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Evaluation of warship impressed current cathodic protection systems

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SYNOPSIS

The effectiveness of the cathodic protection afforded by different warship system configurations has been assessed using a physical modelling technique in which a one-sixtieth scale model hull was immersed in sea water whose electrical conductivity had been reduced by the same factor. The performance of four- and six-anode systems controlled by a single reference electrode sited amidships was unsatisfactory, particularly in simulated under-way conditions. Incorporation of an additional reference electrode at the stern provided a significant improvement in the potential around the hull, although there was interference between the two control zones – this can, however, be avoided. An 'all-aft' configuration, employing a single pair of anodes fitted adjacent to the A-brackets and controlled by a single reference electrode at the stern, performed well under the trial conditions. It is concluded that the design of an efficient impressed current cathodic protection system requires optimum positioning of the reference electrode(s) and the associated anodes, which can be determined by physical modelling.

INTRODUCTION

Impressed current cathodic protection (ICCP) controls corrosion by electrically polarizing a structure so that its electrochemical potential is made more negative. A metal can be regarded as effectively protected when its potential has been depressed some 150 – 200 mV below its free corrosion value; for mild steel in sea water a value of –800 to –850 mV relative to the silver/silver chloride (SSC) electrode is deemed necessary[1,2]. ICCP is widely employed in conjunction with paint coatings for the protection of warship hulls and operational practice is to impose a set potential of –800 mV (SSC). Ideally this should be achieved uniformly over a hull under all operating conditions.

In practice a level potential profile is not obtained because of the galvanic effect of the bronze propellers; thus naval engineering specifications stipulate that values over the hull should lie within limits of –750 and –850 mV.

The basic warship ICCP system comprises a four lead–silver anode fit on the ship's sides, with a single DC power supply controlled by a midships SSC reference electrode (RE). This configuration, which has remained essentially unchanged since entering service in the 1950s, provides poor protection of the stern area.

Physical scale modelling[3] has confirmed this and shown that the potential profile worsens under flow conditions, with a 'see-saw' effect occurring around the RE whereby the stern becomes even less protected and over-protection occurs forward.

Some larger warships are additionally fitted with either a single lead–silver anode or a pair of platinized titanium anodes in the after cut-up. The aim of the present investigation was to assess the performance of existing and new design configurations, with particular respect to the number and location of REs.

D. J. Tighe-Ford joined the then Royal Naval Scientific Service in 1960 following a degree in Biochemistry, and worked on anti-fouling research for 17 years, obtaining his doctorate in the interim. He transferred into the Navy Department of the Ministry of Defence in 1978, joining the Royal Naval Engineering College where he initially carried out research on microbiological corrosion. He is a Principal Scientific Officer and, as part of his present duties as College Research Co-ordinator, leads the cathodic protection research which he and Captain McGrath intiated in 1982.

J. N. McGrath took his doctorate and after a short period in the steel industry joined the Instructor Branch of the Royal Navy in 1967. Following an M.Sc. in Nuclear Science and Technology (1973) he spent 5 years associated with the nuclear propulsion programme. He joined RNEC as Head of the Materials Technology Department in 1982 and worked jointly with Dr. Tighe-Ford on cathodic protection research. Promoted to Captain in 1987 he is currently Head of the Computer Division (Manpower) in the shore establishment HMS *Centurion.*

M. P. Wareham, after initial officer training, graduated with a First Class (Honours) Degree at RNEC in 1986 – this paper is based upon his final year project which was supervised by the other two authors. After completing the Marine Engineering Submarine Application Course at RNEC in 1987 he is presently undergoing sub-specialist training at the Royal Naval College, Greenwich. Following further training at the shore establishments HMS *Dolphin* and HMS *Sultan,* he will take up his first appointment as Assistant Marine Engineer Officer in the nuclear submarine *Flotilla.*

ICCP SYSTEM CONFIGURATIONS

Five systems were examined based upon the disposition of anodes and REs shown schematically in Fig. 1. The configurations were as follows.

