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Theoretical validation of the physical scale modelling of the electrical potential characteristics of marine impressed current cathodic protection

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The criteria for the electromagnetic scaling of electrolytic (seawater) systems are reviewed and are shown to be satisfied in the DACS (dimension and conductivity scaling) physical scale modelling of the potential characteristics of the surface of cathodically protected surfaces and the surrounding seawater.

Nomenclature

$\boldsymbol{r}(x, y, z)$	position vector
t	time
p	physical scaling factor
$\boldsymbol{E}(\boldsymbol{r}, t)$	electric field
$\boldsymbol{E}_\mathrm{f}$	electric field under flow conditions
$\boldsymbol{H}(\boldsymbol{r}, t)$	magnetic field
ϵ	static dielectric constant
μ	magnetic permeability
$\boldsymbol{J}(\boldsymbol{r}, t)$	electrical current density
$\boldsymbol{J}_\mathrm{f}$	electrical current density under flow conditions
J_lim	(diffusion) limited electrical current density
σ	electrical conductivity
V	electric potential (voltage)
V_a	anode potential
V_i	interface potential
V_ia	anode/electrolyte interface potential
V_s	potential in electrolytic solution
V_ic	cathode/electrolyte interface potential
V_c	cathode potential
V_0	cathodic overpotential constant
V_h	hull potential
$V_\mathrm{ic}(\boldsymbol{J})$	current–voltage characteristic of cathode/electrolyte interface
ρ	electrical charge density
ρ_+	electrical charge density of positive ions
ρ_-	electrical charge density of negative ions
$\boldsymbol{v}(\boldsymbol{r}, t)$	velocity of ion
$\boldsymbol{v}_+$	velocity of positive ion
$\boldsymbol{v}_\mathrm{f}$	flow velocity of electrolyte
R_p	polarization resistance at electrode/electrolyte interface
a	Tafel *a*-constant
b	Tafel *b*-constant
T	absolute temperature
P	pressure
$\boldsymbol{n}$	unit normal
n_i	number of ions with charge z_i

1. Introduction

Impressed current cathodic protection (ICCP) is an electrical method of controlling corrosion in aqueous environments. The structure to be protected is negatively polarized by a d.c. power supply so that it becomes the cathode in the system. Its electrochemical potential is thus made more negative and corrosion is reduced. Current is supplied in conjunction with inert anodes, usually made of platinized titanium or lead/silver alloys. ICCP has two forms: galvanostatic and potentiostatic. In the former, the applied current is operator-selected on the basis of cathodic surface area and the current density considered necessary to polarize the structure to a selected cathodic potential. Potentiostatic ICCP (Fig. 1) provides automatic control. Output from the power supply is controlled via a reference electrode which monitors the potential at the cathode and the applied current is adjusted to maintain the selected value. Two major aspects of ICCP are the electrochemical potential to which the cathodic surface is polarized and the current flow in the electrolyte between anodes and cathode.

Dimension and conductivity scaling (DACS) physical scale modelling was developed in 1984 for the design and evaluation of marine ICCP systems. In this experimental technique metal scale models constructed of the same materials as the prototype are floated on or immersed in seawater which has been diluted such that its electrical conductivity has been reduced by the same factor as that used to scale the linear dimensions of the model. Typically, one-sixtieth or one-hundredth scales are employed. Scale anodes are attached, with the d.c. power provided by a potentiostat; under way or tidal conditions are simulated by flowing electrolyte. Surface potentials over the structure are measured by an array of silver/silver chloride (SSC) electrodes attached to the model. Such modelling has been validated against

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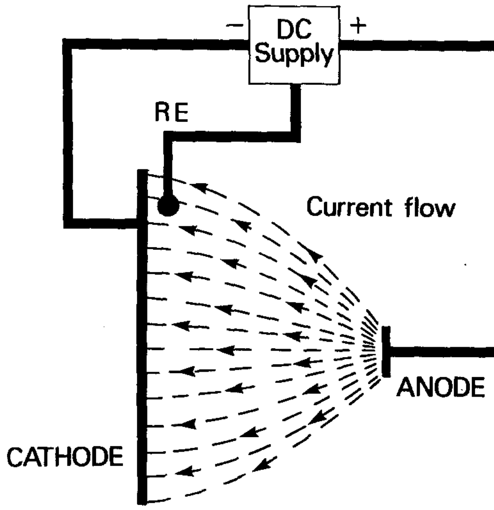

