Shipboard impressed current cathodic protection system (ICCP) analysis

V. G. DeGiorgi[1], E. Hogan[2], K. E. Lucas[3] & S. A. Wimmer[1]
[1]*Multifunctional Materials Branch, Naval Research Laboratory, Washington, DC.*
[2]*Material Science and Technology Division, Naval Research Laboratory, Washington, DC.*
[3]*Center for Corrosion Science and Engineering, Naval Research Laboratory, Washington, DC.*

1 Introduction

In technical work, the world is often described by one of three sources of values; real structure measured response, experimental measurements or calculated computational results. While it is common to discuss results from each of these three methodologies as representing the same condition this is not really the case. Actual measured structural response is the global behavior of a component based on the complex interaction of geometry, materials, boundary conditions, environmental factors and applied loads. Models, either computational or experimental, are simplified representations of the actual structure. In many instances the accuracy and acceptance of experimental and computational methods is based on how well these methods can duplicate the measured response from a real structure. While it is recognized that both experimental and computational modeling must be initially validated by comparison with rather simplistic structural systems, the emphasis must be on simplified structures. If more complex structures or systems are used as validation problems then issues such as real versus conceptual definitions of boundary conditions, loads and material response must be addressed. These issues are often at the core of the complex nature of structural response. Once an experimental or computational methodology has been validated through a series of comparisons with controlled simple structure or system performance predictions, these methods should be considered as equally 'true' in their results as measured data from a real structure is considered 'true'. Important in evaluating any measured or calculated data is an understanding of the structure

WIT Transactions on State of the Art in Science and Engineering, Vol 7, © 2005 WIT Press
www.witpress.com, ISSN 1755-8336 (on-line)
doi:10.2495/1-85312-889-9/02

or system and associated loads, boundary conditions, and material response definitions.

Rather than consider measurements from real structures as 'truth' values and data from modeling as a second best information source, the authors are proposing that each source provides essential insight into how an actual system will perform under a variety of conditions. Insight can be obtained on the underlying physical phenomenon from the more controlled situations of experimental and computational models. Experimental models can be used to help identify issues and further the understanding of computational models. Computational models can be used in the same way to further the understanding of an appropriate application of experimental models. Results from both are combined to better understand the complex real world response.

Modeling is more than just a representation of the actual structure. It is a methodology for advancing the understanding of system performance. It is a methodology for determining relative importance of the many factors that have an influence on system performance. Each type of modeling can be presented as a different means to represent reality. What is crucial in this approach is not only having a technical and theoretical grasp of the modeling technique applied but to have knowledge of and understanding of the real world system being modeled and the complimentary modeling technique. Analysts performing computational modeling cannot be effective without an understanding of the experimentalist's world. The same understanding of the computational approach is required of the experimentalist. The authors are not proposing that each be a specialist in the other modeling methodology. Rather a general working knowledge and understanding of basic approaches and limitations is required. Both analyst and experimentalist also need a working knowledge of the system they are modeling. Simplifying assumptions are standard practice in the creation of computational and experimental models. The better the understanding of the actual system, the better the choices that can be made on the necessary simplifying assumptions.

The authors realize that requiring this cross over of knowledge is not standard operating procedures in many facilities. However, it is an approach that has worked successfully in the past and it is an approach that allows for true multidisciplinary research. Problems in today's world are complex. There is seldom a simple answer. Conflicting requirements due to system performance requirements, material limitations and other issues have driven design problems to the realm of multidisciplinary research. Unified or multidisciplinary design approaches provide for the most effective solution.

The authors have applied this approach to the design and evaluation of shipboard impressed current cathodic protection systems. In a multidisciplinary unified approach an understanding of real structure, experimental methodology and computational methodology is required. This information is presented. This chapter provides detailed information on the development of the computational modeling methodology applied to these systems. In addition, real system information and an introduction to the physics basis for experimental methodologies are provided. Chapter sections are:

Cathodic protection systems – a basic introduction
Ship systems
Experimental modeling
Computational modeling – governing equations
Computational modeling – ICCP systems
The road ahead – unified design approach

The process and information provided is focused on modeling of cathodic protection systems, however, the approach can be applied to any system or structure. It is critical to understand that experimental, computational and real structure data all provide information required to further the understanding of the system performance in changing conditions.

2 Cathodic protection systems – a basic introduction

In a floating structure, the external wetted hull is generally considered to be the cathode or the working electrode, which requires protection. Anodes are co-located on the underwater hull and output current, from the power supplies, which effectively flows through the electrolyte, to the hull, to complete the electrical circuit. Current flow within the electrolyte is accomplished through the utilization of electrons in the electrochemical reactions at the surfaces of the anodes and corresponding cathodes. Where current is impressed on the cathode, the cathode potential is driven in a negative direction which can be measured using standard Silver-Silver Chloride (Ag/AgCl) reference cells. Hull potential measurements provide information concerning relative current distribution from the anodes and a determination of the effective levels of polarization to different areas.

A shipboard ICCP system has three basic components: 1) reference cells, typically Ag/AgCl, 2) controller/power supply, and 3) anodes. Typically marine ICCP systems utilize reference cells to monitor potential levels at critical locations on the hull and to provide an electrical feedback to the controller circuitry which regulates the output current to the anodes. In this way, the ICCP has self-regulating set potential levels for operation, normally between –0.80V to –0.85V versus the Ag/AgCl reference cell, which is sufficient to protect steel structures. The ICCP system also naturally compensates for most environmental factors, which influence the cathodic current demand behavior, by continually regulating the anode current output to maintain the hull polarization to the designated set potential.

The ICCP system in principle works well for this task, but the key to a good design and well functioning system is the proper location of components on the complex hull geometry at the onset. Until 1986, ICCP systems were designed empirically and typically were unable to respond to the variable life-cycle conditions, which resulted in hulls that were either overpolarized, underpolarized or both. Either extreme is dangerous for a hull, because overpolarization tends to cause excess gas evolution and alkali damage that cathodically disbonds the barrier coatings, while underpolarization allows the materials to freely corrode

and/or galvanically interact. The complex hull geometry requires that anodes be located such that the current distribution can be uniformly maintained throughout and correspondingly that the reference cells are placed such that they effectively monitor the hull potential at necessary points.

A schematic of a typical analog ICCP system for a larger ship hull is shown in fig. 1. Often an ICCP system is divided into zones, which consist of a group of anodes, controlling reference cell and associated controller/power supplies. This zone operates essentially independently from other zones, except that the hull is the common ground point and thus each system can influence the operation of the other, depending on system design. The advantage of a zone system, however, is that the reference cells can be placed more proximate to those areas which require protection and the protection can be focused towards more localized hull areas, such as the stern area, which has complex hull, rudders, struts and propellers. More recently, advanced digital ICCP systems have been developed, which are software driven and are less zone oriented. A schematic example of a software controlled system is shown in fig. 2. These systems have the same basic components, and can be setup exactly like a zone system or anode output can be based on a composite of reference cell readings with an algorithm determining individual anode current output. What is imperative to note, however, is that a poorly designed ICCP system, with poor component placement cannot be improved significantly by more sophisticated electronics.

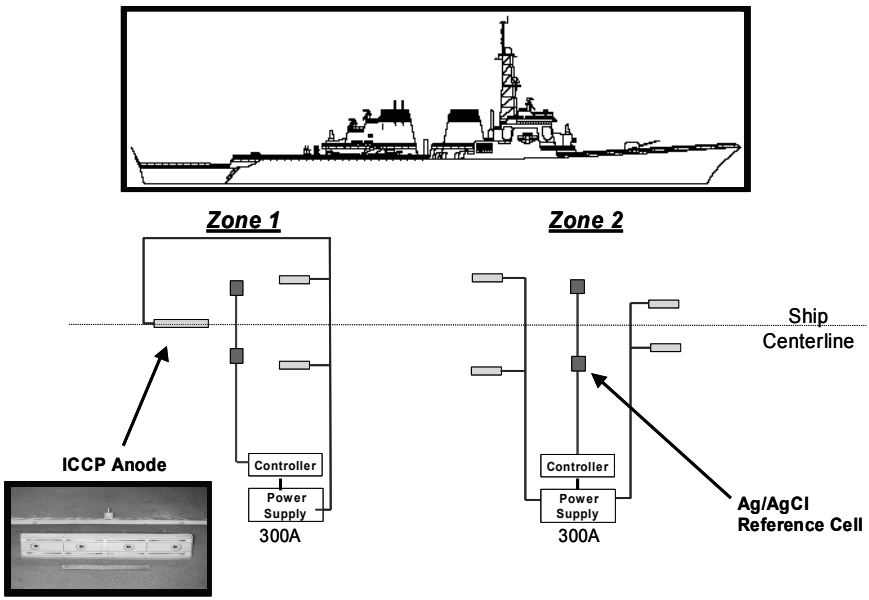

Figure 1: Typical two-zone ICCP system.

