Internal Cathodic Protection of Offshore Wind Turbine Monopile Foundations


Summary

The use of internal CP systems in monopiles is a relatively new application, for which there is no relevant guidance in existing offshore cathodic protection or windfarm standards. There may be disadvantages associated with the application of CP in enclosed spaces if particular secondary effects are not considered; some of these have been well known for many years, some have not. Two independent laboratory studies, reported here, have been completed to elucidate the reactions taking place when galvanic anodes are applied to the protection of steel in enclosed spaces.

In parallel with these laboratory studies a full scale offshore trial installation of galvanic anodes was implemented into real monopile foundations and the performance monitored over several years. Varying levels of water replenishment were established and the effects of these assessed.

The paper presents full details of one of the laboratory studies and compares the data from both laboratory studies and the field trial. These include steel/sea water potential and current density data, changes in water chemistry (pH, oxygen, bicarbonate, and dissolved aluminium and zinc concentrations).

Based on these data two different design approaches for internal monopile CP systems are discussed in detail. The reasons for discarding impressed current as an option for internal applications are detailed.

Conclusions are drawn which include aspects of CP design for monopile internals which should be addressed in Standards. These include an assessment of hydrogen generated in a monopile by the alternative CP systems.

1. Introduction

Although not often appreciated corrosion is a major risk for offshore wind foundations. Its effects could mean costly offshore retrofit work, result in the loss of generation and expose operatives to additional health and safety risks. Corrosion protection therefore is of vital importance to assure the integrity of offshore foundations minimizing exposure to these risks.

The monopile has been the most commonly used type of foundation for offshore wind farms. These large diameter steel piles, which are normally uncoated internally, are flooded with seawater when installed. Although nominally sealed from further
ingress and egress of seawater, there is the potential for such seals becoming ineffective, leading to the possibility of corrosion of the internal surfaces due to the replenishment of oxygen. Accordingly, the application of cathodic protection [CP], in the form of galvanic [sacrificial] anodes, is being considered as a remedy to address such a situation in the event of it occurring.

Current offshore standards were developed for conditions mostly associated with jacket structures in deeper waters, lower tidal currents and uniform anode distribution. The external protection systems of most offshore wind farms differs considerably; additionally no suitable guidance exists for internal corrosion protection of monopile foundations. The use of internal CP systems in monopiles is a relatively new development, for which again there is no relevant guidance in existing offshore cathodic protection standards. Evidence has only recently begun to emerge that there may be disadvantages associated with the application of CP in enclosed spaces if particular secondary effects are not considered.

In 2012 an existing monopile in a North Sea wind farm was fitted with an instrumented trial cathodic protection system [section 2.1], consisting of strings of aluminium galvanic anodes. After only three months operation, current demand on the anodes had increased markedly, accompanied by a diminution in levels of protection. This prompted in-situ pH measurement of the internal contents of the monopile, revealing an unanticipated increase in acidity, to a pH of 4.2, compared to the normal value of 8.2 for seawater.

As a result of this observation, two laboratory studies have been carried out, by different laboratories, to elucidate the reactions taking place when galvanic anodes are applied to the protection of steel in enclosed spaces.

In one of the programmes, the tests conducted explored also the possibility of augmenting the level of protection by using liquid membranes floated on the internal seawater/air interface to restrict oxygen exchange with the air above the waterline [to be used either with CP or as a stand-alone corrosion mitigation method], the effect of the presence of an internal tidal range and the use of aluminium and zinc anodes.

Section 2 describes the offshore and laboratory test programmes, with results discussed in section 3.

2. Test programmes

2.1 Offshore CP trial

The test monopile was fitted with four strings of aluminium galvanic anodes, each string consisting of 6 x 24kg anodes. Initially only two of the strings were connected, with a third being added after approximately one month. The following parameters were measured and transmitted to an onshore data logger:

- Steel/seawater potentials [mV wrt Ag/AgCl/seawater] at six depths in the monopile
- Anode/seawater potential at one location on the anode string [mV]
- Anode string currents [A]
Steel current density \( [\text{mA/m}^2] \)
Dissolved oxygen concentration \([\text{mg/l}]\)

The initial trial ran from 2 March to 24 May 2012. The internal seawater was sampled for analysis, including pH measurement, at the end of this period. The results from this trial led to the commissioning of two, independent, laboratory investigations, reported below, in order to understand in more detail the possible interactions occurring when applying CP in enclosed spaces, and to ascertain how the results from laboratory test may relate to the experience encountered in the field trial.

