INTERNATIONAL STANDARD

ISO 24656

First edition
2022-05

Cathodic protection of offshore wind structures

Protection cathodique des structures éoliennes en mer

Reference number
ISO 24656:2022(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 156, *Corrosion of metals and alloys*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 219, *Cathodic protection,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Cathodic protection (CP), possibly together with protective coating, is applied to protect the immersed external surfaces of offshore wind farm structures and appurtenances from corrosion due to seawater or seabed environments.

CP, possibly together with protective coating, can be applied to protect the internal flooded and seabed and sediment exposed surfaces from corrosion.

The general principles of CP in seawater are detailed in ISO 12473.

CP involves the supply of sufficient direct current to the surfaces of the structure in order to reduce the steel to electrolyte potential to values where corrosion is considered insignificant or acceptably low.

CP is designed to protect the submerged and buried areas of the structure from corrosion. The parts that are not permanently immersed will not be permanently protected by the CP system.

This document introduces guidance for the use of available metocean data to

— assess the CP demand of immersed and frequently wetted areas

— determine seawater flow velocities to assess the CP design parameters

This is in addition to the primary use of the metocean data in structural design.

This document does not require the CP designer to be expert in metocean data; it gives guidance on data which should be available from metocean specialists and which is required in the CP design process.

Cathodic protection of offshore wind structures

1 Scope

This document specifies the requirements for the external and internal cathodic protection for offshore wind farm structures. It is applicable for structures and appurtenances in contact with seawater or seabed environments. This document addresses:

— design and implementation of cathodic protection systems for new steel structures;

— assessment of residual life of existing cathodic protection systems;

— design and implementation of retrofit cathodic protection systems for improvement of the protection level or for life extension of the protection;

— inspection and performance monitoring of cathodic protection systems installed on existing structures, and

— guidance on cathodic protection of reinforced concrete structures.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8501-1, *Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings*

ISO 12473, *General principles of cathodic protection in seawater*

EN 12496, *Galvanic anodes for cathodic protection in seawater and saline mud*

ISO 12696, *Cathodic protection of steel in concrete*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

EN 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 61000-1-2, *Electromagnetic compatibility (EMC) — Part 1-2: General — Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena*

IEC 61400-24, *Wind energy generation systems — Part 24: Lightning protection*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
atmospheric zone
zone located above the splash zone

3.2
buried zone
zone located under the seabed or expected scour level, whichever is lower

3.3
CP design life
time for which the CP is designed to protect the structure

Note 1 to entry: This may be different to the structure design life or structure service life.

3.4
doubler plate
plate welded onto a member to locally reinforce it or to isolate it from further welding work

3.5
electrolyte
medium in which electric current is transported by ions. In the context of this document, seawater or seabed

3.6
frequently wetted zone
FWZ
water level, WL(t), plus significant wave height, H_{mo}

Note 1 to entry: See Annex B for details.

3.7
free board level
FBL
water level for floating structures

Note 1 to entry: For calculation of frequently wetted zone, it will replace WL(t)

3.8
HAT
highest astronomical tide
level of the highest astronomical tide

3.9
hybrid cathodic protection system
system comprising both impressed current and galvanic anodes

3.10
inspection
examination of equipment to determine its continued performance characteristics, whether undertaken on a regular program basis or carried out as a simple operation

3.11
IR error
error in measured steel to electrolyte potential caused by the protection current or any other current flowing through the resistive environment

3.12
jacket structure
multi-legged lattice braced structure

3.13
J-tube
curved tubular conduit designed and installed on a structure to support and guide cables

3.14
LAT
lowest astronomical tide
level of the lowest astronomical tide

3.15
marine sediments
top layer of the seabed composed of water saturated solid materials of various densities

3.16
metocean data
meteorological and oceanographic data, often given as hourly statistics

3.17
monitoring
activity continuously on-going or sporadically undertaken at fixed locations to determine the performance of a CP system or parameters related to the performance

Note 1 to entry: Typically, monitoring utilizes fixed sensors, the data from which can be data logged.

3.18
monopile
foundation element driven or drilled into the seabed to support a transition piece and/or tower

3.19
over-polarization
occurrence in which the structure to electrolyte potentials are more negative than those required for satisfactory cathodic protection

Note 1 to entry: Over-polarization provides no useful function and might even cause damage to the structure

3.20
owner
structure owner, or developer or operator, all or any of which may have responsibility for matters related to corrosion protection

3.21
primary steel
primary load carrying elements (monopile, jacket, hull and other steel structures)

3.22
re-polarization
situation where the steel is polarized after a depolarization event

3.23
retrofit cathodic protection
provision of CP equipment, either as a complete or a partial system, to an existing structure either to remedy CP performance deficiencies or to extend the CP system life

3.24
salinity
quantity of inorganic salts dissolved in the seawater

Note 1 to entry: The standardised measurement is based on the determination of the electrical conductivity of the seawater.

Note 2 to entry: Salinity is expressed in grams per kilogramme (g/kg) or as parts per thousand (ppt or ‰).

3.25
scour
removal of seabed soils by sea currents and waves or caused by structural elements interrupting the natural flow regime above the sea floor

3.26
seabed
interface between seawater and solids of the *buried zone* (3.2) including the *marine sediments* (3.15)

3.27
secondary steel
steel which is not primary steel, hence used for access (boat landing, ladders, decks and support for equipment)

3.28
shallow water
water of such depth that surface waves are noticeably affected by bottom topography

Note 1 to entry: Typically, this implies a water depth equivalent to half the wavelength[33]. For all practical purposes in this document, it is understood as depth less than −30 m LAT

3.29
significant wave height
H_{mo}
mean level of the third largest waves in open sea

3.30
splash zone
external region of support structure that is frequently wetted due to the wave and tidal variations. A more detailed definition of splash zone is given in IEC 61400-3-1[15]. In this document the frequently wetted zone is included as the upper boundary to which current demand for CP shall be included

3.31
structure service life
anticipated life of the windfarm structure.

Note 1 to entry: This includes a period for storage, transport, installation, operating the wind farm and a possible period for decommissioning

3.32
suction bucket
foundation element that is sucked into the seabed

3.33
surveying
process of carrying out inspection using a defined procedure

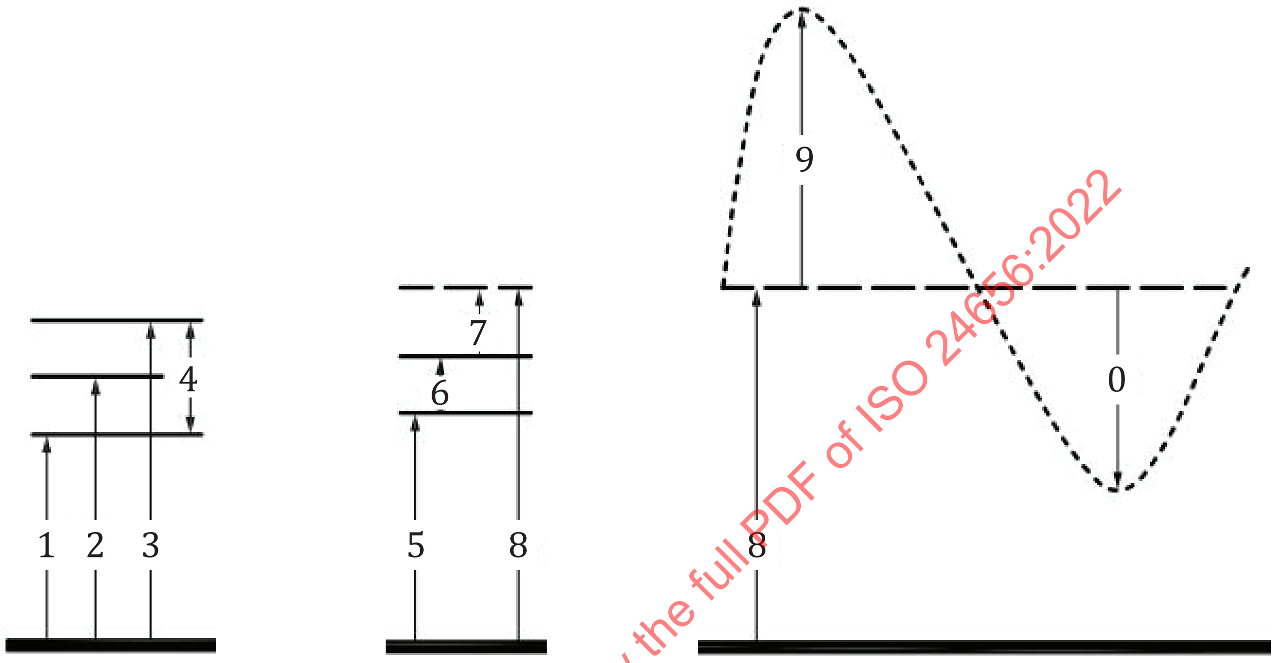
Note 1 to entry: In this document surveying is also used to describe the process of taking cathodic protection measurements, not using fixed and data logged sensors, but using a defined procedure

3.34
tidal zone
zone located between LAT and HAT

3.35
transition piece
intermediate structure between the monopile and the tower

3.36
wave crest and trough
height of seawater above and depth of below still water level due to waves

Note 1 to entry: See Figure 1 below.



a) Tides b) Tide+storm surge=still water level c) Wave profile superimposed on water level

Key

Key to distance elevation

1	lowest astronomical tide (LAT)	6	tide associated with storm (shown positive but may be positive or negative)
2	mean sea level (MSL)	7	storm surge (shown positive but may be positive or negative)
3	highest astronomical tide (HAT)	8	still water (or "storm water") level
4	tidal range	9	crest elevation
5	tidal datum (commonly LAT or MSL but may be other)	0	trough elevation

Key line types

seafloor

tide levels

surge or surge+tide levels

wave profile

Figure 1 — Water depth, tides and storm surges, from ISO 19901-1[10]

4 Symbols and abbreviations

4.1 Symbols

A	Area, m^2
C	Anode cross section periphery, m
c	Coating degradation, %

ΔU	Driving potential, V
f_c	Coating breakdown factor
I	Current, A
$I_{\text{anode(initial)}}$	Initial current output of an individual galvanic anode material, A
$I_{\text{anode(final)}}$	Final current output of an individual galvanic anode material, A
I_{max}	Maximum protection current demand for a CP zone, A
$I_{\text{total(initial)}}$	Total current required for polarization of the structure, A
$I_{\text{total(final)}}$	Total current required for re-polarization of the structure, A
J	Current density, A/m^2
L	Anode body length, m
L_{initial}	Anode initial length, m
L_{final}	Anode final (or end of life) length, m
N	Number of anodes
Q	Practical electrochemical capacity for the anode alloy in the environment considered, Ah/kg
ρ	Resistivity of an electrolyte, Ωm. In this document resistivity may be of an electrolyte (sea or seabed) or a conductor material
R_a	Anode resistance to remote earth, Ω. In the context of this document, remote earth will be in seawater or seabed
r	Anode radius, m
R	Circuit resistance, Ω
S	Arithmetic mean of anode length and width, m
T	Temperature, °C
T_{anode}	Effective lifetime of the anode, years
T_{design}	Required design life, years
U	Flow velocity (m/s)
u	Utilisation factor for CP design calculations
V_{initial}	Initial net volume of anode alloy (excluding the steel insert), m^3
V_{insert}	Volume of the insert only within the anode body, m^3
V_{final}	Final (or end of life) net volume of anode alloy, m^3
V_{gross}	Overall volume of the anode body including that portion of the insert only within the anode body, m^3
m_{anode}	Net mass of an individual galvanic anode material, kg
m_{total}	Minimum total net mass of galvanic anode material, kg

4.2 Abbreviations

ABS	Area Below Seabed
AC	Alternating Current
BEM	Boundary Element Method
CA	Corrosion Allowance
CP	Cathodic Protection
CP design life	Cathodic Protection design life
CPS	Cable Protection System
CSPE	Chlorosulfonated Polyethylene; alternatively abbreviated to CSP
DC	Direct Current
DO	Dissolved oxygen
EMF	Electromotive Force
EPR	Ethylene Propylene Rubber
ER	Electrical Resistance
FAT	Factory Acceptance Test
FBL	Free Board Level
FEM	Finite Element Method
FWZ	Frequently Wetted Zone
GACP	Galvanic Anode Cathodic Protection
HAT	Highest Astronomical Tide
HDPE	High Density Polyethylene
HMMPE	High Molecular Mass Polyethylene
HSC	Hydrogen Induced Stress Cracking
ICCP	Impressed Current Cathodic Protection
IEC	International Electrotechnical Commission
IMCA	International Marine Contractors Association
IP	Ingress Protection Rating
ISO	International Organization for Standardization
ITP	Inspection and Test Plan
LAT	Lowest Astronomical Tide
MIC	Microbially Influenced Corrosion

MMO	Mixed Metal Oxide
MP	Monopile
MSL	Mean Sea Level
MTL	Mean Tide Level
MWL	Mean Water Level
MDFT	Minimum Dry Film Thickness
NACE	National Association of Corrosion Engineers
NDFT	Nominal Dry Film Thickness
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene Fluoride
PVC	Poly vinyl chloride
RCD	Residual Current Device
RMS	Root Mean Square
ROV	Remotely Operated Vehicle
S-N	Stress versus Number of cycles
SMS	Specified Minimum Yield Strength
TP	Transition Piece
TR	Transformer Rectifier
WTG	Wind Turbine Generator
XLPE	Cross-linked Polyethylene

5 Competence of personnel

Personnel who undertake the design (the CP designer), supervision of installation, commissioning, supervision of operation, inspections, measurements, monitoring and supervision of maintenance of CP systems shall have the appropriate level of competence for the tasks undertaken. This competence should be independently assessed and documented. The CP designer shall be competent to assess and determine the appropriate input parameters (such as steel current density, anode potential and anode electrochemical capacity) for the CP design based upon the type of structure, its exposure and the metocean data.

ISO 15257[7] defines a method which may be utilized for assessing and certifying the competence of CP personnel.

Competence of CP personnel to the appropriate level for tasks undertaken should be demonstrated by certification in accordance with ISO 15257[7] or by another equivalent prequalification procedure.

6 Structural considerations

6.1 Structures to be protected

Foundation structures are designed to support a tower and nacelle incorporating a turbine generator and wind driven rotor blades. The structure is subject to fatigue loading, which in many cases is the design driver.

This document can also be applied to the cathodic protection of other foundations associated with offshore wind power generation, such as transformer platform and meteorological mast foundations.

Offshore wind turbine foundation structures can comprise various primary steel structures such as large diameter monopile foundations driven into the seabed, lattice structures fixed to the seabed, floating structures, and concrete gravity-based structures.

NOTE The term “jacket” is commonly used to describe a lattice style structure comprising tubular legs stiffened with cross members. Jacket is the term used in the offshore oil and gas industry since the structure serves to enclose the conductor pipes.

This document defines the requirements for the CP of external and internal surfaces of offshore wind structures in contact with seawater and with seabed or sediment.

It addresses the following structures:

— monopile and transition piece foundations,

— mono bucket foundations,

— jacket structures with driven piles or suction buckets,

— floating structures,

— gravity-based reinforced concrete structures, and

— other foundations associated with offshore wind power generation.

This document addresses specific features of the above listed types of structure. The performance requirements are applicable to all offshore structures associated with generation of power from wind.

The various types of foundation structures, in common use, together with their corrosion strategies are illustrated in Figure 2, Figure 3, Figure 4 and Figure 5.