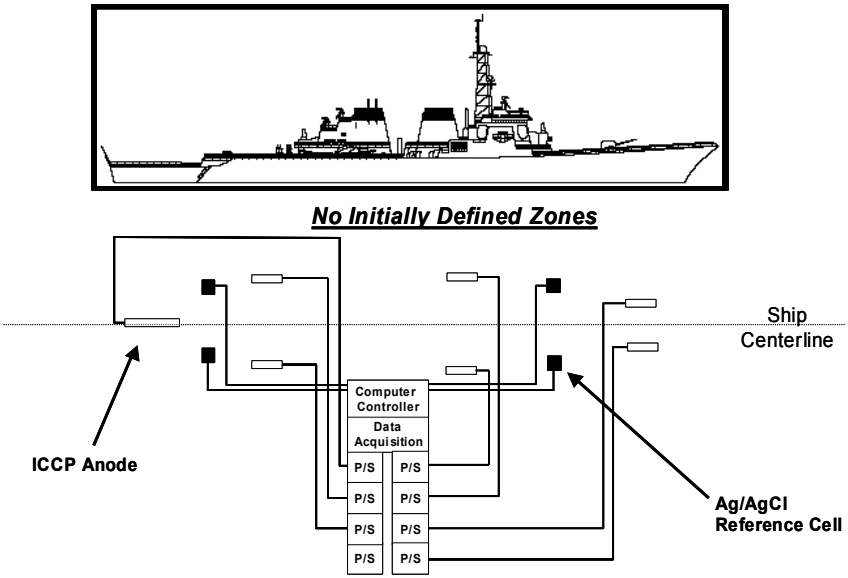

Figure 2: Schematic of the 'next generation' computer controlled ICCP system.

3 Ship systems

We often forget how complex the real world is and a ship ICCP system is no exception. Each ship has its own dynamic sequence of time, from when the hull is new to when it is removed from the water for refurbishment of the coatings. Within a typical maintenance life-cycle, each ship hull undergoes significant changes and differences within operational behavior, docking periods, coatings degradation, and biological fouling. What is acceptable ICCP system performance when the hull is new must also be acceptable throughout the full life-cycle experience.

Simple schematic representations of the structural component or system are often presented as representative of what is being modelled. While these may accurately represent the computational or experimental model, they are simplifications of the real world. In reality the factors which affect the corrosion behavior and signature of the underwater portion of a ship hull are numerous, often highly complex and variable. A partial list of the factors that influence ICCP system performance is shown in fig. 3.

Often measured data from a real structure is presented as a 'truth' value. This requires a detailed knowledge of the condition of the structure when the data measurements are obtained. Unfortunately a real ship, or any complex structure, can provide only limited information about its physical condition and protection requirements. Beyond the changes in performance caused by physical properties, uncertainties in boundary conditions and applied loads also have to be taken into consideration when evaluating data. Natural e nvironmental effects on materials

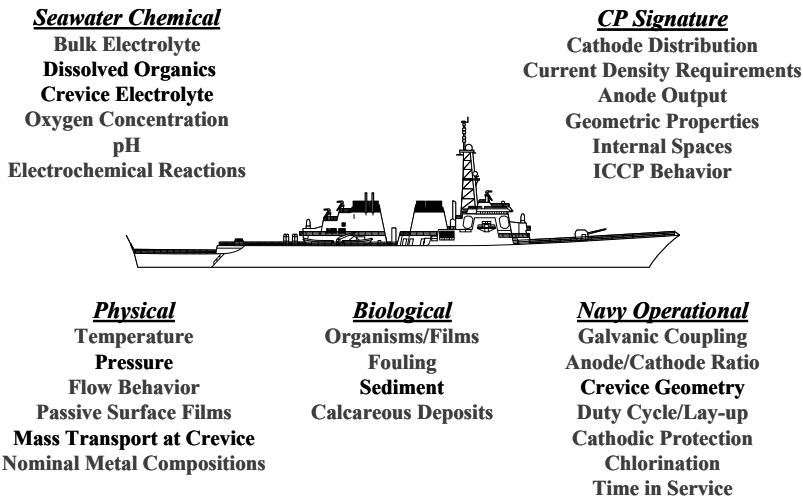

Figure 3: Factors affecting ship corrosion and signature.

also have impact on the ICCP parameters and must be taken into consideration. For example, in the case of ship hulls with a good dielectric barrier coating, it may seem appropriate to assume a total blockage of current but this would not be realistic. Over the life-cycle, these materials may adsorb water in an undefined manner, fail completely and also suffer from unpredictable changes related to mechanical breakdown and other application discrepancies. It is very seldom that a structure can be completely described.

In principle, the major factors that must be considered in protecting a hull from corrosion are: 1) the nominal wetted surface area which requires protection, 2) the material characteristics of metallic components exposed to the seawater and 3) the chemical aspects of the bulk electrolyte (seawater) under operational conditions, such as, seawater conductivity, pH, dissolved oxygen and surface reactions. Directly influencing the kinetic behavior of these reactions are the temperature, velocity and diffusion properties of the surfaces, both with and without cathodic protection applied. In addition to the growth of calcareous deposits while cathodically protected, all surfaces may foul with marine organisms, resulting in a biological system that will further influence the surface properties of the metals involved.

In many cases, unique operating conditions of the ship will have a direct interplay on the ICCP system performance, because at some point the ship may simply turn the system off for an unknown period of time or move rapidly into greatly different waters or nest alongside piers, ships or other geometric features. When nested or in fresh water the ICCP system performance can vary significantly. Hull geometry and composition may further impact the performance by changing flow regimes, eroding surfaces and by creating galvanic corrosion problems, especially at the propeller areas.

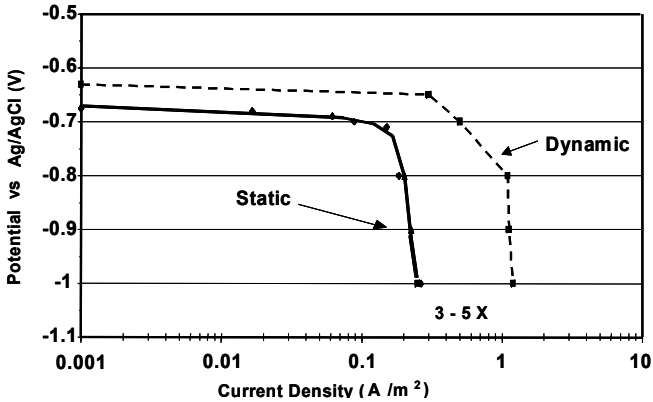

Figure 4: Steel current density requirements as function of seawater flow.

Material interaction is a complexity that exists for most shipboard ICCP systems. In reality there are multiple exposed materials on a ship, not a single material, *i.e.* steel, which require protection. The multiple material systems result in numerous galvanic corrosion problems, most notably the galvanic couple between the steel hull and the nickel aluminum bronze propellers. These galvanic material relationships, while protected under ICCP, greatly influence the current density requirements, location of components and system operation. Structural characteristics also add to the complexity by hosting other types of corrosion, such as crevice or hydrogen effects.

In determining what simplifying assumptions can be tolerated, one must consider the dominant factors in performance. For corrosion protection, bare metallic areas become the dominant corrosion protection issue on any hull and it is these cathodic surfaces (bare areas), rather than any anodic surface that define the behavior of the ICCP system. This is because the system power supplies can easily overwhelm any anodic resistance and will polarize the cathodic surfaces in response to the reference cell feedback to the controller. The rates of corrosion at the cathode are influenced most by the ability to diffuse oxygen across the metal/electrolyte interfaces. This effect is shown in fig. 4 and it can be seen that the relative differences between a static current density requirement and a dynamic state may increase the demand by a factor of three to five times. While the ship is in motion, oxygen transport is significantly increased, but the surface diffusion effect may be decreased depending on the extent of corrosion deposits, prior calcareous deposition and macro-fouling accumulation.

As stated at the beginning of this section, we often forget the level of complexity in the real world. Obviously everything cannot be captured by experimental procedures or included in a computational model. The challenge for modelling, both experimental and computational, is to provide an accurate representation of the many localized environments on the ship hull and to accurately represent the many different operational environments that the ship will experience. Judicial use of simplifying assumptions is required. The better

the entire problem is understood, the closer the final modelling environment created for analysis will be to the real world.

4 Experimental modeling

Physical Scale Modeling (PSM) is the name applied to a technique that has been developed that uses near-exact scale models and scaling factors based on the physics of electrochemical response to provide information on current and potential values on the structure. The near-exact scale models, ranging in length from two to ten feet, such as shown in fig. 5, are the representative geometry that are used along with scaled electrolyte to provide equivalent ohmic paths. Basic aspects of potential and current distributions in scaled systems were originally presented for use in electroplating but can be applied to cathodic protection systems. Works by Kasper [1], Agar and Hoar [2] and Weber [3] define the relationship between scaled geometry, scaled solution conductivity and the resulting interpretation of results. These works can be directly related to the modern practices of PSM as practiced by NRL Center for Corrosion Science and Engineering. Further theoretical basis for PSM has been presented by Ditchfield *et al* [4]. Validation of the application of PSM to surface ship by means of comparison with real ship data has been documented by [5, 6, 7].

PSM was pursued specifically to provide a robust physics based method for the design of ICCP systems. A driving force behind much of this work is the U.S. Navy requirement of ICCP as the standard method to achieve good corrosion protection of the hull. The PSM technique has been utilized to determine the best ICCP component placement, life-cycle performance, zone interaction behavior and various failure modes under both static (dockside) and dynamic (underway) operational conditions for a variety of ship and system configurations. PSM can directly address difficult geometries, areas of restricted flow, protective coatings degradation, advances in ICCP design technology

Figure 5: Example of a near-exact scale model used in PSM.

(*i.e.* use of digital comptrollers – hardware and software, advanced control algorithms) and complex interaction of power supplies and control algorithms (*i.e.* zone behavior). The U.S. Navy has utilized PSM as performed by NRL Center for Corrosion Science and Engineering extensively. There is an established design criteria and PSM is currently the accepted standard technique for design of U.S. Navy ICCP systems [8].