2.2 NPL laboratory investigation

The first laboratory study, carried out at NPL, utilised electrochemical tests in order to understand the interaction between aluminium anodes and carbon steel in unreplenished seawater. This test programme comprised the following:

- Small scale galvanic coupling tests to simulate the cathodic protection process between carbon steel and aluminium alloy in artificial seawater. Investigating the effects of solution volume to cathode/anode area ratio, seawater composition, state of the steel surface, replacement with fresh seawater or stirring.
- Uncoupled tests to simulate the installation of the anodes in the monopile without electrical connection.
- Chemical dosing tests to evaluate the effect of aluminium ion concentration on the pH of seawater.
- Electrochemical potentiodynamic polarisation tests to assess the effects of seawater pH on the cathodic reduction reactions at the steel surface.

The study used carbon steel cathodes and an aluminium-zinc-indium proprietary alloy as the anode material. The test solution was specifically prepared with a composition similar to that found [by analysis] in one of the monopiles. The main difference between this and artificial seawater [ASTM D1141] was a significantly lower bicarbonate concentration. If any adjustments to the pH were made during a test then either HCl or calcium hydroxide was used. A saturated calomel electrode [SCE] was used for potential measurements. The scan rates for electrochemical potentiodynamic polarisation were 0.1, 1 and 10 mV/s and the corrosion rates were determined using the linear polarisation resistance [LPR] technique with a sweep from -10mV to +10mV vs the free corrosion potential. The exposed anode surface areas were 25mm\(^2\) and the steel cathodes 2500mm\(^2\), giving an anode: cathode ratio of 1:100. Solution volume was 3.75l. These area and volume ratios were selected to reproduce those in the offshore test pile, while fitting into a standard 5l laboratory beaker.

Tests were carried out on un-corroded and pre-corroded steel samples. The effect of a sulphide film was also investigated. Changes in anode [but not steel] current density, couple [but not individual anode or cathode] potential and pH were measured during the galvanic coupling tests. Figure 1 shows the NPL test set up.
The second laboratory study was defined by CCAL and carried out by Intertek to evaluate and monitor the cathodic protection response and environmental changes when using sacrificial Zn or Al anodes under various service conditions. The tests, carried out on a much larger scale, simulated typical in-service anode to cathode area ratios and cathode area to seawater volume. Some tests were carried out with an oxygen impermeable membrane on the seawater surface, and one test run simulated tidal replenishment of the seawater.

The following conditions were evaluated:

1. Aluminium anodes with open seawater/air interface [no tidal replenishment]
2. Zinc anodes with open seawater/air interface [no tidal replenishment]
3. Aluminium anodes with gas impermeable membrane at seawater/air interface [no tidal replenishment]
4. Zinc anodes with gas impermeable membrane at seawater/air interface [no tidal replenishment]
5. Aluminium anodes with gas impermeable membrane at seawater/air interface [tidal replenishment simulated [10% volume replaced each ‘tide’]]

The CCAL/Intertek laboratory study utilised significantly larger sample sizes and solution volumes than the NPL study and a special laboratory test rig was designed to simulate, as far as possible, the internal environmental conditions within a monopile, including, the anode to cathode area ratio, cathode area to seawater volume, and seawater diameter to depth ratio. The cathode was a carbon steel
plate, grit blasted to Sa2½ with a surface area of approximately 87550mm². Two galvanic anode materials, aluminium-zinc-indium proprietary alloy and a zinc alloy to US MIL-A 18001 specification, with both having a surface area of 2500mm², were evaluated. Fresh seawater [sourced from the Anglesey coast, Wales, UK] was used as the test fluid, filling a HDPE pipe of 14” ID with a volume of 110L [water depth 1100mm]. For tests 3, 4 and 5 the water/air interface was covered with a proprietary floating membrane impermeable to oxygen. For test 5, 10% of the seawater was withdrawn, and replaced with fresh seawater, at regular intervals to simulate tidal replenishment.

