intertek
Total Quality. Assured.

CATHODIC PROTECTION OF WIND TURBINE MONOPILES – INTERNAL & EXTERNAL CORROSION

World Corrosion Day
24 April 2024 ICorr NW

Dr David Buxton Intertek CAPCIS

Dr Gareth John, Dr J D Stott & Dr Petra Ernst

INTRODUCTION

1. Offshore wind turbines
2. Overview of cathodic protection (CP)
3. External galvanic anode systems
4. Internal galvanic anodes – retrofit issues
5. Leaking seals - protection into narrow gaps

1. OFFSHORE WIND TURBINES

FIXED OFFSHORE FOUNDATIONS

- Monopiles – circular driven pile
- Concrete gravity base substructures
- Tripod (with piles or suction caissons)
- Jacket

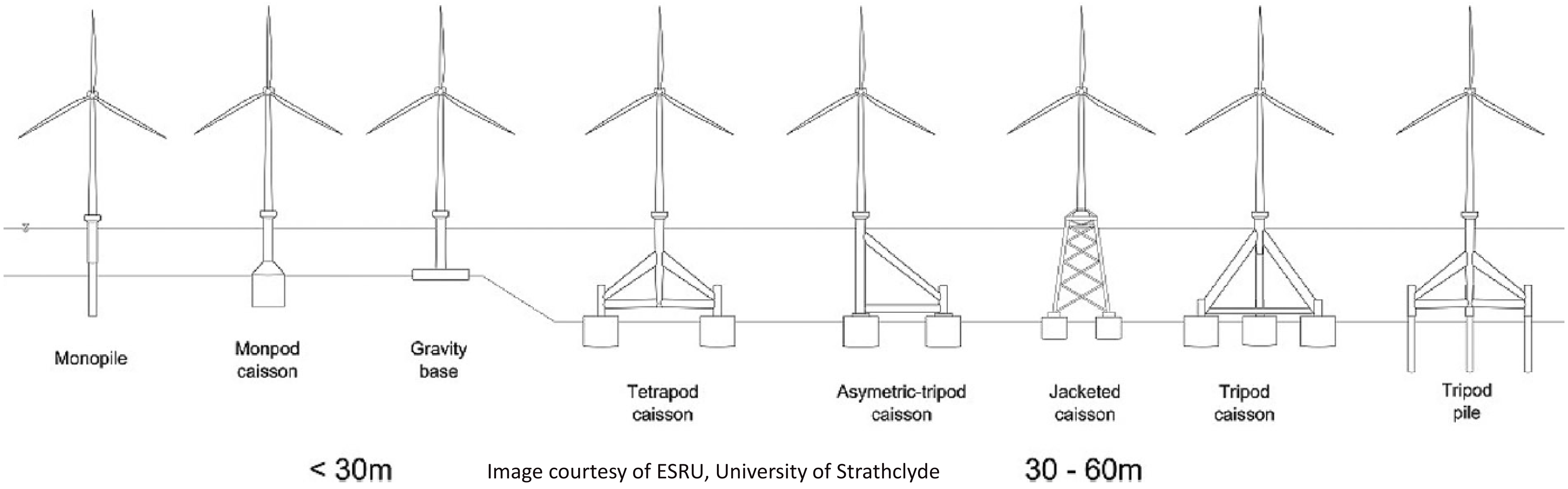


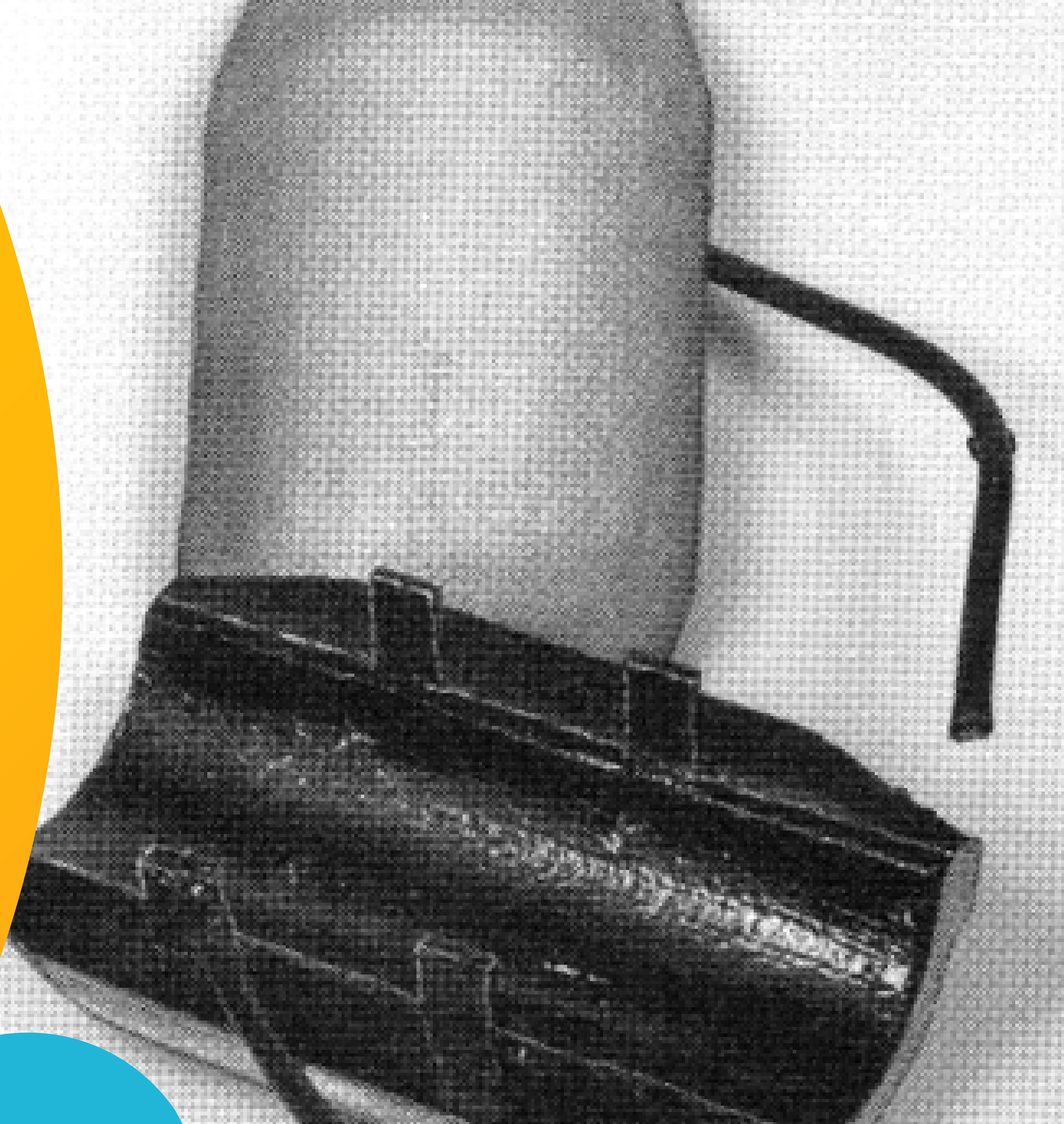
Image courtesy of ESRU, University of Strathclyde

FLOATING OFFSHORE FOUNDATIONS

- Early stage of development
  - Hywind, Scotland
  - WindFloat, Portugal
- Design types
  - Semi-submersible
  - Tension leg
  - Spar

Windpower Engineering & Development

2. OVERVIEW OF CATHODIC PROTECTION (CP)



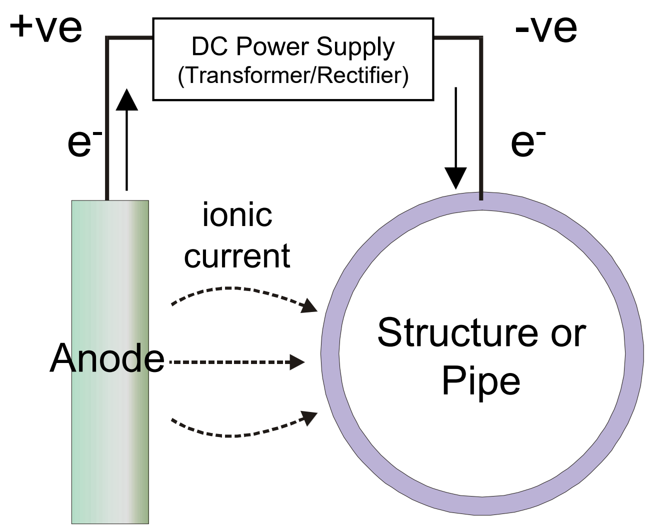
WHAT IS CATHODIC PROTECTION?

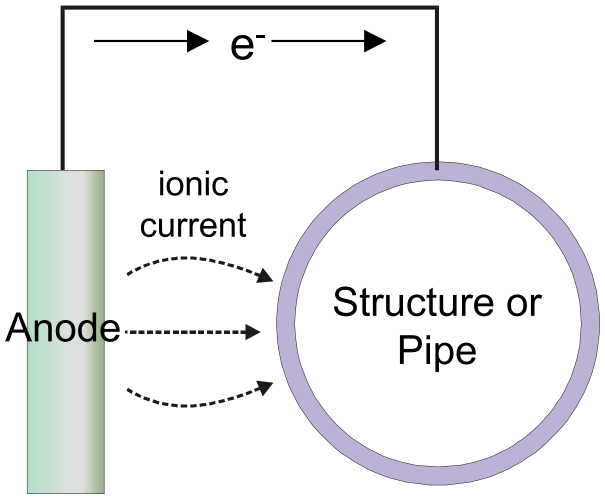
- The aim of cathodic protection is to promote the cathodic reaction (e.g., the oxygen reduction reaction) on the structure to be protected.