Monopile structures, Figure 2, are one of the most common types of foundation structures for offshore wind turbines and have unique features which make special considerations necessary. Single large diameter steel piles (monopiles) are driven into the seabed to a defined level below seabed and with the top typically above MSL. Wind turbine towers are installed on an intermediate structure known as a transition piece (TP) or directly on the monopile (MP). The TP fits over the monopile, extending to some depth and is sealed where the overlap exists and grouted with a cementitious mortar. Alternatively, the TP is provided with a bottom flange and fitted on top of the MP with a top flange and bolted together.

The TP is generally coated as it protrudes out of water, within and beyond the upper limit of full CP protection area, and therefore the coating jointly with a corrosion allowance comprises the corrosion protection strategy.

Generally, the required facilities for the operation of the foundations are pre-installed on the transition piece and/or the jacket structure including boat landings and ladders, grouting systems, boat fenders etc.

Jacket type foundations are similar to many offshore steel platforms and the provisions for CP are described in this document and in EN 12495[18].

Floating structures, Figure 4, are, as the name suggests, structures that are floating. They use chains or tethers to secure the structure to some seabed anchor.

Concrete gravity-based structures, Figure 5, are placed on the seabed and are not normally considered in need of CP if

— designed according to EN 206[14] jointly with the normative annexes for the relevant exposure classes,

— designed and constructed according to EN 1992-1-1[15], and

— produced according to EN13670[20] jointly with the normative annexes.

This document provides guideline for inclusion of CP on concrete structures for cases where premature deterioration has been observed or if an unacceptable risk of corrosion is considered.

This document also addresses the CP current demand of steel in concrete where the steel reinforcement is connected to steel elements that are not encased in concrete e.g. a steel monopile with a reinforced concrete gravity base.

Structural elements that are driven, drilled or sucked into the seabed such as piles or suction buckets, generally do not have anodes or other appurtenances fitted during installation, and hence it also prevents anodes and other appurtenances to be located below seabed level.

6.2 Materials

Offshore wind structures are mainly constructed from bare or coated carbon manganese steels with a specified minimum yield strength (SMYS) not exceeding 550 MPa.

Some parts of the structure can be made of metallic materials other than carbon manganese steel. The CP system shall be designed to ensure that there is complete control over any galvanic corrosion arising from this coupling and also any risk of hydrogen embrittlement, see ISO 12473.

Foundation structures such as monopiles, jackets and floating structures may be coated or partly coated in the immersed zone. The design of the CP shall take this into account.

Gravity based structures are generally made from reinforced concrete foundations, and the structure is placed on the seabed, hence the name gravity based. The tower is fitted to the top of the foundation.

6.3 Corrosion protection strategy

The selected strategy for an offshore wind turbine foundation structure is important since the levels of protection applied for the different structure areas (see Figures 2 to 4) feeds into the structural design, where the S-N curves used in the structural design are selected to match the environment anticipated over the structure service life.

NOTE Offshore steel wind foundations, are subject to fatigue loading and their design lives can be fatigue limited[24], details fatigue design of offshore structures. Within this recommended practice are three major categories of S-N curves for carbon steel. These are S-N curves in air, S-N curves in seawater with cathodic protection and S-N curves for seawater with free corrosion. These curves are utilised in the structural design. The S-N curve 'seawater with cathodic protection' can be applied in the structural calculations, where the protective criteria are assumed fulfilled.

Three possible corrosion mitigation measures are possible: corrosion allowance, coatings and cathodic protection.

The role of cathodic protection is to minimise corrosion losses and to mitigate the effects of corrosion on structural design calculations in respect of fatigue. For parts of structures that are not cathodically protected, the wall thickness of structures may be increased to allow for corrosion losses during service. The additional thickness provides a Corrosion Allowance (CA). Typical areas where corrosion allowance is applicable are noted in Figures 2 to 4.

Cathodic protection is often designed in combination with coatings. Cathodic protection does not need coatings to operate successfully, and coatings are optional in combination with cathodic protection as shown in Figures 2 to 4. If coatings are not used, a higher current demand is needed to protect the structure in immersed and wetted areas.

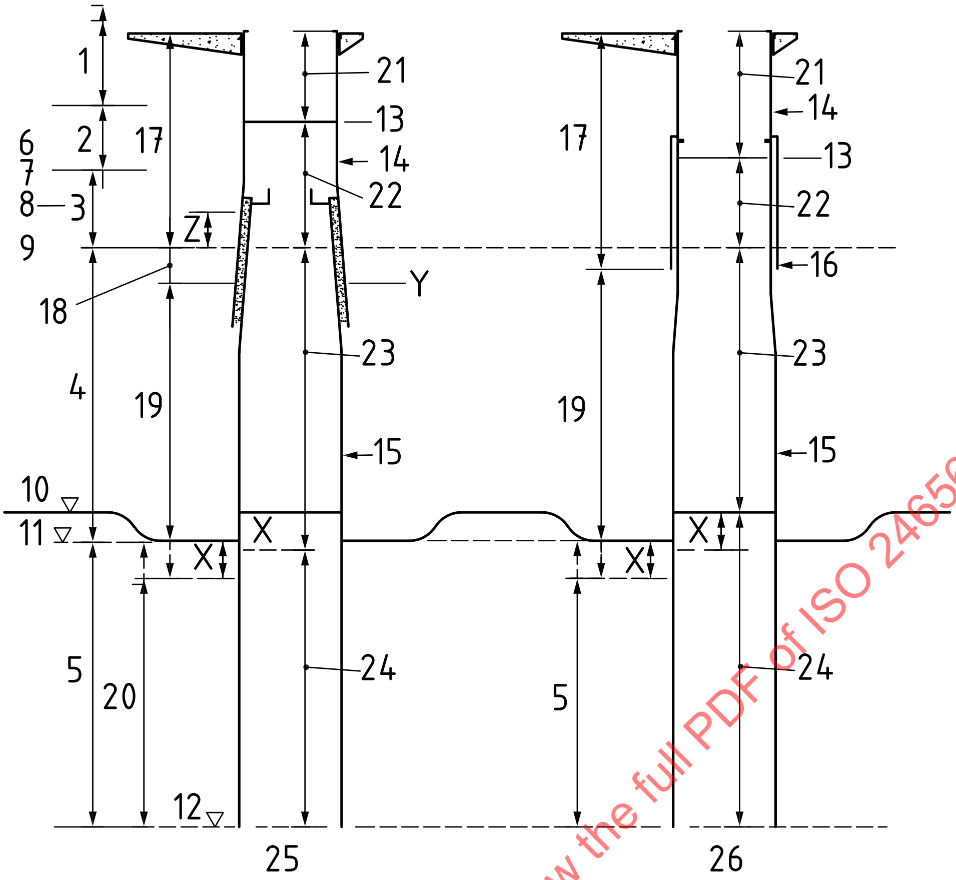
ISO 12944-9[5] provides guidance and requirements for coatings for offshore use and are further described in Annex D. Coatings alone cannot be relied upon in fully immersed areas since some progressive breakdown can be anticipated throughout the structure service life. Annex D gives guidance for coating breakdown factors when used in combination with cathodic protection. The owner should be asked to accept the breakdown factors applied in the design.

Where cathodic protection is fully efficient (meeting the protective criterion), the S-N curve "protected in seawater" applies. Cathodic protection for offshore wind foundations may be provided by either galvanic anode CP systems, or impressed current CP systems, or a combination of both. At the time of selection of the CP system a risk and consequence evaluation shall be made which shall include assessments of, as a minimum:

— the time between installation of the foundation and setting the CP system to work;

— estimates of reliability of the alternative CP systems, the anticipated number of visits to each foundation during the structure service life for CP performance assessment, CP system maintenance and CP system repair or replacement;

— capital costs, operational costs and structural consequences of non-functional CP systems.



Key

X user defined as upper limit of where CP protective criterion is to be met

Y user defined as lower limit of coating

Z user defined as lower limit of where CP protective criterion is to be met

1 atmospheric zone

2 splash zone

3 tidal zone

4 immersed zone

5 buried zone

6 $FWZ_{50\ \%}$ (above HAT)

7 HAT

8 MSL

9 LAT

10 seabed level

11 scour level

12 pile toe level

13 lower internal platform

14 transition piece

15 monopile

16 skirt

17 external: CA + coating

18 external: CP + coating

19 external: CP + optional coating

20 external: CA to be considered

21 internal: coating

22 internal: CA + coating

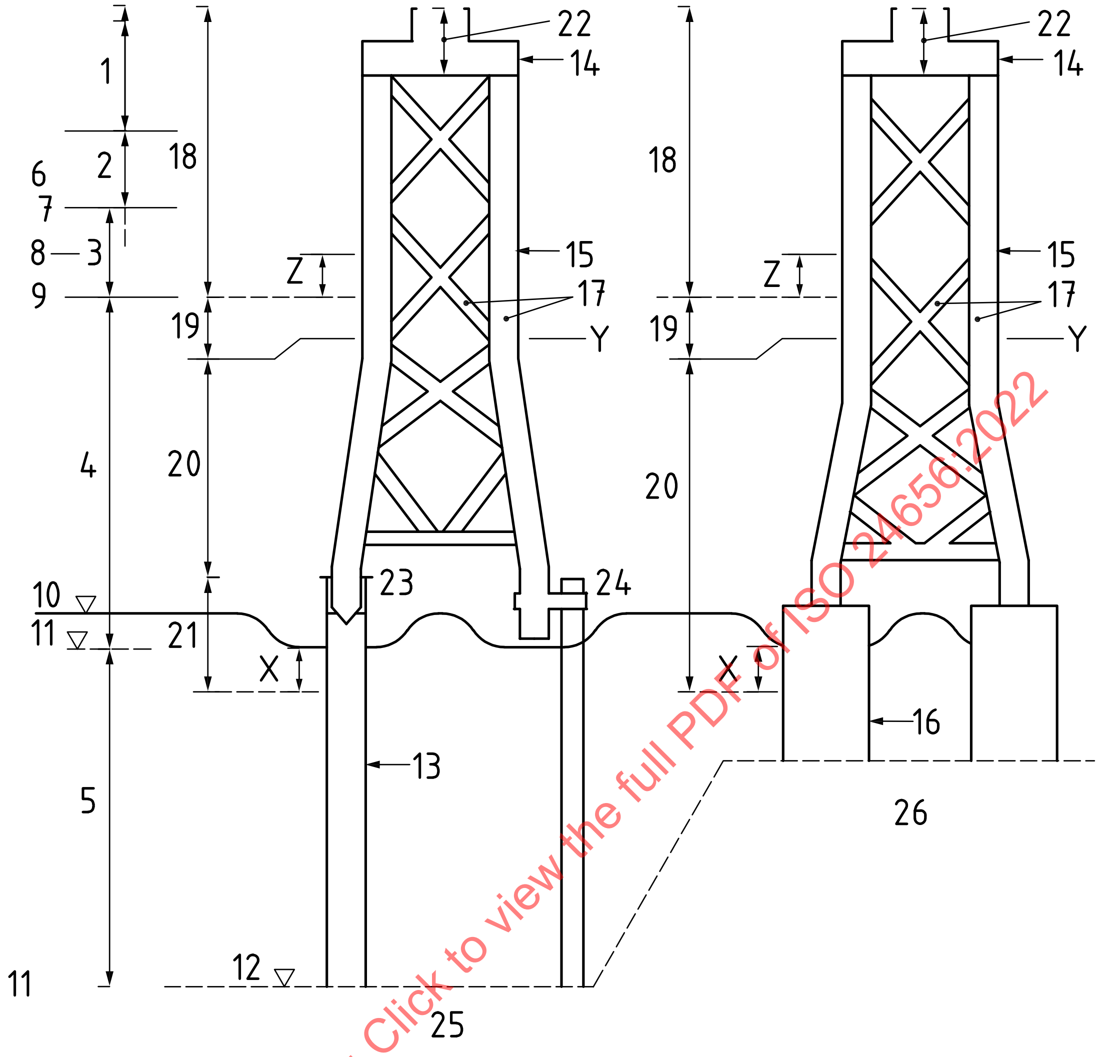
23 internal CA + optional coating and/or CP

24 internal: CA to be considered

25 MP/TP foundation grouted

26 MP/TP foundation bolted

Figure 2 — Corrosion protection strategy for monopile, left side grouted, right side bolted with TP including skirt



Key

X user defined as upper limit of where CP protective criterion is to be met

Y user defined as lower limit of coating

Z user defined as lower limit of where CP protective criterion is to be met

1 atmospheric zone

2 splash zone

3 tidal zone

4 immersed zone

5 buried zone

6 $FWZ_{50\ \%}$ (above HAT)

7 HAT

8 MSL

9 LAT

10 seabed level

11 scour level

12 pile toe level

13 pile

14 transition piece

15 jacket

16 suction bucket

17 sealed compartment

18 external: CA + coating

19 external: CP + coating

20 external: CP + optional coating

21 external: CP

22 internal: coating

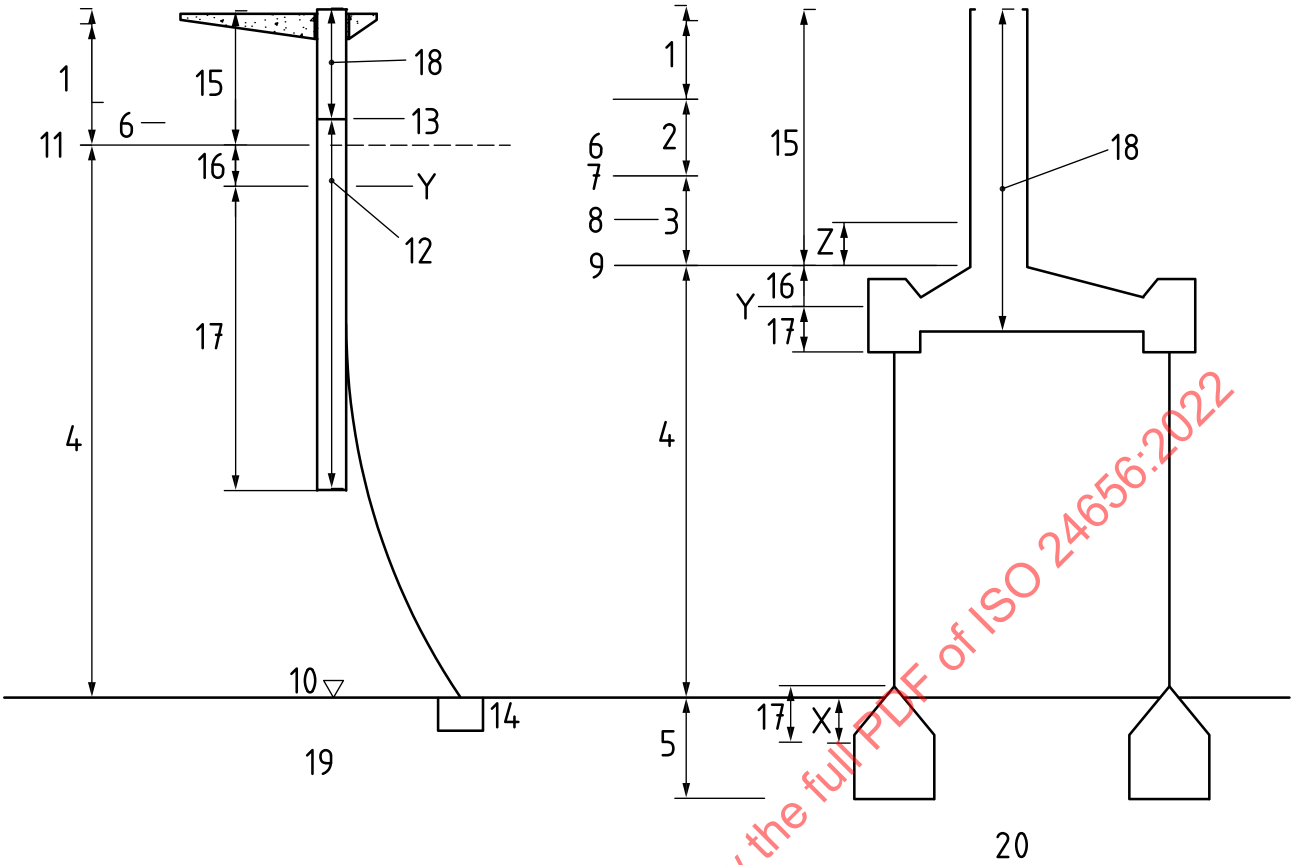
23 pile option 1

24 pile option 2

25 piled jacket

26 suction bucket jacket

Figure 3 — Corrosion protection strategy for piled jacket or suction bucket jacket foundation