For PSM and the computational techniques, cathodic protection behaves in accordance with Ohm's Law:

$$E = I\,(R_P + R_{OHMIC}) \tag{1}$$

where, E = potential (V), I = current (A), R_P = polarization resistance and R_{OHMIC} = electrolyte ohmic resistance. In scaling, necessary in the PSM technique, $R_{OHMIC} = \rho L/A$, and where, ρ = electrolyte resistivity, L = length of ship or model and A = area. For exact scaling, it is desired for potential relationships to exist, such that $E_{SHIP} = E_{MODEL}$ and for current density (i) behavior, such that $i_{SHIP} = i_{MODEL}$, where $i = A/m^2$. For a relationship where:

$$\begin{aligned} E_{SHIP} &= I_S(\rho_S L_S/A_S) = i_S\,(\rho_S L_S) \\ E_{MODEL} &= I_M(\rho_M L_M/A_M) = i_M\,(\rho_M L_M) \end{aligned} \tag{2}$$

It is necessary that $R_{P\,(SHIP)} = R_{P\,(MODEL)}$ for the model to scale exactly, by definition. For scaled models $L_S/L_M = k$ and $\rho_M = \rho_S(k)$, where k = scale factor, the relationship becomes:

$$\begin{aligned} E_{SHIP} &= E_{MODEL} = i_S\,(\rho_S L_M)(k) = i_M\,(\rho_S L_M)(k) \\ i_S &= i_M \end{aligned} \tag{3}$$

For PSM current measurement on the model, it follows from eqn (2) and eqn (3) that:

$$I_S = I_M(k)^2 \tag{4}$$

Basic assumptions in the derivation of the modeling process provide for precision measurement of potential and current on the model with a direct mathematical relationship between the model and full scale system. These assumptions are:

- The surface areas and geometry are exact and scaled such that $A_{SHIP} = A_{MODEL}\,(k)^2$.
- The current density relationship, $i_{SHIP} = i_{MODEL}$ is true, by definition, when the model size, electrolyte dilution and polarization resistance components obey the scaling law.
- $R_P = \Delta E/i_C$ must be same for the model and full scale system, where ΔE represents the polarization from E_{CORR} to the cathodic protection set potential of –0.85V.

The key to the modeling methodology, in addition to the correct implementation of model size and correct electrolyte ohmic scaling is the polarization resistance behavior. In order to preserve the relationship $R_{P\ (SHIP)} = R_{P\ (MODEL)}$ for direct scaling, NRL has established a pre-conditioning sequence. In pre-conditioning the models are first cathodically protected in full scale seawater (to –0.85V Ag/Ag Cl electrode), to allow the deposition and adsorption of natural calcareous films on the model surfaces prior to testing. It has been experimentally shown that once a calcareous film was deposited, prior to placement in the scaled electrolyte, the R_p component of the metallic surface would behave in a manner very similar to natural seawater behavior and that the scaling equation was correct. Measurements on the model produced correct potential values, correctly scaled current behavior and normal cathodic surface responses. When operational conditions in the experimental facility are varied, such as velocity, coatings damage or anode/cathode ratios, the system compensates in a natural manner because it is in dynamic equilibrium. For computational modeling measurements, this critical parameter is controlled by the use of polarization curves for each of the ship states, materials properties and hull conditions.

Like the real ship, the PSM technique utilizes a controlling reference to provide a potential set point and feedback circuit for control. Accordingly, the system current output can be monitored, but instead of dealing with an unknown hull surface state, the model is well defined into specific cathode areas which have independently monitored/controlled cathodic behavior, monitored anode sites and multiple additional hull potential sensing points from the reference cell array. Thus, in addition to what would be basis ship data, the model provides detailed cathodic current demand, anode currents outputs and an array of potential data, for a variety of coatings damage conditions, under static and dynamic states. Outside of the rules for scaling defined above, assumptions in the PSM technique for ICCP design lie primarily in the selection of the metal percentages for the cathode areas and in the selection of the design current densities. Electric field (EF) behavior produced as a result of the ICCP current flow through the test electrolyte can also be rigidly evaluated using reference cell pairs located discretely or scanned under the model. An example of the electric field signature obtained during the PSM process is shown in fig. 6. Results for EF calibration, as compared to theory for dipole measurements, are exceedingly accurate and hull signature can thus be evaluated in real time.

All methodologies have limitations. The limitations associated with the PSM technique tend to be associated with the mechanical aspects related to PSM modeling. For instance there are physical limitations in defining a detailed model and reduction in current density demand due to scaling factors. Financial and time limitations are also predominately associated with the mechanical aspects of PSM. Limiting factors are the ability (cost and time) of procuring a detailed model, the time associated with the natural polarization changes and setting up the model to perform the iterative tasks associated with optimizing component placements. Experimental control in the modeling is maintained by testing only when the cathodic current density requirements are within the defined protocol ranges. This results in testing conditions that are always repeatable, but it also results in the model falling out of the required test range and therefore requires

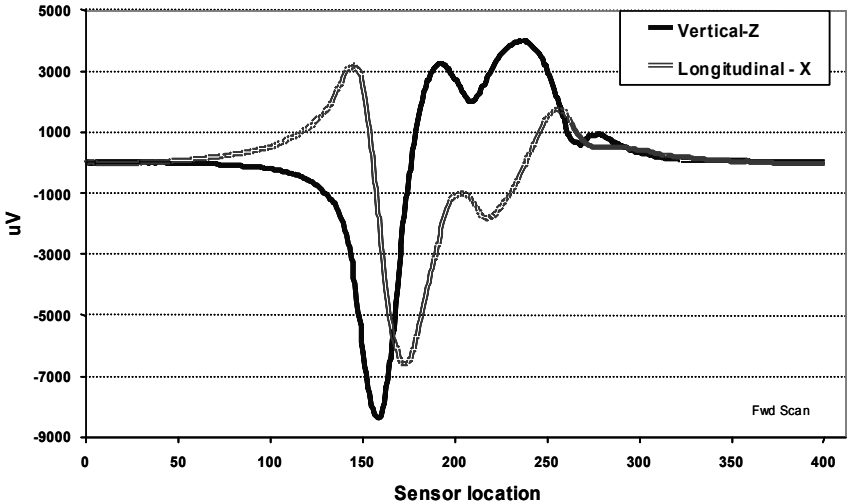

Figure 6: An electric field scan obtained during the PSM process.

periodic re-conditioning of the surfaces. The PSM process is schematically represented in fig. 7. For many of the cumbersome and time-consuming tasks, the computational modeling technique offers an immediate enhancement from the iterative design repetition of PSM and can be a highly beneficial and cost effective partner in a comprehensive design and verification process. This is one way in which the two modeling techniques result in complimentary information gathering with the end result being more detailed information to help in determining system performance characteristics.

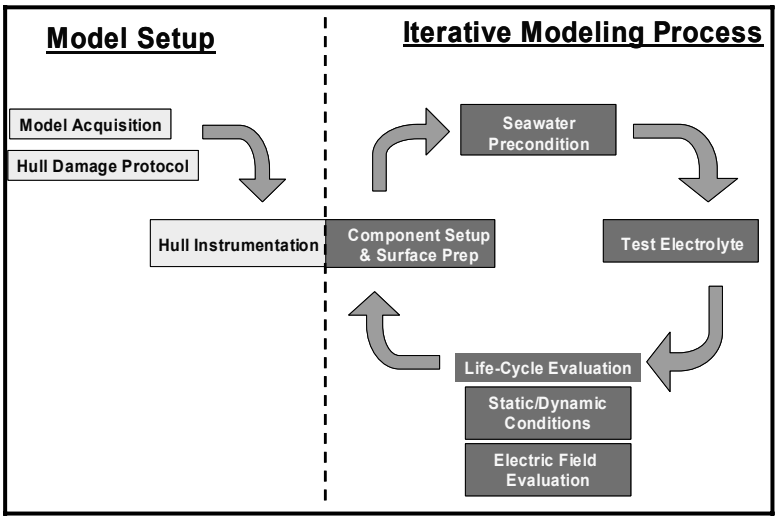

Figure 7: PSM technique iterative process.

5 Computational modeling – governing equations

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

$$k\nabla^2\Phi = 0 \tag{5}$$

Where Φ is the electric potential and k is the conductivity of the electrolyte in domain Ω. For Laplace's equation to be valid the volume surrounding the structure cannot contain either electrical sources or sinks and the total current in must equal the total current out of the system. The equation models steady state conditions and does not address corrosion initiation.

The solution space for the problem is the surface Γ, which bounds the domain Ω and is defined as:

$$\Gamma = \Gamma_A + \Gamma_C + \Gamma_I \tag{6}$$

Where A, C and I are anodic, cathodic and insulated regions. In the case of a shipboard ICCP system the surface is the wetted surface of the ship's hull. The domain is the open sea surrounding the ship. It is assumed that the seabed is a large distance removed from the water surface and lowest point of the ship's hull. Interactions between the hull and other objects, such as a second ship or pier, or between the hull and seabed are not addressed by the presented analysis method.

The surface is divided into anodic regions, cathodic regions and insulated regions. Each region represents a specific component of the ICCP system and ship hull. Anodic regions are the ICCP system anodes and are defined as either a constant current source, q_A:

$$\partial\Phi(x,y)/\partial n_{(x,y)} = q_A \tag{7}$$

Where n is the surface normal, or as a constant voltage source, Φ_A:

$$\Phi(x,y) = \Phi_A \tag{8}$$

Where $\Phi(x,y)$ is the electrical potential at the point (x,y) and $n_{(x,y)}$ is the normal to the surface at the point.

Electric current to anodes can vary with time for an ICCP system. The approach taken is to model each instant in time as a separate boundary element solution. Therefore changes in electric current are not incorporated into the model. Anodes are not defined as electrical sources in the model but as fixed-value boundary conditions. This maintains the validity of use of LaPlace's equation for the steady state solution. An individual computer solution defines steady state conditions at a specific point in time at a specific anode current level.