Fig. 1. Principle of potentiostatic impressed current cathodic protection; (RE) reference electrode.

data from warship hull-potential surveys [1, 2]. Its achievements in the evaluation of ICCP system configurations and in the development of design criteria have been recently reviewed [3]. The technique has also been used to examine the underwater electric fields around protected structures by employing remote pairs of SSC electrodes to measure potential differences in the electrolyte [4]. Results can be presented as potential difference profiles at various distances from the structure and as maps of the magnitude and direction of the electric field.

Scale modelling has long been used as an accurate and economical method of simulating the characteristics of prototype physical systems in hydrodynamic, aerodynamic radio and radar systems [5, 6]. Despite the recent advances in computer assisted design (CAD) the experimental validation of theoretical predications, taking account of the often complex geometries and uncertain boundary conditions involved, continues to have extensive application as an efficient, cost-effective design and development tool.

The theory of the scale modelling of electromagnetic systems was established over 40 years ago and applied to the design of radio and radar antennas [5]. The use of physical scale modelling to incorporate the effects of fluid flow on the surface electrochemical potentials of cathodically protected structures, together with the associated underwater electrical potentials, requires a precise understanding of the relationships between the scale model characteristics and those of the real structure. This paper aims to present a theoretical derivation of the transforms necessary for true scale modelling of ICCP systems and to show how the theory is confirmed by practical results.

2. Theoretical considerations

2.1. *The absolute model of electromagnetic scaling*

A linear transformation model was derived by Sinclair [5] in which the characteristic behaviour of electromagnetic waves can be exactly replicated in suitably constructed scale models. It is essential that the gauge invariance of Maxwell's equations under linear transformation is maintained in any model of electrical and magnetic effects so that the absolute relations derived by Sinclair must also hold true for underwater electrical conduction.

The basis of physical scaling is a mechanical scale factor, p, such that the physical dimensions of the system and its environment, $\boldsymbol{r} = (x, y, z)$, are reduced to $\boldsymbol{r}' = (x', y', z')$ which can be expressed:

$$\boldsymbol{r} = p\boldsymbol{r}' \tag{1}$$

To encompass the electromagnetic parameters it is necessary to introduce additional scaling factors: t for time, $\boldsymbol{E}(\boldsymbol{r}, t)$ for electric field and $\boldsymbol{H}(\boldsymbol{r}, t)$ for magnetic field, such that, using the prime notation for the scaled model,

$$\boldsymbol{E}(\boldsymbol{r}, t) = \alpha\boldsymbol{E}'(\boldsymbol{r}', t') \tag{2}$$

$$\boldsymbol{H}(\boldsymbol{r}, t) = \beta\boldsymbol{H}'(\boldsymbol{r}', t') \tag{3}$$

$$t = \gamma t' \tag{4}$$

where α, β and γ are constants. The scaling factor p is generally determined by the size limitations of the modelling facility: the three remaining factors, provided they satisfy the inherent interrelations derived below, can be selected to incorporate particular features of the model. The remaining physical parameters are used as defined in Tables 1 and 2.

To preserve the physical reality of the scaled model it is essential that the form of Maxwell's equations is identical in both reference frames i.e.:

$$\operatorname{div}(\epsilon\epsilon_0\boldsymbol{E}) = \rho \quad \text{and} \quad \operatorname{div}'(\epsilon'\epsilon_0{}'\boldsymbol{E}') = \rho' \tag{5}$$

Table 1. The conditions necessary for the scale modelling of electromagnetic fields

Quantity	*Full scale*	*Absolute model (Sinclair)*	*Electrochemical model*
Length	l	$l' = \frac{l}{p}$	$l' = \frac{l}{p}$
Time	t	$t' = \frac{t}{\gamma}$	$t' = \frac{t}{p}$
Velocity	$\boldsymbol{v}$	$\boldsymbol{v}' = \frac{\gamma}{p} \cdot \boldsymbol{v}$	$v' = v$
Electric field	E	$E' = \frac{E}{\alpha}$	$E' = pE$
Magnetic field	H	$H' = \frac{H}{\beta}$	$H' = \frac{H}{p}$
Conductivity	σ	$\sigma' = \frac{(p\alpha)\sigma}{\beta}$	$\sigma' = \frac{\sigma}{p}$
Voltage	V	$V' = \frac{V}{\alpha p}$	$V' = V$
Current density	J	$J' = \frac{pJ}{\beta}$	$J' = J$