1. Four lead–silver anodes, with a single power supply/control unit (CU) controlled by the midships RE (Fig. 3).
2. Six anodes, with the forward pair of lead-silver anodes driven by one CU (controlled by the midships RE) and the after pair plus the platinized titanium anodes driven by a Variable Geometry Slave Unit (SU) controlled by the output signal from the CU to the forward anodes (Fig. 4).
3. Six anodes, as in 2 above, but with all of the lead–silver anodes driven by the CU and only the platinized titanium anodes by the SU (Fig. 5).
4. Six anodes, as in 3 above, but with the platinized titanium anodes driven by their own independent CU, controlled by the stern RE (Fig. 6).
5. Only the two platinized titanium anodes, with a single CU controlled by the stern RE (Fig. 7).

MATERIALS AND METHODS

The performance of the different system configurations in static and simulated under-way conditions was assessed using the Dimension and Conductivity Scaling (DACS) technique developed at the Royal Naval Engineering College for the study of ships and other marine structures[3,4]. In this technique the reduced dimensions of a physical scale model are compensated for by a corresponding reduction in the electrical conductivity of the electrolyte.

Hull

A 1/60 scale model of a warship hull was constructed from mild steel, with an overall length of 1.89 m, beam of 0.21 m and draught of 74 mm. Rudders, stabilizers, shafts and A-brackets, also constructed from mild steel, were covered with an impermeable epoxy resin. Two nickel–aluminium bronze propellers were fitted and the hull was painted with a coal tar epoxy paint to a thickness of 225 µm (i.e. not scaled).

Six anodes were fitted as shown in Fig. 1. Four were of lead–silver alloy taken from an actual ship's anode; these measured 60 x 1.5 x 0.16 mm thickness and were mounted on polymethyl methacrylate (PMMA) shields (71 x 10 mm). Two 0.05 mm platinum foil anodes, each measuring 2 x 4.4 mm, were mounted on 15 x 19 mm PMMA shields to model the platinized titanium disc fits on real ships.

Power supplies

The main power supply/control units were simulated by one or two potentiostats (Thompson Type 251), each controlled by its own miniature SSC reference electrode prepared as previously described[3].

The circuit diagram for the model of the slave unit (Fig. 2) is based on Type 741 and 759 operational amplifiers. The SU responds to the voltage output from the 'master' power supply by providing a proportionately higher current to its own anodes. The unit employs voltage control and saturates at 10 V output in response to a 4 V input from the 'master'. Input and output ranges were altered by varying the 50 kΩ and 10 kΩ potentiometers respectively.

Experimental procedures

The hull was immersed in a 4.25 x 0.45 x 0.45 m GRP flow tank system containing sea water diluted with tap water to a conductivity of 88.3 mS^{-1} (i.e. 1/60 that of standard sea water at 25°C). Water velocities past the hull were measured by Pitot tube and varied by the number of pumps employed, valves and a thermoplastic sheet formed to the shape of the hull; this flow guide, which could be positioned at different distances from the hull, also acted as a support for an array of 18 miniature SSC measuring electrodes around the port side and under the keel of the model (see Fig. 1). Turbulence and aeration around the after cut-up was produced by bubbling air around the propellers. Temperature was maintained at 20±5°C. After immersion the hull was left unprotected for 7 days while the water-permeable paint became saturated. Thereafter a set potential of −800 mV was imposed, controlled by the port midships and/or stern RE. For each test configuration a period of 24 hours under static conditions was allowed before the hull potential profile was measured. Flows of 0.31, 0.54 and 0.76 ms^{-1} were then applied consecutively, with each trial lasting 3 hours. The Froude approach to flow modelling was adopted, in which the