Fig 2: Intertek test cell arrangement

Note: Data loggers on ground. Access ports at 3 levels for oxygen and pH sensing. Not visible but in place: sight glass for water level, bottom valve and internal diffuser plate for bottom tidal replenishment.

The test assembly was designed to allow for monitoring the environmental changes resulting from the application of cathodic protection using galvanic anodes. Parameters, such as oxygen levels, pH, and accumulation of anode dissolution products were determined at intervals throughout the test duration. The design allowed for measurements, and water samples, to be taken at three elevations in the HDPE pipe, bottom, middle and top. The results presented herein are those taken at the centre elevation. The cathodic current was measured using a ZRA and the potentials were measured with respect to Ag/AgCl/sea water reference electrodes. These data were continuously logged using appropriate data loggers. The water chemistry was analysed for Al, Zn and Fe using Flame Atomic Adsorption, and bicarbonate by titration to pH 4.5. Oxygen and pH were analysed in-situ using
optical sensors. The pH was also measured for each water sample taken. At the end of the test the extent of calcareous scale formation on the steel, and its composition were also analysed.

All tests were preceded by a two week “pre-corrosion” period to allow for corrosion products to form on the cathode steel plate as would be the case in the construction phase and installation of a monopile. Thereafter, the seawater was exchanged with fresh seawater and the CP was initiated by coupling the anode to the cathode via a ZRA.

3. Results

3.1 Offshore CP trial

The results from the initial, 3 month offshore trial showed potentials gradually becoming less negative with time, with eventual under-protection [Figure 3].

![Figure 3: Offshore trial potentials [first three months] [Upper curve is anode/electrolyte potential wrt Ag/AgCl/sea water]](image)

Concurrently the anode string currents increased [Figure 4].

![Figure 4: Offshore trial anode string currents [first three months] [Green lower curve is an anode string connected mid trial to improve protection]](image)
There was a corresponding increase in cathode current density [Figure 5],

![Figure 5: Offshore trial cathode current density [first three months]](image)

Measured oxygen levels dropped below 1ppm [Figure 6].

![Figure 6: Offshore trial oxygen levels [first three months]](image)

An analysis of the contents of the pile, prompted by these data, revealed that the pH had dropped over the three month period, from 8.2 to 4.2, explaining the observed changes.
3.2 NPL laboratory investigation

The data from the NPL testing cannot be directly related to the offshore data, as different parameters were measured, other than in respect of pH, where the increase in acidity in a closed cell was confirmed. Figure 7 shows a typical example from the NPL data:

![Figure 7: NPL test - typical pH change](image)

3.3 Intertek laboratory investigation

The NPL study used very small sample sizes, whilst the field trials represent the actual service condition. The Intertek programme took an intermediate approach, using extended cylindrical test cells with larger anode and cathode areas.

3.3.1 CP potentials and current densities

CP current densities and potentials for both anode materials are exhibited in Figure 8:

![Figure 8: Potential and cathode current density vs time for zinc anodes with no membrane](image)
These data are from tests 1 and 2 (No water replenishment and no membrane): very similar behaviour occurred in all tests. As can be seen from these graphs, the steel/seawater potentials with aluminium anodes were more negative than the zinc, as would be expected. However, it is also clear from the graphs, that the anode resistance in the test cells was overestimated, resulting in excessive initial current output and in steel/sea water potentials of the steel plates being more negative than -1000mV vs Ag/AgCl/seawater. To reduce the current and polarisation levels to those experienced in service, the circuit resistance between the anode and cathode was increased [by the addition of resistors] to allow the cathode potential to attain more realistic values. The final steel cathode current densities were greater for the aluminium anode [16.8mA/m²] than for the zinc anode [14.8mA/m²] at comparable steel/seawater cathode potentials [-896mV and -879mV respectively]. The application of a membrane and hence restriction of oxygen reduced the cathode current density to 14.9mA/m² for the Al anode and 12.7mA/m² for the Zn anode at slightly more negative but still comparable cathode potentials [-921mV and -912mV respectively]. Seawater replenishment [with membrane in place] led to a slight increase in the cathode current density, as would be expected.