Where p is the linear scaling factor, and α, β e γ are arbitrary constants (5).

$$\mathrm{div}(\mu\mu_0\boldsymbol{H}) = 0 \quad \text{and} \quad \mathrm{div}'(\mu'\mu_0\boldsymbol{H}') = 0 \tag{6}$$

$$\mathrm{curl}\ \boldsymbol{E} = \frac{-\partial}{\partial t}(\mu\mu_0\boldsymbol{H}) \quad \text{and} \quad \mathrm{curl}'\ \boldsymbol{E}' = \frac{-\partial}{\partial t}(\mu'\mu_0\boldsymbol{H}) \tag{7}$$

$$\begin{aligned} \mathrm{curl}\,\boldsymbol{H} &= \boldsymbol{J} + \frac{\partial}{\partial t}(\epsilon\epsilon\boldsymbol{E}) \quad \text{and} \\ \mathrm{curl}'\,\boldsymbol{H}' &= \boldsymbol{J}' + \frac{\partial}{\partial t'}(\epsilon'\epsilon_0\boldsymbol{E}) \end{aligned} \tag{8}$$

where ϵ is the static dielectric constant, ρ is the charge density, μ is the magnetic permeability, σ is the electrical conductivity and $\boldsymbol{J}$ is the current density.

From Ohm's law

$$\boldsymbol{J} = \sigma\boldsymbol{E} \tag{9}$$

In an electrolyte with positive charge density, ρ_+, and negative charge density, ρ_-, travelling with velocities v_+ and v_- respectively then

$$\boldsymbol{J} = \rho_+\boldsymbol{v}_+ + \rho_-\boldsymbol{v}_- \tag{10}$$

Noting that $\mathrm{div}' = \partial/\partial\boldsymbol{r}' = (\partial\boldsymbol{r}/\partial\boldsymbol{r}')\partial/\partial\boldsymbol{r}' = 1/p\ \partial/\partial\boldsymbol{r} = 1/p\,\mathrm{div}$ and similarly $\mathrm{curl}' = 1/p\,\mathrm{curl}$ and $\partial/\partial t = \gamma\partial/\partial t$, then substituting the relations in Equations 1 to 4 into Equations 5 to 8 yields the absolute transformations of the electric and magnetic properties summarized in Table 1.

2.2 *The electrolytic model*

The original work on antenna design resulted in the so called 'geometrical model' in which the dielectric and magnetic properties of the transmission medium (air) are held invariant to scaling which requires adjustments to be made in the conductivity of the boundary materials and the transmission frequencies to satisfy the scaling conditions [5]. The geometrical model is clearly unsuited for use with underwater effects in which the actual structural materials form the interactive interface. However, the same principles apply in that it is essential to find a model in which the characteristics of the propagation processes are preserved accurately.

Table 2. The conditions necessary for the scale modelling of electrolytic fields

Quantity	*Full scale*	*Model*
Anode voltage	V_a	$V_a' = V_a$
Cathode voltage	V_c	$V_c' = V_c$
Electrical conductivity	σ	$\sigma' = \dfrac{\sigma}{p}$
Cathode contact potential	V_{ic}	$V_{ic} = V_{ic}'$
Anode contact potential	V_{ia}	$V_{ia} = V_{ia}'$
Flow velocity	$\boldsymbol{v}$	$\boldsymbol{v}' = \boldsymbol{v}$
Electrolyte temperature	T	$T' = T$
Electrolyte pressure	P	$P' = P$
Pressure gradient	grad P	$\mathrm{grad}'\ P' = \mathrm{grad\ P} = 0$

Where p is the linear scaling factor.