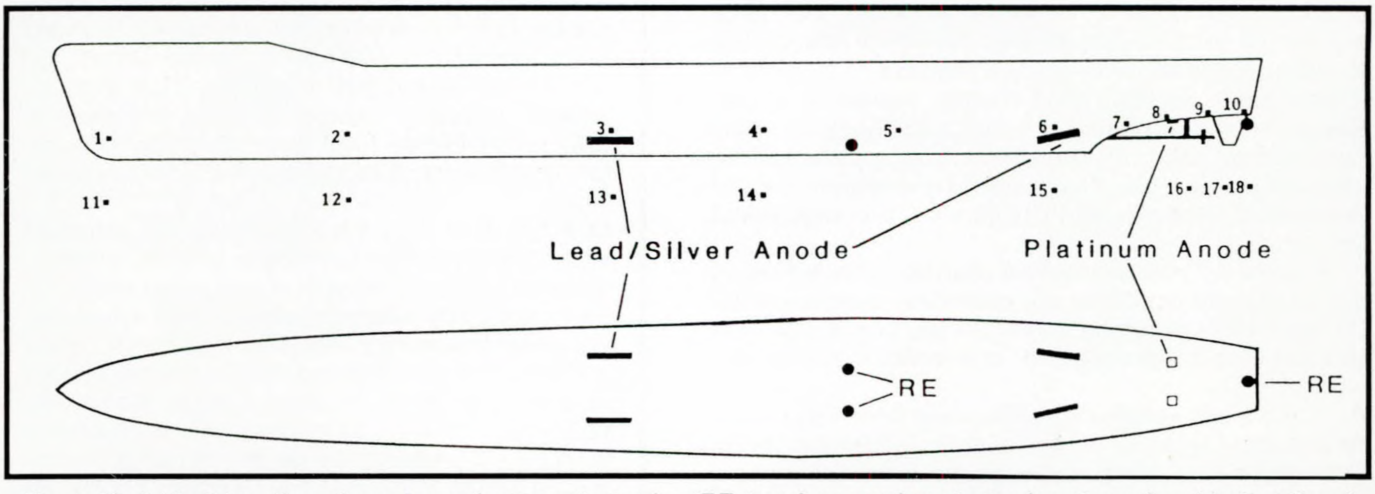

Fig. 1. Model hull location of anodes, reference electrodes (REs) and measuring electrodes along the side (1–10) and under the keel (11–18)

ratio of full ship to model speed is equal to the square root of the scaling factor; on this basis the experimental flow rates would be equivalent to full-size ship speeds of 2.4, 4.2 and 5.9 ms^{-1} (4.7, 8.1 and 11.6 knots) respectively.

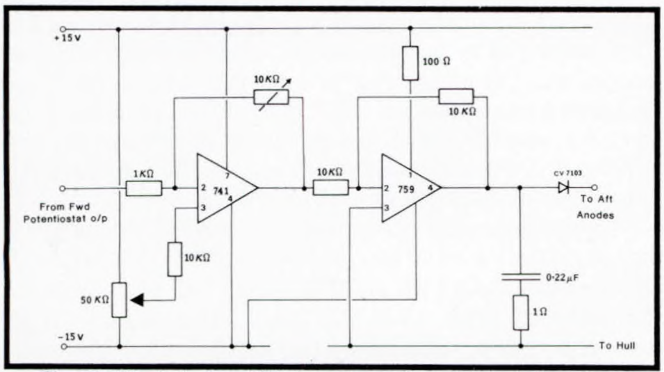

Fig. 2. Model of variable geometry slave unit circuit diagram

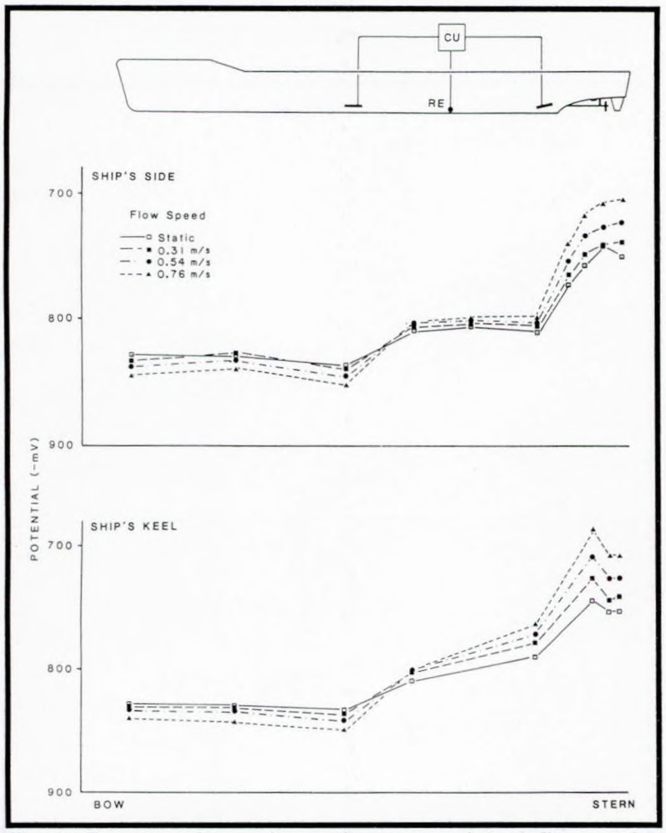

Fig. 3. Four anode configuration–potential profiles under static and flow conditions; CU-power supply/control unit; RE-reference electrode

RESULTS

A preliminary examination of the potential of the painted hull without propellers showed that a value of –670 mV was obtained uniformly over the hull after 4 days immersion. Addition of the bronze propellers resulted in a potential of approximately –460 mV around the hull.