3.3.2 Water chemistry

3.3.2.1 pH

In tests 1 [Zn anode] and 2 [Al anode, both without water replenishment or membrane] the water chemistry for both anodes changed with time. The most significant changes were in the pH of the seawater [Figure 10] which, for the aluminium anode, reduced from 7.8 to 5 after ca. 2 weeks and remained at this pH for the remainder of the test. The pH of the zinc anode test remained relatively constant between 7 and 8. Very similar changes in pH were observed with a membrane in place [tests 3 and 4], while the repetitive 10% tidal replenishment, with the Al anode and membrane [test 5] reduced the fall in pH to 6.
It is considered that the initial buffering capacity [bicarbonate] of the seawater was the reason for the delayed reduction in the pH observed in the aluminium anode tests. The reduction of the pH as a function of the aluminium concentration was confirmed in a small scale laboratory test where AlCl$_3$ was added to synthetic seawater: at a concentration of 200mg/l of AlCl$_3$ the pH reduced suddenly and significantly to 4.7. This was not observed when ZnCl$_2$ was added to seawater. In this case, the pH reduced initially from 7.8 to 7.1 at 500mg/l ZnCl$_2$: any further addition of ZnCl$_2$ did not affect the pH which remained more or less constant at pH7. The effect is shown in Figure 11.
3.3.2.2 Oxygen

In tests 1 [Zn] and 2 [Al, both with no replenishment and no membrane] the dissolved oxygen concentration of the seawater reduced within the first two weeks from 9ppm [saturated with air] to 0.4ppm for the Al anode test and 2.5ppm for the Zn anode test [Figure 12].

![Oxygen concentration vs time for zinc (Test 1) and aluminium (Test 2) anodes as well as with addition of membrane and tidal replenishment (Tests 3-5)](image)

**Figure 12:** Oxygen concentration vs time for zinc [Test 1] and aluminium [Test 2] anodes as well as with addition of membrane and tidal replenishment [Tests 3-5]

The reason for this difference is considered to be the initial higher cathode current in the Al anode test 2 and hence higher oxygen consumption at the cathode. After two weeks the oxygen levels rose in both tests 1 & 2 to 4 - 5ppm, possibly due to thermal convection currents in the test cells allowing air absorption at the seawater surface. At the end of the tests, the oxygen concentration was ~4ppm in both tests. The presence of the membrane [tests 3, 4 & 5] prevented this surface absorption of oxygen, with levels falling to the limit of detection in tests 3 and 4 [no replenishment] and stabilising at ~ 0.5ppm in the 'tidal' replenishment test 5 where oxygen is replenished as part of the tidal simulation.
The concentration of both aluminium ions [in the case of the aluminium anode test 2] and zinc ions [in the case of the Zn anode test 1] initially increased as would be expected due to the liberation of both anions as the anodes dissolve, Figure 13.

![Zn and Al concentration](image)

**Figure 13: Al$^{3+}$ and Zn$^{2+}$ concentration vs time for zinc [Test 1] and aluminium [Test 2] anode as well as [Tests 3-5] with addition of membrane and tidal replenishment**

The Zn$^{2+}$ ion concentration increased slowly as the test proceeded. However, the Al$^{3+}$ concentration appeared to reach a steady state concentration at 10mg/L after three weeks. In both tests, the bicarbonate concentration decreased within the first few weeks of the test. The bicarbonate levels in the electrolyte in the Al anode tests reached a steady state [10mg/L] after 2 weeks, whilst a steady state in the Zn anode test was reached in three weeks, at a much higher concentration [70mg/L]. It should be noted that the reduction of the bicarbonate concentration to a steady state value is also reflected in the change in the pH for the Al anode containing tests thereby underlining the assumption that the pH is closely related to both the Al ion concentration and the ability of bicarbonate to buffer the pH of seawater for a time.

The addition of the membrane to the tests did not affect the Al$^{3+}$ ion concentration but lead to a significantly lower Zn$^{2+}$ ion concentration in the centre of the monopile test column [but a significantly higher Zn$^{2+}$ ion concentration at the bottom of the monopile. It is argued that the application of a membrane reduced the natural convection inside the monopile leading to a type of stratification such that the Zn$^{2+}$ ions accumulate at the bottom of the monopile due their higher density. The tidal replenishment lead to a reduced Al$^{3+}$ ion concentration due to dilution with fresh seawater.