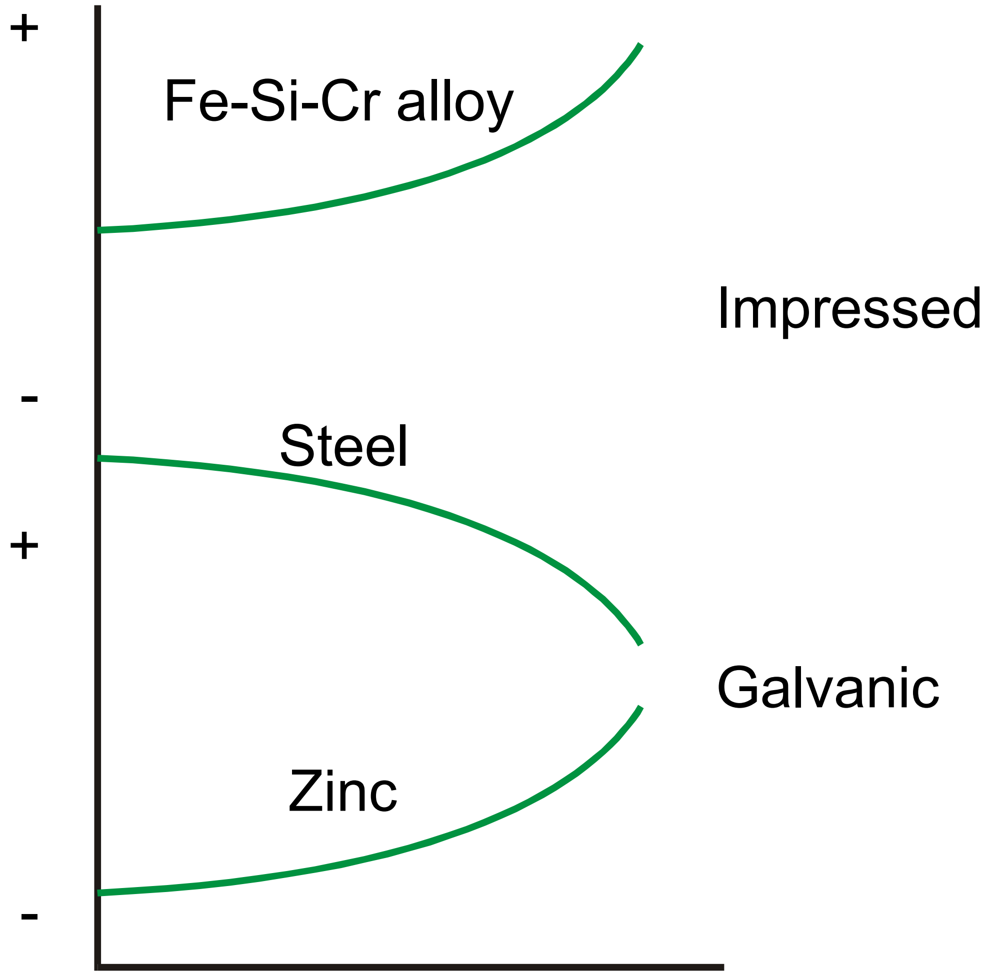
→ Alkaline environment generated

- When the only reaction on the metal surface is the ***cathodic reaction***, corrosion is suppressed, and the system is protected.
- The steel to electrolyte potential is reduced to a value where corrosion is insignificant.
- Potential criteria are used to determine whether CP has been achieved (e.g. ISO 12473:2017 General principles of cathodic protection in seawater)

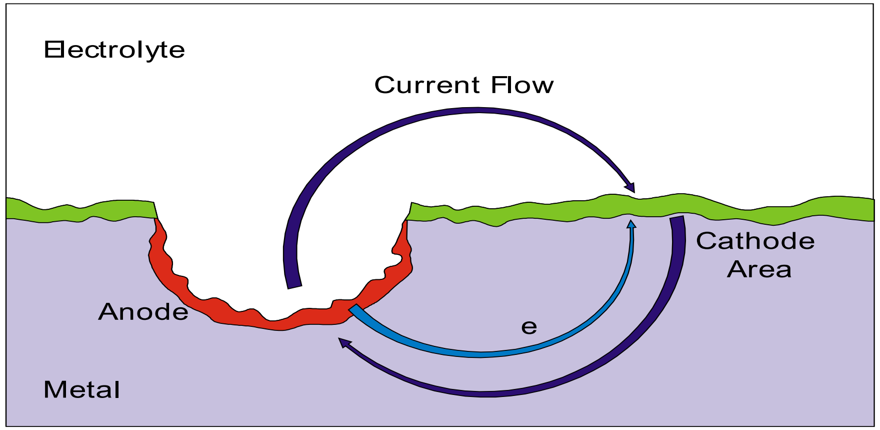
POLARISATION FROM IMPRESSED CURRENT AND GALVANIC CP SYSTEMS



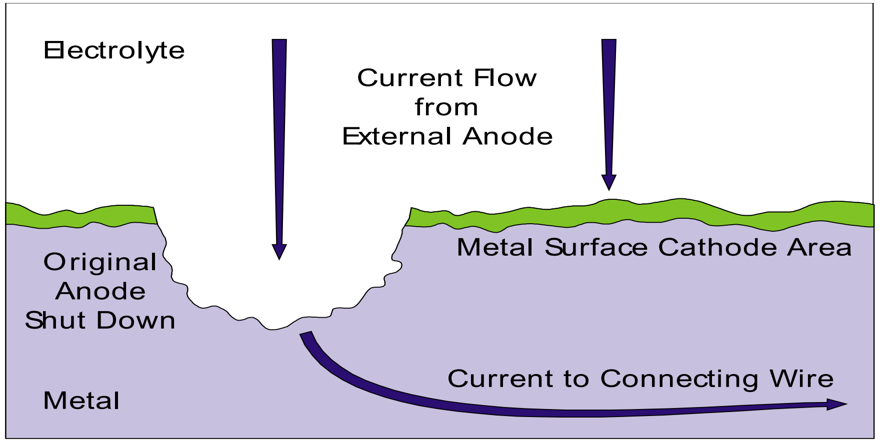




EFFECT OF CATHODIC PROTECTION CURRENT ON CORROSION CELLS



Before CP Current is Applied

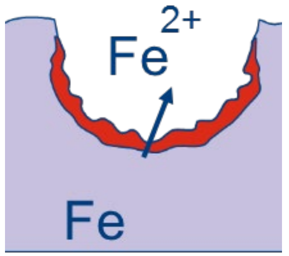


Effect of CP Current

ANODIC AND CATHODIC REACTIONS

- Metal dissolution (oxidation) is the primary **anodic** reaction

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

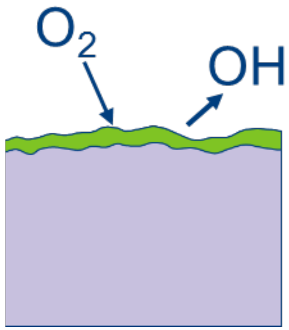


- Alternate anodic reaction

$$Fe^{2+} \longrightarrow Fe^{3+} + e^-$$

- Oxygen reduction is the main **cathodic** reaction (for natural corrosion)

$$\mathbf{O_2 + 2H_2O + 4e^- \longrightarrow 4OH^-}$$



- Alternate cathodic reactions
  - Hydrogen reduction

$$\mathbf{2H^+ + 2e^- \longrightarrow H_2}$$

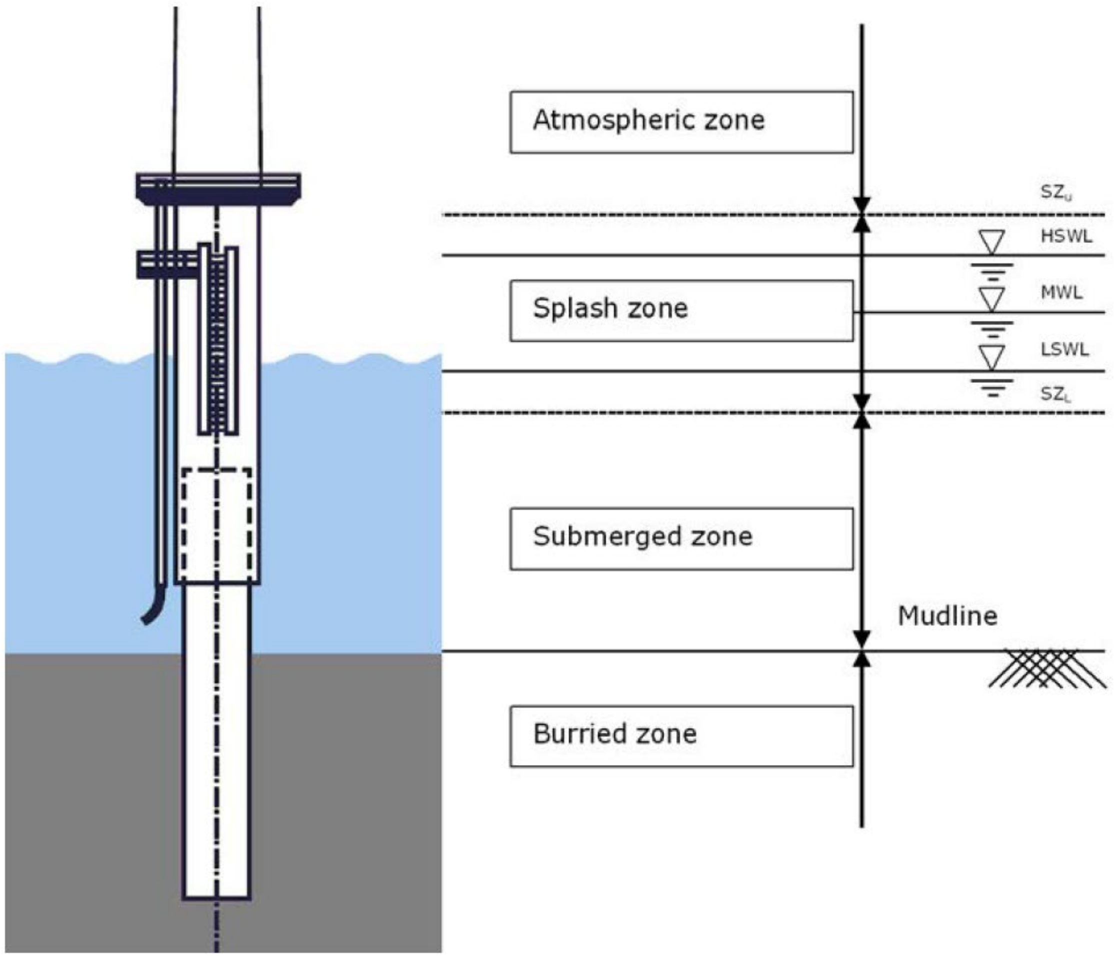
  - Water reduction

$$2H_2O + 2e^- \longrightarrow 2OH^- + H_2$$

3. EXTERNAL PROTECTION

EXTERNAL PROTECTION

- **DNV-RP-0416:2021 Corrosion protection for wind turbines**
- **BS EN ISO 24656:2022 Cathodic protection of offshore wind structures**
- The documents provide the latest recommended practice for all types of wind turbines:
  - Atmospheric, splash, submerged and buried
  - Internal and external
- CP required for external surfaces with an optional protective coating
- Both standards address issues of historical poor performance.