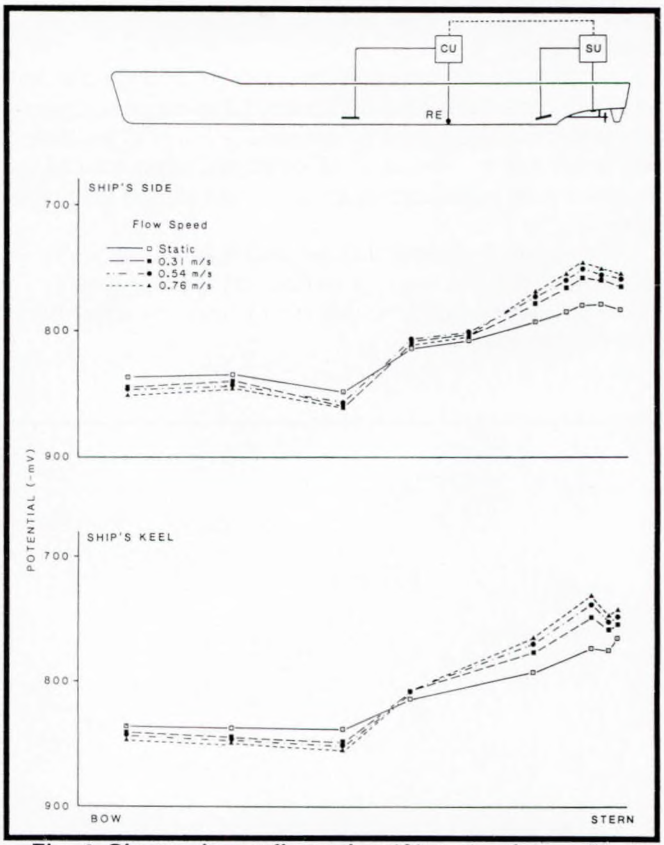

Fig. 4. Six anode configuration (A)–potential profiles under static and flow conditions; SU-variable geometry slave unit; other symbols as before

Configuration 1 – four anode system

In this configuration the midships RE controlled a single potentiostat supplying power to the four lead–silver anodes as illustrated in Fig. 3, which shows the potential profiles obtained under static and flow conditions. As expected the set potential was achieved only at the RE. Under static conditions potentials forward of the RE became more cathodic to a maximum of –837 mV adjacent to the anode, with a value of –829 mV at the bow. Abaft the RE, the non-ferrous propellers caused less negative potentials with the least protected area (above the propellers) having a value of –743 mV, i.e. outside the engineering specification of –750 to –850 mV. Under flow conditions potentials towards the bow became increasingly more negative, whilst those at the stern became even less protective. At the maximum flow rate, considered to be equivalent to a full-size ship speed of 11.5 knots, there was severe under-protection in the after cut-up (–687 mV).

These trials included a study of the effect of air bubbling which showed that this produced a change of only 2–3 mV in the potential profile. Bubbling did, however, increase the current output from the potentiostat and as the SU employed in subsequent trials responds to potentiostat output the air bubbling was continued.

Configuration 2 – six anode system (A)

This configuration employed the potentiostat, still controlled by the midships RE, to drive only the forward pair of lead–silver anodes; the SU supplied the after lead–silver and the platinum anodes (as shown in Fig. 4). This resulted in some improvement over the previous system. Under static conditions, potentials forward of the RE reached a value of –848 mV adjacent to the anode, with the least protected area of the stern having a value of –766 mV, i.e. unsatisfactory but within specification.

As flow speed increased the profile towards the bow changed in a manner similar to that of the previous system, and at the highest speed slightly exceeded (–860 mV) the limit of the specification. Potentials abaft the RE again became less negative with significant under-protection around the propellers (–732 mV).