The effect of the membrane on the bicarbonate levels was less noticeable and in general there were no differences between the tests of the same anode with and without the application of a membrane. However, the tidal replenishment predictably
meant that the bicarbonate concentration was replenished as can also be seen in pH data for this test.

![Bicarbonate concentration vs time for zinc [Test1] and aluminium [Test 2] anode as well as [Tests 3-5] addition of membrane and tidal replenishment](image)

Figure 14: Bicarbonate concentration vs time for zinc [Test1] and aluminium [Test 2] anode as well as [Tests 3-5] addition of membrane and tidal replenishment

### 3.3.3 Scale composition and membrane

The scales were analysed using EDX and were shown to be stable calcareous deposits comprising carbonate, magnesium hydroxide and constituents of the respective anode materials and sea water as was expected if CP is applied to steel in seawater. Since the analysis was carried out on scraping, the results are not representative of the exact composition of the scale and are therefore not presented.

Further, no corrosion of the steel plate was observed within the membrane area and tidal range suggesting that once the membrane [inhibitor] has filmed the steel surface, corrosion is not expected to take place [Figure 15]. Scaling was also not observed within the membrane area suggesting that the CP current is not able to conduct through this type of product.

![Test 4 [Zn Anode, membrane, no tidal effect], Scale on the cathode [steel plate] centre/top including membrane](image)

Figure 15: Test 4 [Zn Anode, membrane, no tidal effect], Scale on the cathode [steel plate] centre/top including membrane
However, and more importantly, at the end of test 3 [Al anode plus membrane] and to some extent test 5 [Al anode plus membrane plus tidal replenishment], black deposits were found to be present at the bottom of the steel plates and a smell of H₂S [rotten eggs] was noticed when the seawater was drained from the test vessels. Using scrapings from the Test 3 steel plate and digesting this in a boiling tube using a mixture of 50% c. HCl and 50% deionised water vol/vol a hydrogen sulphide was detected. In addition, moistened lead acetate indicator paper turned brown thereby verifying the presence of hydrogen sulphide.

The condition in Test 3, low pH and active but deaerated seawater were within the stable range of H₂S. The pH in Test 5 was not as low as in Test 3 and hence H₂S may not be as stable in this range.

In actual service it is assumed that there would be natural seabed material in contact with the seawater. The seabed would be likely to contain sulphate reducing bacteria [SRB], carbonate based material and organic matter which could stimulate Microbially Influenced Corrosion (MIC) within the monopile if not adequately controlled by CP. This could further the presence of H₂S with attendant dangers.

4. Discussion

There are many interacting factors which affect the cathodic current densities and changes in water chemistry caused by the application of cathodic protection. These were clearly evident in the offshore trial data.

The subsequent laboratory studies sought to clarify some of these factors with specific focus on CP systems using galvanic anodes in enclosed spaces. The tests clearly demonstrated a marked difference between the use of aluminium and zinc anodes, in particular in respect of pH.

For aluminium, after an initial two weeks in which the pH was initially stable, a sudden reduction of the pH from pH 8 to pH 5 was noted. This also occurred in a small scale laboratory test where AlCl₃ was added to seawater: at a concentration of 200mg/l of AlCl₃ the pH reduced suddenly and significantly to 4.7. The sudden acidification [reduction of pH] also coincided with a low bicarbonate concentration, which reduced slowly at the start of the test but reached a steady state after three weeks into the test [10mg/L]. A similar observation was made with regard to the aluminium ion concentration which initially increased and after about three weeks also reached a steady state [10mg/L]. It is argued that aluminium hydrolysis is a main factor in reducing the pH which is initially buffered by the bicarbonate within the seawater. On exhaustion of the bicarbonate, the pH reduced, being acidification of the seawater.

The use of Zinc anodes did not replicate this fall in pH.

While the use of a proprietary floating membrane impermeable to oxygen proved successful in reducing levels of oxygen, it had no significant effect on the formation
of acid conditions within the test cells. Tidal replenishment, to the extent tested, ameliorated the formation of acidity by aluminium anodes, but did not fully prevent it.