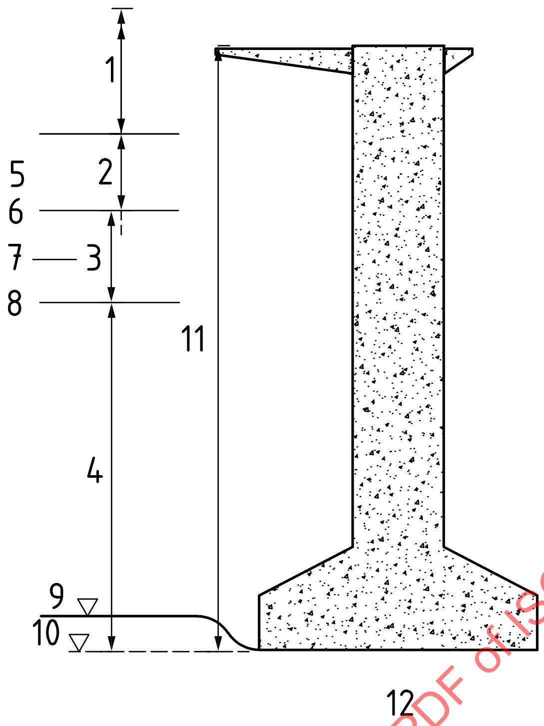


Key

X user defined as upper limit of where CP protective criterion is to be met
Y user defined as lower limit of coating
Z user defined as lower limit of where CP protective criterion is to be met

1 atmospheric zone
2 splash zone
3 tidal zone
4 immersed zone
5 buried zone
6 $FWZ_{50\,\%}$ (above HAT)
7 HAT
8 MSL
9 LAT
10 seabed level
11 rise and fall of spar with sea level
12 sealed
13 lower internal platform
14 anchor
15 external: CA + coating
16 external: CP + coating
17 external: CP + optional coating
18 internal: coating
19 floating spar
20 floating TLP (tension leg platform)

Figure 4 — Corrosion protection strategy for floating foundation, left side floating spar, right side floating TLP



Key

1 atmospheric zone
2 splash zone
3 tidal zone
4 immersed zone
5 $FWZ_{50\,\%}$ (above HAT)
6 HAT
7 MSL
8 LAT
9 seabed level
10 scour level
11 external: optional CP
12 gravity based foundation

Figure 5 — Corrosion protection strategy for reinforced concrete gravity-based foundations

7 Cathodic protection criteria

7.1 Temporary protection

Temporary cathodic protection, to achieve the protection criteria, see 7.2 and 7.3 to the immersed and buried surfaces detailed in Figure 2, Figure 3, Figure 4 and Figure 5, shall be provided for the period between construction and commencement of operation of CP (impressed current or galvanic) unless it can be demonstrated that any corrosion occurring before cathodic polarization protection does not compromise the structural integrity. A strategy could be to coat fatigue sensitive areas such as welds and nodes to protect these against corrosion, until power is available.

If coatings alone are used before cathodic protection is applied, it may be necessary to undertake an assessment of probable coating damages, its distribution and corrosion, before cathodic protection is commissioned.

7.2 Steel structures

The required structure to electrolyte potential limits for a range of metals and alloys in seawater are detailed in ISO 12473.

NOTE 1 In this document, all potentials are referenced to the silver/silver chloride/seawater reference electrode (Ag/AgCl/seawater) except when otherwise stated.

The accepted criterion for protection of carbon manganese steels in aerated seawater is a protection potential more negative than −0,80 V measured with respect to (wrt) Ag/AgCl/seawater reference electrode. This corresponds approximately to +0,23 V when measured wrt pure zinc electrode (e.g. alloy type Z2 as defined in EN 12496:2013, Clause 2 or +0,25 V when measured wrt zinc electrode made with galvanic anode alloy types Z1, Z3 or Z4 as defined in EN 12496.

When different metals and alloys are in electrical contact, the protection potential shall be sufficiently negative to control any galvanic corrosion of the less noble of them. In practice, the less noble metal is usually carbon steel, where −0,80 V is appropriate.

Ag/AgCl/seawater reference electrodes are sensitive to seawater salinity. A correcting factor shall be applied when not used in 3,5 % seawater salinity. Guidance to conversion between reference electrodes and correction factors are given in ISO 12473:2017, Annex C.

The protection potential of steel in anaerobic environments and where there is a risk of Microbially Influenced corrosion (MIC) shall be more negative than −0,90 V wrt Ag/AgCl/seawater, unless another criterion can be justified.

A negative limit of −1,10 V wrt Ag/AgCl/seawater is recommended in order to avoid coating disbondment. For conventional steels with a SMYS equal or lower than 550 MPa (grade S355 per EN 10025[17], there is no enhanced risk of cracking at this negative limit. This limit will not be exceeded on structures protected by zinc or aluminium galvanic anodes, see ISO 12473.

Where there is a possibility of hydrogen induced stress cracking (HISC) and hydrogen embrittlement, which may be adversely affected by cathodic protection to excessively negative values, a safe, less negative potential limit shall be adopted. If insufficient documentation is available for a given material, this specific negative potential limit relative to the metallurgical and mechanical conditions shall be determined by mechanical testing at the polarized potential limit. These potential limits apply to all cathodically protected structural components, including fasteners.

Ferritic and ferritic-pearlitic structural steels with specified minimum yield strength (SMYS) up to at least 550 MPa have proven compatibility with CP systems, provided they are manufactured and fabricated according to relevant standards. However, laboratory testing has demonstrated susceptibility to HISC during extreme conditions of yielding. All welding should be executed according to a qualified procedure with 350 HV10 as an absolute upper limit. With a qualified maximum hardness in the range 300 HV10 to 350 HV10, design measures should be implemented to avoid local yielding.

Austenitic stainless steels and nickel-based alloys are generally considered immune to HISC in the solution annealed condition. Similarly, welding or hot forming according to an appropriate procedure does not induce HISC sensitivity. Bolts of AISI 316 stainless to ISO 3506-1[2], grade A4, property class 80 and lower, i.e., up to SMYS 640 MPa, have proven immunity to HISC with a negative limit of -1,10 V wrt Ag/AgCl/seawater.

Martensitic carbon, low-alloy and stainless steels can present HISC at steel to electrolyte potentials less negative than -1,10 V Ag/AgCl/seawater in materials with an actual YS of about 700 MPa and hardness of about 350 HV10, respectively. Untempered martensite is especially prone to HISC. Welding of materials susceptible to martensite formation should be followed by post welding heat treatment to reduce heat-affected zone (HAZ) hardness and residual stresses from welding. The same recommendations for hardness limits and design measures as for ferritic steels apply. Bolts in martensitic steel heat treated to SMYS up to720 MPa, e.g. ASTM A193[21] grade B7 and ASTM A320[22] grade L7 have proven immunity to HISC with a negative limit of -1,10 V wrt Ag/AgCl/seawater.

Failures due to inadequate heat treatment have occurred and for critical applications, batch testing should be employed to verify a maximum hardness of 350 HV10.

Ferritic-austenitic (duplex) stainless steels are potentially susceptible to HISC, independent of SMYS, typically 400 MPa to 550 MPa or specified maximum hardness. Welding may cause increased HISC susceptibility in the weld metal and in the HAZ adjacent to the fusion line. This is related to an increased ferrite content rather than hardness. Qualification of welding should prove that the maximum ferrite content in the weld metal and the inner HAZ, about 0,1 mm wide can be effectively controlled. Ferrite contents of maximum 60 % to 70 % are typically specified. Coarse microstructure is more susceptible because HISC propagates preferentially in the ferrite phase. Design precautions should include measures to avoid local plastic yielding[26].

NOTE 2 There is no generally recognised test method to verify CP compatibility of different metallic materials. Constant extension rate testing, also referred to as slow strain rate testing, is applicable to compare HISC susceptibility of materials of the same type, e.g., relative susceptibility of martensitic steels. For more quantitative testing, uni-axially loaded tensile specimens, with constant load, 4-point bend specimens with constant displacement, crack tip opening displacement (CTOD) and other testing configurations have been applied at controlled CP conditions. Such testing is, however, beyond the scope of this document.

For steels with a SMYS higher than 550 MPa, a negative limit of potential in the range −0,83 V to −0,95 V wrt Ag/AgCl/seawater shall be applied, as specified in ISO 12473. Where potential limits are not defined in ISO 12473 the specific negative potential limit relative to the metallurgical and mechanical conditions shall be determined by testing the material/environment combination at the polarized potential limit. These potential limits apply to all cathodically protected structural components, including fasteners.

Potential limits for high strength steels may also apply to fastener materials.

High strength steels, corrosion resistant alloys (stainless steels and copper alloys), particularly high strength and high hardness materials, may be adversely affected by cathodic protection in accordance with the protection criteria above. ISO 12473 provides guidance as do References [53][28] and [26].

The general guidance is that if the SMYS is ≤ 550 MPa and the hardness is below 350 HV10, cathodic protection is safe to the above criteria limits. But particular materials and their metallurgical condition may be sensitive to hydrogen induced stress cracking (HISC) at less negative values.

7.3 Reinforced concrete structures

Steel reinforced concrete structures or parts of structures fabricated from steel in concrete might not require cathodic protection, see 6.1. However, if their reinforcement is electrically continuous with parts of a steel structure that do require CP, the reinforcement will be a 'drain' on the CP system. In such cases the provision of CP current shall be in accordance with ISO 12696 for 'cathodic prevention'.

If CP of steel in concrete is required for durability of the structure or parts of the structure, it shall be designed in accordance with ISO 12696.

No instant off steel to electrolyte (concrete) potential more negative than −1,10 V wrt Ag/AgCl/0,5 M KCl for plain reinforcing steel or −0,90 V for prestressing steel shall be permitted.

The required structure to electrolyte potential limits for reinforcement in concrete structures are detailed in ISO 12696.

ISO 12696 also details the appropriate reference electrodes to be used in reinforced concrete.

8 Cathodic protection design

8.1 Objectives

The objective of a CP system is to deliver sufficient current to each part of the structure and appurtenances in need of protection, in order to meet the potential criteria. The anodes shall be distributed so that the structure to electrolyte potential of each part of the structure to be cathodically protected is within the limits given by the protection criteria throughout the CP design life, see Clause 6.

The design objectives may be achieved by the design of a CP system using either an impressed current or a galvanic anode system or a combination of both (hybrid systems).

8.2 Design considerations

8.2.1 General

CP systems may be combined with a coating system which will reduce the amount of protective current required and lead to more uniform distribution of the current.

ISO 12944-9[5] specifies the performance requirements for protective paint systems for offshore and related structures to be used in corrosivity class CX (offshore) and immersion conditions Im4 as defined in ISO 12944-2[4].

This document introduces the concept of a frequently wetted zone (FWZ) to recognize the full impact of water flow rate, tidal ranges and wave height on CP requirements. This concept is important to offshore wind turbine foundation structures. It is an essential part of the required CP design calculations, see 8.6 and Annex B.

Offshore wind turbine foundations are exposed to variable seawater velocities as a result of tidal variations and wave actions. Further, the location of a structural member in flowing water also results in increased flow velocity around the same member.

Because each offshore wind farm is in a geographically unique location in respect of these features, each CP design shall be based on the metocean data unique to that particular location, see Annex B.

The CP system shall be designed with due regard to environmental conditions, see 8.6.

Current drain to all surface areas below seabed level and above the fully protected area including the frequently wetted area shall be taken into account when calculating CP current requirements.

Current drain to structures which cannot be directly fitted with anodes such as anchors and mooring chains shall also be taken into account when calculating CP current requirements. The distribution of current, its attenuation and the ability of the CP system to provide relatively uniform current density to all immersed surfaces shall be assessed and ensured e.g. by mathematically modelling the CP system, using appropriate and proven input parameters in order to indicate the distribution of current and structure to electrolyte potential values over the structure under conditions that reflect the full CP design life.

The required inputs to the design which shall be considered and documented are detailed generally in Clause 15 and particularly in 6.3. Each step of the CP system design shall be undertaken and checked in accordance with a fully documented design plan and the final CP design shall be fully documented in a CP design report.

A quality management system and an environmental management system shall be used in conjunction with this document.

ISO 9001[3] constitutes a suitable quality management systems standard which may be used, and ISO 14001[6] gives guidance on the selection and use of an environmental management system. CP designs should be subject to quality management and include an assessment of environmental impact.

The anulus between a TP skirt internal surface and the MP external surface, see Figure 2, for the bolted MP/TP, may present particular difficulties in respect of CP design. The environment within the anulus may have features of both ‘external’ and ‘internal’ CP. The CP design shall document the specific design parameters used for such an anulus. The corrosion assessment should take into account any area within the anulus that is above the water level.

8.2.2 External cathodic protection

CP shall be applied to the external immersed or partially immersed surface of steel structures. Monopiles and tubular piled jackets may be coated, partially coated or bare. In the case of monopile (MP) structures the transition piece is generally coated.

Both galvanic anode CP systems and impressed current CP systems can protect an offshore wind turbine foundation structure against corrosion.

For galvanic anode systems intended for MP installations, the time between driving the monopiles and protecting the MPs with CP should be minimised, or other corrosion mitigations employed.

Early corrosion may have an impact on structural integrity.

In the case of ICCP systems, the CP designer (see Clause 5), in conjunction with structural engineering, shall determine if temporary CP will be necessary to cover the period between foundation installation and the ICCP system becoming operational.

The possibility of power disruptions or intermittent failures to either temporary or permanent ICCP systems shall also be considered.

8.2.3 Internal cathodic protection

8.2.3.1 Monopiles

Experience has shown that it is difficult to completely seal the internal space in monopiles when J-tubes are routed inside the MP and some oxygenation of water should be expected. Even if completely sealed, entry for inspection will introduce oxygen.

Where CP is installed in closed compartments, ventilation shall be included in the structural design to prevent build-up of gases and consequent risk of an explosive mixture. All CP systems generate hydrogen. Aluminium anodes generate more hydrogen than zinc anodes. Impressed current anodes generate chlorine gas as well as hydrogen gas on the protected steel and this may be particularly corrosive to the “head space” immediately below the airtight deck. There can be an incendive spark risk with both hydrogen (with oxygen in air) and with chlorine (with hydrogen).

In closed monopiles without water replenishment aluminium galvanic anodes should not be used due to known acidification issues[33][34] and hydrogen gas generation and ICCP systems should not be used due to potential safety hazards from chlorine and/or hydrogen gas generation. Zinc anodes may be used with measures to prevent risks from hydrogen gas build up.

Where perforations are introduced into the monopile to ensure a flow of oxygenated seawater, the perforations shall be of sufficient size to preclude their accidental sealing by marine growth or calcareous deposits. The extent of water replenishment in the water column inside the monopile shall be confirmed based on water flow studies.

If CP is not employed internally, the use of protective coatings should be considered and fixed monitoring of the internal environment and corrosion rates at sensitive locations, above and below water and just below the internal seabed/sediment level of representative structures should be considered. Inspection procedures shall be appropriate to ensure detection of localized corrosion before this can impact the structure service life.