The electric flux at a point on the surface of the cathodic region is defined by:

$$\partial\Phi(x,y)/\partial n_{(x,y)} = f_c \tag{9}$$

Where f_c is the cathodic polarization function. The polarization function is experimentally determined and is typically non-linear. In the current analysis, polarization response is modeled as piece-wise linear through use of a look-up table format. In general, if the value of the potential is defined the current can be determined and if the value of current is defined the value of potential can be determined.

At insulated surfaces, such as typically used to define painted surfaces, the flux is constant through time and equal to zero:

$$\partial\Phi(x,y)/\partial n_{(x,y)} = 0 \tag{10}$$

A 'zone' is a power supply. The anodes attached to that power supply and the associated reference electrode(s) comprise a zone. Each zone has its own control algorithm. In the computational work done to date the control algorithms have been simple feedback control based on the potential at the reference electrode(s). Each power supply is controlled independently. Anodes are defined by assigning specific elements in the boundary element model potential, current or current density values. Mathematically the solution does not matter on the choice of boundary conditions to define the source anodes. In all cases anode values are defined as input values. Reference electrode values are determined in the solution process and are not boundary condition defined values.

Input values, boundary conditions and material properties are combined for the mathematical solution of LaPlace's equation as represented by eqns (5)–(10). In addition to mathematical criteria for a solution there are two additional criteria for a feasible solution:

(1) Potential values at the nodes representing the reference electrodes equal to the target value;
(2) Total current to anodes associated with a single power supply is less than the power rating of that power supply.

A candidate solution consists of a computer run in which the potential of the reference cells is at the target potential –0.85V Ag/AgCl electrode (criteria (1)). Reference cell readings are calculated potential values. A feasible solution occurs when the reference cell is at the target potential (criteria (1)) and the total power required is within the power supply capacity as defined in the ICCP system design (criteria (2)). This is not a constraint required by LaPlace's equation or the representations used for material response. A feasible solution is determined through a multiple run process in which anode input values are varied. A feasible solution is typically the solution of interest.

There are two basic material characterizations required for evaluation of ICCP systems: the conductivity of seawater and the polarization response for all

materials used to define the hull. Seawater is treated as a uniformly mixed solution with a single value of conductivity for all depths. The accuracy of the polarization data used to define material response is critical to the overall solution accuracy. In a perfect world the modeler would be able to define material properties that were determined from conditions that exactly duplicated the environment of interest. This unfortunately is not generally the case. Most polarization data are obtained from small specimens, tested in the laboratory, without the influence of material interactions and under controlled flow conditions. As in all laboratory testing, the tests define material response in a very controlled situation. Even with good control it has been determined that material polarization response is highly sensitive to many parameters. Engineering judgment is used to determine the best fit between service and material characterization test conditions.

There are four distinct material definitions that have been used in the NRL computational analysis work: perfect paint, finite resistance paint, steel, a nickel aluminum bronze alloy (NAB) and seawater. Perfect paint is by definition a perfect insulating surface. Perfect paint is not defined using a polarization curve as input but is defined using boundary conditions. The other three materials are defined using nonlinear polarization curves as input data. Polarization responses for steel and NAB can be found in the literature. Values used in the NRL analyses were those experimentally measured specifically for projects related to PSM. The performance of a 'real' paint has been modeled by shifting the polarization response of steel by three orders of magnitude on the current demand axis. Paint response is discussed in more detail later in the chapter.

Despite the best estimates of material response, boundary conditions, ICCP system anode performance and geometry definitions, it is essential to remember that these methods are modeling techniques that require simplification from the real world. This is not done in ignorance or with any intention to misrepresent the structure or system and its environment. In fact, defining what factors are simplified is often the most challenging aspect of setting up a new computational model. The goal is to create the most accurate representation of the real world model while remaining within computational system or operating defined limitations. One often hears those involved with computational modeling discussing element type and number limitations. Even with today's high-speed computers, large storage memory capabilities and advances in solution algorithm complexity, the complete real world picture cannot be incorporated into a model.

Another factor that is important for the analyst to remember is that, typically, operating parameters in the real world are defined in ranges rather than point values. Maximum and minimum calculations based on key conditions are necessary to create a range of operation performance. In computational models where the end goal is to determine maximum structural performance the concept of range can be collapsed by collocating worse case conditions (*i.e.* maximum possible load, minimum dimensions and minimum material strength) in the computational evaluation. The resulting calculations can be considered upper bounds in terms of deflections, strains and stresses. If these values are within safe margins then all anticipated operating conditions will be within safe margins

of operation. In general, in the design of ICCP systems, this collapsing of ranges into a single point is not the desired approach. The limiting value that must be applied to all conditions is the power supply capacity. This value, when calculated, should be done using worse case combinations. Otherwise, the power required and voltage set points for protection at one operating condition are of equal interest as those at another slightly different operating condition. Beginning of life and end of life damage conditions are used to bound system performance. Ultimately the end-user is interested in a range of operating parameters corresponding to uniquely identifiable operating conditions.

6 Computational modeling – ICCP systems

The mathematical development of boundary element techniques and aspects of the method as applied to electrochemical corrosion systems have been traced by other researchers. ICCP systems are based on the electrochemical corrosion phenomenon. Review articles by Adey [9], Munn [10] and Gartland *et al* [11] have clearly shown the case for the usefulness of the boundary element method. Some computational codes, such as described in [12], are based on an analogy between electrochemical corrosion and heat conduction. Other commercial programs and specialized codes directly solve LaPlace's equation for steady state corrosion.

The boundary element technique has been applied to a variety of cathodic protection systems. Structures studied range from pipelines that can be represented by 1D models to geometrically complex structures such as ships that require full 3D modeling. Pipeline analyses that examine the electrochemical corrosion behavior as well as determining the effectiveness of cathodic protection systems have been presented from the mid-1980s on. Bardal *et al* [13] examined the behavior of carbon steel and stainless steel components. Sacrificial anode configurations for pipelines have been studied by Adey [14]. Brichau and Deconinck [15] evaluated parallel pipes buried in the ground. Lee *et al* [16] evaluated the effects of a non-uniform electrolyte composition on the protection system of a buried pipeline. Yan *et al* [17] and DeGiorgi [18] discussed galvanic material couples in straight piping systems. Amoya and Aoki [19] used boundary element techniques to determine the optimum anode locations in storage tanks. The use of boundary element techniques to model offshore oil structures is well established [20]. Offshore structure modeling is unique in that polarization response can be determined from *in situ* measurements eliminating issues related to laboratory development of polarization data. Significant work, as collected in [21] has been completed on ship systems. Work continues to date by many researchers on ICCP systems. Diaz and Adey [22] have recently presented a methodology based on boundary element techniques to determine the optimum anode configuration for shipboard ICCP systems.

Since 1987 NRL has actively pursued computational modeling of shipboard ICCP systems using boundary element techniques. Issues addressed include initial proof of concept modeling and validation of the approach through comparison with PSM experimental results. The work performed, once the

process was validated, branched into evaluating basic modeling boundary condition assumptions as well as geometric simplifications. Later work has addressed issues related to PSM experimental work. The commercial boundary element codes BEASY-CP [23] and Frazer-Nash Detailed Modeler [12] have been used for the analyses presented. The commercial code PATRAN [24] has been used for model generation. The commercial code TECPLOT [25] has been used for results visualization. In addition, customized computer programs for translation and display of data have been developed at NRL. Modeling results and guidelines generated from the analyses are applicable to any code used. BEASY-CP solves LaPlace's equation for steady state corrosion. The Frazer-Nash Detailed Modeler uses the thermal-electrochemical corrosion analogy. Guidelines have been found to be equally valid for both codes.

The boundary element problem requires a mathematical representation of the outer surface of the ship hull and the surrounding volume of electrolyte. The ship hull is modeled by a boundary element mesh. The surrounding volume of electrolyte can be modeled in one of two ways; either by a mathematical boundary condition that defines an infinite or semi-infinite volume or by an outer meshed surface that defines a volume. NRL has typically opted to use a large but finite volume of seawater to represent the open ocean around the ship hull. This domain is defined sufficiently large enough so that edge effects on the potential profile of the surface ship are negligible. Typical domain dimensions are 12 to 20 ship lengths. All analyses reported to date have been interested in the open ocean environment.

In all NRL studies symmetry conditions have been invoked for both the ship hull and to represent the water surface. Ship hulls and ICCP systems were defined as symmetric with respect to port and starboard characteristics. This was done in the interest of saving computational time and resources. There is no requirement for symmetry. Symmetry conditions were also used to define the water surface. This is a standard approach in boundary element methods.

A basic design matrix consisting of four cases was created by the pairing of two service flow conditions, static and dynamic, with two paint damage conditions. Static flow represents dockside conditions. Dynamic flow represents ship underway conditions. The two paint damage conditions are minimum (2.8% of the hull surface area is damaged paint) and maximum (15% of the hull surface area is damaged paint). The location and size of damaged paint regions is defined by protocols provided by NRL Center for Corrosion Science and Engineering and Naval Sea Systems Command. Damaged paint areas are defined as exposed metal surfaces in the boundary element models. This duplicates the conditions in PSM where painted surface is represented by fiberglass and damaged paint areas are represented by strips of uncoated metal attached to the model hull.

Reference cells and anode locations in the computational model duplicate as close as possible the locations in the PSM models. In cases where port and starboard anode locations are not symmetric, the boundary element model anode is placed at the average of the port and starboard locations. The decision to use port-starboard symmetry in the computational model was based on model size and existing computational resources when the analyses were initiated.