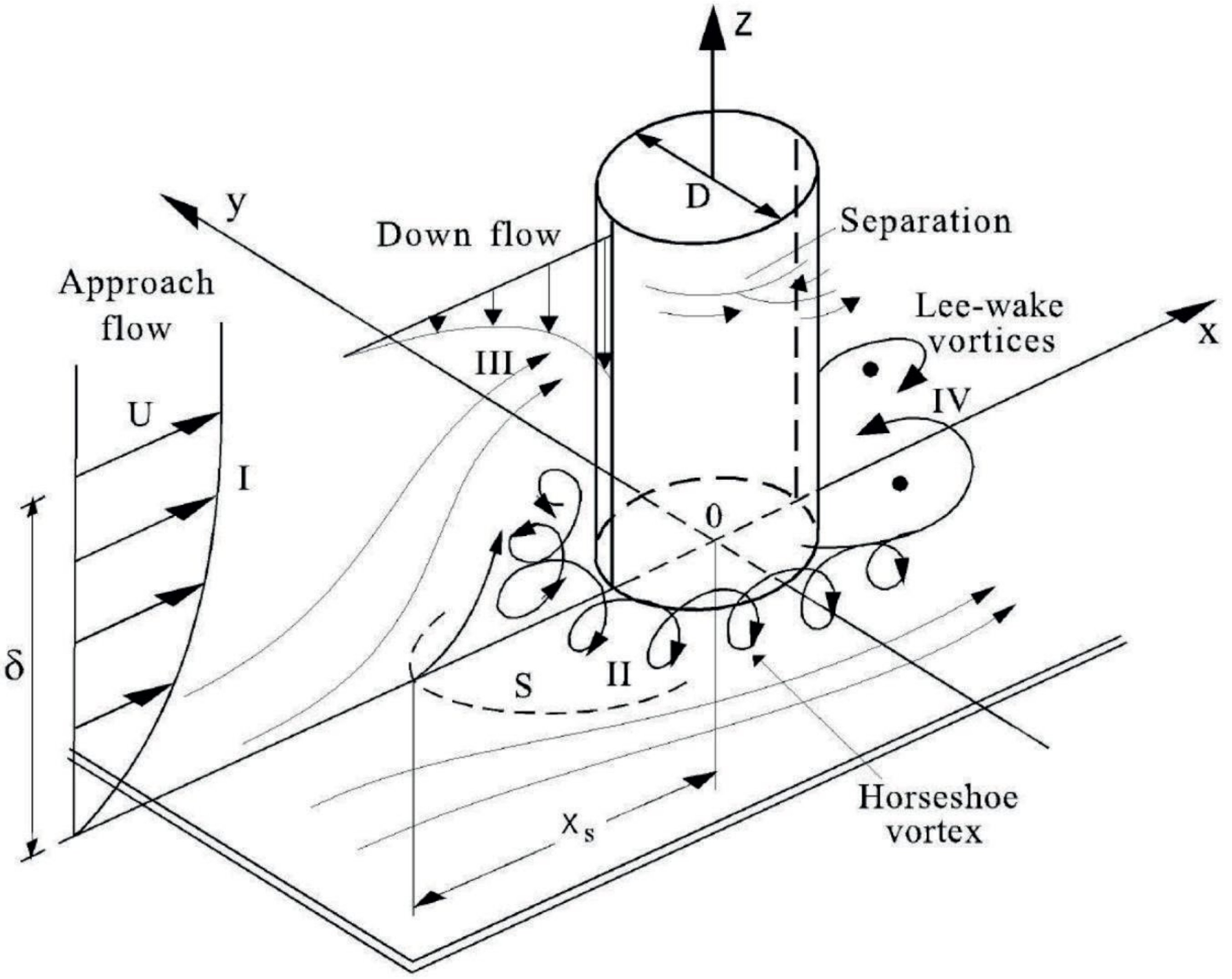


From DNV-RP-0416 Figure 4-1

DESIGN CURRENT DENSITY

- Wind turbines are generally located in shallow waters close to the shore.
  - Tendency for high levels of dissolved oxygen
  - Tidal currents
  - Structure generated flow amplification and turbulence
    - Wave or current dominated flow

➡ **INCREASED CURRENT DENSITY REQUIRED FOR PROTECTION**



From BS EN ISO 24656 Figure B.5

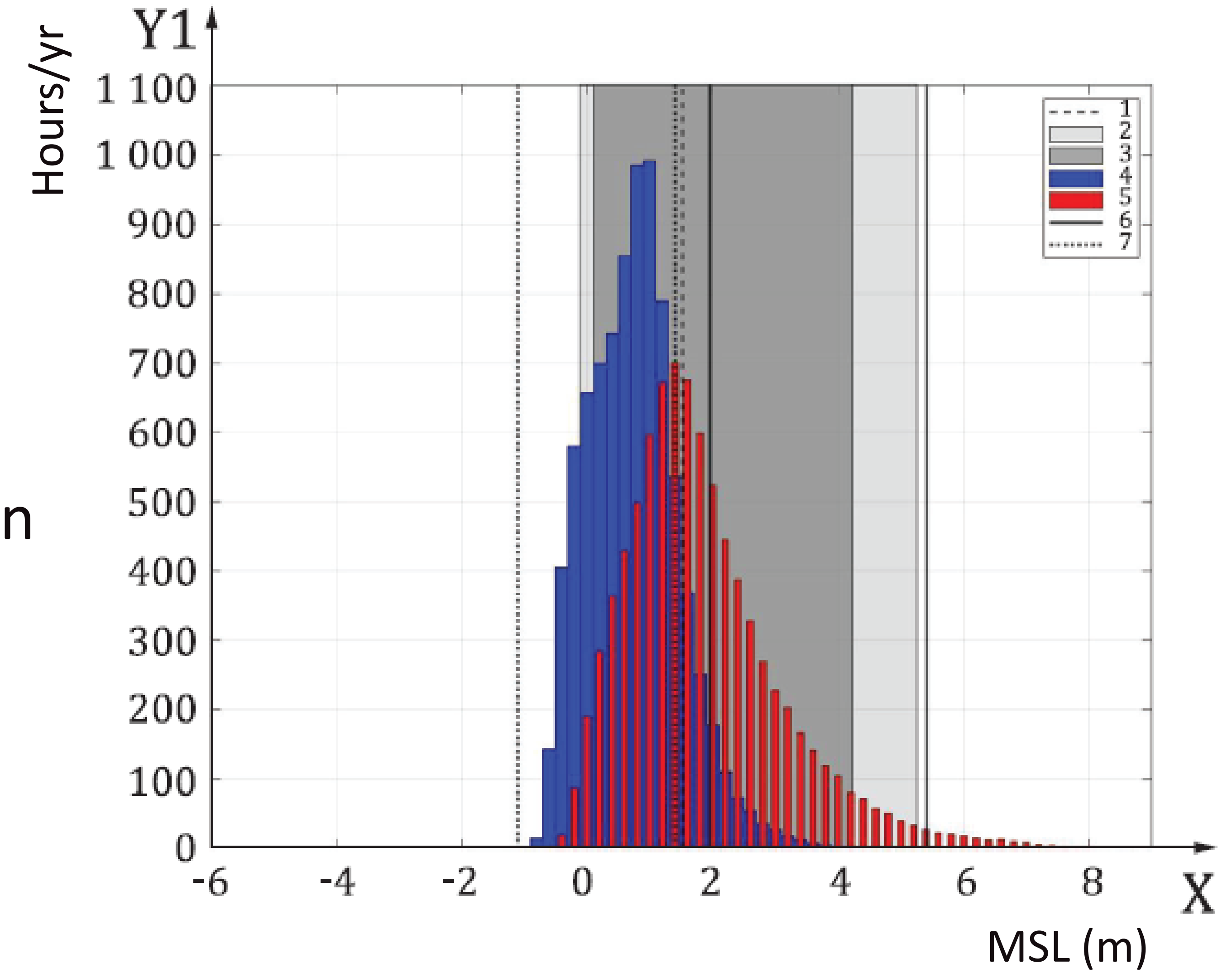
METOCEAN DATA (1)

- The ISO 24656 provides guidance for the use of metocean data to assess CP demand for design:
  - Determine long-term averaged seawater flow velocities (wave and current).
    - Structure generated flow amplification and turbulence localised to sides and base
    - Apply an area and time average mark-up factor of 1.5.
  - Indicative CP design current densities (Initial/Mean/Final) mA/m^2 for bare steel in seawater external (Table C.1)

Marked-up seawater flow velocity (m/s)	Temperate region 7 to 11°C	Artic region <7°C
0.3	210/60/120	250/75/150
1.0	300/75/180	360/90/180
3.0	520/130/260	625/155/310

METOCEAN DATA (2)

- Frequently wetted zone – variations in tide (water) level and wave conditions will determine how much of the structure is immersed at any time and the amount of CP drain current.
- Still water level (SWL) plus significant wave height
- $FWZ_{50\%}$ is taken as an estimate of the level for mean current demand – estimation of anode mass required.

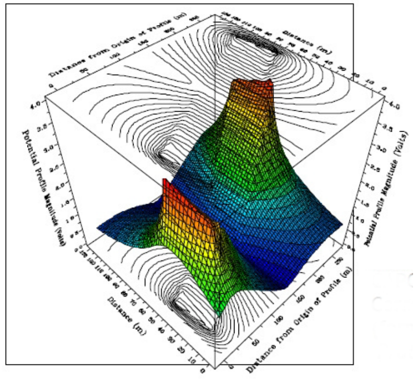


1 $FWZ_{50\%}$
4 FWZ:IWR
5 FWZ: SWL + H_{m0}
7 LAT & HAT

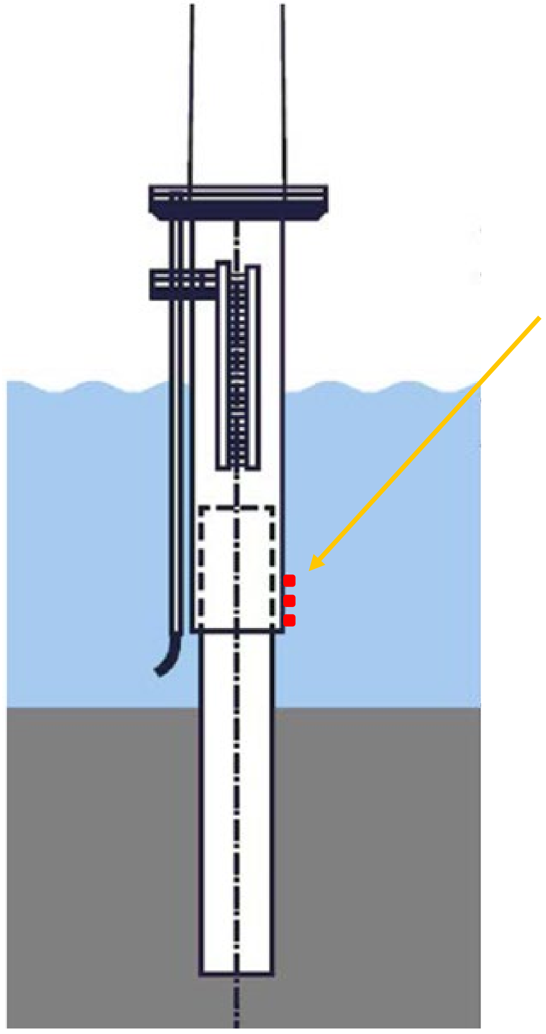
ANODE INTERFERENCE

- Where anodes are soley fitted to the transition piece in close proximity (anode clustering), interference between anodes can decrease the anode outputs
- Large number of anodes and limited surface area available for distribution
- Lower salinity in estuary areas also increase anode resistance