Internal CP designs require particular attention to distribution of structure to electrolyte potential over the surface within restricted electrolyte volumes, see 9.6 and EN 17243. Mathematical modelling of the CP system [see Annex I] is recommended.

8.2.3.2 Flooded compartments in jacket structures

For jacket legs with welded and valve sealed flooded compartments with no oxygen access after time of sealing, oxygen will be available for corrosion processes for a relatively short period until it is consumed. The level and extent of corrosion and the impact of corrosion on the structural integrity in this period shall be considered.

NOTE As an example of impact of oxygen only: For a 2 m diameter vertical tubular with 10 m water column (with 8 ppm dissolved oxygen) and 5 m of air (20,9 % oxygen) a total reduction of wall thickness of 26 µm based on uniform corrosion can be expected before the available oxygen is fully depleted. If corrosion is taking place primarily in the upper meter of column, the corresponding reduction in wall thickness would be 260 µm.

When a jacket has flooded compartment(s) which are not sealed and there is continual replenishment of oxygenated seawater, CP is required. The CP current densities are reduced due to reduced seawater velocities compared with conditions externally. The possible locations for installation of anodes in such a case makes the possibility of uneven potential distribution and attenuation significant and this shall be considered. Further information is given in EN 17243.

8.3 CP Design life

The CP design life is normally specified by the owner. Due to the unmanned and multiple remote installations of offshore wind turbine structures in a wind farm asset it is inevitable that regular access may be difficult and limited. It is normal practice therefore for the CP design life to be for the entire anticipated life of the offshore wind turbine structure.

The CP design life should include both the installation period as well as offshore wind farm turbine operating lifetime. If there is a period without protection before installation and commissioning of the CP system or before energizing (for impressed current systems), then this shall be considered in connection with the structural design. In addition, service life for the decommission phase may be considered. If it is envisaged that the effective life of the CP system will be shorter than that of the structure (including installation and decommissioning periods) then this shall be justified and documented in the design report, see 15.1 and provision for replacement or retrofit as appropriate included in the design.

8.4 Surface area considerations

8.4.1 General

To calculate the CP current demand, it is necessary first to determine the surface area of the structure to be protected. This includes areas where the protective criteria are to be met and areas which will drain current.

Design drawings of the structure to be protected should be the basis of the surface area calculation. Information on the extent and type of coatings if any and any associated appurtenances shall be included in the CP design report.

It may be practical to apply some simplification when calculating surface areas for complex structural parts. However, such simplifications shall be conservative to ensure that the resultant calculated current demand is not underestimated. If necessary, an additional contingency factor should be considered, if the exact dimensions of all immersed components are not known.

8.4.2 Structure subdivision

Structures to be protected should be divided into separate CP zones, which can be considered independently with respect to CP design, although electrically connected.

A schematic representation of different zones requiring separate consideration due to installation depth characteristics is indicated in Figure 2, Figure 3, Figure 4 and Figure 5.

Annex C gives indicative design current density and data for use in the buried zone and for different marked-up seawater flow velocity rates (see 8.6).

Surface area calculations and their separation into various zones shall be documented in the CP design report. Reference shall be made to structural drawings including revision numbers and all items affecting CP current demand shall be included in the calculation.

For piled structures, including monopile foundations, all surface areas that will receive CP current shall be considered, irrespective of any assessment that may infer that the corrosion rate or corrosion risk is low for driven piles into the seabed. CP current will be distributed to the driven pile surfaces and if these surfaces are not included in the CP design there will be a current deficit in the overall CP system design. This shall apply to both internal and external CP designs.

To what extent coatings are provided below seabed/scour depth is for the corrosion protection designer (see Clause 5) to decide. Any global and local scour shall be included into the CP design, the immersed zone for surface area calculations shall include the level to seabed plus maximum scour depth.

Where scour protection is placed internally, due to the constrained electrolyte, it may affect the electrolyte resistivity, and this should be considered. Externally, due to the huge volume of electrolyte, any issues are normally insignificant.

Anchoring systems on floating offshore wind structures shall be considered as separate zones and shall have their own independent CP systems.

8.5 Environmental factors

8.5.1 General

This document is applicable to the immersed and buried parts of any offshore wind turbine structure located in seawater of all compositions and for all soil types.

For surfaces that are alternately immersed and exposed to the atmosphere, CP is only effective when the immersion time is sufficiently long for the steel to become and be maintained polarized.

CP is effective to bare (uncoated) steel. It is also often used, and is effective, in combination with protective coatings (paints) which reduce the required CP current requirements and improve current distribution.

Friction between the driven part of the structure and the soil can damage coating applied to the structure. Annex D provides guidance for coating break-down factors that may be applied.

The application of coatings can be precluded by the need for friction between the structure element and the seabed, for example, suction buckets.

Design current densities and therefore the total CP current demand depend upon the seawater velocity, the seawater temperature, erosion, dissolved oxygen content, and the ability to build up and maintain protective calcareous deposits on bare metal surfaces. Some informative guidance is given in Annex C.

The environmental factors listed below that affect CP current requirements and the ability of CP systems to provide this current shall be assessed. These effects are significant in the determination of adequate CP for offshore wind foundations. The effects of significant reduction in anode current output caused by anodes close to each other shall be calculated, see E.1.8. The effects of current and potential attenuation over the steel structure from close to the anodes to points most remote from anodes shall be calculated, see Annex E.

8.5.2 Seawater flow velocity

CP current density requirements for both initial polarization and maintenance of polarization throughout life vary significantly with seawater flow velocity. Figure 6 describes the increase in velocity vertically from seabed/scour level upwards and B.7 describes horizontal flow rate effects. Horizontal velocity will accelerate around vertical tubulars and, for CP design purposes, the determined velocity at varying depths, see 8.6.2 shall be marked-up as indicated in Annex B and Figure 6 in order to determine the appropriate CP current density required.

8.5.3 Electrolyte resistivity

Electrolyte electrical resistivity is of importance in the design of galvanic anode systems since it is a factor in the calculation of anode to remote seawater resistance and hence anode current output, see Annex E. For impressed current anodes the electrical resistivity shall be taken into account during system design to provide sufficient output voltage. However, electrolyte resistivity also affects distribution of current from anodes and hence the degree of structure polarization. Higher resistivity results in polarization over a shorter distance from the anodes.

Seawater electrical resistivity (ρ in Ωm) is dependent on seawater salinity and temperature. In open seawater the value of salinity is reasonably constant within a relatively narrow limit, as shown in Annex E. However, in some offshore wind farm locations, for example inshore areas (particularly near river estuaries and where tidal currents are significant) or in areas affected by snow melts/seasonal freshwater ingress (e.g. Baltic Sea and Caspian Sea), resistivity may vary considerably both with location and with time. In some conditions there can be stratification of different salinity at different depths, causing variations in resistivity with depth.

All of these factors shall be taken into account in the CP design.

Resistivity values shall be based on actual data from the specific location and the data shall reflect the mean and variation over an annual period and any variation with depth. The resistivity corresponding to an average temperature for the coldest month of the year (or the month with the highest electrical resistivity due to a combination of temperature and freshwater dilution of the salinity) shall be used in the design. In the absence of measured seawater electrical resistivity, accurate assessment shall be by use of local salinity and temperature measurements and Annex E.

If anodes are to be installed in the seabed sediment, the seabed resistivity shall be determined or estimated by the CP designer (see Clause 5) in the absence of measured values. If actual data are not available for sediment resistivity, a default value of 5 × seawater resistivity used for the design shall be used.

8.5.4 Seawater temperature

Temperature has a significant effect on seawater resistivity, See 8.5.3, on levels of dissolved oxygen and on calcareous deposit formation. The range of temperatures to be anticipated for the structure shall be considered in the CP design.

Increasing water temperature decreases oxygen solubility and therefore reduces CP current density required. It however also increases the corrosion rate and increases the CP current density required.

Thus, the effects of seawater temperature on CP designs are complex and they shall be addressed in detail. Annex C provides informative guidance regarding the impact of temperature on CP design parameters.

Decreasing temperatures increase the solubility of the calcareous deposits and affects their formation rate and morphology reducing the protective nature of the deposits given in ISO 12473.

8.5.5 Calcareous deposits

Calcareous deposits on the structure surface occur as a result of cathodic reactions during the CP process, see ISO 12473. The current requirement to protect a structure is decreased when calcareous deposits have formed. The mean current density is largely determined by the nature of the calcareous deposits for steel in seawater when effective CP has been achieved.

Allowance shall be made for the influence of water flows, suspended silts, sands, ice or by ice flows on stability of calcareous deposits. The stability of calcareous deposits is also affected by storms. Guidance is given in Annex D and Reference [35].

8.6 Protection current demand

8.6.1 General

The current demand of each metallic component of the structure is the product of its surface area exposed to the electrolyte and the selected current density. The demand can be reduced by the presence of coatings where appropriate. The term “current density” is the CP current per uncoated unit surface area of the structure being protected. The selected current density is that which is required to achieve and maintain polarization of the structure to be protected.

The current densities shall be selected either from proven experience from similar installations in the same locality, from full scale testing or based on published data relating measured environmental conditions to current density for instance as detailed in Annex C.

Caution should be exercised in using ‘proven design practice’ from past projects if the CP performance of these past projects has not been accurately assessed. The assessment should include potential surveys, fixed potential monitoring (data logging) and current or current density measurements or surveys that verify the effectiveness of the design in delivering full conformity with CP design criteria for all times of the year, with all environmental conditions.

The current demand calculations shall include the initial (or polarization), the mean (or average) and the final (or re-polarization) current densities, informative values given in Annex C.

For galvanic anodes, the initial and final current requirements shall be used to determine anode number and geometry based on anode resistance calculations, see Annex E.

The mean current demand often called maintenance current demand shall be used to determine the requirement of total galvanic anode mass i.e. net mass of the cast alloy required for the design life.

For impressed current the anode design shall be based on the maximum calculated current requirement of the initial and final current values with an added contingency factor. A minimum factor of 25 % is recommended, see 10.2.2.

While coatings are not necessary for effective CP, they are often used in conjunction with CP to reduce the current demand and improve current distribution/reduce attenuation, see Annex E.

For coated structures the CP design shall take into account the increased current demand over time as the coating loses its electrical resistance effectiveness. This is achieved by the application of a coating breakdown factor in the formulae for current demand calculation, see 8.6.2. Annex D explains the process of coating breakdown and has suggested coating breakdown factors and breakdown rates for a range of coating systems which may be suitable for use for offshore wind turbine foundation structures.

8.6.2 Calculation of current demand, external surfaces

For external surfaces, the frequency of wetting of the structure shall be included in the design.

For driven or drilled piles, suction buckets or anchors below the seabed, their full external surface area shall be included in the CP design, refer to 8.4. Guidance on which items are to be cathodically protected and which items only act as a drain on the CP system is provided in Table C.4. Any anode support structure shall also be included in the CP current calculation requirement.

To account for the effect of seawater velocity, metocean data shall be used to derive a marked-up seawater flow velocity profile across the water depths. Recommended methodology is described in Annex B. The upper water level shall be the frequently wetted zone at 50 percent non-exceedance level, $FWZ_{50\ \%}$.

The current demand shall be calculated based on the surface area including the frequently wetted zone (FWZ), to structure pile toe level or suction bucket toe level. The structure should, as a minimum, be divided into the following zones:

a) $FWZ_{50\ \%}$ to $FWZ_{5\ \%}$

b) $FWZ_{5\,\%}$ to seabed/scour

c) Seabed/scour to pile toe/suction bucket level

The current demand shall be calculated for the initial, mean and final (re-polarization) event.

The total current demand shall be calculated as the sum of current demands from each of the zones, defined above from $FWZ_{50\,\%}$ to toe level.

The total current, I_{total}, required shall be calculated as given in Formula (1):

$$I_{total} = I_{zone(FWZ\,50\,\%\text{ to }FWZ5\,\%)} + I_{zone(FWZ\,5\,\%\text{ to seabed–scour depth})} + I_{zone(\text{seabed–scour depth to toe level})} \quad (1)$$

i.e. summation over the individual zones.

The zone $FWZ_{5\,\%}$ to seabed/scour shall be subdivided into zones of maximum 10 m depth to account for changes in marked-up seawater flow velocity, see Figure 6.

The 10-meter increments may be adjusted if the marked-up flow velocity profile provides justification for this, for instance where the profile is very steep, larger increments may be used.

The current for the subzones from $FWZ_{5\,\%}$ to seabed/scour shall be calculated as given in Formula (2):

$$I_{zone} = j_{zone} \cdot A_{zone} \cdot f_c \quad (2)$$

where

I_{zone} is the current in A,

j_{zone} is the current density in A/m^2,

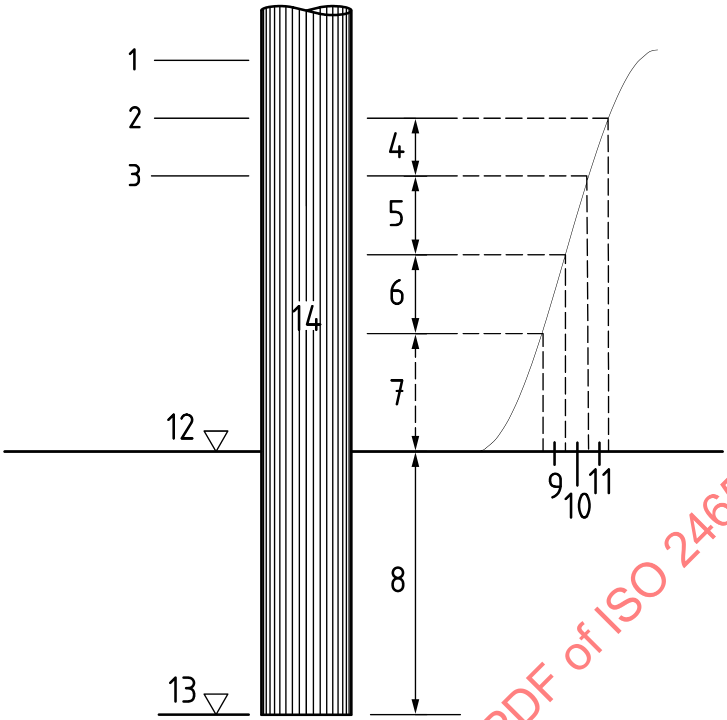
A_{zone} is the surface area of the zone in m^2,

f_c is the coating breakdown factor, for uncoated bare steel parts of the structure, $f_c = 1$

The current densities for the initial, mean and final (re-polarization) events for structural steel foundations shall be calculated:

— Below seabed/scour: For instance, as per the guidance in C.4.

— Above seabed/scour: The derived marked-up seawater flow velocity profile shall be used to find the current density for instance as provided in C.2 for each of the above zones. The marked-up seawater flow velocity in the vertical centre of the zone shall be used as basis.



Key

1 $FWZ_{95\ \%}$
2 $FWZ_{50\ \%}$
3 $FWZ_{5\ \%}$
4 $A_{(FWZ50\ \%\ -\ FWZ5\ \%)}$, m^2
5 $A_{1.(FWZ5\ \%\ -\ max.\ 10\ m\ below\ FWZ5\ \%)}$, m^2
6 $A_{2.(max.\ 10\ m\ below\ FWZ5\ \%-\ max.\ 20\ m\ below\ FWZ5\ \%)}$, m^2
7 $A_{z.(to\ seabed)}$, m^2
8 A_{BS}, m^2
9 U_{CP2}, m/s
10 U_{CP1}, m/s
11 $U_{CP(FWZ50\ \%-5\ \%)}$, m/s
12 seabed/scour
13 toe
14 structure

Figure 6 — Steel structure areas and zones relative to seawater flow velocity

Figure 6 shows the structure to the left with structure levels on the y-axis: toe, seabed/scour and levels for frequently wetted zones ($FWZ_{5\ \%}$, $FWZ_{50\ \%}$ and $FWZ_{95\ \%}$). Annex B provides information on how to derive the frequently wetted zone based on metocean data.