The results indicated that the platinum anodes under the control of the SU were providing insufficient current for adequate stern protection; this is supported by observations from actual warships.

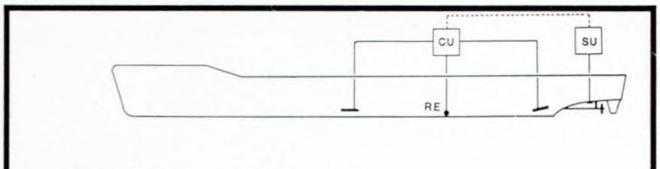

Fig. 5. Six anode configuration (B)–potential profiles under static and flow conditions; symbols as before

Configuration 3 – six anode system (B)

This development of the previous six anode system, whereby all four lead–silver anodes were supplied by the potentiostat and only the platinum anodes by the SU, produced more uniform potential profiles under both static and flow conditions (Fig. 5). Under static conditions potentials forward of the RE were only slightly more cathodic than the –800 mV imposed, with a value of –813 mV at the bow. The profile was almost level to the after cut-up. In this region, however, protection was barely adequate.

Overall, the potential profiles were less sensitive to flow than in the previous two configurations, hence only results for maximum flow conditions are presented. Under flow the least cathodic potential around the stern (–744 mV) was an improvement of only 12 mV over the previous six anode configuration. Protection at the stern, as before, showed a steady decrease with higher flow speeds suggesting that again there was insufficient current output from the platinum anodes and that potentials could be expected to fall further outside specification at higher speeds.

Configuration 4 – six anode system (two control zones)

Unlike the previous three systems this configuration employed two independent power supplies each with its own RE. One, controlled by the midships RE, drove the four lead–silver anodes and the other, with its own RE fitted at the stern, powered the two platinum anodes (Fig. 6). Under static conditions the potential profile approached the ideal of a level line at –800 mV. Values only slightly more cathodic were recorded around the platinum anodes (–811 mV).

The configuration performed well under flow conditions and did not exhibit the 'see-saw' effect of the previous, single RE systems. In fact the potential of the hull adjacent to the forward lead–silver anode was rather less cathodic than the surrounding area, suggesting a current reversal; this was corroborated by measurement of the current output from the forward potent- iostat. It thus appeared that as flow speed increased the increased output from the after system was interfering with the forward system via the midships RE.

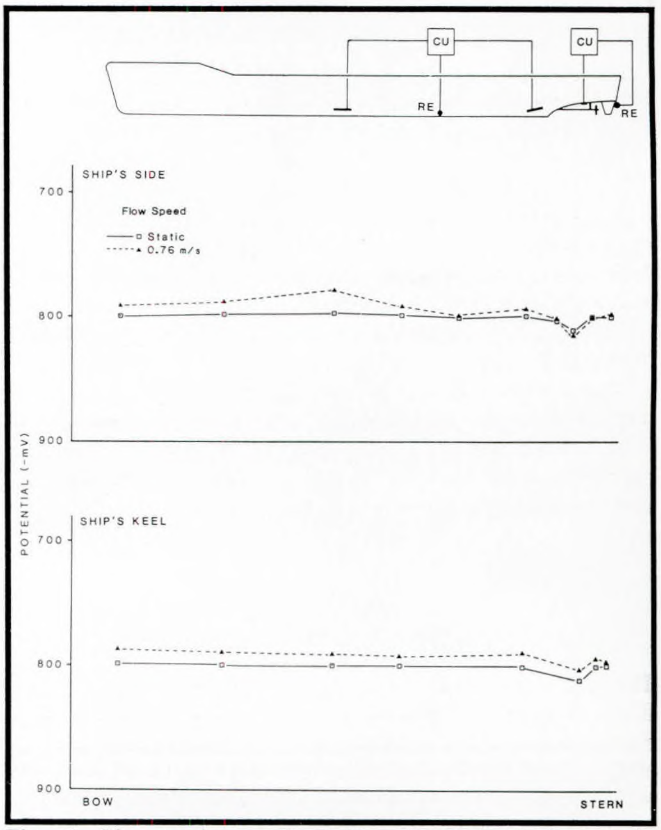

Fig. 6. Six anode configuration (two control zones)–potential profiles under static and flow conditions; symbols as before

Configuration 5 – two anode system ('all aft')

The results from the two control zone configuration suggested that the model could be effectively protected by the two platinum anodes alone, with a single power supply controlled by the stern RE (Fig. 7).