The boundary element mesh of the ship hull is the geometric representation of the actual ship structure. Levels of detail and accuracy in geometric representation, as well as appropriate use of boundary conditions and material definitions, will have a direct influence on resulting computational accuracy. A series of guidelines for analyses have been established based on the body of work performed. These guidelines, divided into 3 categories, are:

- Model Definition.
  - A more refined model is needed than is traditionally associated with boundary element techniques.
  - Accurate modeling of relatively small-scale features, such as bilge keels, is necessary.
  - Propellers can be represented by thin disks. Further detailed modeling of this feature is a goal of future work.
  - Variations in seawater conductivity that correspond to changes in deployment region can be significant to system performance and should be incorporated into the design basis.
- Material Definitions.
  - The accuracy of computational results is directly dependent on the accuracy and appropriateness of the polarization data used as material characterization input data.
  - Preliminary design and trend studies can be successfully completed using less than optimum polarization data. Trends in performance can be determined even though magnitudes will be suspect.
  - Modeling damaged paint as totally bare metal is a conservative approach.
- Boundary Condition Definitions.
  - Modeling paint as a perfect insulating material is acceptable depending on the accuracy of results required.
  - Experimental tank size influence on results can be evaluated prior to testing.
- Determination of scaling factor prior to experimental work can be based on tank sizing considerations.

Analysis results that support each of these guidelines will be presented in the next sections.

6.1 Model definition

Initial analyses performed by NRL addressed whether boundary element techniques could be used to accurately predict system performance [26, 27, 28]. The hull geometry investigated was a U.S. Navy CG hull class destroyer. Three different ICCP systems were evaluated. Mesh refinement as well as the level of detail required were identified early as critical modeling issues. The ability to use boundary element techniques for both detailed design and trend analyses, relying on different levels of mesh detailing and refinement, was also identified as capability.

Table 1: Current demand (Amps) for CG analysis. Three measurements for evaluating results; total current to components (props. and docking blocks), current from forward and aft systems and total current. Reference cell reading = –0.85V Ag/AgCl

	Props	Docking Blocks	Forward System	Aft System	TOTAL
Min.Damage					
Calculated	50.3	13.7	22.3	41.8	64.0
PS Model	44.5	14.1	25.8	39.1	64.9

The original model used in the CG analysis consisted of 573 rectangular elements and yielded unsatisfactory results. Initial results were encouraging but it was felt that closer agreement between experimental and calculated results could be achieved. Two issues were identified; mesh refinement and polarization response input data. A mesh refinement study demonstrated that a significantly higher degree of mesh refinement was required. The mesh refinement study was determined to be complete when a level of refinement was determined that did not produce any additional changes in calculated results with additional refinement. Calculated results were compared with calculated results.

The original model only included propeller and rudder representations. In reviewing calculated potential profiles it was determined that there was a need to include the bilge keel. This was consistent with early model development results for PSM. After the level of mesh refinement was determined, a 3D representation

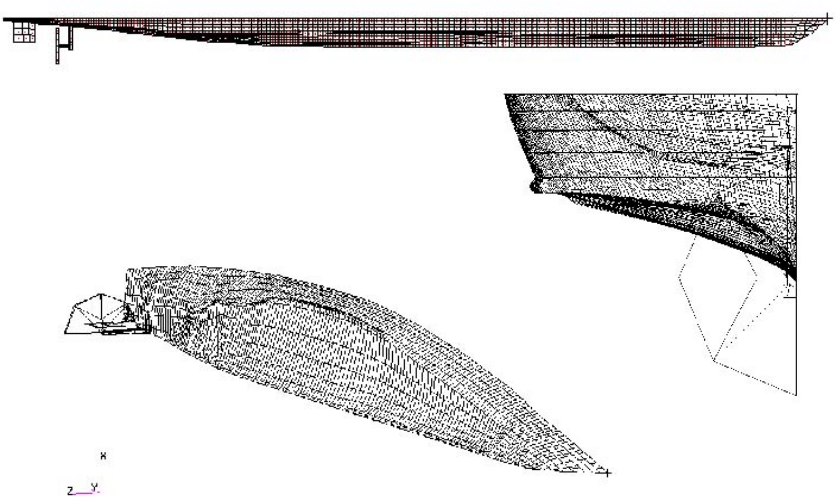

Figure 8: Boundary element mesh for CG hull class ship.

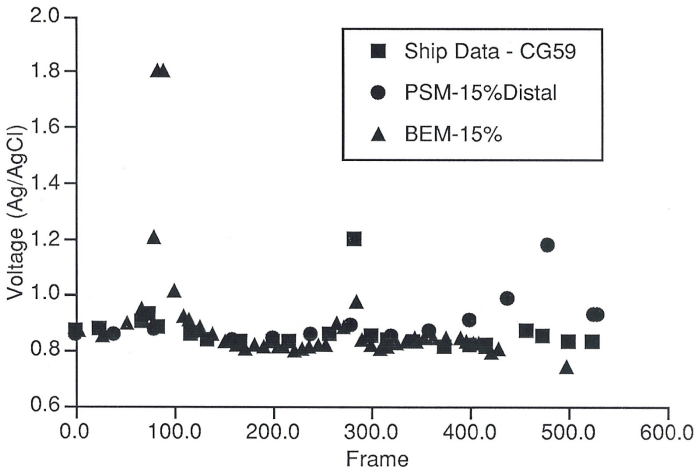

Figure 9: Comparison of CG hull potential profiles for real ship data, PSM and computational results (BEM) using maximum damage conditions (15%).

of the bilge keel was added to the model. This model was used in the later CG work and consists of 1583 8-noded rectangular elements (fig. 8). The elements were flat surfaces so the curved ship hull was modeled as a faceted surface. These elements were the most advanced element appropriate for use at the time. Representative results are shown in table 1 for current values and fig. 9 for potential profiles. A more detailed discussion of results is in the following section, Material Definitions.

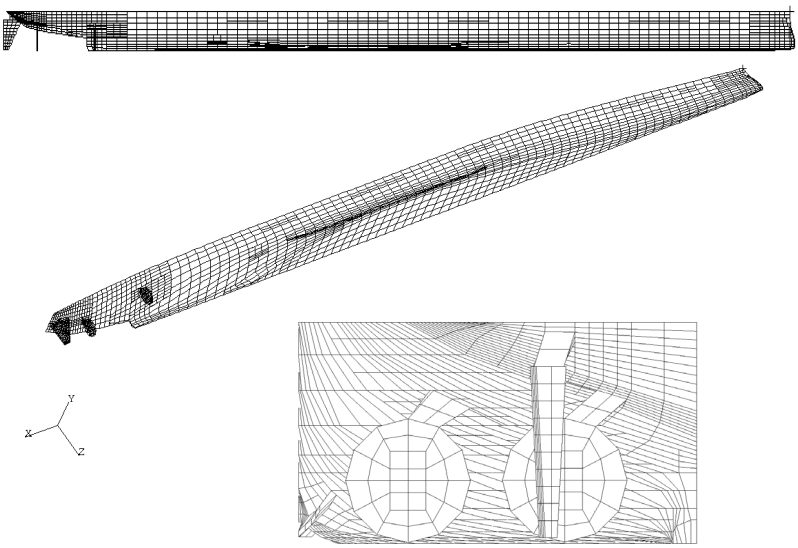

Figure 10: Boundary element mesh for CVN hull class.

The guidelines for mesh refinement and detail construction were applied when the mesh of the CVN aircraft carrier hull class was generated [29] as shown in fig. 10. Propellers were modeled as thin disks. The bilge keel was included in the mesh. In fact, the bilge keel is significantly smaller in relationship to the overall hull size as can be seen by comparing figs. 8 and 10.

The CVN boundary element mesh consists of 1884 linear-quadratic displacement 9-noded rectangular elements. The 9-node configuration consists of 8 exterior mesh points that define the element geometry and 1 mesh point placed at the centroid of the element. The centroidal node allows for curvature of the element. This element type was not available for the earlier work. The 9-noded element allows for more accurate modeling of the curved hull surface. This element was not available at the time the CG model was created. It was the most advanced appropriate element for use at the time the CVN model was created.

In the CVN analysis the source of polarization data was chosen so that PSM testing procedures would be represented by the polarization response. Typical potential contours are shown in fig. 11. Total current requirements for dynamic conditions are shown in table 2. Detailed comparisons of calculated and experimental results are presented in [29]. While potential profiles and magnitudes were accurately predicted, there was a larger degree of variation in amperage values than for the CG analysis. Possible reasons for these differences were identified as model simplification and polarization response.

All computational models are simplifications of the actual geometry. One difficult area in the CVN hull that required simplification was the bilge keel. Despite best efforts to match bilge keel profile and attachment angles there were differences between computational and PS models. These variations in bilge keel geometry are probably a contributing factor in variations observed for amperage required for mid-hull, *i.e.* bilge keel region, damaged areas. The differences in results, attributed to the variation in bilge keel geometry, highlight the need for accuracy modeling of geometric details.

Table 2: Current demand (Amps) for CVN system, dynamic flow conditions; reference cell reading = –0.85V Ag/AgCl.