5. Conclusions

The following deductions from the laboratory study can be made in respect of optimising CP designs for offshore wind farm monopiles:

- If no seawater replenishment takes place and aluminium anodes are used, the increase of acidity [lowering of pH] will increase the cathode currents required for protection of the steel, increase the self-consumption rate of anodes and increase the rate of hydrogen evolution. It is possible that protection of the steel may not be maintained and MIC may proceed, with the production of $\text{H}_2\text{S}$ and accelerated corrosion rates.

- Zinc anodes do not significantly alter the pH and will, therefore, not have the adverse consequences described for aluminium anodes in non-replenished conditions. They will also evolve less hydrogen than aluminium anodes.

- The use of a gas impermeable membrane to reduce oxygen exchange at the seawater surface does not change the pH variations due to CP effects in a non-replenished situation but is effective in reducing oxygen level in the water which would be expected to reduce long term cathode current densities.

- If tidal replenishment can be achieved, the pH may be maintained at levels close to those in natural seawater, depending on the percentage seawater exchange on each tide, and aluminium anodes may be used. However, care in the design of the flushing system is important to mitigate against the stratification of the water column; this could present problems of decreasing pH even if tidal replenishment is employed, in particular for those monopiles that were drilled and have deeper water columns below the sea bed.

6. Application of the data

6.1 Tidal replenishment

In light of the results reported above, it was decided to modify the monopile used for the full scale CP trial to allow flow of seawater in and out of the pile interior on each tide, retaining the aluminium anode strings in place. Flushing commenced in October 2012, with an immediate improvement in the recorded potentials as shown in Figure 16.
Figure 16: Effect of replenishment on protection potentials in trial monopile

This replicates the initial, 3 month, data shown in Figure 3, when the pH fell from an initial [normal seawater] value of 8.2 to 4.2 and adds results for a further 4 months before flushing started, which show that the under-protection remained established. This water replenishment by tidal flushing permitted the achievement of steel/water potentials well into the protected range, a condition which has prevailed to date, as shown in Figure 17.

Figure 17: Potentials in test monopile since establishment of flushing
It may be noted that in Fig. 17 there was a positive-going trend in steel/water potential at around August 2013, which may reflect flushing becoming less effective, and pH decreasing, at that time. This would appear to be confirmed by a corresponding increase in anode currents [Figure 18], although it is not reflected in the cathode current density [Figure 19] or oxygen content [Figure 20] data.

![Figure 18: Anode string currents in test monopile since establishment of flushing](image)

![Figure 19: Cathode current density in test monopile since establishment of flushing](image)
The cathode current densities are as expected for seawater with \(~2\text{mg/l}\) oxygen, and confirm that acid conditions are not being established if sufficient replenishment of the internal water column is ensured. pH is not regularly monitored in this trial, but it is measured during offshore visits, with the latest reported value being pH 7.04 in November 2013, confirming the conclusions from the logged data.

**If sufficient seawater replenishment can be assured, conventional aluminium galvanic anode cathodic protection can be used in offshore monopiles.**

### 6.2 CP design for un-replenished conditions

Although the focus here is on the use for retrofit solutions, as most known applications have been in this configuration, the applicability of these findings is equally valid for designers considering internal anodes for new structures.

Two cathodic protection designs [based on aluminium and zinc anodes] informed by the results obtained in these test programmes have been developed to maturity and the zinc option further into detailed design level. This exercise has enabled an understanding of the key differences between the two materials, both in terms of performance but also the practical challenges posed by installation, cost and Health & Safety considerations.

Focusing on the system designed in detail, it would utilise cast galvanic anodes of Zinc to US MIL-A-18001 specification, cast onto steel bar cores. The anodes would be assembled together into ‘strings’. In this application strings consisting of ca. 50Kg gross weight individual anodes [to facilitate ‘two man’ manual handling] spaced at ca. 1 metre spacings would be assembled offshore, within the transition piece [TP], and suspended into the water filled monopile [MP].
Assessments have been made of the current/voltage attenuation down the anode strings and novel design steps have been taken to ensure that the currents delivered by anodes at all elevations are similar, such that the provision of current and the polarisation of the steel/sea water interface of the MP will be uniform as will be the life of the anodes. It is postulated that some anode string designs, not following these novel steps, will discharge higher currents and will suffer early anode depletion at the top of strings whereas lower elevations of MP may be inadequately protected and their anodes under-utilised.