INSUFFICIENT CURRENT FOR PROTECTION

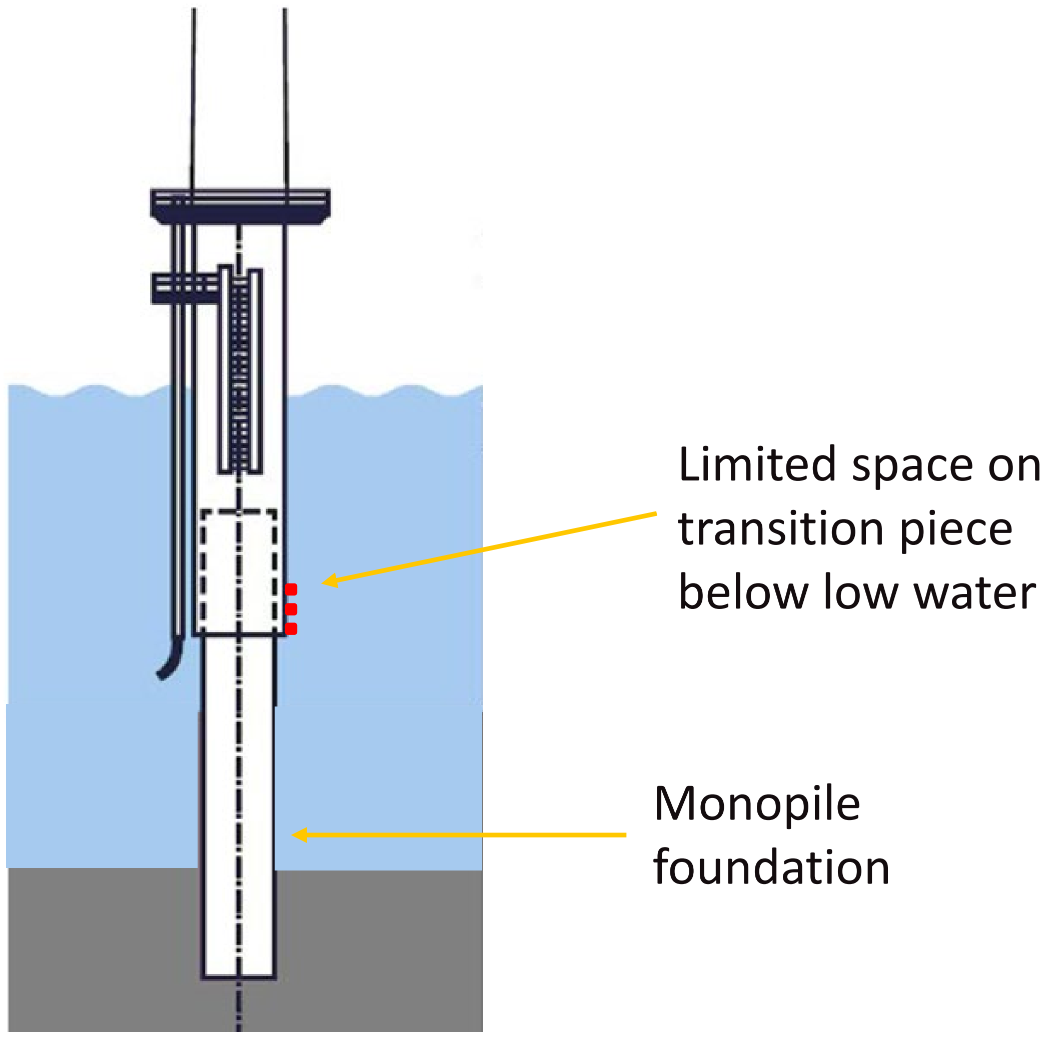


- Detailed analysis by computer modelling enables an anode current output current reduction factor.
- Application of a coating will reduce current demand (particularly during initial exposure)



ATTENUATION

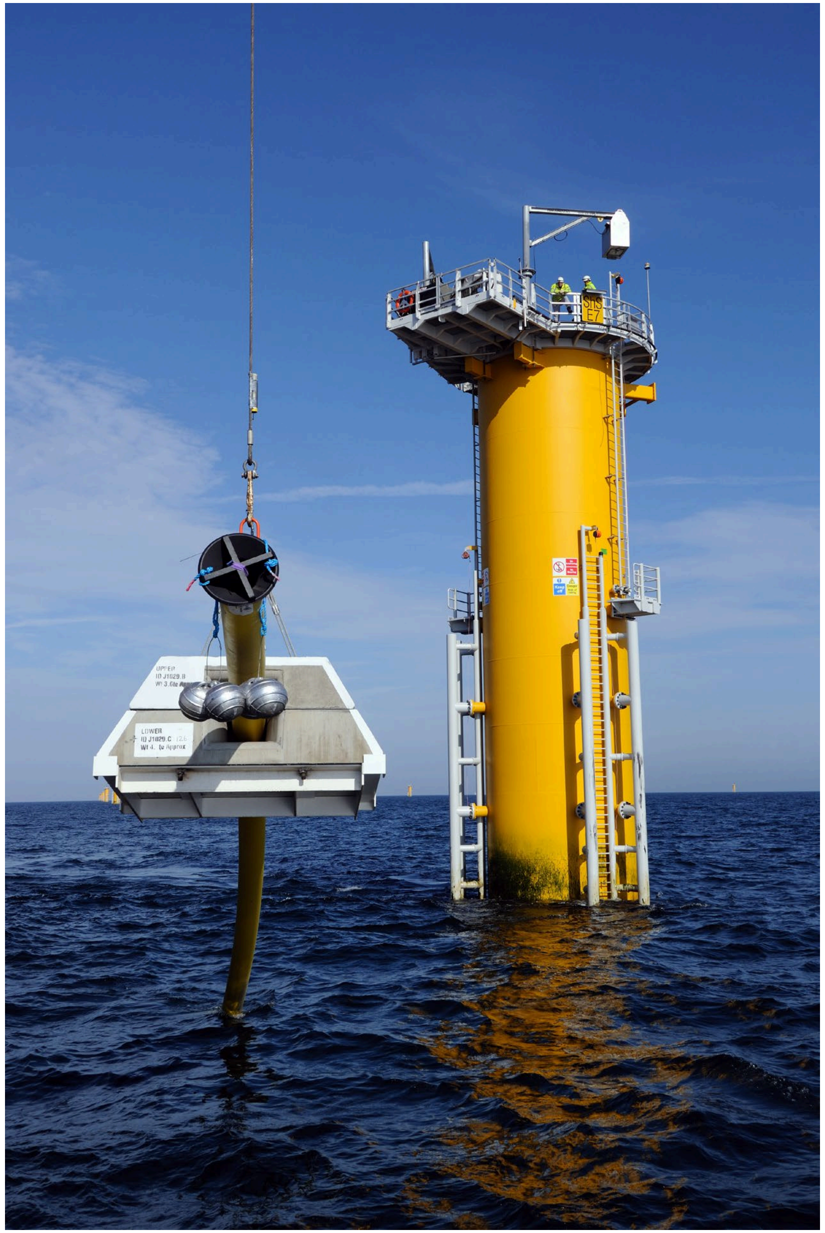
- Where anodes are soley fitted to the transition piece of larger monopiles (e.g., 20 to 25 m water depth) distribution of current to the seabed level and buried sections may be poor.
- Ideally anodes would be distributed uniformly down the foundation length.
- Again, application of a coating will reduce current demand (particularly during initial exposure) and aid current distribution.



4. INTERNAL PROTECTION

INTERNAL RETROFIT CP

- Initial monopile internal corrosion control was based on stagnant seawater conditions with consumption of oxygen leading to low corrosivity.
- This was not reliable due to:
  - Leaking water seals.
  - Water exchange through permeable seabed.
  - Headspace not sealed - internal airtight deck not airtight.
  - Regular deck hatch opening.
  - Therefore, protection required and a standard approach would be to install galvanic anodes (aluminium)



Sheringham Shoal courtesy of Alan O'Neill chpv

ALUMINIUM GALVANIC ANODES – RETROFIT

- Retrofitted aluminium anodes were not successful in some cases.
- In situations where there was negligible water exchange, the pH of seawater dropped:
  - Around pH 8 to less than pH 4 within a few weeks.
  - Acidification due to reaction of hydrated aluminium anodes with water.

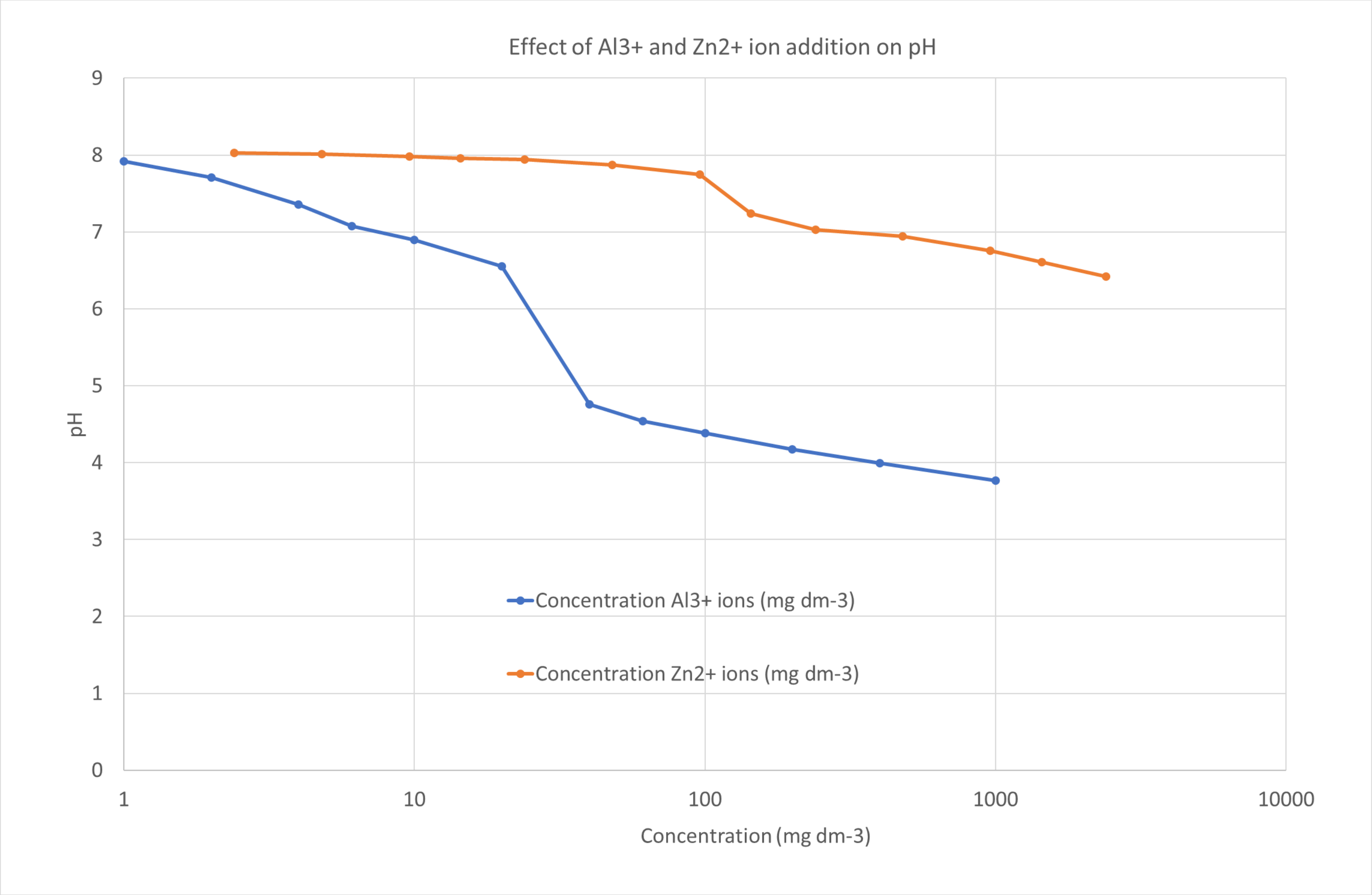
$$Al(H_2O)_6^{3+} \rightleftharpoons (Al(OH)(H_2O)_5)^{2+} + H^+$$

  - Intertek CAPCIS was appointed to carry out laboratory testing to investigate the issue.