	Minimum Damage		Maximum Damage	
	Calculated	PS Model	Calculated	PS Model
Propellers	118.9	201.1	189.8	228.2
Docking Blocks	71.7	110.6	185.2	181.8
Rudder	NA	NA	85.0	43.0
Bilge Keel	NA	NA	174.4	290.8
Waterline	NA	NA	206.8	229.8
Struts	NA	NA	85.8	104.4
Hull	NA	NA	791.0	759.5
Total	190.6	314.7	1718.0	1837.7

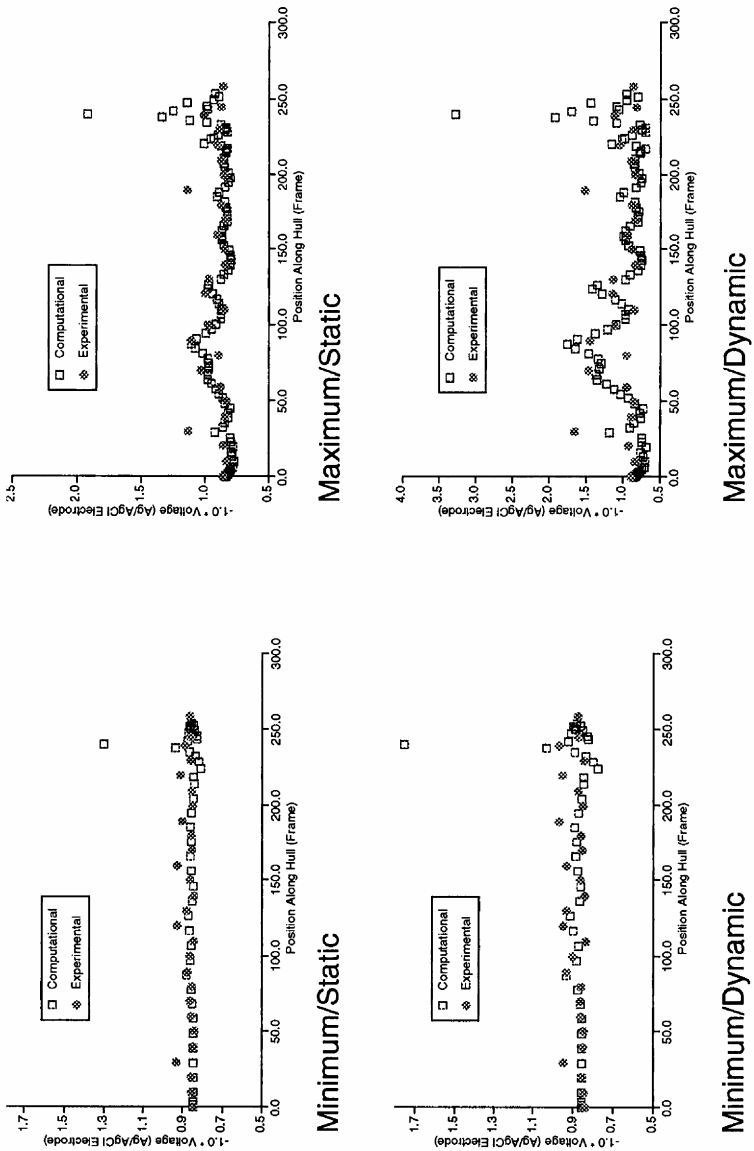

Figure 11: Potential profiles for CVN hull class; comparison of experimental (PSM) and computational (BEM) at 10ft below the waterline.

6.2 Material definitions

The CG and CVN hull meshes were both used for polarization, seawater conductivity and paint conductivity studies. Three topics will be addressed in this section; bare material polarization response, paint polarization response and seawater conductivity definitions. As noted in the real ship section of this chapter the cathodic regions of the hull are the dominant force in determining ICCP system performance. In the computational model these areas are defined geometrically by selection of elements and mathematically by polarization response data.

Once the mesh refinement study was completed for the CG hull class geometry the issue of polarization response was addressed. Initial results for the refined mesh were poor when compared with experimental measurements. Changing polarization input response to data that more accurately represented the PSM environment resulted in good agreement as shown in table 1. The change in polarization response source moved the analysis away from depending on small test specimen results from laboratory based using small specimens to data obtained from larger specimens in an open ocean environment.

A typical potential profile is shown in fig. 9 for the refined hull with bilge keel. Figure 9 shows the comparison between sea trials data, PSM experimental data and computational modeling calculated results for the USS Princeton. The comparison of experimental and calculated results determined that the accuracy of computational results is directly related to the accuracy of the input polarization data used. However, in the process of developing the refined mesh and in evaluating the impact of changing polarization input data, it was observed that performance trends were similar even when magnitudes showed poor agreement. This is an important observation since it allows for basic system design work to be performed using any reasonable polarization data. Regions of overpolarization and underpolarization can be identified quickly using standard input data curves and relatively coarse boundary element meshes. This means preliminary design work can be done quickly and for reasonable computational costs.

In the CVN analysis the polarization data used were determined from small-scale single material specimens tested in scale seawater to match the experimental environment. Despite this there were larger than expected variations between computational and experimental results for maximum paint damage-dynamic flow conditions. A review of data after the analyses were completed, indicated that there were other significant differences between the PSM test environment and the laboratory polarization experiments. While material interactions were not included in the laboratory determination of polarization response it is highly likely that these occurred due to the geometry of the hull, location of damage and location of appendages. Also the presence of film coatings, not taken into account in the laboratory polarization response, was noted on some metal surfaces of the PSM model. These variations are contributing factors to the differences in results. This evaluation again highlights the need for accurate and appropriate polarization response data as observed in

the CG analyses. Polarization input data values will have a direct and dominating affect on solution accuracy.

Finally, the issue of how to represent damaged paint was addressed. It has been a convention in computational modeling to represent damaged regions of paint as regions of bare metal. In actuality damaged paint can take several forms. For instance, wear or poor application may result in thinned layers that have reduced protective capability. There may be regions where paint has been removed by scraping or other mechanical abrasive action. There may be regions where small regions of damage, holidays, may result from a variety of causes. All of these cases have been approximated by defining damaged paint regions as elements with bare metal properties.

Two parametric studies have been completed on this topic. In the first the CG hull geometry was used and the use of large areas of damage on the propeller versus the use of holidays, or small regions of damage, was examined. In the second the CVN hull geometry was used and the effect of regions of diminished paint protection, but not to the point of bare metal, was considered.

The CG hull model was used in a parametric study to determine the affect small levels of damage to the propeller region had on system performance [30]. Paint damage in this case was modeled as an effective reduction in the efficiency of the coating. The polarization curve was scaled by the effective surface area. For example, a 90% coating efficiency was defined as corresponding to 10% exposed metal. The intent in this analysis was to evaluate the effects of small areas of damage, less than the area of one element, on system performance. The effective coating efficiency is one means to model this type of damage. What was demonstrated was that the system responded synergistically. Even though changes in damage were concentrated in the aft section, both forward and aft power sources were influenced.

In a later study the impact of representing paint as a real material with degrading material properties with time was evaluated [31]. The CVN hull geometry was used to evaluate different levels of paint effectiveness associated with partial loss of paint protection but without gaps in paint coverage (holidays, or patches of removed paint). The baseline condition for this analysis was dynamic flow-minimum damage. Damaged area was added by decreasing the paint effectiveness associated with the damaged pattern used for 15% damage surface area. This results in 2.8% of the hull being defined as bare metal and in an additional 12.2% distributed over the ship hull described as intermediate between perfectly insulated and bare steel. When all damaged paint elements are assigned the polarization response of bare steel 15% of the wetted surface area is bare metal, the maximum damage condition. Input voltages values were maintained for all analyses at levels required for adequate protection at minimum damage dynamic flow conditions. Table 3 shows the changes in current draw associated with specific damaged regions. As more area is added to the damaged state, the current attracted to the original region of damage (minimum damage state) is reduced. Increased current draw is seen in the additional damaged areas as the paint effectiveness is decreased. Of note in the results is that the potential profile does not fall below protected levels until the ratio of paint polarization to

Table 3: Current total (Amps) for dynamic flow*, selected damage areas. Material properties of damaged surface varied. Damage condition varied from 3% (minimum) to 15% (maximum).

Condition	Minimum Damage		Paint Level			
	PS Model	Perfect Paint **	2	3	4	5
Paint Effectiveness ***	N/A	0	0.001	0.01	0.1	1.0
Propellers	204.1	118.9	123.8	120.0	99.9	88.4
Docking Blocks	110.6	71.7	63.8	59.3	34.5	14.9
Waterline	0	0	0.3	3.8	15.6	22.8
Bilge Keel	0	0	0.2	1.6	13.4	47.4
Struts	0	0	0.1	1.2	6.8	9.8
Rudder	0	0	0.1	0.5	6.6	10.4

* Average current in and current out of computational results.

** Perfect paint results as reported in [29].

*** Ratio of current demand to bare steel; 0 = insulated, 1 = bare steel.

steel polarization has reached 0.1. One interpretation of the results is that paint with a relative performance of 0.001 or less of bare steel is 'good' while any paint with a relative performance of 0.1 results in significant changes in current draw to the damaged regions. 'Good' here implies performance very similar to perfectly insulating material with minor differences in results.

There are two materials required in computational modeling: (1) polarization response for any and all different materials used and (2) the conductivity of the surrounding electrolyte. The conductivity of the seawater surrounding the ship hull has an impact on ICCP system performance. PSM has a limited range of seawater conductivity that can be evaluated due to scaling considerations. The more brackish the water, the harder it is for PSM to create the scaled conductivity seawater required for testing. There is no such limitation associated with computational modeling.

The affect that a small but realistic variation in seawater conductivity had on ICCP system performance was determined to be of interest. The refined CG mesh with bilge keel was used for the seawater conductivity analysis [32]. A twenty percent range of seawater conductivity centered on the nominal value was evaluated. This range was defined based on reported variation in seawater in different temperate zones. The analysis indicated that these moderate variations in seawater do result in moderate changes in system power requirements to maintain the set point. Of more importance was the fact that reference cell placement was shown to become a critical issue with changing seawater

conductivity. Reference cell placement that provided adequate system performance at one conductivity level may or may not provide adequate system performance at a different level. Full field contours of potential levels can be obtained from the computational model and used for reference cell placement in the design process. Potential profiles at a single depth were shown to not provide a true picture of hull performance.