The anode shape/dimensions have been determined such that the current output should be close to the optimum for achieving steel/sea water potentials that stimulate the most protective calcareous deposits [in the range -930 to -1000mV Ag/AgCl/seawater]; this is intended to ensure that any microbiologically influenced corrosion would be controlled and the minimum current and maximum life delivered.

The generation of hydrogen at both the cathode and the anodes has been assessed and specialised venting would be an integral part of the system to prevent potentially explosive atmospheres forming above the water column in the MP and below the airtight deck of the TP.

For such a system, representative foundations should be monitored to ensure that the CP performance is properly assessed along the sea water chemistry variations, in order that the design is fully verified. It is highly recommended that a small number of foundations are fitted with these detailed monitoring systems by way of a trial and that in any full implementation, lower cost, less detailed CP monitoring is implemented into a larger number but representative small proportion of the foundations.

6.3 Implications for design codes

The data from these investigations and from related work by, or reviewed by, the authors should inform the wider application of cathodic protection to the internals of foundations. The following general conclusions can be drawn:

1. The reliance on oxygen depletion for corrosion control of the internals of monopiles achieves mixed results and needs to be considered on a project by project basis.

2. The chemistry changes in non-replenished, closed systems have not been fully reported in the past. This is possibly because many fully closed CP systems have used zinc anodes and the widespread internal CP application of aluminium anodes has been in systems that are regularly replenished. These changes need to be addressed in foundation internal CP designs and Standards

3. Whilst the greater anode capacity [amp hours per kg] of aluminium anodes makes them lighter and easier to install, and less costly, than zinc anodes,
the latter are a more secure choice if there is no, inadequate or uncertain replenishment of the sea water within monopile foundations

4. The laboratory studies present detailed and credible data to inform the design of internal CP systems for monopiles. As would be expected for a closed and non, or marginally, replenished systems, the steel cathode current density values for polarisation are much lower than the default design figures in offshore platform CP Standards and recommended practices which are often, wrongly, used as a basis for wind farm monopile CP designs.

5. The design of galvanic anodes strings for foundation monopile internal applications requires design steps that are not documented in existing standards. These include:

   a. the competent addressing of anode/anode and anode/monopile resistance within the string

   b. assessment of anode/anode and anode/cathode mutual interaction that will reduce anode output from that calculated from classical resistance to remote anode calculation,

   c. the calculation of attenuation down anode strings

   d. the proper practice of casting anodes onto properly prepared steel core [do not cast aluminium onto galvanised steel cores, this results in exothermic dissolution of the iron/zinc intermetallics to the detriment of anode quality and foundry safety]

   e. the addressing of corrosion of the anode suspension system above the water level within the foundation.

6. Impressed current CP systems have been proposed, by some, for foundation monopile internal protection. This is considered to be a flawed approach presenting considerable threats to asset management:

   a. the anodic reaction products include chlorine and hydrogen, these will present corrosion risks in the air space above the water in the monopile and a significant increase in the incendive spark risk along with an increase in hazards to personnel entering the confined space

   b. the effectiveness of the CP system will be dependent upon secure electrical supplies

   c. the reliability of impressed current systems, offshore, has been significantly lower than competently designed galvanic anode systems.
7. All internal CP designs should address gaseous anode and cathode reaction products. Detailed assessments of hydrogen generation at both anodes (Al and Zn alternatives) and at the steel cathode have been necessary in the execution of the designs outlined above. Gas venting has been necessary and has been engineered and proven as part of these works.

It is clear that, while the wind-farm offshore standards and Classification Society requirements permitted the original ‘oxygen depletion’ corrosion mitigation solution to be applied in many developments; this has proved difficult to achieve in practice. This work has shown that the existing standards and codes which are widely used for the design of CP systems for offshore structures and monopile foundations have inadequacies in respect of the protection of internal [almost] closed compartments.

It is suggested that the Classification Societies address these matters urgently in their Design Codes; it is known that there is proposed action within the European Standards Organisation (CEN) to generate a new European Standard for the internal surfaces of monopile windfarm foundations. It is suggested that more effective and rapid improvement would come from Classification Societies immediately improving their documents in this area. The key issues are outlined above and suggested wording for a revised DNV-OS-J101 in respect of internals of monopiles will be presented in Graz.