LABORATORY TESTING

- To simulate aluminium anode dissolution aluminium chloride ($AlCl_3$) was added to synthetic seawater and the pH recorded.
- The pH was recorded after stirring and when the value had stabilized (10 to 15 minutes).
- For comparison the test was repeated using zinc chloride ($ZnCl_2$).

LABORATORY TEST RESULTS

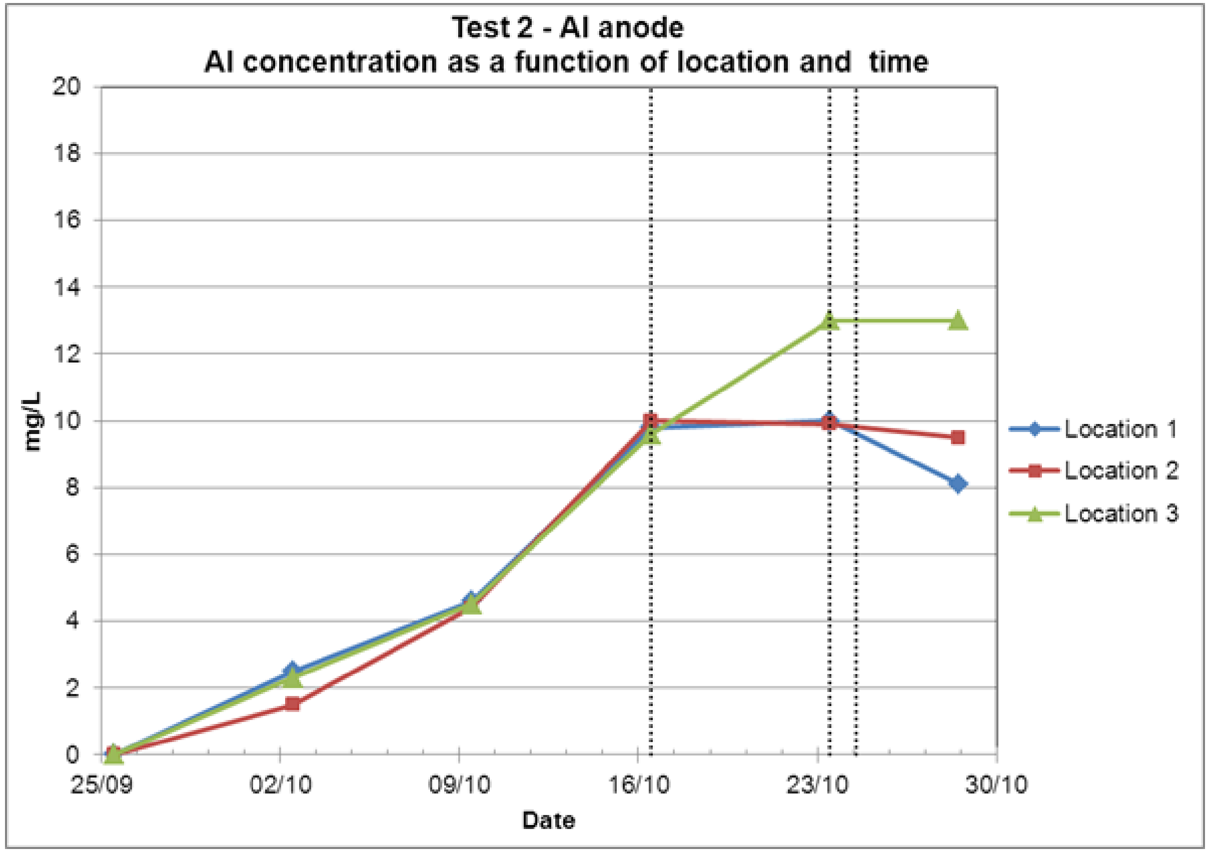


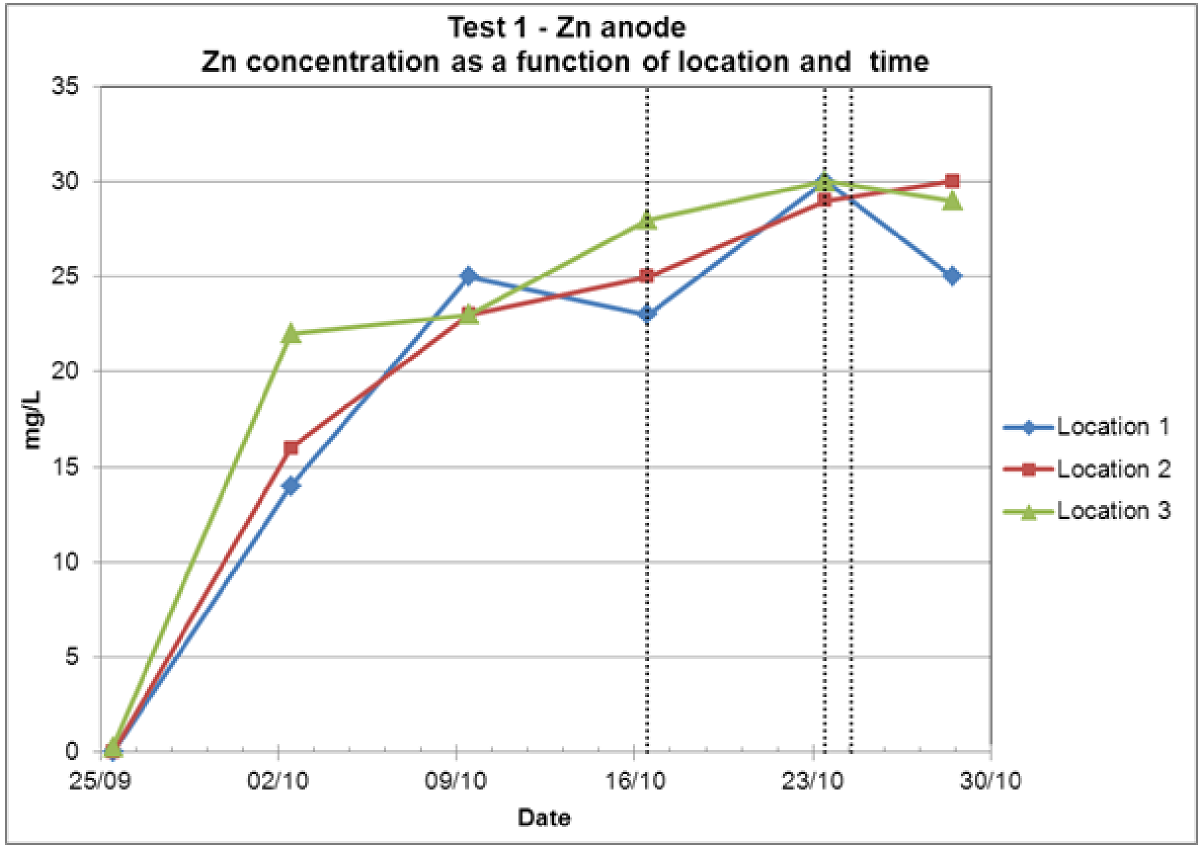
- The critical Al^{3+} concentration is approx. 10 mg/L (gm/m³ or ppmv), which limits the reduction of pH to around neutral (pH 7) levels.
- Above 10 mg/L the pH drops rapidly, with pH 4 occurring when the Al^{3+} concentration exceeds 100 mg/L.
- Zn^{2+} ion additions did not significantly reduce the pH.

LABORATORY SIMULATIONS

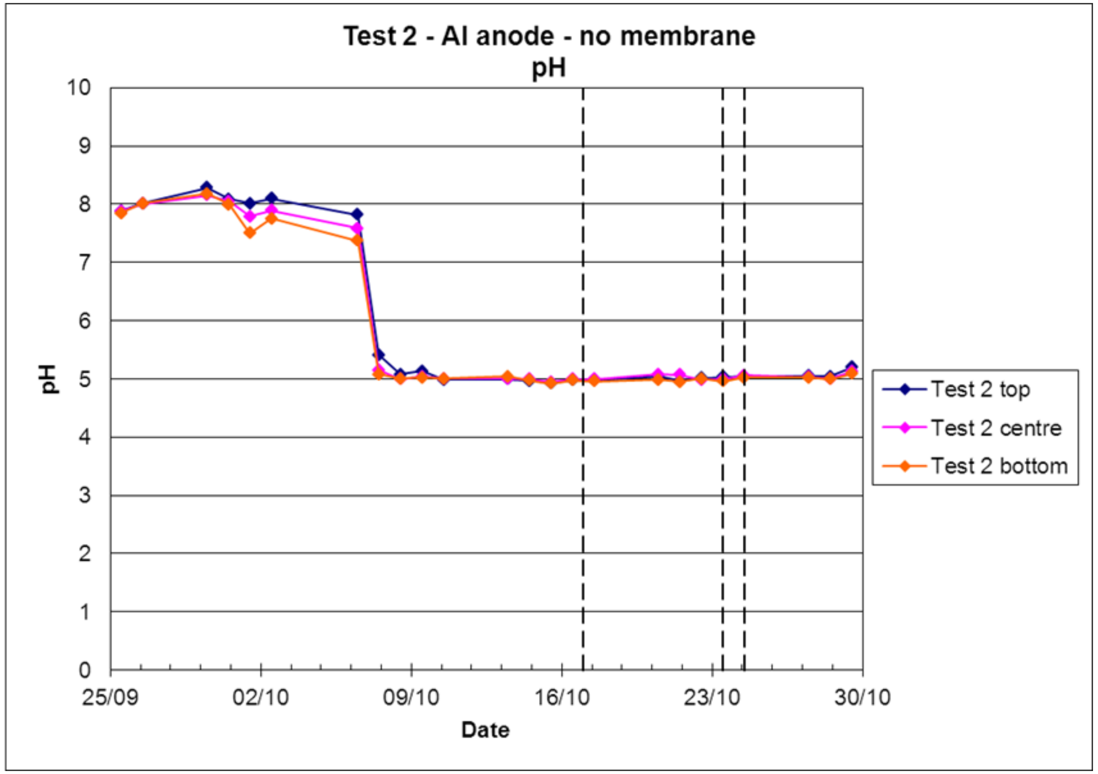
- Aim - to simulate conditions within a monopile
  - Anode : cathode area ratio
  - Cathode area : seawater volume
  - Seawater diameter to depth ratio
- Test setup & measurements
  - Al and Zn anodes used
  - Steel coupon
  - 14” HDPE vessels with access ports for oxygen and pH measurements
  - Natural seawater at ambient temperature
  - 2 week pre-exposure with no CP
  - Potential and current monitoring
  - Water sample analysis and surface analysis to check for calcareous scale formaiton