A represents the surface areas in the individual zones to subdivide the structure into:

— $A_{FWZ(50\ \%–5\ \%)}$,

— $A_{FWZ(5\ \%-Max\ 10\ m\ below\ FWZ5\ \%)}$,

— $A_{FWZ(Max\ 20\ m\ below\ FWZ5\ \%-Max\ 10\ m\ below\ FWZ5\ \%)}$, etc until seabed or scour depth, and

— A_{BS} for below seabed.

The X-axis represents the marked-up seawater flow velocity as defined and derived as detailed in Annex B. Above seabed/scour the marked-up seawater flow velocity ($U_{CP(FWZ50\ \%–5\ \%)}$, U_{CP1}, U_{CP2}, etc) as shown on the X-axis shall be used to find the current density for instance as shown in C.2 for that given zone. U_{CP} is the vertical centre of the zone to be used in the calculations.

Below seabed, the surface area may be subdivided as shown C.4 with the corresponding current densities shown. Guidance on calculation of current densities for reinforced concrete foundations can be found for instance based upon C.5.

8.6.3 Calculation of current demand, internal surfaces

Internally, the surface areas for compartments with free-flowing seawater shall extend to the highest internal water level, which for free-flowing conditions will be HAT.

Flow inside a monopile is dependent on the size, number, and location of the openings in the surface and the sea state outside the monopile. In order to estimate the appropriate current densities a detailed study of the seawater flow velocity within the structure is required along with study of the environmental factors, dissolved oxygen concentration, pH, salinity etc.

Guidance on current requirements for different dissolved oxygen contents can be found for instance in Annex C.

8.7 Electrical continuity and continuity bonds

Where the foundation structure incorporates bolted flange to flange connections or where a welded jacket structure is used, the electrical continuity in the structure may allow for adequate current flow from the anodes to the structure.

Electrical continuity bonding shall be established between the MP and TP where the MP and TP are grouted, and where either

— external galvanic anodes are welded to the TP,

— internal galvanic anodes are connected to the TP, or

— impressed current systems are utilized with the negative return or 'drain point' connected to the TP, or all

These continuity bonds shall be designed so that the full current from both an external and internal CP system can be carried between the MP and TP and that the voltage drop across the bonds and connection points is not such that it adversely affects the CP system performance. The continuity bond design (cross section, length and contact resistances) shall meet the requirements of the CP and the electrical safety and earthing for lightning purposes.

Some redundancy in the provision of continuity bonds is recommended. Design of the continuity bond may be based on a total of 10 mV voltage drop across all the parallel connections using the maximum design CP current (see 8.6). This recommendation is relevant to galvanic anode systems in which case the design driving voltage for the anodes for galvanic anode systems shall be reduced accordingly (see Clause 10 for ICCP systems).

If the connection is bolted, the connection shall be made using appropriate methods to avoid loosening as a result of vibration and deterioration due to corrosion.

NOTE Direct pin brazing ensures a metallurgical bond between the copper core of the cables and the steel of the MP and TP and is a suitable low resistance connection method.

Bond resistance measured using AC or DC resistance measurement methods is not an accurate measure because of the many parallel connection points through, for example continuity bonds and wedges etc. and should always be conducted in conjunction with visual inspection of the bond integrity. Current flowing across the bonds can be measured using a high accuracy DC clamp meter.

Material selection and corrosion protection of the contact points shall be chosen so that the connection is durable, reliable and maintainable over the CP design life, bearing in mind that these connections often are placed above water and will not receive protective current, but they will be in a humid, saline and sometimes tidal exposure area.

These details shall be documented in the CP Design Report along with the extent to which the volt drop in cable bonds between TPs and MPs and between anode cages or arrays and MPs has been calculated, which reduces galvanic anode currents and what provision has been made in the design to remedy this.

8.8 Current drains and interactions

Current can be drained by structures or elements of the structure that are not intended to be fully protected by the CP system.

NOTE 1 Examples are

— cable protection systems,

— cable armouring,

— the area of the foundation or structure above and below the level where full protection is required, and

— mooring and anchor chains.

These items shall be documented and considered in the CP design and an additional current demand as appropriate to the particular circumstance shall be applied to the calculated additional surface areas.

The amount of current that will be drained, depends on the surface area and local environment. Some indicative current densities are given in Annex C if actual measured data or experience from other nearby structures is not available. Mathematical modelling may indicate the amount of current likely to be drained, see Annex I.

NOTE 2 Theoretically all structures in a typical windfarm development will be electrically interconnected via the armouring of the array cables. In practice there is no evidence of significant currents flowing between adjacent structures; the electrical resistance of the steel wire armour and the localized distribution of external anodes dictate that one structure will not significantly affect its neighbour’s CP system performance.

The interconnection between structures should be acknowledged and could, theoretically, affect any future novel foundation designs or CP systems.

8.9 Installation considerations during design

For jacket structures, galvanic anodes and ICCP anodes with their cables and conduits can be installed in the fabrication yard before launch. Mathematical modelling see Annex I can be used to predict the distribution of potential and inform the optimum choice of anode location.

For monopile or transition piece structures, due to installation constraints during pile driving, galvanic and ICCP anodes are not normally pre-installed on driven monopiles. Anodes are either fixed to the transition piece or separate anode cages on the monopile or anode array on the seabed are used. These shall be electrically connected to the MP at the offshore site after driving operations are completed.

In this case the uniform distribution of potential is more difficult. Inadequate anode distribution and attenuation of current and potential over monopile surfaces apply equally to ICCP systems as to GACP systems. Mathematical modelling at the design stage can optimize the design in respect of adequate current and potential distribution across the structure, see Annex I, allowing optimum placement of anodes and minimize the risk of under or over-polarization.

The CP design shall ensure that anodes and monitoring systems are installed where the possibility of disturbance or damage from external sources is minimal and, where appropriate, anode replacement is facilitated.

For the internal protection of MP/TP foundation structures, anodes may be suspended from the deck of the transition piece or from the lower internal platform. The suspension of anodes will take place after the monopile has been driven into the seabed and the TP has been installed.

Either the time between installation of monopiles and transition piece may be significant, or the coupling of anodes to the structure is completed sometime after installation, or both.

The periods where the CP system is not operational should be recognized and any effect on structural integrity should be accounted for in the structural design.

If galvanic anodes are suspended as 'strings' or vertical arrays, particular attention shall be given to the resistances, voltage drops and attenuation within the anode string and to the durability of suspension system, including any use of wire rope above the water level.

Cable conductor size selection, bond cable length and low contact resistance structure connection details shall be documented in detail in the CP design report, Clause 15.

9 Galvanic anode systems

9.1 General

Galvanic anode CP systems provide the current required for CP of the steel structure by connecting it directly to anodes manufactured from alloys that are more electronegative than steel in seawater. Preferential corrosion of the anodes in the resultant galvanic couple generates the current without the need for any additional power source.

The current available from galvanic anodes depends upon the material properties of the galvanic alloy, the shape of the anode, the extent of polarization of the steel structure and the environmental conditions in which it is operating. Each anode has therefore a predetermined current output which can be calculated and used in the CP system design. With careful anode selection and distribution, the calculated CP current demand for the structure can be achieved.

Correctly designed galvanic anode systems are simple, robust, reliable and self-controlling.

9.2 Anode current availability

For purposes of CP design, the driving potential for current output from a galvanic anode is taken to be the difference between the polarized potential for the steel and the closed-circuit potential of the anode alloy which is determined by the anode alloy and the anode current density at any time. As the steel structure begins to polarize from its rest potential, the driving potential will initially be higher but will decrease and the anode current output (calculated from Ohm's law) reduces with increasing polarization of the structure thus making the system self-regulating.

As the anode is sacrificially consumed, its dimensions decrease with consequent increase in resistance to remote seawater and resultant decrease in current output.

The available life from a galvanic anode depends on the total current output (charge) throughout its life, its initial mass, a utilization factor recognizing that not all 100 % of the anode mass may be available for reactions and its electrochemical capacity.

Annex E details the calculation procedures to determine anode resistance to remote earth (seawater) and describes anode utilization factors. Annex E describes the calculation procedures to determine anode life or conversely the anode alloy mass required to supply the total current demands over the CP design life.

9.3 Galvanic anode alloys

Aluminium and zinc alloys are the materials most often used as galvanic anodes in open seawater.

Aluminium based galvanic anode alloys developed for marine applications have been specifically formulated to perform in seawater with a slightly alkaline pH, high salinity and a significant content of oxygen. For some areas the seawater and seabed conditions can be outside predefined ranges of the above, and in these cases aluminium anodes should not be used. Unless otherwise documented, aluminium anodes should not be used in conditions where the electrolyte resistivity exceeds 2 Ωm.

In some circumstances, such as some monopile internals, when replenishment with fresh oxygenated seawater does not freely occur, it has been found that significant reduction in pH of water in the enclosed compartment can occur due to reaction of aluminium with seawater and this significantly affects the efficiency of the alloy and the efficacy of CP, see References [33] and [34].

The behaviour of certain aluminium alloys can also be adversely affected by burial in seabed mud, particularly if the current output remains low, see ISO 15589-2[8].

Zinc based anodes can be used for offshore structures, but their higher density can lead to a higher CP system mass. Zinc anodes can be used in brackish and freshwater applications. Zinc does not cause significant acidification in non-replenished seawater and it may be used in internal CP of structures if oxygenated water replenishment is uncertain.

Magnesium anodes shall not be used in internal spaces containing seawater due to excessive hydrogen generation.

NOTE Some studies in the relatively quiet waters of harbours and marinas have indicated that the effect of dissolution of zinc anodes can give rise to environmental concerns, see zinc in estuaries[32]. Contamination of sediment around dissolving aluminium anodes in a sheltered harbour location has also been observed but the effect is considered insignificant for the surrounding water[36]. There are no conclusive studies of the effect in open seawater.

EN 12496 describes galvanic alloys and their electrochemical properties in seawater. Alternative values for closed circuit potential and electrochemical capacities of galvanic anodes can be used if these data are properly documented including the relevant anode operating temperatures and using the actual anode alloy composition. However, caution should be used when considering an alloy tested in a particular set of conditions (and for a particular limited time period) for use in a different set of operational conditions.

A commercially available aluminium galvanic alloy suitable for protection of most low carbon manganese structural steels is that described as A2 in EN 12496 and where zinc alloys are required, Alloy Z1 of EN 12496 is suitable. For steel and corrosion resistant alloys sensitive to hydrogen embrittlement other advice is given in ISO 12473 and Alloy A4 of EN 12496 may be an appropriate choice if other potential restricting measures are not employed.

9.4 Anode selection

The shape of an anode (whether aluminium or zinc) determines its resistance to remote earth (seawater) and current output for a selected driving potential.

Most galvanic anodes used for both external and internal CP for offshore wind farm foundations are of trapezoidal cross section and considerably longer than the cross-section dimensions. The length is the main determinant of anode current output and the alloy mass determines the anode life.

Anodes are either of the stand-off type or flush-mounted to the structure. Long slender stand-off anodes generally have a higher current output availability. Flush mounted anodes are often shorter and with less current availability due to increased resistance.

It is preferable if all the anodes for an individual CP zone are the same size e.g. external anodes on a monopile structure or anodes for the internal space of a monopile structure. Mixing anode sizes and types is not desirable since different anodes will consume at different rates throughout the CP system life. When the use of anodes of different sizes and shapes in an individual CP zone is unavoidable then the total charge availability (current capacity) from all the anodes shall be considered. EN 12495[18] and DNVGL-RP-B401[23] have further details.

The selection of an anode shape for any situation shall be made with due consideration to the CP design and the required distribution to achieve uniform potential distribution on the protected structure. External anodes mounted directly on the structure will result in hydrodynamic drag forces from the anodes and cyclic stresses which impact structural design. Anode location may also be dictated by the need to avoid impeding future operations.

For external anodes, the exposed anode steel insert (core) is generally welded to the structure, TP or frame of an anode cage or sled. The insert material shall therefore be of a weldable grade of steel. Flush mounted anodes may be bolted to the supporting structure especially if their eventual replacement is being considered, see also 8.3.

Anodes for use inside a monopile or a jacket are normally smaller in size than anodes for use externally. If internal anodes are to be used, there are likely to be size limitations in respect of access and handling mass issues. Anodes suspended in strings within the internal spaces of a monopile structure may have lifting eyes and cable connection points integral with the exposed insert ends.

Anode inserts (cores) shall meet the requirements defined in EN 12496.

Inserts for aluminium anodes shall be grit blasted to a surface finish complying as a minimum to grade Sa2½ of ISO 8501-1. This finish shall be maintained up to the time of casting and any further surface contamination prior to casting shall not be permitted.

Inserts for zinc anodes can be treated the same as for aluminium anodes or can be hot dip galvanised to ISO 1461[1]. Any further visible discolouration prior to casting shall not be permitted.

Electroplated zinc coatings are not suitable for anode inserts. A suitable minimum surface profile for grit blasted insert surfaces is 75 µm. The use of steel or chilled iron shot for blasting is not permitted.

Inspection criteria for anodes as manufactured are detailed in EN 12496 and DNVGL-RP-B401[23]. However, these are based on sometimes relatively large tonnage procurement for a single structure as is common in the offshore oil and gas industry.

The inspection criteria for anodes, frequency and nature of physical and electrochemical testing, shall be considered in respect of the overall anode requirements for the offshore asset and its individual foundation structures and shall form part of the anode supply requirements and documentation.

9.5 Anode requirements

To satisfy the CP design, the current demand, see 8.6.2, shall be satisfied at all times by the anode type selected and quantities installed when correctly distributed. This current demand includes that required for initial polarization and also any increased demand for re-polarization purposes when required throughout the CP design life and the anodes shall be able to satisfy the demand for re-polarization at the end of their life when full utilization has been reached. This is often called the "final" current demand i.e., it is the current to be supplied by the anodes at the end of the anode's life, as defined in the CP design life, not necessarily the end of the structure service life. Guidance on the calculation method for determining the current output from a particular shape and size of anode is given in Annex E.

The life of an anode will depend on its mass, the current output, its utilization factor and the electrochemical capacity of the alloy, Annex E. The alloy mass required to be installed initially to operate for the whole of the CP design life is calculated from the mean current demand according to the formula given in Annex E.

The alloy mass required can be determined for the whole of the structure or for each individual structural member or for each surface area zone.

The number of anodes (N) required of the type selected can be calculated from Formulae (3) to (5):

$$N \geq W_{\text{total}}/W_{\text{anode}} \text{ and} \tag{3}$$

$$N \geq I_{\text{total(initial)}}/I_{\text{anode(initial)}} \tag{4}$$

$$N \geq I_{\text{total(final)}}/I_{\text{anode(final)}} \tag{5}$$

where

m_{total} is the minimum total net mass of galvanic anode material required, in kilogram (kg)

m_{anode} is the net mass of an individual galvanic anode material, in kilogram (kg)

$I_{total(initial)}$ is the total current required for polarization of the structure, in amperes (A)

$I_{anode(initial)}$ is the initial current output of an individual galvanic anode material, in amperes (A)

$I_{total(final)}$ is the total current required for re-polarization of the structure, in amperes (A)

$I_{anode(final)}$ is the final current output of an individual galvanic anode material, in amperes (A)

All three criteria shall be satisfied to achieve an adequate CP design.

For well coated structures the final or maintenance current demand may be the design controlling factor.