6.3 Boundary condition definitions

Polarization response of bare metal is a necessary material input for computational analysis. In early analysis conventional modeling practices were followed that defined painted surfaces as performing as perfect insulating materials. This does not accurately represent paint systems. While painted surfaces are much less active than bare metal regions these surfaces are not perfect insulating materials. The basic question to be answered was: Is the use of a perfectly insulating material boundary condition an adequate representation of a real material?

The definition of painted surfaces as perfect insulators, and the use of a boundary condition to identify these regions, is an assumption that simplifies the modeling process. When material definition is used all elements must be defined with a material value; this can, and did in early analyses, create problems with file sizes and program limitations. If one chooses to define paint as a material rather than use a boundary condition simplification it raises the question of what material properties to use. These values are not readily available and when exist may be proprietary. In evaluating whether it is necessary to incorporate material response for paint in the computation modeling process ranges of values are considered to identify trends. In a computational model, paints and passive coatings are similar; both passive coatings and paints result in materials that have a higher resistance level. Passive coatings have been observed to reduce conductivity values by an order of magnitude or more [33]. Paints are engineered materials and are much more effective in the reduction of conductivity, however, paints vary in their effectiveness by several orders of magnitude [34]. One rule of thumb is that paints increase metal resistance by 3 orders of magnitude. The range of paint properties presented was based on the effects of natural passive coatings and this rule of thumb.

The CVN hull mesh was used to determine the impact of modeling paint as a real material [31]. Results from previous studies are incorporated and the undamaged painted surface is assigned a polarization response scaled from that of steel. This defines a finite resistance for the undamaged painted surface. Current values were adjusted until the reference electrodes were at the target potential (–0.85V Ag/AgCl electrode). The influences of reduced effectiveness of different conceptual paint systems were evaluated. It was shown that the current to identified damaged regions increases with decreasing paint effectiveness as seen in table 4. Differences between the perfect paint and other calculated results are due to the presence of a relatively small current draw on the 85% of the ship hull defined as paint. The small draw over the distributed surface area represented by undamaged paint results in an increase in current demand to

Table 4: Current total (Amps) for 15% damage dynamic flow, selected damage areas. Material properties of damaged surface area varied.

Condition	Maximum Damage		Paint Level		
	PS Model	Perfect Paint *	3	4	5
Paint Effectiveness **	N/A	0	0.01	0.1	1.0
Propellers	228.2	189.8	136.2	160.9	282.3
Docking Blocks	181.8	185.2	3.0	29.6	178.3
Waterline	229.8	206.8	2.6	26.0	210.6
Bilge Keel	290.8	174.4	1.6	16.6	146.1
Struts	104.4	85.8	1.1	12.3	113.8
Rudder	43.0	85.0	0.9	10.0	102.7

* Perfect paint results as reported in [28].

** Ratio of current demand to bare steel; 0 = insulated, 1 = bare steel.

maintain the reference electrode target point. As the polarization response of paint becomes closer to steel, the total current required to obtain the target reference electrode value increases. Results based on the series of studies are:

- Paints with a relative polarization response of 0.1 or greater show significant differences in calculated results.
- Replacement of the perfect paint with a material that has a resistance representative of real paint results in minimal differences. 'Good' paint can be defined as that with a relative polarization of 0.001 or less of the polarization response of steel.
- Variations in calculated results that incorporate finite material behavior for painted surfaces are complex and show varying trends; however, in general, changes in calculated results for paints with a relative polarization of 0.001 or less of that of bare steel are marginal.

Most importantly for validation of established practice in the computational community:

- Paints with a relative polarization response of 0.001 or less than that of steel can be modeled as perfectly insulating materials without decreasing the validity of the computational model.

Another boundary condition that has recently been evaluated is the affect of PSM tank size on modeling results. In this case computational methods were used to determine any influence the different tank sizes, geometries and wall

materials would have on data gathered experimentally. The influence of the surrounding tank wall on models of different sizes was calculated to provide a basis for scale factor selection.

The CVN mesh was used in a series of studies that evaluated the effects of tank geometry and model size on experimental results [35, 36]. This study evaluated the possible edge effects that may occur for a model of a defined size when placed in different tanks as part of the PSM process. Possible effects based on tank wall material and tank geometry were evaluated. The containment conditions are shown in fig. 12. The same ship is shown in each tank, however, a different viewing scale is used for each tank. In the work presented, three different containment geometries and two different wall material conditions per containment were evaluated. The geometry–material combinations represent not only the NRL Center for Corrosion Science and Engineering facility but also possible combinations that may be used in testing. The evaluation of these other combinations is to determine if open sea equivalent information can be experimentally obtained for the combinations of ship geometry (size), tank geometry and wall conditions defined. Identical hull geometry, material conditions for the hull and system performance levels (anode strengths) were used in all cases. Three different containment conditions were examined.

The first is the far field box, 12 by 5 by 5 ship lengths, used to represent open sea conditions. Ship lengths refer to full size ship dimensions. The second containment condition examined represents the actual test tank at the NRL Center for Corrosion Science and Engineering facility. The cylindrical tank at the NRL facility is 10m in diameter and is filled with scaled conductivity seawater for testing. The cylindrical tank is made of galvanized steel and has a 0.76mm neoprene liner. Natural seawater is scaled by the addition of fresh water to obtain the desired resistivity. Scaling factors used range from 1/40 to 1/96 depending on full size ship dimensions. In the current analysis the tank dimensions were scaled up so that the computational model makes use of a full-size ship model and full-strength conductivity seawater. The third containment condition examined is a rectangular tank similar to that used by Defense Research Establishment Atlantic Dockyards Laboratory. As in the case of the cylindrical tank, the computational model is scaled to contain a full-size ship model. The rectangular tank is 1.92 by 0.38 by 0.24 ship lengths.

The studies demonstrate that all results of interest are affected to some level by tank geometry and tank wall material. The results are important to both computational modeler and experimentalist since an understanding of the total system performance (ship hull and surrounding environment including tank geometry) is important for both methods of evaluation. It was determined that the boundary element method provided a useful tool for the experimentalist in the interpretation of measured results.

As the design team learns to rely more on computational results as independent data on the physical phenomenon associated with ICCP systems there is an increased need to quantify the impact of simplifying assumptions. This need is being addressed at NRL through a series of on-going and planned analyses. Some are computational in nature while others rely heavily on input

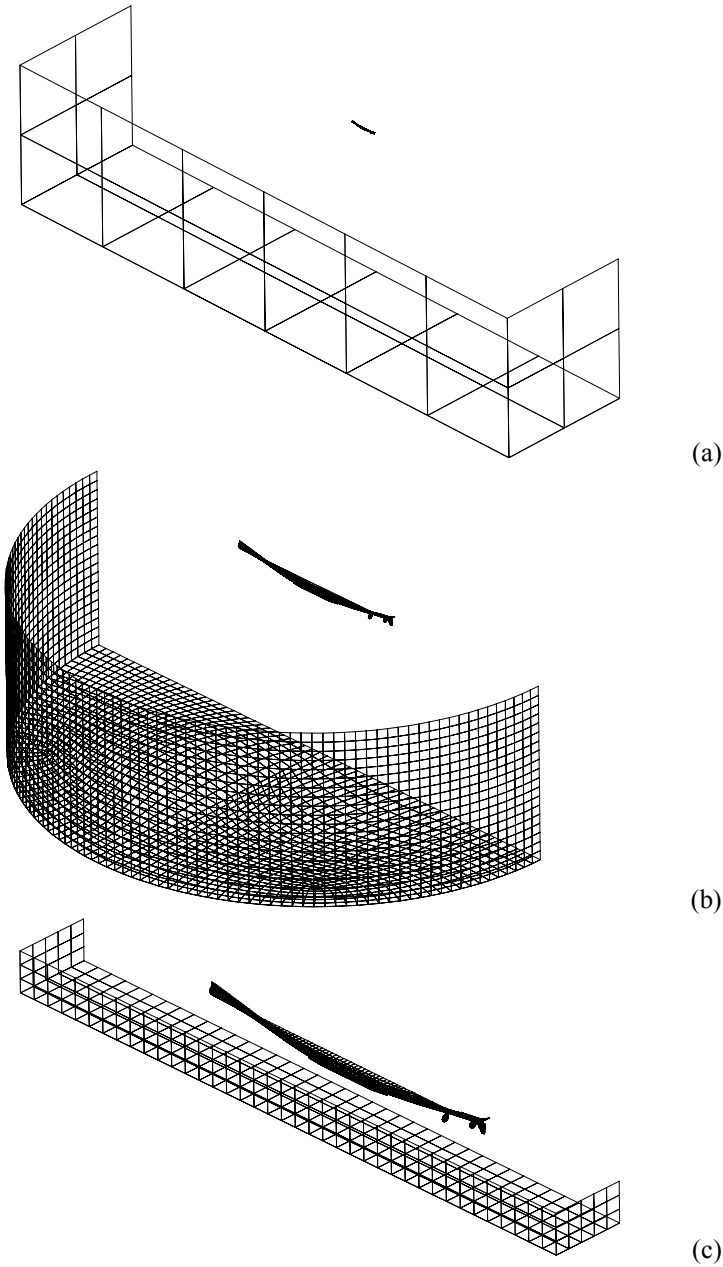

Figure 12: Computational boundary element meshes used with the CVN Hull for three different containment geometries: (a) the far field boundary, (b) the cylindrical tank and (c) a small rectangular tank.

from PSM. Topics that have been identified for evaluation include detailed modeling of propellers instead of using an idealized disk representation, evaluation of inputting the actual water surface, inclusion of free flood spaces, variations in damage patterns, littoral environment effects on system performance, seabed characteristics and ship hull symmetry. Results from these analyses will assist in the creation of a model that can best approach the complexities of the real structure. In the future, decisions on selection of model simplifications will be based on impact evaluations rather than computational size limitations or conventions.