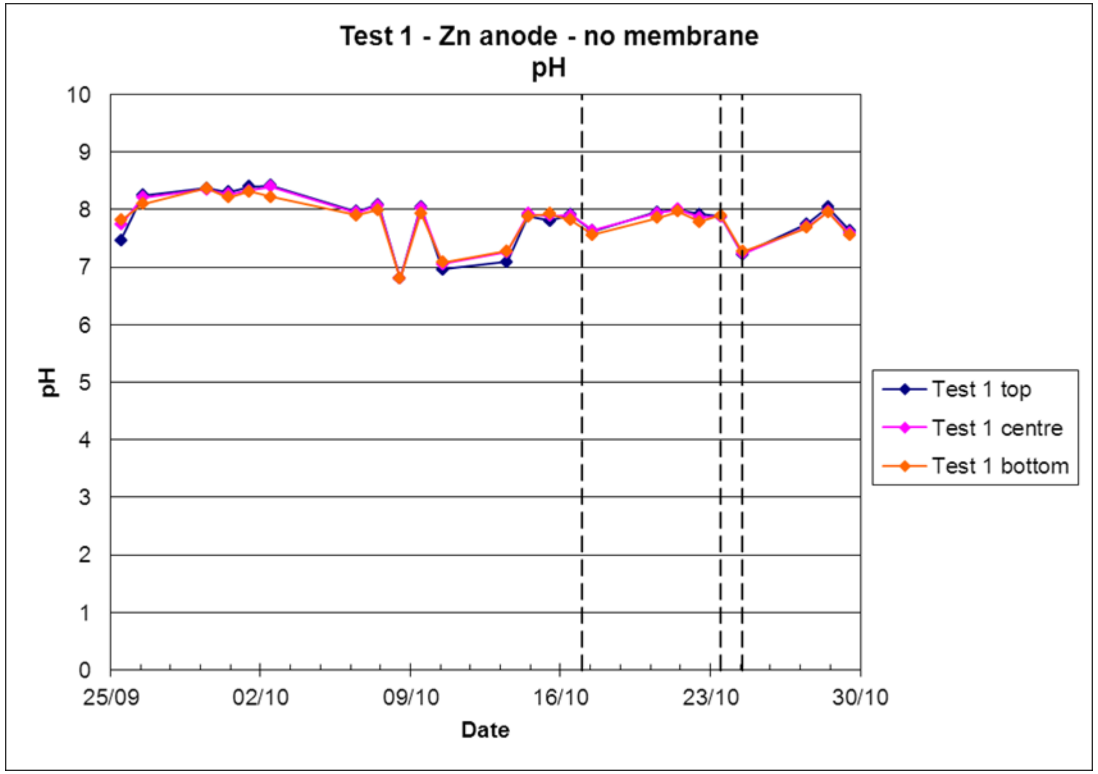
SIMULATION RESULTS – AL & ZN ION CONCENTRATIONS