9.6 Anode distribution

Galvanic anodes placed on jacket structures are typically welded onto the structure and shall be distributed to provide an adequately uniform current distribution and correspondingly uniform protective level in order that the CP criteria are met for all surfaces intended to receive CP.

Anode distribution is critical to the successful design of a galvanic anode CP system and should be fully documented in the CP design report, see Clause 15. The location of all individual anodes shall be shown on construction and as-built drawings.

Galvanic anodes are not normally pre-installed on monopiles and are located on the TP or as post-installed anode cages on the monopiles or on the seabed.

Where it is necessary to group anodes together either on the TP, on one or more anode cages on the MP or on mats on the seabed, the result is that current is uniformly distributed to the structure. Dependent on water depth and whether coatings are used in conjunction with CP or not, it may be necessary to have anodes installed at different elevations, in order to achieve the CP criteria over all surfaces intended to receive CP.

If anodes are not uniformly distributed on the structure, the reduction in anode current output caused by mutual interference between anodes shall be evaluated. Mathematical modelling techniques can be used. The impact of mutual interference shall be factored into the design calculations.

If modelling is used for calculating the reduction in anode current output caused by mutual interference of anodes, it shall be undertaken by specialists in modelling. However, the input parameters, in particular the anode and cathode polarization curves, shall be selected by the CP designer, Clause 5.

The calculated current output in seawater (electrolyte) is based on the calculation of the resistance of the anode to remote earth. The current output is reduced by close proximity of

— anode to anode,

— anode to structure,

— anode to the sea/air interface, and

— anode to seabed.

It is recommended that anodes are placed below −1 mLAT so that they are always immersed. See Reference [37] for the reduction in current output for the proximity to seawater surface. These effects are significant even if the anodes are below −1 mLAT, and it is recommended to evaluate the effects and take it into account in the design.

Anodes should be located to minimize their exposure to mechanical damage, for instance not near boat landings. Anodes should not present a risk of snagging for items used for operation or maintenance, such as cables, tethers or umbilicals.

When anodes are attached to intermediate structures such as anode cages or sleds mounted on the foundation structure or remote from it, then electrical connection shall be ensured by cable. Cable connections from the anode support structure to the foundation structure can be by attachment to specific connection points. Cables can be preinstalled on the anode assembly before installation leaving only the foundation structure attachment to be made.

When cables are used for anode attachment, these are likely to be relatively longer than the shorter cable bonds used for continuity purposes, see 8.7 and due consideration shall be given to cable sizing and volts drop down the cables, see Annex F.

Cable connection points are vulnerable to movement due to sea currents and due consideration shall be given to the security of cable connections at each end. Intermediate connection plates and bend restrictors or cable clamps are recommended.

Further general installation requirements are described in 8.9.

EN 17243 has information of potential distribution on internal surfaces of tubulars. Anodes installed internally within flooded monopiles required to be subjected to particular design requirements. If installed as anode 'strings,' the attenuation of current along the string shall be calculated and documented; it is generally necessary to connect anodes with insulated and sheathed copper cables, Clause 11 and to connect these to the TP or MP. The MP and the water column within it, forms a restricted electrolyte volume within which the anodes shall deliver current to the MP surfaces; the vertical volt drop in the seawater will not be insignificant and will be significantly greater below the seabed. The anode to anode spacing and the anode/cathode (steel) spacing shall be small and this will reduce the anode current output. Mathematical modelling of the proposed arrangements is recommended.

10 Impressed current systems

10.1 General

Impressed current systems provide the DC current required for CP of the steel structure by connecting the structure to the negative terminal of a controllable DC power supply and connecting the positive terminal of the power supply to one or more impressed current anodes immersed or buried in the same electrolyte as the structure.

The DC current output delivered by the power supply is controlled to obtain and maintain an adequate protection potential level on the whole steel surface of the structure. This control of the current and the dimensions, number and location of the anodes, along with number and location of reference electrodes, shall be determined so that the protection potential criteria is achieved and maintained over the whole surface of the structure intended to receive 'full' CP for the expected CP service life, for zones see Figure 2, Figure 3, Figure 4 and Figure 5.

Impressed current system anodes are generally smaller in size and mass than galvanic anodes, while being able to provide high current output due to the driving voltage from the power supply being, typically, in the range 0 V to 24 V DC. Impressed current systems require an electric power supply and related cabling to operate and need adjustment to ensure that the polarization limits are within the requirements. They require automatic potential control using reference electrodes to measure and maintain within criteria, both most negative and least negative steel to electrolyte (seawater) potentials. They will not function if there is either a loss of electrical power or damage to connecting cables or reference electrodes, or both.

Offshore wind farms have numerous unmanned structures which makes operation and maintenance difficult and expensive. This results in a risk from a non-functioning CP in cases of power failure, fuse or circuit breaker trip activation, reference electrode failure, electrical or software system failure and anode, or cable failure. Also, there is a risk of system failure as a result of lightning events where the anodes act as part of the earthing system, through the power supplies.

Key features in the impressed current CP system reliability are:

— data infrastructure to ensure continuous performance data available for the owner enabling him to respond in a timely manner;

— owner organization ability and commitment for timely operation, maintenance and repair;

— an upfront operation and maintenance manual and failure response plans; the operation and maintenance manual shall include directions on how and when repairs are to be handled.

The design of impressed current CP systems is complex.

An operation and maintenance manual should be provided for each impressed current system, see Clause 14. Cable failures shall to some extent be expected, and the design shall take this into account. Cable routing internally within the structure is a possible way of reducing the risk of cable failure. The mean time before failure (MTBF) of electronic components shall be carefully evaluated, and a replacement procedure is recommended to be in place at time of installation.

Any application of the impressed current systems in closed compartments will generate hydrogen and chlorine gas (corrosive and explosive) see 8.2.3.1. Precautions should be taken to avoid corrosive or explosive conditions when ICCP is used. Safe ventilation of chlorine and hydrogen gas is essential. These gases are potentially an explosion risk and chlorine presents both corrosion and personnel hazards. The risk of accelerated corrosion above the water level, particularly to the 'airtight' deck, ladders, lower working platforms and support beams shall be assessed, documented and mitigated.

10.2 Design considerations

10.2.1 General

Installation of foundation structures take time for a large wind farm, and electrical power will not be available before typically 6 months or more after installation of the foundations, when towers, nacelle and wings/blades have been installed and the power grid connected. Temporary corrosion protection until power is available shall be provided, using for example:

— galvanic anodes;

— protective coating;

— electrical power from alternative sources, such as solar panels, diesel generators or similar may be applied.

The design calculations and material, installation, commissioning and operation specifications shall be fully documented in the Design report, see Clause 15.

10.2.2 Resilience of impressed current CP system by design

In order to provide a degree of resilience and increase the reliability of impressed current CP systems, the designer (see Clause 5) shall consider and document if multiple power supplies should be installed and operated on each foundation. After initial polarization it is expected that the maintenance CP current demand will be such that power supplies will normally operate at < 50 % of current capacity for uncoated structures. If two units are operated in parallel and one fails, it is possible that an appropriate design will enable adequate CP criteria to be maintained, at least in non-storm conditions, with only one unit operational. This would give time for planned repair or change out of the failed DC power supply.

Similarly, the designer shall consider and document if more than two reference electrodes per DC power supply shall be installed, so that if one fails another can be selected, remotely or locally, to control the least or most protected conditions. In addition, it shall be possible to operate the DC power supply in a constant current or constant output voltage mode if all the reference electrodes fail. Even if all reference electrodes fail, the DC power supplies shall not revert to nil or maximum current output; it shall be automatic or possible by remote control for the power supply current to be set at an appropriate constant value to maintain polarization but prevent excessive polarization. This will not permit optimum performance but will permit a degree of CP during the period between failure and replacement of reference electrodes. Where the ICCP system is in potentiostatic mode, it is recommended to have a limit to voltage and current in the rectifier system to avoid overprotection.

Due to the operation and maintenance demands of impressed current CP systems, the operation and performance data should be available in real time at a central monitoring location, anticipated to be onshore and linked to the turbine performance central monitoring location. This should generate out of optimal performance alarms. The operating procedures and personnel requirements for operation and seeking specialist advice, where necessary, shall be documented.

Location of permanent reference electrodes below seabed could be considered, where conformity with a protective potential is required by the CP design.

Anode system designed in accordance with this standard shall be capable of providing the high current densities required for initial polarisation, therefore some loss of anode system output can generally be tolerated during normal operating conditions, when the maintenance current density is sufficient to maintain polarisation of the structure.

The CP scheme and the anodes shall be rated and distributed to provide the initial or polarization current density and to ensure that even the most remote areas of the structure are able to fully polarize to the design criteria. It is expected that the design criteria potentials will be established over the entire structure within 2 to 3 months of the CP system being set to work, for a bare structure and 2 to 3 weeks for a well-coated structure. Full polarisation with approximately stable conditions and stable current densities may take up to 12 months for bare structures and up to 3 months for well coated structures. The mean or maintenance CP current density, generally being <50 % of the initial or polarization values, will provide resilience by way of this ‘spare’ capacity.

The CP designer (see Clause 5) shall consider and document if the reference electrodes and anodes can be replaced, underwater, by diver or ROV.

10.2.3 Current requirement of impressed current CP system

The maximum protection current demand for a CP zone (I_{max}) shall be calculated using formulae according to 8.6.

The CP system should be designed with a contingency factor so that it is able to provide a current I_{total} which is at least 25 % more than the calculated maximum protection current demand I_{max}, depending on the geometry and the coating of the structure. This factor may be increased based upon the mathematical modelling as recommended in 8.9. CP systems with anodes only on the TP of monopiles may require a factor in excess of 1,25 and should be subject to modelling for best estimate, as given by Formula (6):

$$I_{total} \geq 1{,}25 \cdot I_{max} \qquad (6)$$

10.2.4 Impressed current CP system components

The components of the impressed current system shall include

— DC power source,

— anodes,

— reference electrodes,

— dielectric shields, if a sufficient distance between anodes and the steel structure cannot be achieved,

— anode positive and structure negative cables, along with their connections, see Clause 11, and

— seals, where cable penetration of watertight components is required.

10.2.5 DC power source

The DC power supply is typically a transformer-rectifier (TR) which converts AC input to DC output. Alternative power supplies such as switch-mode devices, solar power, wind energy may also be used, but their ability to deliver the necessary DC voltage and current continuously for the full CP design life shall be assessed and documented in the CP Design Report.

NOTE 1 Simple thyristor-controlled transformer rectifiers are generally reliable. However, the added complication of integrated data logging and remote monitoring and control, can reduce reliability although there is merit in the use of simple thyristor-controlled transformer rectifiers with separate data logging/control devices of proven high reliability.

The DC power supply output voltage shall be calculated taking account of the resistance of the electric circuit (cables, anodes and cathodes), the ohmic voltage drops in seawater and the EMF generated at anode and cathode interfaces (typically 2 V) under the operating conditions and the recommended operating voltage of the anodes, Annex G.

All electrical equipment shall be sized to provide the calculated maximum current, see 10.2.2 at the maximum expected driving voltage for the required CP design life.

NOTE 2 National electrical regulations apply to all electrical equipment. DC power supplies shall normally operate with potential (potentiostatic) control where the steel to electrolyte (seawater) potential of the structure is measured with respect to fixed reference electrodes and the current and voltage output adjusted to maintain the structure to electrolyte potential within set limits of most negative and least negative potential, see 7.2 and 7.3. The power supply shall have the ability to remotely change the potential set points (least negative and most negative) and to switch from potential control to constant current.

Subject to the planned location of the power supply, the equipment shall comply with the electromagnetic compatibility requirements of IEC 61000-1-2.

Offshore wind turbine assets are highly susceptible to lightning strikes. Surge protection shall be provided on the AC input, the DC output and all CP monitoring circuits, in accordance with IEC 61400-24,. The competent person (see Clause 5) shall determine the appropriate surge protection levels to reflect both possible electrical system earth faults and surges due to lightning. The surge protection level shall be coordinated with the lightning protection planner for the structure.

Impressed current systems shall have their performance monitored and surveyed, Clause 13. This is not possible by diver if the owner or the diving contractor requires that dc current to anodes be switched off during diving activities.

The impressed current power supply where anodes using platinum or mixed metal oxides or where the intention is to meet the IMCA Safe Use of Electricity Underwater Code[31] shall meet the following criteria:

a) be in full phase rectification with a maximum of 100 mV AC RMS ripple from 5 % to 100 % DC current output, tested at 5 % current at 2,5 %, 5 % and 10 % voltage, at 30 % current tested at 10 %, 30 % and 60 % voltage and at 100 % current tested at 30 %, 60 % and 100 % voltage;

b) be fitted with ripple detection that will shut down the equipment and isolate the DC output circuit if the AC ripple exceeds 100 mV AC RMS;

c) be fitted with a residual current device (RCD) on its AC supply with a trip current of 30 mA at 40 mS;

d) have a DC voltage not exceeding 24 V.

For other anode types than platinum based these requirements may be different; but if divers are to work safely near energised anodes, these requirements shall be met.

The design of the CP system shall be documented by a competent person, Clause 5 to be incapable of exceeding the safe body current of 40 mA DC at a calculated safe distance between the diver and any operating impressed current anode at the maximum rated output of the CP system (which may be in excess of the design current). Guidance on the calculation of safe distances is given in IEC 60479-1, IEC 60479-2 and IEC 60479-3.

NOTE 3 Some guidance can also be found in the IMCA Safe Use of Electricity Underwater Code[31].

Some owners or diving contractors may require the impressed current CP system to be switched off during inspections, see Clause 12 and 16.3. This might not allow full operating data to be collected by divers, but ROVs can be used. The diver safety criteria stated here are for guidance only. Establishing the conditions to be met before divers operate in the vicinity of operational anodes is not within the scope of the standard, but they are available within Reference [31].

10.2.6 Impressed current anodes

10.2.6.1 General

Annex G presents the characteristics of commonly used impressed current anode materials, that is the expected anode consumption rate (wear rate) expressed as g/Ay for environmental exposure. Anode consumption rate depends highly on anode composition and some manufacturers may not wish to disclose the composition that they use.

Impressed current CP anodes, fabricated from platinum coated or clad anodes based on titanium, niobium or tantalum substrate, or mixed metal oxide coated titanium (also known as MMO/Ti) have low consumption rates at high anode current densities[38].

Magnetite anodes also have low consumption rates with high current densities but larger surfaces and are free of added heavy metals such as ruthenium and/or iridium.

NOTE There is less extensive track record for the performance of magnetite anodes in seawater than is available for Pt coated, clad Ti or Nb, or MMO/Ti anodes.

As the current output of the impressed current CP anodes is generally higher than for an individual galvanic anode, in theory fewer impressed current anodes can be used to protect a structure. However, attenuation of current and potential from an area of steel polarized by an impressed current will occur and shall be taken into account in the CP design.

As the impressed current CP anodes are usually smaller and lighter in mass than galvanic anodes, they may result in lower loads affecting the structure to be protected than galvanic anodes.

Anode to electrolyte resistance shall be calculated and documented. It shall be used in the calculation of the necessary DC output voltage to deliver the maximum design current in seawater at its highest electrical resistivity which, due to low temperature, may be in the late winter or early spring months. Some impressed current anodes have limits to anode/electrolyte voltages as in Annex G; these should not be exceeded without data demonstrating that it is secure to do so.

10.2.6.2 Location of anodes

The number and location of the anodes shall be determined to achieve the protection criteria in Clause 6. Particular attention shall be given to not exceeding the negative limit adjacent to the anodes and to achieving the appropriate least negative protection criterion at points most remote from the anodes, in particular at the seabed or below the seabed.