The principles of modelling electrolytic cells were considered by Agar and Hoar [8]. From consideration of the invariance of the potential difference between the anode and the cathode, it was concluded that the small cell is a true model only if:

(i) The current densities are the same at corresponding points, i.e.

$$\boldsymbol{J} = \boldsymbol{J}' \tag{11}$$

(ii) The potential differences are the same at corresponding points, i.e.

$$V = V' \tag{12}$$

(iii) The polarization potentials at the anode and cathode are the same in both the model and the real cell,

(iv) The potential drop across the electrolyte is the same, i.e.

$$l/\sigma = l'/\sigma' = \text{constant} \tag{13}$$

In this way the voltage drop across the electrolytic cell is preserved in that

$$V_a = V_{ia} + V_s + V_{ic} + V_c \tag{14}$$

where V_a is the anode voltage, V_{ia} is the potential drop across the anode/solution interface, V_s is the potential drop across the solution, V_{ic} is the potential drop across the cathode/solution interface and V_c is the cathode potential.

The three components of the electrical potential in seawater systems are considered separately as follows.

2.2.1. *Modelling the electrolyte* (V_s).

The model of Agar and Hoar treats the electrolyte as a uniform distribution of positive and negative charges ($\rho_+ = -\rho_-$) to which can be ascribed a static dielectric constant, ϵ, and an electrical conductivity, σ. This is in accord with classical electrical theory [8, 9] which did not explicitly take account of the plasma (Debye–Hückel) screening characteristics. The modern quantum mechanical formulations of the dielectric constant take account of the correlation effects whereby the plasma screening and transport effects are incorporated automatically so that the electrolyte can be described completely by its dielectric function [12]. This being the case, the Sinclair criteria (Table 1) must apply. The Agar and Hoar conditions establish that:

$$l' = l/p \tag{15}$$

and

$$\sigma' = \sigma/p \tag{16}$$

It follows directly from comparison with Table 1 that the conditions in Equations 11–16 are satisfied if

$$\alpha = 1/p \text{ and } \beta = \gamma = p \tag{17}$$

It is now possible to construct the 'conversion table' for the electrolytic model as shown in Table 1.

It should be noted that invariance of the electrical current density under scaling requires that the velocity of the carriers remains invariant (see Equation 10) so that

$$\boldsymbol{v} = \boldsymbol{v}' \tag{18}$$

The model exhibits certain salient features notably: the electric fields measured in the model will be a factor p times higher than those found in practice, due to the compression of scale; the potentials (voltages V) measured in the model are identical to the true potentials found with the real system.

However, the scaling down of the dielectric constant, and consequently the electrical displacement, makes the model unsuitable for direct measurement of dielectric properties effects, while the scaling down of the magnetic field makes it unsuitable for assessing the magnetic properties such as the degaussing characteristics of the hull. Further, the requirement that velocity remains invariant under transformation requires that true (actual) velocities be used in any investigation of the effects of fluid flow on the associated cathodic currents and electric fields. Nevertheless this criterion has the additional advantages that the true corrosion potentials and corrosion currents will continue to be created at the hull surface so that the problems of selecting and interpreting the parameters for hydrodynamic scaling are avoided [6, 13]. It also follows that the electrodynamic effects of fluid flow can be incorporated directly into the model by adding the flow velocity, $\boldsymbol{V}_\mathrm{f}$, in Equation 10 to give the appropriate current density, $\boldsymbol{J}_\mathrm{f}$, and electric field, $\boldsymbol{E}_\mathrm{f}$, under flow conditions, such that

$$\boldsymbol{J}_\mathrm{f} = \rho_+(\boldsymbol{v}_+ + \boldsymbol{v}_\mathrm{f}) + \rho_-(\boldsymbol{v}_- + \boldsymbol{v}_\mathrm{f}) = \sigma\boldsymbol{E}_\mathrm{f} \tag{19}$$

However, it should be noted that, whereas the electric field moves the charge densities ($\rho^+ = -p^-$) in opposite directions ($\boldsymbol{v}_+ = \boldsymbol{v}_-$) so that the electric currents are additive, the fluid flow moves both charge distributions in the same direction so that there is no resultant current, i.e.

$$\boldsymbol{J}_\mathrm{f} = \boldsymbol{J} \tag{20a}$$

Where fluid velocity could be a factor the real velocities must be used in the model as explained at Equation 18. In the case of impressed cathodic protection [12] an equilibrium current flow is established so that $\boldsymbol{J}_+ \gg \boldsymbol{J}_-$ therefore

$$\boldsymbol{J}_+ = \rho_+(\boldsymbol{v}_+ + \boldsymbol{v}_\mathrm{f}) \tag{20b}$$

and consequently a linear increase in current would be expected under flow conditions.