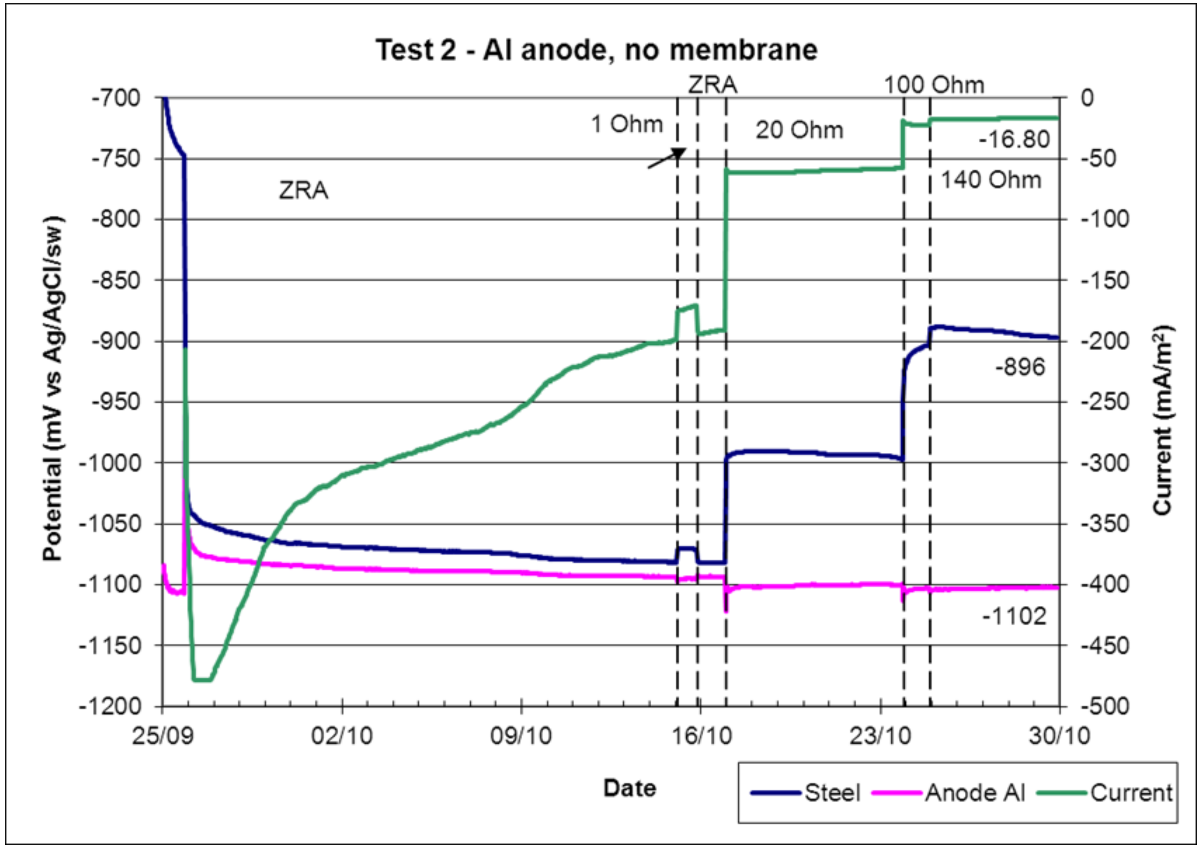


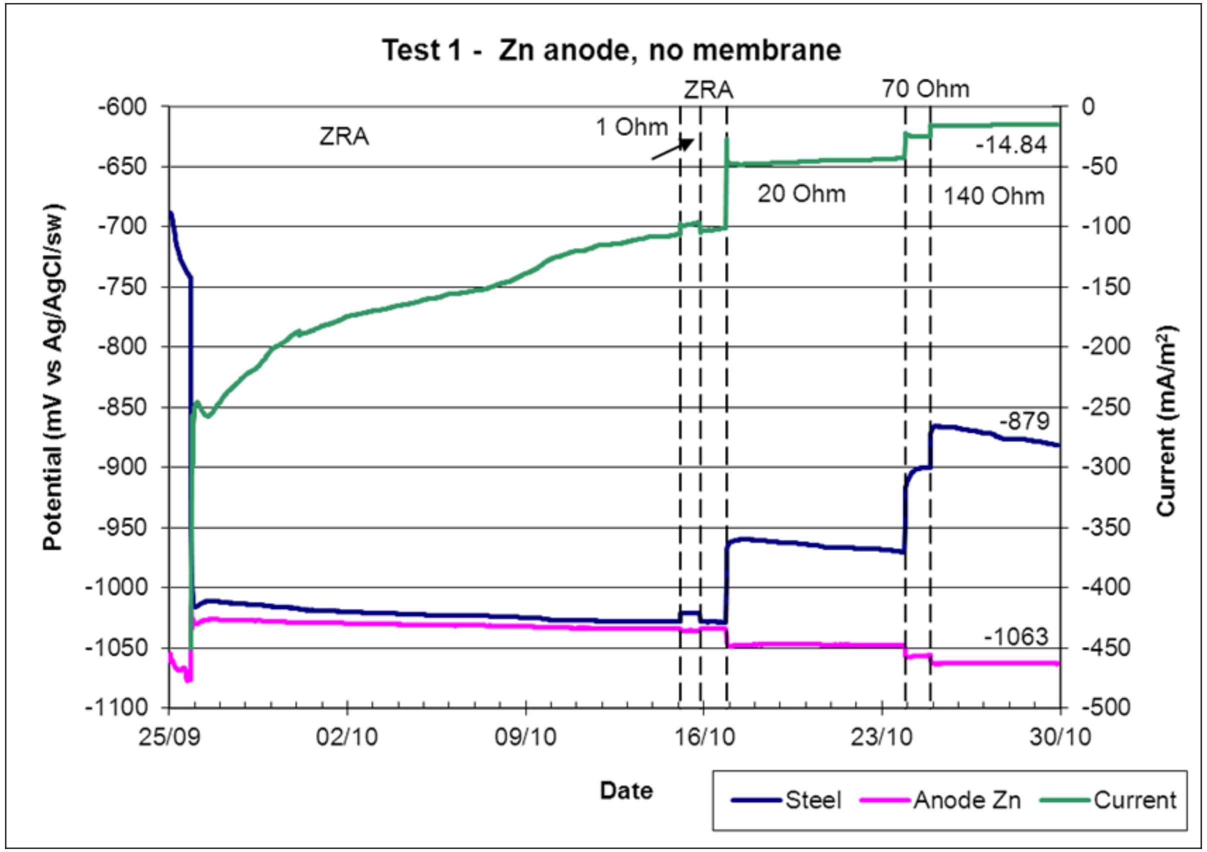
SIMULATION RESULTS – PH





SIMULATION RESULTS – CP MONITORING





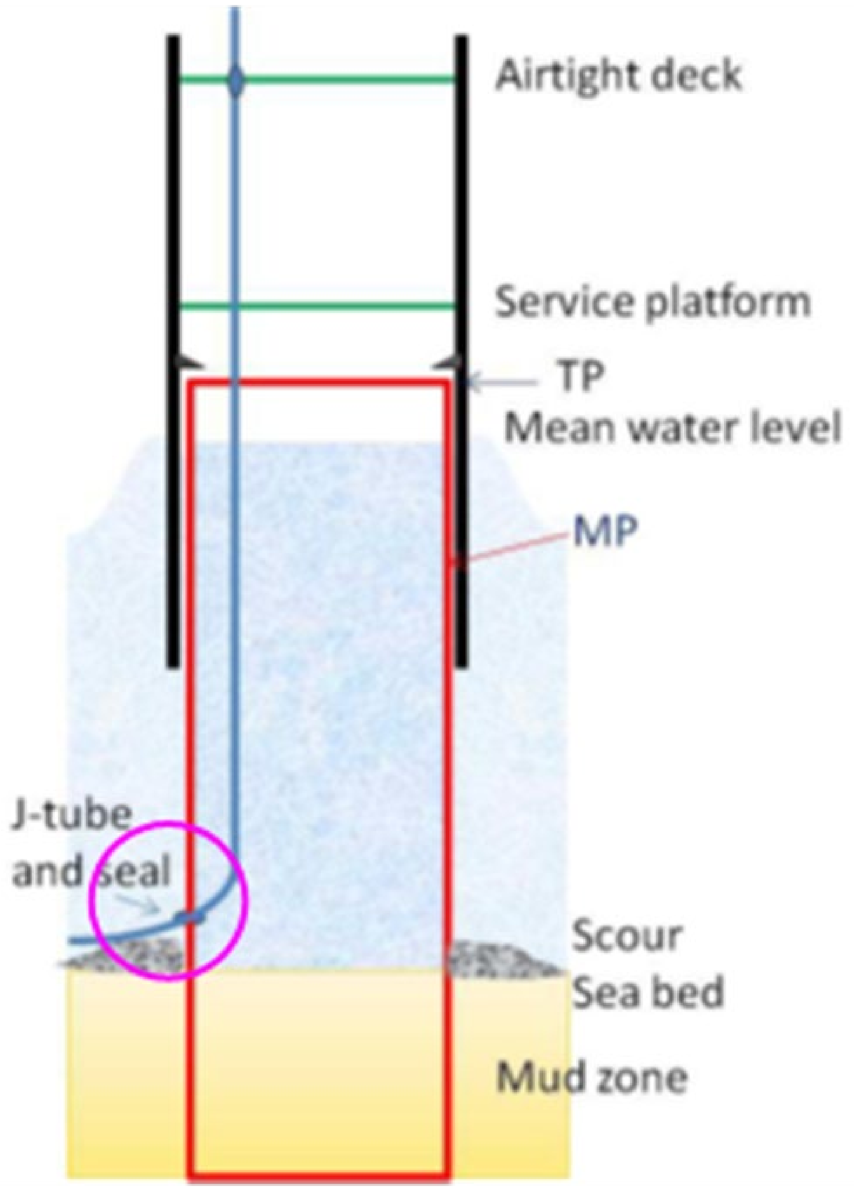
CONCLUSIONS

- The test design was able to reproduce the service conditions and allowed for monitoring the cathodic protection response and any environmental changes.
- Stable scale (calcareous deposit) has formed on all cathodes consisting of calcium carbonate, magnesium hydroxide.
- The use of aluminium anodes lead to a reduction in the pH to around 5 within a relative short time span. A critical Al ion concentration of 4-8mg/L was measured.
- The use of Zn anodes did not affect the pH which remained fairly contact throughout the test period.

5. LEAKING SEALS - PROTECTION INTO NARROW GAPS

BACKGROUND

- Power cable routed through the MP wall close to the seabed
- Cable protection system (seal)
- If seal fails a narrow gap is created
- Dimensions variable:
  - Length
  - Width
  - Depth



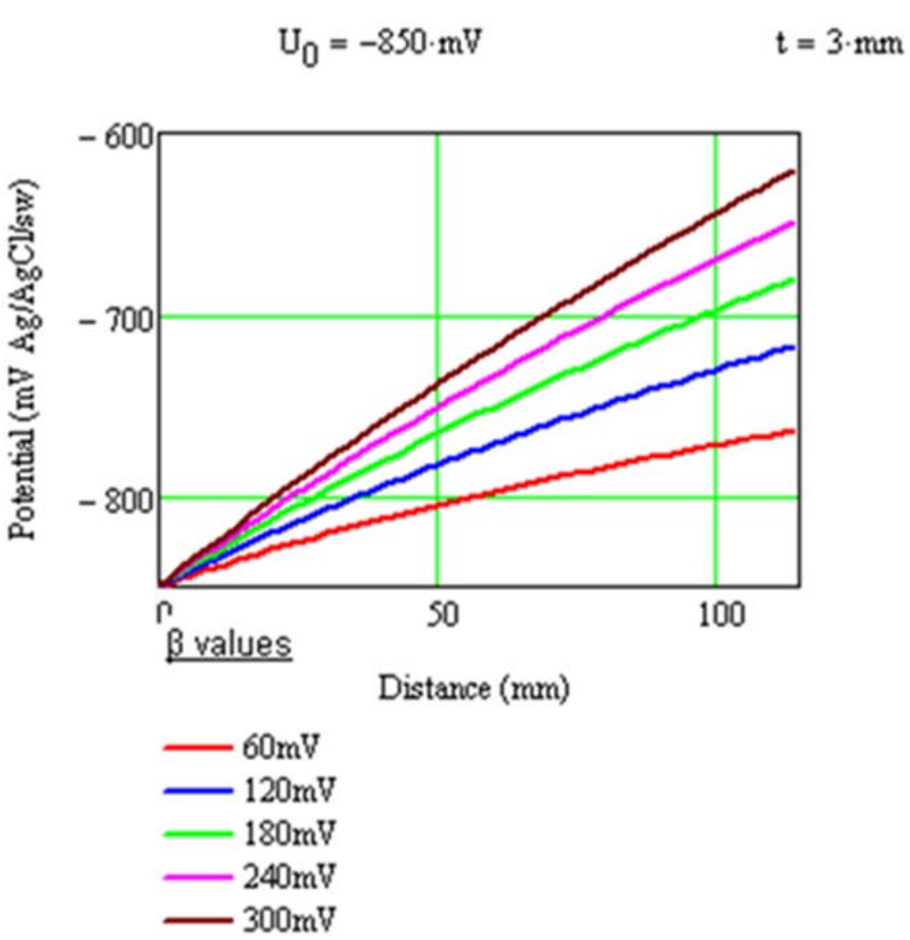
BACKGROUND

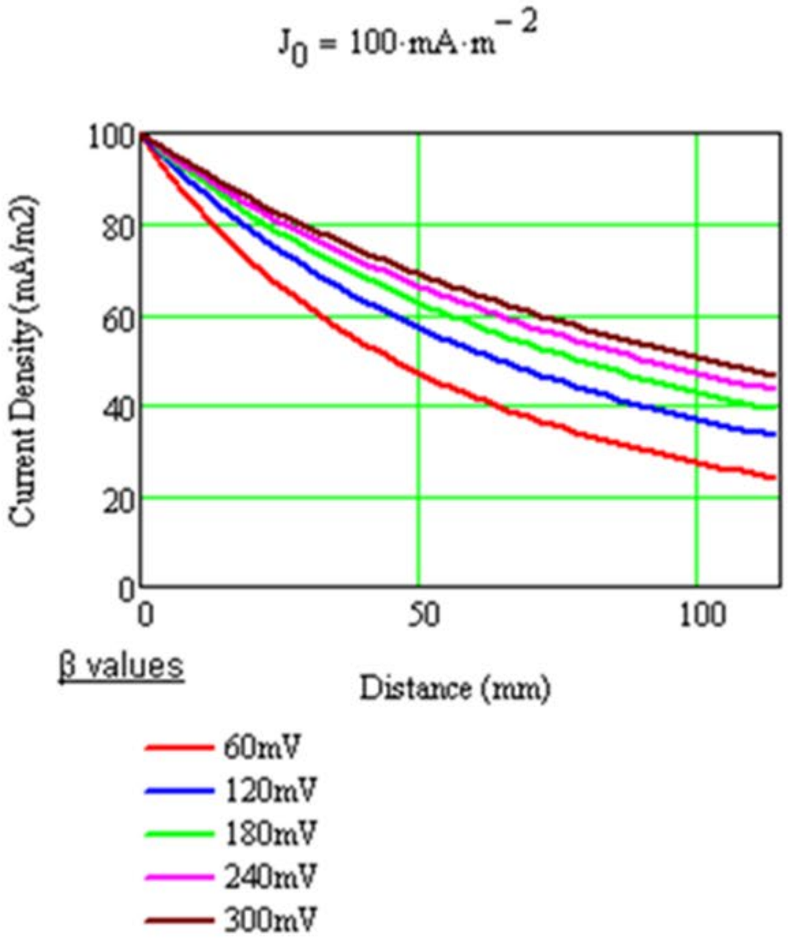
- MP external surface protected by CP:
  - Corrosion
  - Fatigue
- If seal fails CP also applied internally
- Will CP penetrate into the narrow gap to protect the surfaces in the restricted area?

- Review of published information
- Previous studies:
  - Under disbonded coatings - pipeline field joints
  - Stagnant conditions – no oxygen replenishment therefore reduction in cathodic current density
  - Cathodic reaction produces alkaline conditions (OH-)
- Calculations – one dimension model

Inputs:

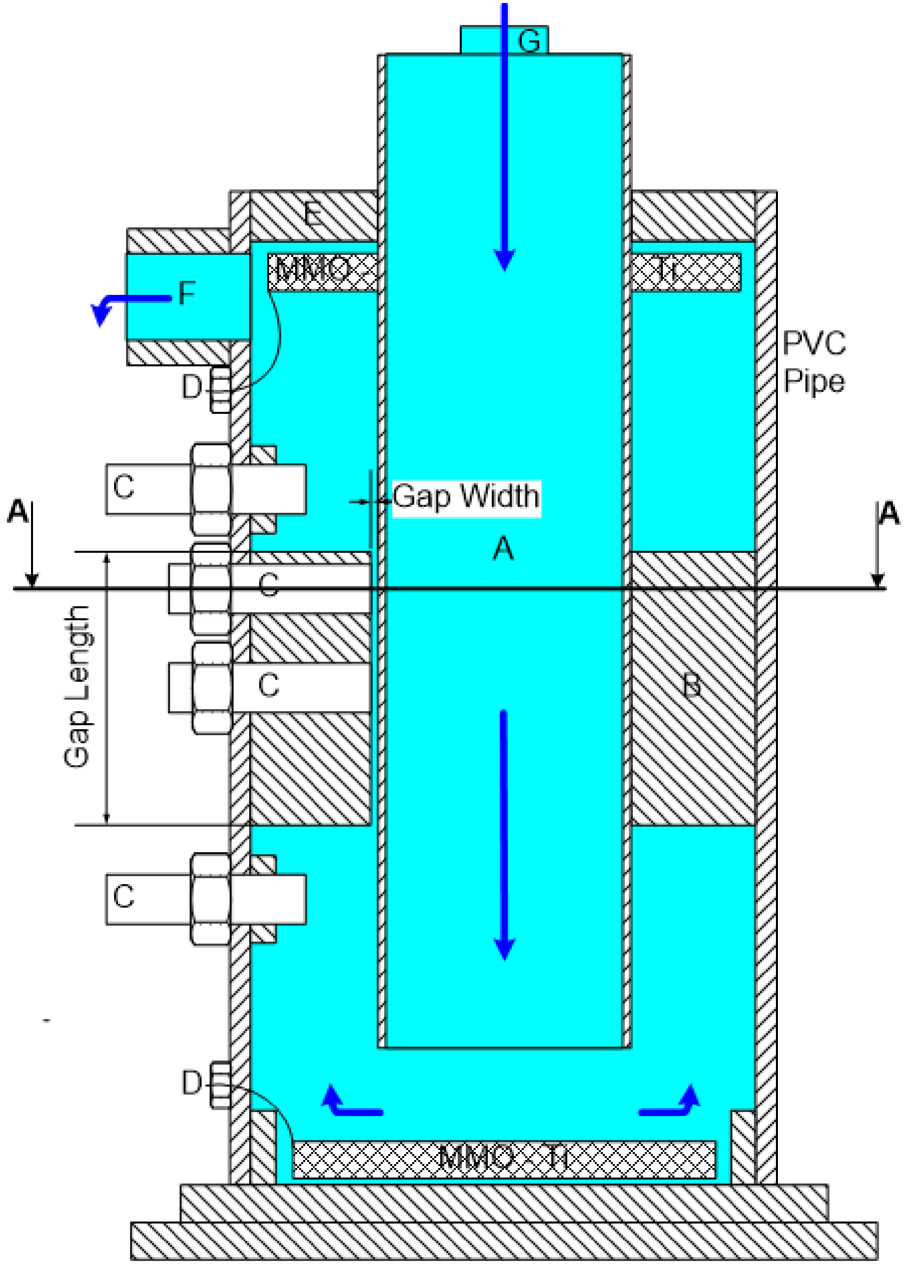
- Gap dimensions
- Potential & current density
- Tafel slope
- Electrolyte conductivity





SIMULATION DETAILS

- Aim to replicate real life gap
- Dimensions:
  - Length 110 mm
  - 1, 3 and 7 mm width
- Natural seawater
- Flowrate – up to ~4 m/s using raised header tank
- Control CP at mouth/end with potentiostat and anode
- Measure potential and current density with reference electrodes and coupons



TEST PROGRAMME

Flow	Velocity	Applied potential (mV)	
(L/hr)	(m/s)	External	Internal
1 mm gap			
0 - 340	0 – 1.2	-950	None
0 - 340	0 – 1.2	-950	-950
3 mm gap			
0 - 3000	0 – 3.25	-950	None
0 - 3600	0 – 3.9	-950	-950
7 mm gap			
0 - 3000	0 – 1.4	-950	None
0 - 5000	0 – 2.3	-950	-950

Short term test – stagnant conditions to represent 'slack water' (at high and low tide points)

TEST RESULTS - STAGNANT

Flow	Velocity	Applied potential (mV)		Results
(L/hr)	(m/s)	Ext.	Int.	
1 mm gap				
0	0	-950	None	-708 & -768 mV
0	0	-950	-950	Criteria met
3 mm gap				
0	0	-950	None	Criteria met
0	0	-950	-950	Criteria met
7 mm gap				
0	0	-950	None	Criteria met
0	0	-950	-950	Criteria met

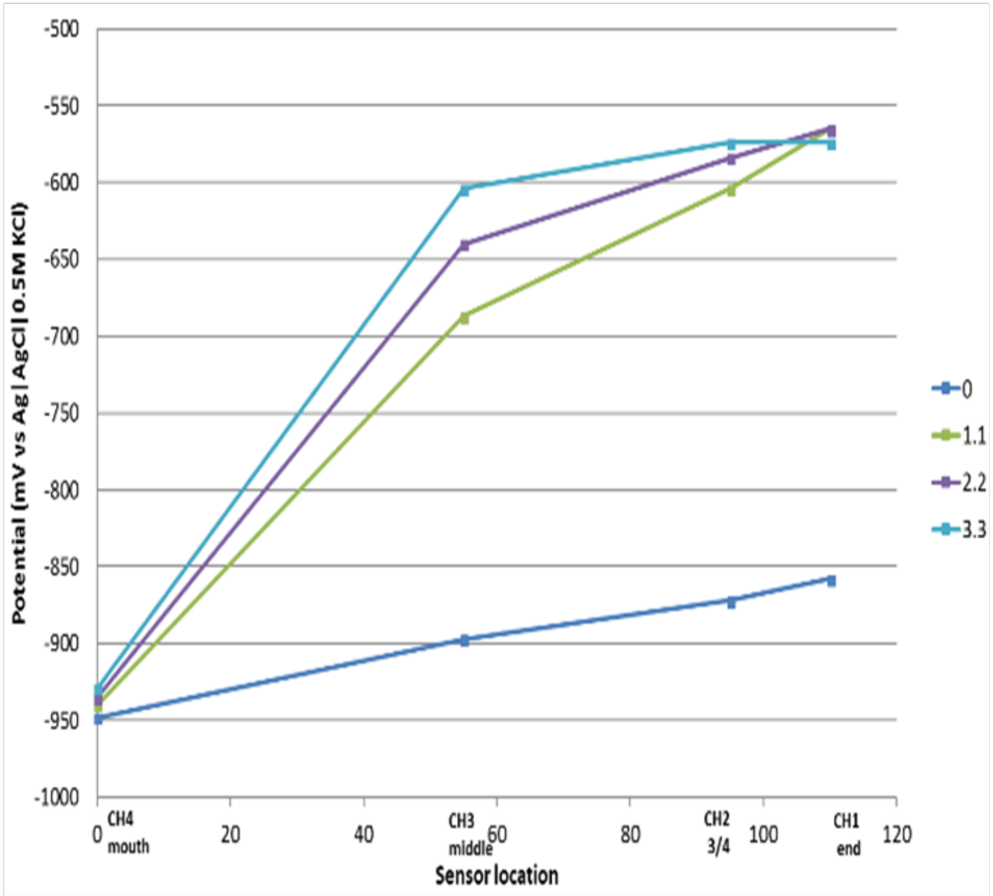
TEST RESULTS - FLOWING

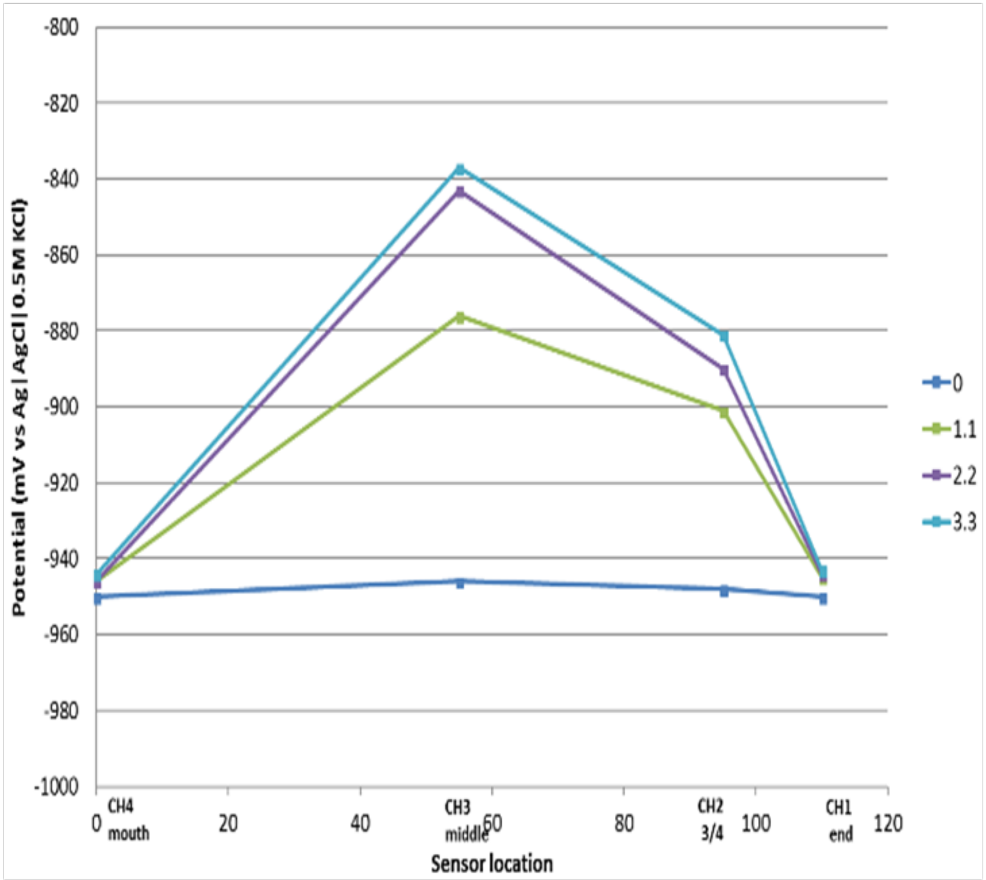
Flow	Velocity	Applied potential (mV)		Results
(L/hr)	(m/s)	Ext.	Int.	Centre & ¾
1 mm gap				
340	1.2	-950	None	-696 & -669 mV
340	1.2	-950	-950	Criteria met
3 mm gap				
1000	1.1	-950	None	-687 & -604 mV
3600	3.9	-950	-950	Criteria met
7 mm gap				
1000	0.5	-950	None	-809 & -710
5000	2.3	-950	-950	Criteria met

STAGNANT & FLOWING CONDITIONS – 3 MM GAP

External CP

Both external and internal CP





As flow increases the potential becomes more positive – less protection

CONCLUSIONS

- In stagnant conditions protection could be achieved in all cases except 1 mm gap and external anode only.
- Protection was less likely to be achieved in flowing environments.
- In flowing environments protection criteria could only be met if CP was applied both internally and externally.
- The potential became more positive (less protection) with higher flow and narrower gaps.
- In all cases the test commenced with a short stagnant phase which will have had an influence on the calcareous deposit formation and assisted the penetration of CP.

SUMMARY

- In past years the application of cathodic protection to offshore wind turbine monopiles was not always successful.
- Externally, the typical design did not always provide sufficient current and the revised standards provide additional requirements to ensure a more robust design.
- Internally, where corrosion control strategies failed primarily due to leaks, use of aluminium anodes was found to cause seawater acidification and high corrosion rates.
- Intertek CAPCIS carried out laboratory tests and simulations to investigate conditions where acidification might occur.
- In cases of low seawater exchange only zinc anodes should be installed internally.
- Where seals are leaking, the steel in the narrow gap is likely to be protected if cathodic protection is applied both internally and externally.

Thank you for your attention

Any questions?