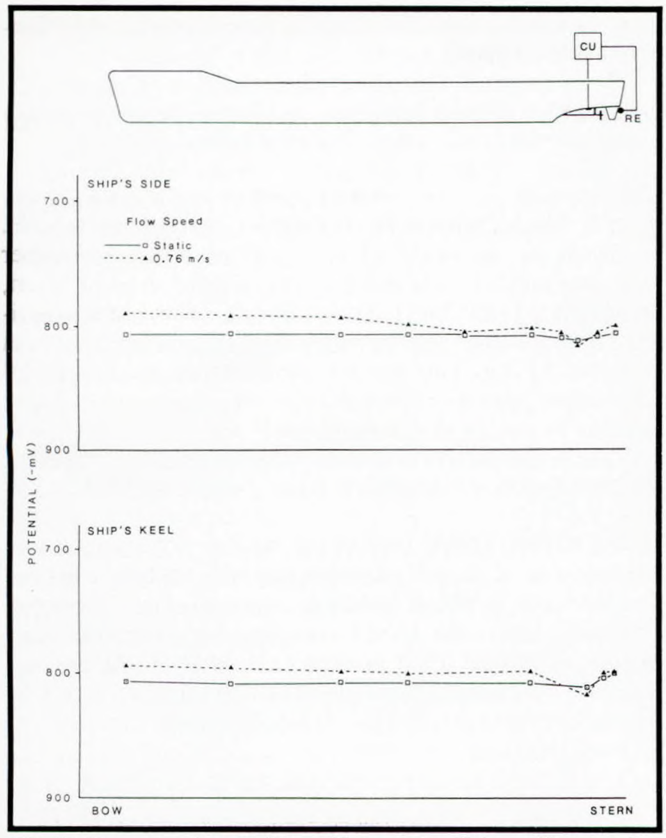

Fig. 7. Two anode configuration–potential profiles under static and flow conditions; symbols as before

The potential profile produced was virtually level and, except at the RE, was slightly more cathodic than the set value. Performance under flow conditions, also, was excellent; potentials around the after cut-up remained more negative than –800 mV and protection at the bow changed only to –790 mV (from –806 mV).

The improved protection afforded by this system, together with the observation that a reduced current output was required at each flow velocity when compared with the two control zone configurations, provided further evidence that the forward potentiostat in the latter system had been driving in reverse.

DISCUSSION

The results demonstrate that the protection afforded by ship ICCP is critically dependent upon system configuration. Furthermore it is clear that flow can have extremely adverse effects upon poorly designed systems which may not be manifest under static conditions. As the effectiveness of ship systems is at present assessed only by measurements taken when stationary the need to subject all proposed designs to this type of model evaluation is clear. Configurations employing only a single, midships RE provide unsatisfactory protection. It is obvious that protection is most difficult to achieve around the propellers and that there is a requirement for an RE in this region. This is confirmed by the extremely good performance of the six-anode, two control zone configuration, employing both a midships and a stern RE, which resulted in an almost level potential profile. There was, however, interference between the zones and such a phenomenon has been reported in previous modelling of a four anode, two control zone configuration[5], where it was avoided by relocating the midships RE the scale equivalent of 10 m ahead of the forward anode, i.e. away from the influence of the after systems. The results from the alternative, two anode configuration suggest that it may be possible to protect warships by using only two anodes sited close to the propellers and controlled by a single, stern RE. Many commercial vessels employ an 'all-aft' configuration in which anodes are sited towards the after cut-up. This is considered sufficient to protect a ship provided that the bow is no further than 150 m forward of an anode.

The overall protection afforded by present ship ICCP systems could be improved by increasing the set potential from –800 to –850 mV which would produce more negative profiles, resulting in a reduction in overall hull corrosion. This is possible because modern developments in paint technology have resulted in coatings which are much less susceptible than previously to the alkaline conditions produced at the metal surface by cathodic protection. It should be noted that the investigations reported above were carried out using an intact paint film. The response of the different ICCP systems to coating damage is being examined. Performance may well depend not only upon the extent but also the location of holidays, and it is possible that the two anode configuration, with its single RE at the stern, may be the least responsive to damage forward.