In practice, the electrolyte is diluted to reduce the electrical conductivity in proportion to the scaling without introducing any chemically active salts so that the condition $J = J'$ has to be relaxed. However, the electrical current can be calculated, during the reprocessing of the data by integrating the calculation of the current density $\boldsymbol{J}(= \sigma E = -\sigma \,\mathrm{grad}\, V)$ over the surface area [13].

2.2.2. Modelling the electrodes (V_a, V_c). In the modelling of cathodic protection systems the important criteria are ensuring that the electrical characteristics of the medium are realistically scaled and the interface conditions between the medium and the model hull accurately represent the polarisation mechanisms involved. This is achieved by using the actual structural materials and coatings in the model. Although the formation of cathodic chalking deposits is reduced by dilution of the electrolyte their beneficial effects are long-term in the real scenario. The use of diluted seawater thus models "worst case" conditions for protection – which is desirable. If required for specific circumstances, models can be pre-chalked in full-strength seawater before studies are undertaken.

2.2.3. The interface (contact) potential (V_ia, V_ic). Having established the specifications for the electrodes and the electrolyte it is clear that the model will only be realistic if the contact potentials across the interface are the same in both systems. The contact potential arises from the polarization due to plasma screening at the interface of the metal and the electrode. Each electrode/solution interface is characterised by the current–voltage profile, $V(J)$, generally called the polarization curve [10, 11] which is measured experimentally.

Wagner [16] showed that the potential difference between the equilibrium electrode potential at the cathode (inner Helmholtz potential) and the electrolytic solution potential (outer Helmholtz potential) was, for a first order approximation, due to a polarization term. Thus,

$$V_\mathrm{ic}(J_\mathrm{c}) = \left(\frac{\mathrm{d}V}{\mathrm{d}J}\right)_\mathrm{c} J_\mathrm{c} \tag{21}$$

where $(\mathrm{d}V/\mathrm{d}J)c$ is termed the 'polarization resistance' (R_p). A similar reaction holds for the anode.

To meet the Agar and Hoar criteria it is necessary that

$$V_\mathrm{ia} = V'_\mathrm{ia} \quad \text{and} \quad V_\mathrm{ic} = V'_\mathrm{ic} \tag{22}$$

then

$$(R_\mathrm{p})_\mathrm{c} J_\mathrm{c} = (R_\mathrm{p})'_\mathrm{c} J'_\mathrm{c} \quad \text{and} \quad (R_\mathrm{p})_\mathrm{a} J_\mathrm{a} = (R_\mathrm{p})'_\mathrm{a} J_\mathrm{a} \tag{23}$$

It follows that in order for the model to simulate identical electrical potentials to the real system the products of the anodic and cathodic polarization resistances and the equilibrium current density at the equilibrium overvoltages must be identical to those in the real system [18].

It is important in interpreting the polarization curves that the dominant conduction mechanism is identified [15]. In aqueous solutions polarization characteristics are normally described by the Tafel relation [10, 18].

$$V = a + b \log J \tag{24}$$

where a and b are the Tafel constants. In this case the polarization resistance, R_p, is equal to b/J so that the contact potential at the interface is equal to the Tafel b constant and is independent of the current density. That is,

$$V_{\mathrm{int}} = (b/J)J = b \tag{25}$$

This proves to be the case until potentials are reached at which the number of ions available becomes limited then the concentration term becomes dominant when the polarization characteristic is of the form

$$V = V_0 \log\left[1 - \frac{J}{J_{\mathrm{lim}}}\right] \tag{26}$$

where V_0 is the appropriate overpotential constant [17]. It follows that the interface potential is

$$V_{\mathrm{ic}} = \left(\frac{\mathrm{d}V}{\mathrm{d}J}\right)_{\mathrm{c}} J_{\mathrm{c}} = V_0\left(1 - \exp\left(-\frac{V}{V_0}\right)\right) \tag{27}$$

for a cathodic regime of this type. This effect is also independent of the current density.