7 The road ahead – unified design approach

Design of complex systems, such as shipboard ICCP systems, is by its very nature a multidisciplinary problem. In order to successfully apply computational or experimental methodologies to this problem the analyst has to have a basic understanding of how the system operates in the real world. Experimental and computational methodologies provide unique insights into system performance. In addition there are limitations to both experimental and computational techniques. Consequently both methods should be utilized to provide the designer with a more complete understanding of the underlying physical phenomenon. The use of experimental and computational methods in conjunction for design results in a unified design approach, shown schematically in fig. 13 [37]. The approach presented in fig. 13 involves the rapid and continual passing of information between experimental and computational approaches. In

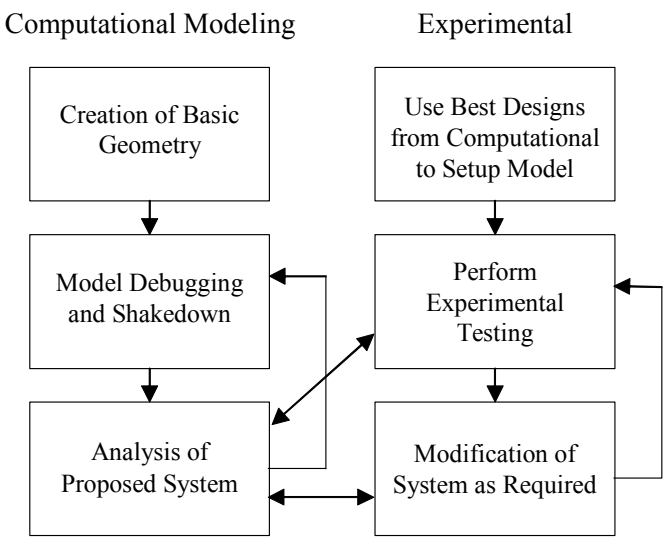

Figure 13: Unified computational and experimental design approach for shipboard ICCP systems.

the past NRL had proposed a combined design methodology that relied on both computational and experimental procedures [38] but the earlier approach was not truly integrated. Computational modeling was seen as primarily a means to reduce the number of iterations experimentation required in the design cycle. Recent advances in computational techniques and associated increased confidence in the results of computational modeling of ICCP systems has provided the basis for a full partnership between the methodologies. Computational modeling provides a means for preliminary design and can be used to establish the PSM test matrix. Key test parameters, such as model scale and relative size to tank size, can be determined computationally. In addition to linking the two methodologies it is also a means for clear and constant communication between the experimentalist and computational analyst. Each of these practitioners must realize that their particular portion of the overall design approach has its own strengths and weaknesses. For instance PSM does not have the polarization response as input data concerns that worry computational modeling. In a like manner computational modeling can provide quick evaluations of changes in system or environmental parameters that requires a much greater time experimentally. Working together the two approaches can result in a more effective design. The interchange should be seen as continual rather than a linear iterative process.

Design of shipboard ICCP systems will become more challenging in the future. Advances in hardware design, controller design, and control algorithms will increase system complexity. The next generation systems will be beyond the capability of simple design approaches. Since computational or experimental design basis are limited in their capabilities a combined unified design approach that relies on both processes is necessary. A unified design will be capable of addressing these advanced systems. On-going advances in computational and experimental methodologies will only provide greater ability to understand and apply this understanding to the design of systems.

Acknowledgements

The support of Dr Alexis Kaznoff and Mr E. Dail Thomas, Naval Sea Systems Command, is gratefully acknowledged.

References

[1] Kasper, C., *Trans. of Electrochemical Society*, **77, 78**, Papers I–IV, 1940.

[2] Agar, J.N. & Hoar, T.P., *Discussions of Faraday Society*, **1**, pp. 162–168, 1947.

[3] Waber, J.T. & Fagen, B., *Journal of Electrochemical Soc.,* **103(1)**, pp. 64–72, 1956.

[4] Ditchfield, R.W., McGrath, J.N. & Tighe-Ford, D.J., *Journal of Applied Electrochemistry,* **25**, pp. 54–60, 1995.

[5] McGrath, J.N., Tighe-Ford, D.J. & Hodgkiss, L., *Corrosion Prevention and Control*, **April**, pp. 33–36, 1985.
[6] Thomas, E.D. & Parks, A.R., *Proceedings of Corrosion 89*, Paper 274, NACE: Houston, 1989.
[7] Parks, A.R., Thomas, E.D. and Lucas, K.E., *Proceedings of Corrosion 90*, Paper 370, NACE: Houston, 1990.
[8] Lucas, K.E., Thomas, E.D., Kaznoff, A.I. & Hogan, E.A., *STP 1370*, ASTM: West Conshohocken, pp. 17–33, 1999.
[9] Adey, R.A. & Niku, S.M., *Computer Modeling in Corrosion,* STP 1154 ASTM: West Conshohocken, pp. 248–264, 1992.
[10] Munn, R.S., *Computer Modeling in Corrosion,* STP 1154, ASTM: West Conshohocken, pp. 215–228, 1992.
[11] Gartland, P.O., *et al*, *Proceedings of Corrosion 93*, Paper 522, NACE: Houston, 1993.
[12] Frazer-Nash Consultancy, *FN Remus Detailed Modeler User Guide*, Frazer-Nash: Surrey, 2001.
[13] Bardel, E.R., Johnsen, R. & Gartland, P.O., *Corrosion,* **40(12)**, pp. 628–633 1984.
[14] Adey, R.A. & Niku, S.M., *Galvanic Corrosion*, STP 978, ASTM: West Conshohocken, pp. 96–117, 1988.
[15] Brichau, F. & Deconinck, J., *Boundary Element Technology VII*, Computational Mechanics Publications: Southampton, pp. 389–404, 1992.
[16] Lee, S.H., Townley, D.W. & Eshun, K.O., *Boundary Element Technology VII*, Computational Mechanics Publications: Southampton, pp. 423–440, 1992.
[17] Yan, J.F., *et al*, *J. Electrochemical Society*, **139(7)**, pp. 1932–1936, 1992.
[18] DeGiorgi, V.G., *Boundary Element Technology IX*, Computational Mechanics Publications: Southampton, pp. 319–326, 1994.
[19] Amaya, J. & Aoki, S., *Boundary Element Technology VII*, Computational Mechanics Publications: Southampton, pp. 375–388, 1975.
[20] Gartland, P.O., Bjoernass, F. & Osvoll, H., *Corrosion 99 Research Topic Symposium CP Modeling and Experiment*, NACE: Houston, pp. 17–28, 1999.
[21] DeGiorgi, V.G., *Boundary Elements XIX*, Computational Mechanics Publications: Southampton, pp. 829–838, 1997.
[22] Diaz, E.S. & Adey, R., *Boundary Elements XXIV*, WIT Press: Southampton, pp. 475–485, 2002.
[23] Computational Mechanics, *BEASY-CP Users Manual*, Computational Mechanics Int.: Billerica, 2000.
[24] MSC Software Corp., *MSC PATRAN 2001 Users Manual*, MSC: Los Angeles, 2001.
[25] Amtec Engineering, Inc., *Tecplot User's Manual*, Amtec: Bellevue, 2001.
[26] DeGiorgi, V.G., Thomas, E.D. & Kaznoff, A.I., *STP 1154*, ASTM: West Conshohocken, pp. 265–276 (1992).

[27] DeGiorgi, V.G., *et al*, *Boundary Element Technology VII,* Computational Mechanics Publications: Southampton, pp. 405–422, 1992.
[28] DeGiorgi, V.G., Kee A. & Thomas, E.D., *Boundary Elements XV*, Computational Mechanics Publications: Southampton, pp. 679–694, 1993.
[29] DeGiorgi, V.G., Thomas, E.D. & Lucas, K.E., *Engineering Analysis with Boundary Elements*, **22**, pp. 41–49, 1998.
[30] DeGiorgi, V.G. & Hamilton, C.P., *Boundary Elements XVII*, Computational Mechanics Publications: Southampton, pp. 395–403, 1995.
[31] DeGiorgi, V.G., *Engineering Analysis with Boundary Elements*, **26(5)**, pp. 435–445, 2002.
[32] DeGiorgi, V.G., *Boundary Element Technology XII*, Computational Mechanics Publications: Southampton, pp. 475–583, 1997.
[33] Ulhig, H.H. & Revie, R.W., *Corrosion and Corrosion Control*, John Wiley and Sons: New York, 1985.
[34] Frechette, E., Compere, C. & Ghali, E., *Corrosion Science*, **33**, pp. 1067–1081, 1991.
[35] Wimmer, S.A., DeGiorgi, V.G.,Hogan, E. & Lucas, K.E., *Proceedings 2002 Tri Service Corrosion Conference*, In Press, 2003.
[36] DeGiorgi, V.G., Wimmer, S.A., Hogan, E. & Lucas, K.E., *Boundary Element Method XXII,* WIT Press: Southampton, pp. 439–447, 2002.
[37] DeGiorgi, V.G., Hogan, E., Lucas, K.E. & Wimmer, S.A., *BETECH2003,* WIT Press: Southampton, In Press, 2003.
[38] DeGiorgi, V.G., Thomas, E.D. & Lucas, K.E., *Boundary Element Technology XI*, Computational Mechanics Publications: Southampton, pp. 335–345, 1996.