CONCLUSIONS

1. Designs for ship ICCP systems should be evaluated in simulated underway conditions as flow has an extremely adverse effect upon the performance of poorly designed configurations.
2. The location of REs is a critical factor in determining the level of protection over the hull.
3. The use of a single midships RE provides unsatisfactory protection towards the stern, which worsens under way.
4. There is a requirement for an RE in the stern region either as part of a two control zone configuration or by itself in an 'all-aft' configuration.
5. The performance of present ship ICCP systems could be improved by employing a set potential of –850 mV (SSC).

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Discussion

M. J. MOFFAT (Corrintec U.K. Ltd): When carrying out trials with only an aft system functioning, did the hull of the vessel have a coating system that was 100 per cent perfect? Alternatively, was a trial carried out on a vessel with simulated coating defects towards the bow? If so, did the potential profile remain similar to that of a perfect coated hull? If the author is recommending the use of an all-aft system, it would be beneficial to introduce permanent forward reference electrodes to establish that the bow remains fully protected under all operating conditions.

Does the author consider the use of diluted, simulated sea water, i.e. one-sixtieth, as being an electrolyte providing accurate results that are truly representative of those found in practice? Sea water can often be beneficial to a cathodic protection system by assisting with the formation of calcareous deposits on the hull's surface. This can act as an insulator and improve the distribution of protective current from the cathodic protection system.

J. CROOK (Technical author): I should like to congratulate the authors on an interesting paper in a subject which is familiar but rarely considered in an original manner. The DACS (dimension and conductivity scaling) technique, briefly mentioned at the start of the paper, would appear to have wide application to marine structures of all types and would be of interest to offshore platform designers.

Could the authors expand on the justification of the scaling techniques? In particular, has there been a comparison between model results and actual measurements on a warship? It may be interesting to compare results from models of different scales to ensure that the technique is valid. All the tests described in the paper appear to refer to a one-sixtieth scale model. Could the authors expand on any studies used to justify the technique?

M. B. THURMAN [Wilson Walton International (U.K.) Ltd.]: The conclusions of the author, with respect to location of anodes and reference cells in the stern area of a ship to ensure the correct level of protection throughout the length of the ship, is a philosophy that has been applied and used on merchant ships for 20 years. Anodes and reference cells are located within aft 0.2 lengths of the ship.

The potential surveys carried out on marine ships with the arrangement as described above show that potentials exist throughout the hull. We would be concerned if any potentials were more positive than –0.8V (to silver chloride reference cell).

The normal marine set points used are –220 mV (to a zinc reference cell). Does the Navy, with the good quality paint schemes now available (e.g. coal tar epoxy), use operating potentials lower than the range of –750 to –850 mV?

Are the propellers bonded to the hull?

Fig. 6 shows a positive alteration in potential with variation in the location of the forward midship anode. I would have expected the opposite effect. Can the authors please comment on this?

H. CAPPER (Wilson Walton International Ltd.): I am rather concerned about the use of scale models in marine applications. This is particularly arguable when considering corrosion problems. The number of variables in sea water corrosive conditions are so diverse, and their extent is so difficult to simulate, that one must be very careful not to interpret the findings from a model as applying directly to a ship in service.

I am surprised that silver/silver chloride reference cells were used in these experiments, rather than the more conventional zinc half-cells, unless RN ships in service are fitted with the former. If this is the case, I wonder why silver/silver chloride cells are used, which I consider much more susceptible to damage apart from electrochemical considerations?

However, the results of the model trials are comparable with one another. Although reference cells, in practice, are usually fitted aft, I find it interesting that a half-cell, placed as far aft as possible, still provides very good control over the length of the ship. I wonder if this would be the case in a service ship where paint damage at the bow frequently occurs due to scoring by anchor cables and/or ice?

The authors do not state in this paper whether the propellers in these tests were electrically bonded to the steel hull or not.

J. C. ROWLANDS (Admiralty Research Establishment): Dimensional scaling of corrosion reactions is usually difficult to relate to the full-scale condition, as dilution of the electrolyte invariably alters the anodic corrosion reaction. However, scaling of marine ICCP systems is feasible, as the cathodic reaction is the reduction of oxygen and the solubility of oxygen is similar in both distilled and natural sea water. However, the cathodic reaction:
$\frac{1}{2}O_2 + H_2O \rightarrow 2OH^-$ is not changed due to the dilution of the electrolyte.