It should be noted that the derived conditions relating to the voltages (Equation 12) and the use of real velocities (Equation 18) define the required physical state variables of the systems. The thermal distribution of the conductive ions in both the real and model systems is given by the Maxwell–Boltzmann relation,

$$n_{\mathrm{i}} \alpha \exp\left(\frac{-z_{\mathrm{i}}eV}{kT}\right)$$

where n_{i} is the proportion of ions of charge z_{i} at voltage V and temperature T [19]. As n_{i} is the same in both the model and the real system, n i.e. $n'_{\mathrm{i}} = n_{\mathrm{i}}$ then it follows that

$$\frac{V'}{T'} = \frac{V}{T} \tag{28}$$

As $V = V'$ it follows directly that

$$T' = T \tag{29}$$

Thus the temperature of the electrolyte must be the same in the model and the real system. It follows directly that as the particle density and temperature are the same in both the model and real systems then the pressure (P) must also be the same, (for example, see [19]). That is

$$P' = P \tag{30}$$

It should be noted, however, that this restricts the use of the model to problems in which there is no pressure gradient (grad $P = 0$) otherwise it would be necessary that

$$\mathrm{grad}\, P = 1/p\, \mathrm{grad}\, P' \tag{31}$$

That is the pressure would have to fall through the same amount over the scaled down distance. This is not achievable in practice: if pressure gradients are to be taken into account then they must be simulated artificially, for example by introducing external voltages to reproduce their effects [6].

In summary, the electrical potentials in electrolytic systems can be modelled exactly provided the necessary and sufficient conditions are generated as detailed in Table 2.

3. Application in DACS

A cathodically protected structure such as a ship hull immersed in sea water is an electrolytic system of the type analysed by Agar and Hoar. In DACS the mechanical scaling conditions adopted are to reduce the size of the hull by the mechanical scaling factor p (say 60) and to dilute the electrolyte (sea water) with tap water until the electrical conductivity is also reduced by the same amount p (i.e. 60): this satisfies the conditions described by Equations 20 and 21. So far as the modelling of the properties of the electrolyte is concerned there should be exact correspondence as described in Table 2 and the salient features described above will apply to DACS, in particular the need to use real values of velocity in modelling flow conditions.

The 'impressed potential' for a Royal Navy warship hull protected by ICCP is −800 mV relative to the SSC electrode. Jones [12] established that the contact potential for steel in seawater is given by the Tafel b coefficient and is, within the limits of experimental error, 100 mV and this work has been confirmed by potentiostat measurement using real ship anode materials in both seawater and diluted seawater: i.e. the contact potential is the same in both the model and the real system as predicted at Equation 23 above, in that $b'_{\mathrm{a}} = b_{\mathrm{a}} = 100\,\mathrm{mV}$ [20].

However, with such a high overpotential the dominant oxygen reduction process at the cathode has saturated, as detailed by Jones [14], such that the cathodic polarization curves are identical for $V_{\mathrm{c}} = -800\,\mathrm{mV}$. Again the interface potentials are the same in both diluted and undiluted seawater as given by Equation (27) where at 15° C, $V_0 = 90\,\mathrm{mV}$ (for H–O reaction) so that $(R_{\mathrm{p}})_{\mathrm{c}} J_{\mathrm{c}} = (R_{\mathrm{p}})'_{\mathrm{c}} J'_{\mathrm{c}} = 90\,\mathrm{mV}$. Thus DACS does indeed satisfy the required conditions in Table 2 [18]. This is borne out in practice. The effectiveness of the technique has been examined for the modelling of surface potentials and of the underwater electrical field.

3.1. *Modelling of surface potentials*

A direct comparison has been made between the surface potentials measured along a 1/60th scale model of a ship floating in sea water diluted to 1/60th of its standard conductivity and those from a survey of the prototype floating in sea water [3]. The model hull and underwater fittings were constructed of real materials and full scale paint layers applied to conform with the requirements specified by Agar and Hoar [8]. Agreement between the model results and those taken from the returns of monthly hull surveys was good, [3]. This was despite both the comparative crudity of the model and the coarseness of the results of a typical hull survey taken at a very few stations along the ship's side. A separate detailed validation has been carried out by the US Navy [24].