As many structures are to be fitted with anodes, and as offshore installation is costly, the most frequent method of using impressed current CP on offshore wind turbine structures has been to locate these on the TP sometimes on cantilevered arms. Verification by modelling that the current spread fulfils the protective criterions is recommended to be completed before any design is adopted.

Optimization of anode locations, either on the TP or elsewhere on the structure (jacket or monopile), or on the seabed should be subject to computer modelling, see 8.9 and Annex I.

Impressed current CP anodes may be located remote from the structure, which will provide a more uniform current distribution, but this also gives challenges in relation to connecting anodes to the DC power supply, in particular in respect of protecting the anode cables from damage during installation and the full CP design life.

Impressed current CP anodes will normally be more efficient if not embedded in seabed, but anodes can be specifically designed for seabed embedded operation if there are specific reasons for doing so.

Location and orientation of anodes should take into account the following:

— environmental loading;

— avoidance of damage from debris, falling objects and boat movements;

— reduction of problems of fabrication, transportation and launching or installation;

— the possibility of interference with other metallic conductors such as armoured cables with possible outer sheath damage, if they pass between structure and remote anodes.

10.2.6.3 Anode and attachment mechanical design

Anodes, their mounting/attachment devices and the cable conduits supplying them are particularly vulnerable to mechanical damage. The effect of the attachment and mechanical protection on the anode performance shall be considered and the structural sufficiency of anodes and cable management systems (conduits, tubes etc) to withstand predicted peak sea/wave loads shall be documented. The loss of a small number of impressed current CP anodes can significantly reduce the performance of the CP system due to the relatively high current output of individual anodes.

The design shall include and document measures to prevent direct contact (short circuit of the CP system) between the anodes and the structure, either by cable failure or by deformation of the anode mounts or the anodes themselves.

10.2.7 Reference electrodes

Reference electrodes shall be placed in a representative number and at representative locations to enable both adequate performance monitoring and to serve as the source of controlling structure to electrolyte (seawater) potential for potential (potentiostatic) control. Reference electrodes shall measure both:

— most negative structure to electrolyte potentials typically at a location proximate to an anode, and

— least negative potentials at a location most remote from anodes and, optionally

— at a location that is anticipated to be representative of the mean potential on the structure.

A minimum of two reference electrodes per DC power supply shall be provided. For CP system resilience additional reference electrodes should be provided, with a minimum of four per DC power supply. In foundations of complex geometry more reference electrodes should be provided.

10.2.8 Dielectric shields

Individual impressed current CP anodes usually deliver higher current than individual galvanic anodes. To prevent localized over polarization, and to improve the electrical current distribution to the structure, impressed current systems shall therefore utilize:

— dielectric shields, or

— a spacial separation between anode and cathode, or

— a combination of a dielectric shield and a spacial separation

The overall arrangement shall be such that, at maximum design current output from the anode the critical negative potential limit, see 7.2 shall not be breached. Calculations for sizing shields are in ISO 20313:2018, Annex K.

The electrochemical reactions occurring at the anode surfaces produce corrosive products and gases which may deteriorate the dielectric shield. The electrochemical reactions occurring at the cathode close to the anode can result in disbonding of the dielectric shield. The selection of materials and their application of the dielectric shield shall be resistant to these reactions and the dielectric shields shall have a realistic design life equal to the CP design life.

Materials selected shall be resistant to cathodic disbonding and to corrosive chemicals produced at the anodes (notably chlorine and acidic conditions) and not be prone to significant deterioration or ageing. Anodes and their dielectric shields may be subject to wave and impact damage. They shall be supplied with documentary evidence of performance in the anticipated environment.

Liquid applied coatings, glass reinforced resins, prefabricated plastic or elastomeric sheets can be used on the structure adjacent to the anodes or incorporated into the anode assembly subject to their suitability as immediately above.

Dielectric shields can comprise a thick (e.g. 4 mm) primary shield, generally provided with the anode, and a secondary shield comprising a coating with known good performance under cathodic disbonding conditions.

High build liquid applied coatings and glass reinforced resins can be considered for dielectric shield use if the CP design life is comparable to the coating/resin life time.

High density polyethylene (HDPE) is a polymer with good acid, seawater and hydrogen resistance characteristics. High build epoxy coatings, some with glass flake, can also have suitable performance for dielectric shields, subject to the precise polymers used.

If new materials are proposed for use as dielectric shields, they shall be rigorously tested for resistance to chlorine, hypochlorite, hypobromite and if the material is applied to steel, for cathodic disbondment at voltages in excess of the normal cathodic disbondment, tests for protective coatings. The Design report shall document the testing and/or long-term track record of the selected dielectric shields.

10.3 Installation of impressed current CP systems

The CP and monitoring systems shall be installed so that the design objectives and functionality are reached and are reliably delivered for the full CP design life.

The installation of the materials and equipment shall be carried out in accordance with the relevant drawings, specifications and procedures.

Junction boxes and the connections within them are a source of unreliability in CP systems. They should be avoided wherever possible. They should not be used externally on the foundation structure. If external junction boxes are unavoidable, they should be made more resilient by filling with dielectric paste or gel.

Installation work shall be in accordance with applicable codes, regulations and standards.

All materials and assembled systems shall be inspected and tested at appropriate stages during supply and installation.

Inspection and testing shall be in accordance with inspection and test plans (ITPs).

The ITPs shall be sufficient to establish that the overall CP system is

a) manufactured and tested in accordance with the drawings and specifications

b) installed and tested in accordance with the drawings and specifications

c) fit for purpose for offshore deployment and use for the full CP design life

ITPs shall be prepared and used to meet the above requirements by competent personnel meeting the requirements of Clause 5 or similar.

NOTE National and international regulations can apply to the location and connection of the DC power supply enclosure

Due to many structures being installed in a wind farm, it is often seen as cost beneficial to install the anodes on the structure itself. If remote anode locations are used, great care shall be taken that the anodes are not covered in the seabed at time of installation or over time, unless the anodes are specifically designed for this application. Local and global scour movement shall be considered when routing cables. In addition, special considerations shall be given to cable management and durability over the service of the system.

Monitoring and control reference electrodes and the data logging and remote-control systems are an integral part of the impressed current CP installed equipment, see Annex H.

10.4 Hybrid systems and temporary power for impressed current systems

If the structural design dictates that there should be no corrosion during the installation period of the asset or during times when the impressed current system is inoperable, either a hybrid system (a combination of both galvanic and impressed current CP systems) shall be used or the use of a temporary power impressed current system shall be considered and documented in the CP Design.

NOTE The provision of a full stand by impressed current system is unlikely to be practical or economic.

In a hybrid CP system, the galvanic anodes shall be distributed and shall have sufficient current output to achieve the CP criteria, see Clause 7, for such periods as defined in the design documentation.

Where bare steel structures or partly coated structures are planned with impressed current CP systems, it should be born in mind that the design driver also for a temporary galvanic anode CP system is the initial stage, and the number of anodes in such case would be the same as for a sole galvanic anode CP system. Alternatively, temporary power may be considered.

It is recommended that reference electrodes are placed remote from the galvanic anodes in the GACP system.

10.5 Continuity bonds

Electrical continuity between parts of the foundation shall be as in 8.7. However, the design of the bonds shall be appropriate for the higher total current of the impressed current system. Due to the higher driving voltage available with impressed current systems, the CP designer (see Clause 5) may propose higher voltage drops in the bonds than can be permitted for galvanic anode systems.

The cable bonds between TP and MP shall be designed to be suitable for both the CP system design and for the electrical fault current and lightning surge.

11 Cable systems

11.1 General

CP cables to include cathodic impressed current anode positive cables, negative structure return cables and reference electrode and structure test cables.

Galvanic anode cage/MP bond cables and connection systems require particular attention. Cables connecting suspended anodes within internal spaces shall also be properly considered.

All the cable management include penetrations, tubular/conduits, mechanical supports, junction boxes and terminations.

Within offshore wind farm developments, cable systems also include the AC inter array cables and the AC export cables from the wind farm sub-stations to shore. Depending upon their characteristics and construction these can impact the CP design requirements.

Cable systems apart from these have no influence on CP system design or performance and are not a subject for this document.

11.2 Cathodic protection DC cables

CP and monitoring cables exposed to seawater shall have a minimum of an insulation and an outer sheath.

For CP cabling, whether galvanic anodes or ICCP systems, copper conductors shall be used. Aluminium conductors shall not be used. Suitable cables are stranded copper cables, with a minimum of seven strands per core and with separate insulation and sheathing. Only cables having proven performance immersed in seawater in conjunction with CP shall be used.

PVC should not be used for immersed CP cable insulation. It should neither be used as an insulation nor as sheath for impressed current anode cables nor near to anodes as it is water permeable and is not resistant to chlorine.

NOTE 1 XLPE/XLPE insulation and sheathing is water resistant, tough and resistant to acid and chlorine.

NOTE 2 EPR/CSPE insulation and sheathing is flexible; it is widely used for ship cabling. The outer sheath is a chlorosulfonated polyethylene (CSPE or CSP) and is ductile and notch resistant. It is resistant to acid and petroleum hydrocarbons. The inner insulation is ethylene propylene rubber (EPR), which is resilient and resistant to most organic and inorganic substances. It is often used in conjunction with flexible or very flexible (IEC 60228[12] Class 5 or 6) stranded copper. It is often used for bonds between TP and MP and is suited for direct pin brazing. It has acceptable performance in seawater except when exposed to active chlorine generated from impressed current anodes. For this reason, it is recommended to provide an additional shielding (e.g. PTFE sleeves) to that part of the cable that is in close proximity of the anode. The additional shielding is recommended on the cable for a distance of at least 25 cm from the anode's edges.

NOTE 3 PVDF (Kynar)/HMWPE insulated and sheathed cable is widely used on cables used to feed impressed current anodes in onshore applications, due to its excellent chlorine and acid resistance. However, the minimum bend radius and low temperature properties are poor; the insulation can be subject to cracking, leading to failure of the cable.

The cable shall be sized to be both sufficiently mechanically strong and, electrically, to have full design current capacity and a low voltage drop in accordance with the design. These elements shall be documented in the CP design report. The specified maximum current rating for a given size of cable shall never be exceeded.

Cables for bonding and for impressed current anodes should be a minimum of single core 16 mm^2 (7/1,70 mm) copper, insulated and sheathed as above. Internal anode connection cables may, however, have a smaller cross-section in accordance with their maximum current output, but not less than 6 mm^2 subject to the size being sufficient robust for its location. The size will depend on maximum current, length and calculated voltage drop. Bond cables may be multiple single core 25 mm^2 or 50 mm^2. The cable cross section shall be large enough to be mechanically robust, the size will depend on maximum current and length, see 8.7.

For CP monitoring purposes a minimum size of single or multi-core 2,5 mm^2 (50/0,25 mm) copper, insulated and sheathed cable shall be used.

For permanently fixed reference electrodes monitoring cable should be 2-core with one core connected to the reference electrode element and the other connected to the nearest part of the structure (via the electrode housing).

The electrical termination between the anode cable and the anode shall be watertight, chemically resistant and mechanically robust. As even small damage in an anode cable can result in rapid system failure, it is recommended that all anode to cable connections are factory made at the manufacturer's facility under controlled conditions. Total encapsulation of splices and connections is required to prevent water permeating into the splice, which will eventually destroy the connection. Encapsulation is achieved using heat-shrink sleeves containing adhesive mastic manufactured for CP purposes or multi-component wrapped or moulded connections.

In the external immersed zone and in the tidal and splash zones, all cables shall be protected by a pipe or similar conduit that can withstand the forces at hand, storm waves, ice, debris etc. Consideration may be given to incorporating the cables into substantial secondary steel tubulars such as boat bumpers or internal cable routing in the structure.

There may be installation advantages to connect cables from instrumentation and anodes into intermediate junction boxes between the anodes and the TR/CP monitoring and control unit. However, this practice can result in a loss of reliability and particular care is required in the design, specification and installation of any such junction boxes. The environmental classification of the junction box shall be appropriately rated with regards to the environmental location and the specified relative to EN 60529 and consideration may be given to encapsulating of connections within the junction box.

For voltage drop calculations, see 8.7.

11.3 Inter-array and export AC cables

Inter array cables and export AC cables are terminated at wind turbine generator (WTG) installations and offshore sub-stations. They may be installed via cable entries and often short J-tubes inside monopiles or they may be installed externally to both monopile and jacket foundations, within external J-tubes for both WTGs and substations.

Export cables have lead or semi-conductive sheath. Array cables have either Cu sheath with Al-laminate and non-conductive sheath or Cu sheath only. All export and array AC cables are armoured for mechanical strength, typically with galvanized steel wire, for export cables it can also be stainless steel armour wires.

All outer metals are electrically bonded to the foundation structure, typically at the hang off point from which the cable is supported. The cable, including its armour, is outer sheathed providing additional mechanical protection to the cable. Typically Inter Array cables are sheathed with a variety of materials; these include:

a) A 'serving' of bituminous compound impregnated hessian tape and polypropylene strands

b) A 'serving of polypropylene strands

c) An extruded sheath of XLPE.

NOTE All of these cable constructions are likely to have their copper or aluminium conductors insulated with XLPE. Many are described as 'XLPE cables'; this does not necessarily confirm that the outer sheath to the armouring is XLPE.

Steel wire armouring and metallic sheathing when earthed to a structure receiving CP can be a source of current drain. They can also form an electrical connection between structures. Further information is given in 8.8.

The CP design shall document these issues and how they have been addressed. For CP systems installed inside monopiles, the design shall take account of the locations of any internal AC cables and any other installation aids for the cables or restraints for J-Tubes. These may impede the proper distribution of internal anodes if not appropriately considered and they may also affect current distribution and current output from anodes by being a non-conductive surface close to the anodes (if XLPE or similarly sheathed) or by being a close cathode (if 'served' with a poorly insulating material).

If there is no CP within the internals of the MP, and above the immersed zone, there will be no CP to the armour wire and the galvanising will be consumed also attempting to provide CP to the MP internal surfaces. Mechanical cable protection systems (CPS) of power cables will often not be electrically continuous with the structure. They may need their own CP system.

J-tubes are normally welded on to the structure, and hence in continuity with the structure, they will receive current where placed in the CP electrical field, and should be considered, both externally and internally, where run inside MPs. Export cable armouring wires and array cable armouring wires running inside J-tubes do not in general receive CP, and mitigation should be considered to ensure the durability of the cables themselves.

Generic sketches of array and export cables are seen in Figure 7.

Key

1 conductor
2 conductor screen
3 insulation
4 insulation screen
5 bedding (tape)
6 metallic screen
7 laminated sheet
8 polymeric sheet
9 thin outer electrode
10 bedding (tape)
11 armouring
12 serving
13 fibre optic cable
14 filters and binders

1 conductor
2 conductor screen
3 insulation
4 insulation screen
5 metallic screen
6 wrapping layer
7 separation sheet
8 armouring
9 outer sheet
10 filling

Figure 7 — Array cable to the left and export cables to the right

12 Commissioning and surveys

12.1 Objectives

CP system commissioning shall be as soon as possible after the structure is installed offshore and the CP system has been set to work (galvanic anodes have been connected to the structure, or impressed current system is energised). If other means of temporary protection than cathodic protection are used, e.g. coating, then CP system commissioning may be postponed, provided that the extent of corrosion protection and any residual corrosion does not compromise structural integrity, i.e. the fatigue life of the structure, until commissioning is completed. The time from commissioning until protection has been achieved shall be taken into consideration as relevant.

NOTE 1 The CP system is expected to reach an approximately steady polarized state after a few months for uncoated structures, with protection criteria being achieved more quickly. For well coated structures protection criteria may be achieved within few weeks and an approximately steady polarized state within a month or so.

