint based on resistance changes with time.

CONCLUSIONS ON VALIDITY OF ASSUMPTIONS

The work presented here is a series of studies that examine the effects of basic modeling assumptions on computational results. The goal is to determine computational analysis sensitivity to basic modeling assumptions and the analyses presented are not meant to be ICCP system performance predictions. It is recognized that the use of constant values of anode input voltage for changing conditions is not representative of the operation of ICCP systems. However, it is an appropriate approach to determining the computational sensitivity to variations in modeling assumptions.

The results of the seawater variation study confirm that computational modeling provides a greater level of detail in system performance than is available from instrumentation. This is true for both experimental models and shipboard systems. In many instances, computational modeling may be the only avenue to examine system performance variations with environmental changes since computational modeling provides additional insight and information for system design that would not be otherwise available.

There are implications from this study for ICCP system design and performance. The variations in potential contours indicate that an existing system may not provide adequate protection for moderate ranges of variation in seawater resistivity. Spatial variations in potential contours can be such that target potential is maintained at reference cells however other regions can be under-protected. Reference cell locations may not longer be appropriate for the system in the changed environment. When such ranges in seawater resistivity are expected, system design modifications may be necessary to provide the required level of protection. Anode and reference cell placement may need adjustment due to changes in potential contouring based on seawater resistivity variations. Therefore, a range of seawater resistivity values should be incorporated into the design analyses based on ship deployment considerations.

The paint and paint damage study demonstrate the effects of incorporating a finite paint resistivity and accounting for partial paint damage into computational evaluation of shipboard ICCP systems. Rather than focus on a particular paint, ranges of paint performance were evaluated. Results do not indicate that increased accuracy in computational results could be generated by the inclusion of finite paint resistivity. In particular when paint is assigned the polarization scaling factor similar to that associated with a standard US Navy surface coating [x] there is minimal impact on calculated results. Variations are within the range of scatter observed between experimental and calculated data. However, detailed study of the interaction between damaged areas with different paint resistivity could increase the understanding of the spatial and material interactions inherent in electrochemical corrosion systems.

Conclusions relating to established computational modeling assumptions are:
(1) Correct seawater resistivity values are required for accurate design and performance predictions. Ranges of seawater resistivity should be evaluated based on ship deployment expectations.

(2) Assumptions of infinite resistivity paint and bare metal to represent paint damage are conservative. Refinement of these assumptions will not increase accuracy of computational modeling based on comparisons with experimental results.

In closing computational modeling is an important means for designing and evaluating the performance of shipboard ICCP systems. The computational analyst needs to consider the working environment for the ship and must insure that correct assumptions are made for key parameters used to define environment and materials. This may lead to a design condition matrix that is larger and more inclusive than has been traditionally used. The analyst must take action and assist the system designer in developing an ICCP system that will perform well in all expected service environments. Care has to be given to basic assumptions.

ACKNOWLEDGEMENTS

The support of Dr. A. I. Kaznoff, Naval Sea Systems Command, is gratefully acknowledged.

REFERENCES


Figure 1-Boundary element mesh of cruiser hull geometry.
Figure 2: Potential profiles at 3 m (10 ft) depth, cruiser system, variations in seawater resistivity.
Figure 3. Potential contours, cruiser system, variations in seawater resistivity.
Figure 4: Boundary element mesh of aircraft carrier geometry.
Figure 5: Potential profiles for a depth of 3 m (10 ft) below waterline, transition from 3% to 15% paint damage by transitioning from perfect paint to steel polarization response.