The required condition for the scaling of secondary current distribution can be obtained from the Wagner similarity law[1,2]:

$$W = \frac{k R_\rho}{L}$$

which can be modified to the form,

$$W = \frac{k B}{L i_c}$$

where W=Wagner number, and must be maintained constant for scaling purposes; R_ρ=polarization resistance; L=characteristic length of system, i.e. scaling dimension, such as hull length; i_c=corrosion current density, which is proportional to the corrosion rate; k=electrolyte conductivity; B=a conversion factor.

Thus the authors have maintained a constant Wagner number by equal scaling of the characteristic length L and electrolyte conductivity k, and not changing the polarization resistance R_ρ. This condition of not altering the polarization resistance also requires the thickness of the paint film on the model hull not to be scaled.

References

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Author's reply

In reply to M. J. Moffat: The profiles presented were all determined using an undamaged coating system. When paint representing an approximately 7 x 0.5 ft strip was removed the 'all-aft' configuration maintained excellent protection (approx. –800 mV) in this region. With heavier damage, equivalent to an approximately 7 x 6 ft strip, protection at the bow was reduced to –775 mV. A new two-zone system has been selected for warships, with the forward of the two REs sited towards the bow.

The beneficial effects of chalking are long-term. The use of diluted sea water models 'worst case' (which is desirable) and protection will improve with time, excepting damage to paint coatings.

In reply to J. Crook: We believe that DACS has application to marine structures of all types and have used the technique to examine the impressed current cathodic protection of an unpainted shallow water oil jacket and its structural components (ref 4). I would be most interested in collaboration with operators/designers of offshore structures and merchant ships.

A one-sixtieth scale has been employed to date as this results in a 6 ft long model of a typical warship, which is convenient to construct and use. Results from model hulls under static conditions have been compared with routine monthly returns from moored warships. The profiles are very similar (refs. 3 and 4), particularly bearing in mind that such returns are based upon approx. six or seven measurements along a hull under operational conditions where the exact location of the measuring electrodes cannot be guaranteed and there may or may not be tidal currents. Under-way profiles are not available, although it is hoped to carry out trials in the near future.

Potentiodynamic scans of mild steel and bronze have been carried out in natural and one-sixtieth conductivity sea water which show that dilution of the electrolyte does not alter the nature of the cathodic polarization curves in any significant way. Thus the response to protection is the same in both electrolytes.

In reply to M. B. Thurman: Clearly, our results from an 'all-aft' configuration are in agreement with merchant ship philosophy and experience, which can be regarded as another validation of the technique.

Past and present operational practice in the Royal Navy is to impose a set potential of –800 mV (SSC). We have carried out other studies which have shown that if a value of –850 mV (commonly employed on merchant ships) is impressed the whole profile is made 50 mV more negative, thus increasing the overall protection afforded by any system. The widespread use of coal tar epoxy coatings would permit such an impressed value. Propellers in service and in the models are in complete electrical contact with the hulls, as evidenced by their galvanic effect upon the potential profiles.

Fig. 6 illustrates the important phenomenon of possible interference between two or more control zones. Under flow the potential profile around the forward anode did indeed become more positive than the surrounding area. As mentioned in the paper and in refs. 4 and 5 the increased output from the aft system in response to flow resulted in a potential of approx. the forward RE which was more negative that –800 mV; thus the forward potentiostat reversed its polarity.

In reply to H. Capper: Corrosion reaction in sea water would be difficult to scale and I am obliged to **J. C. Rowlands** for his supportive comments on impressed current cathodic protection. As mentioned in the reply to **J. Crook** the cathodic polarization curves are not significantly affected by dilution. DACS was developed and is being employed to evaluate the comparative performance of existing and candidate ICCP systems, particularly in response to flow, and to investigate the effects of changes in the location of anodes and reference electrodes, with the aim of developing design criteria.

Silver/silver chloride REs are standard fit on RN ships as they are well suited to use in a high concentration of chloride ions and have proved to be extremely reliable.

As detailed in the reply to **M. J. Moffat,** an 'all-aft' configuration can continue to provide protection in the event of damage to the bow area.