3.2. *Modelling of the underwater electrical field*

The modelling of the cathodic protection of ship hulls has concentrated on the anode and cathode configurations and the associated current flow. The underwater electrical potential (V) is generally established by solving Laplace's equation given the practically determined polarization curves of the protected hull $V_h(J)$. The direct incorporation of the surface current avoids the difficulties of incorporating the surface contact potentials used in Wagner's formulation. Thus the system can be treated rigorously [22] noting that:

(i) $\nabla^2 V = 0$
(ii) $V = V_h(J)$ where $J = -\sigma \partial V / \partial n$, n being the normal to the surface.
(iii) The whole system is open to infinity, but all currents flow between finite surfaces.

Finite element analysis or boundary layer analysis methods are normally used with the detailed hull geometries which is an expensive and extensive procedure. However, it is essential that the correct boundary conditions are used in such calculations. With ICCP systems hull potential is a dynamic variable determined by the agitation of the seawater [3, 4, 17], the degradation of the surface and the control mechanism of the system itself which gives rise to variable anode potentials (and consequently hull current). That all such factors are simulated directly in DACS makes it a most valuable tool for the validation of theoretical calculations.

The underwater electrical potential (UEP) can be measured directly with DACS as the Agar and Hoar conditions are satisfied. However the UEP is so small (typically microvolts) that extremely sensitive probes will have to be used in an electrically shielded environment using accurately referenced probes to avoid any contact potential between the probe and the electrolyte [10, 11].

4. Discussion

This paper has examined the theoretical basis for the scale modelling of ICCP systems and has shown that the relationships between scale models and their prototypes are as predicted, thereby establishing very firmly the pedigree of physical scale modelling as an appropriate investigative technique and design tool for ICCP. The examples were chosen to embrace the three most important features of the system about which a designer is likely to require accurate quantitative data.

There are, of course, limitations to the general applicability of the technique and these as discussed above: the model is unsuitable for direct measurement of dielectric polarization effects in the electrolyte and electrical current densities (but these can be calculated using Maxwell's equations) and for assessing magnetic properties. Similar arguments can be used to show that this modelling technique is not directly applicable to the case of sacrificial cathodic protection in which the current provided to the cathodic surface is derived from anodic dissolution. Attention has been drawn to this limitation by Hack [13].

Physical scale modelling is one of two possible techniques for predicting the performance of an ICCP system; the other is computer modelling. Based upon solution of the diffusion equation by one or other numerical technique, computer modelling suffers from a number of obvious disadvantages when compared with physical scale modelling. Chief among these is the need for experimental data on the polarization behaviour of all the materials involved over the whole range of operational conditions envisaged for the system. Much of this data does not exist and the relevance of that which does is often questionnable as it has been determined under nonrepresentative laboratory conditions. Furthermore, the computational power needed to perform the necessary calculations on the complex grids required to describe real engineering structures is formidable.

Computer and physical modelling have been used to predict the behaviour of the same very simple system [23] and the conclusion reached that, at least for the present, physical scale modelling offers the more attractive proposition. Certainly, the advantages of physical scale modelling have been recognized by the US Navy which has used it successfully in the design of the system retrofitted into the battleship USS IOWA and has embodied the method in its design protocol for all newly installed ICCP systems on its warships [24].

5. Conclusions

It is concluded that any system for modelling the electrical potential and characteristics of cathodically protected marine structures must satisfy the conditions detailed in Table 2.

DACS physical scale modelling satisfies these conditions and displays the following useful practical characteristics:

(i) Real hull materials can be used.
(ii) Surface electrical potentials measured are the same as those found in real structures which can be compared directly with results from surveys.
(iii) The electrical effects under flow conditions can be quantitatively assessed by using true flow velocities in the model.
(iv) The electrical potentials generated in the electrolyte by the method are identical to the true fields. As such they are reliable parameters from which to calculate the real electric fields, electrical currents and polarization fields around marine structures.

Physical scale modelling of ICCP systems has been shown to have a sound basis in theory and to produce practical results which accord with the theoretical predictions, although there are a few limitations to its general applicability and attention has been drawn to these.

Mention has been made of computer modelling to achieve the same result and the two techniques briefly compared. It is concluded that, at present, physical scale modelling is the more effective option.

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