NOTE 2 There can be a cost or operational reasons to undertake the commissioning survey while the structure installation contractor is on site, or to wait until the installation contractor has cleared the site of high cost vessels and to return with lower cost access. It is important to know as soon as possible if there are problems with the CP system, but it is also important that the survey is not planned before polarization to within criteria is possible. See 12.2 and 12.4 (g and h) for guidance on the timing of initial post installation surveys.

The principle objectives of the CP system commissioning and commissioning survey are:

a) to document that the CP systems function in accordance with the performance requirements, see 7.2 and 7.3

b) to determine, in as far as is possible, if the CP system will continue to perform in accordance with the design objectives and the structure will remain satisfactorily protected from corrosion for the full CP design life.

Commissioning and surveying specifications shall be prepared by competent persons meeting the requirements of Clause 5. The competent person may be the CP designer.

For CP surveying and monitoring, see Clause 13.

Commissioning and survey reports shall be provided. Requirements to documentation can be found in Clause 15.

The commissioning and survey reports shall recommend any necessary changes to the CP systems, their operation and management (mainly applicable to impressed current systems) and the survey methods and intervals, see 12.2 and 12.4.

12.2 Galvanic anode systems

12.2.1 General

The as-built location number, dimension and masses and any particulars of the anodes shall be recorded and verified against the detailed design.

A structure to electrolyte potential survey (baseline measurements) should be carried out after minimum 30 days of polarization for coated structures and minimum 60 days for non-coated structures and before one year after the installation of the structure and after connecting the galvanic system.

The conformity of the CP systems to the appropriate protection criteria, see Clause 6 shall be established in detail on a representative percentage of structures, taking best and worst-case structures, hence deepest water depths, deepest pile toe level, but also considering variation in seabed composition and variation in seawater flow velocity across the developments.

For wind farms with +100 structures a minimum of 25 % of the structures should be subject to detailed surveys (baseline measurements). For smaller developments with a lesser number of foundations, the ratio of number of structures subjected to detailed survey should be increased.

For galvanic anode CP systems, where the function relies on a cable connection or a physical connection between TP and MP, or between anode cages and anode sledges and the structure, the baseline monitoring should be increased to 100 %.

NOTE 1 These are baseline measurements, against which future performance may compared. The number of foundations required to be surveyed at this time do not necessarily reflect the number requiring survey during service, 13.4.

It is recommended that some foundations are surveyed at fixed positions, to permit an evaluation of the developments of polarization and any deterioration in anode or cable bond performance. As actual installation and commissioning time across an asset or development will differ, it should be considered if more foundations should be subject to baseline measurements, in order to provide polarization data for a range of installation dates and environmental conditions during the early months of operation.

Measurement of anode to electrolyte (seawater) potential should not be part of a normal detailed survey (for jackets or monopiles) but may be helpful in any investigation of inadequate performance.

The structure to electrolyte potential surveys shall be undertaken in accordance with Clause 13.

All data shall be assessed by a competent person, Clause 5. The competent person may be the CP designer.

If the survey results do not provide a consistent and clear picture of the protection levels, or if some structures are inadequately protected, the number of structures measured should be increased, to achieve representative baseline measurements and the structures with inadequate performance shall be investigated.

12.2.2 Detailed external surveys

For monopile structures a detailed survey of each foundation shall measure the structure to electrolyte potential at seawater surface (clearly identifying level relative to LAT) and in increments each 1 m to 2 m to seabed or scour protection level.

For jacket structures each survey shall measure the structure to electrolyte (seawater) potential at the individual jacket legs and at representative braces. The measurement shall represent relative scenarios, as uncoated nodes, at braces, close to and far from anode location.

Measurements shall be undertaken as indicated in Clause 13.

12.2.3 Detailed internal surveys

For monopiles with internal galvanic anode CP systems each detailed survey of each foundation shall measure the structure to electrolyte (seawater) potential at seawater surface (clearly identifying level relative to LAT) and in increments 1 m to 2 m to seabed, scour or heave level.

At the same time as the potential survey, the anode string or assembly currents shall be measured.

Internal environments may change as a result of operating cathodic protection in fully or partially closed compartments, in these cases water quality and air quality parameters like pH, temperature, dissolved oxygen (DO), and gas detection for chlorine, hydrogen and hydrogen sulphides shall be considered.

Measurements shall be undertaken as indicated in Clause 13.

12.3 Permanent CP monitoring systems

Permanent CP monitoring systems are recommended for representative structures fitted with galvanic anode CP and shall be applied to all structures fitted with impressed current systems. In the latter case they provide the ability to operate the CP system in potential (potentiostatic) mode.

The as-built location number and dimensions and any particulars of the internal or external CP monitoring system, including reference electrodes, any monitored anodes and any cable management systems shall be recorded and verified against the detailed design.

The current output from any installed monitored anodes shall be recorded at the commissioning survey. The current output from non-monitored anodes may be determined using techniques described in Annex E.

12.4 Impressed current systems

Commissioning of the impressed current CP system shall include the following, in the order indicated:

a) check wiring to ensure security of all connections, continuity of all circuits and correct polarity (negative terminal to structure, positive to anodes);

b) perform structure to electrolyte (seawater) potential measurements with respect to the installed reference electrodes (before energising the CP system) to have a baseline corrosion potential;

c) on selected foundations: perform steel to electrolyte potential measurements immediately adjacent to all installed fixed reference electrodes using immersible potential measurement equipment comprising a reference electrode and a voltmeter to determine the accuracy of the fixed reference electrodes;

d) carry out electrical tests to confirm electrical safety of the DC power supplies first before any checks are performed on the DC output;

e) switch-on the DC power supplies to supply direct current to the structure at approximately 10 % of design current output; check polarity of DC current output at the DC power supply. Check output voltage and current with calibrated portable instruments;

f) repeat steel to electrolyte potential measurements with respect to all installed fixed reference electrodes (after energising the CP system to 10 % of design current) to confirm that these values are more negative than those measured at 12.4 b);

g) set the TR auto potential (potentiostatic) control circuit ‘set point’ at a potential (less negative than −1,00 V wrt Ag/AgCl/seawater) anticipated by the competent person, Clause 5 to be the correct level to ensure that all immersed locations on the foundation meet the appropriate potential criteria, see Clause 6 and that no location shall be more negative than −1,10 V wrt Ag/AgCl/seawater;

h) continuously data logging monitoring the structure to electrolyte potentials with the permanent monitoring system; the competent person, Clause 5, shall assess the data after 30 days of operation to 60 days of operation; the DC power supply settings shall be adjusted until the appropriate potential criteria are attained over the entire foundation as indicated by the fixed reference electrodes; the competent person may be the CP designer;

i) At the earliest when the online CP monitoring data indicates that sufficient polarization has been reached, or at the latest after 100 days after energizing, a detailed potential survey shall be undertaken on all foundations fitted with the impressed current CP, to document that the system meets the performance requirement.

During surveys using ROVs or drop cell reference electrodes, the impressed current CP shall be switched ON and shall be operating in its normal auto potential (potentiostatic) control condition.

See 10.2.4 on monitoring during operating ICCP.

Particular attention should be given to ensuring that any CP system that has been switched off is turned on again and its performance confirmed before personnel leave the structure.

The physical condition and specific location of all DC power supplies, anodes, cables, conduits, and monitoring system components shall be verified and recorded at time of commissioning. The current and voltage output of each transformer rectifier shall be measured with calibrated portable instruments as shall the AC ripple at the DC output terminals of the equipment. The function of the RCD trip shall be proven. The DC current from each anode shall be measured with calibrated portable instruments.

13 CP surveying and monitoring

13.1 Objectives

The principal objective of CP portable survey and fixed monitoring is to determine the effectiveness of the CP system in preventing corrosion of the structure in the immersed zone and the buried zone close to or in the immersed zone. The structure to electrolyte potential data and other inspection results shall be used to assess whether any remedial measures are necessary in either the short or longer term to either fulfil the CP design or to ensure that cathodic protection is achieved for the structure service life, or both.

13.2 General considerations

The effectiveness of the CP is determined by measuring the structure to electrolyte potential at as many locations as are considered necessary. The assessment of the necessary locations shall be determined by the competent person, Clause 5 and 13.4. The locations shall include those most likely to be the least well protected (remote from anodes) and, in the case of impressed current systems, locations that may be excessively protected (close to anodes).

ICCP systems require fixed monitoring of all structures. It is recommended that GACP systems are fitted with fixed monitoring of representative structures.

Potentials measured using fixed reference electrodes installed on the structure on galvanic anode CP protected structures may be considered as essentially IR error free potentials. Potentials using “drop cell’s” will include a voltage drop in the larger distance in seawater between the electrode and the steel as explained above and will also indicate average data over a range of water depth. Hence potential readings obtained with drop cells should be considered as including errors and will almost always indicate potentials more negative (better protected) than reality.

Attention should be given to shielded areas and areas where large current drains are expected (e.g. jacket nodes and pile guides).

Due to structural effects of any corrosion, if fixed monitoring systems fail, or manually conducted drop cell measurements indicate inadequate CP system performance, this shall be immediately investigated and either rectified and mitigated with a minimum of delay, or both.

In addition to potential measurements, measurement of the anode current output provides information that may be used to verify that the installation is operating as intended and, in the case of galvanic anodes, to determine their remaining life, Clause 14. Current flow onto (or from) the structure can be assessed using field gradient methods.

Permanent CP monitoring systems have the significant advantage over portable surveys in being able to collect data in all weather conditions, all sea states and all tidal flow rates and close to the structure minimising IR drop errors. Depending on the extent of polarization, the quality of calcareous deposits and the water velocity, structure to electrolyte (seawater) potentials can be significantly less negative (less protected) during storms and high-water flow rates than in quiescent conditions. There are records of de-polarization of as much as 100 mV, see Reference [39].

Best practice in assessment of CP system performance is to assess the combined fixed monitoring and portable survey data, with the survey data informing the potential variations over the structure due to anode distribution, attenuation and variations in seawater flow velocity with depth, and fixed monitoring data informing potential variations due to environmental changes with time. This is particularly important because most foundation external CP surveys are undertaken by divers and small ROVs, or drop cell electrodes, and these are deployed, for safety reasons, in calm weather and often at slack tide. Under these conditions the CP performance will be unrepresentatively better (more negative) than during 'average' conditions of wave height, tidal flow rate and temperature.

Measurements using portable reference electrodes should supplement those from the permanent reference electrodes at the commissioning survey. It is recommended to perform comparative measurements between permanent electrodes and drop cell measurements, as the latter will be significantly in error due to being distant from the structure which adds IR error and results in measurements of average structure to electrolyte potentials and not local ones at the location of the electrode. If the portable electrodes are accurately placed by diver or ROV they can be used to 'calibrate' or validate the permanent electrode accuracy.

Techniques for monitoring the CP system are described in EN 13509[9].

NOTE 1 Potential measurements conducted at the galvanic anode only represents the anode to electrolyte potential as measured not the structure to electrolyte potential.

NOTE 2 Bare steel in seawater, with a CP system that operates in a way that most offshore CP systems have operated, will have begun to have established calcareous deposits within the first month of the CP system operation. After one month it can be expected that the structure to electrolyte potential will have reached the designed protection criterion, see Clause 7. Although there is merit in any data measured before this, structure to electrolyte potential data collected before the CP system has been working for a month is unlikely to indicate the longer-term performance. Over the following months, if the seawater flow velocity is static (it seldom is), the structure to electrolyte potentials will stabilize and, as the calcareous deposits become fully formed, the current density will reduce. This process of achieving protection levels and reducing current density will be disrupted by periods of high-water velocity (tidal currents and/or storms).

NOTE 3 The current density demands of bare steel in seawater at any given location will vary considerable with seawater flow velocity and to a lesser extent with temperature and oxygen concentration, see Annex C and Reference [39].

Factors affecting offshore wind structure CP performance and its assessment:

a) areas remote from anodes and controlling reference electrodes are likely to become less well protected in times of high seawater flow velocity;

b) high water velocity occurs with high tidal variations;

c) for those locations affected by estuarine fresh water flows galvanic anode system in particular will be affected by changes in water electrical resistivity. Less saline water will have a higher electrical resistivity, and this will reduce the ability of galvanic anodes to deliver current; levels of protection may deteriorate;

d) all survey data taken in calm weather, in the summer, is likely to be falsely optimistic if used alone to estimate full year performance;

e) for monopile foundations there will often be continuity cable bonds between the TP and MP; well-designed bonds in good condition may have voltage drops of 10 mV to 20 mV; bonds in poor condition or of inadequate design may have volt drops of ca. 100 mV. Most surveys, diver, ROV or drop cell measurements are undertaken with a connection to the TP; if the bond volt drop is 100 mV, a measured structure (monopile) to electrolyte (seawater) potential of −0,80 V wrt Ag/AgCl/seawater will actually be −0,70 V wrt Ag/AgCl/seawater. For this reason, a survey inspecting the physical condition of the MP/TP connections should be made and damage rectified if needed;

f) accurate structure to electrolyte potentials can only be measured with the reference electrode close (ideally < 50 mm) to the steel; although there are volt drop errors (making the data appear better than reality), as the electrode is further away from the structure the largest effect is that the measurement taken is increasingly an average of the entire structure and not a local potential level; for monopiles with the anodes on the TP, where there may be 200 mV attenuation down a bare monopile and where the least well protected values are close to the seabed, an electrode that is not located close to the structure may collect data some 100 mV more negative (better) than is the case on the MP near the bed; accurate reference electrode placement can be achieved by diver or ROV; drop cell surveys can produce poor data with electrodes taken many metres away from the structure by water current flow; the use of weighted guide wires shall be used to reduce these errors;

g) potential measurements utilizing 'direct metallic contact' (the test connection to the immersed foundation) at the point of measurement, either by diver or ROV, the measurements avoid errors due to volt drops in the TP/MP bonds, for coated structures this is however not recommended as stabbing electrodes will damage the coating.

As in 10.2.1 the operation and performance data for impressed current CP systems, including as a minimum, power supply dc output voltage and current and steel/electrolyte potential at all reference electrode locations should be available in real time at a central monitoring location and should generate out of optimal performance alarms.

For both galvanic anode and impressed current CP system detailed surveys, visual inspection reports (impressed current systems only), impressed current DC output voltage and current and fixed monitoring data shall be accurately reported, in detail, with fully identified data in respect of date, asset and foundation, locations and depths of measurements and, wherever possible, tide level, sea state and tidal flow rate.

It is essential that full records of any CP monitoring be maintained so that any trends are identified, and any necessary remedial measures can be planned and effectively carried out. In the case of retrofit considerations, additional surveys may be required either for the whole structure or parts of it, Clause 14.

Other observations of galvanic and impressed current anode physical state and visual inspections of both anodes and structure should also be recorded as part of the CP records, even if such observations are not part of a dedicated CP monitoring regime but see NOTE in 14.5.

13.3 Reference electrodes

The zinc/seawater electrode (Zn/seawater) and the silver/silver chloride/seawater (Ag/AgCl/seawater) reference electrode are the ones most commonly used in offshore applications. Where seawater salinity is expected to be variable or less than 30 ‰, then silver/silver chloride/0,5 M potassium chloride (Ag/AgCl/0,5 M KCl) reference electrodes may be used. The Zn/seawater electrode is not very accurate, but it is robust.

For measurements in sediments or below seabed, the Ag/AgCl/seawater electrode may not be useable due to sulphide contamination, and here Zn electrodes or Ag/AgCl/0,5 M KCl reference electrodes may be considered.

Dual reference electrodes with both the Zn and the Ag/AgCl/seawater (or 0,5 M KCl, where the seawater reference electrode is not suitable) elements are recommended to be used in fixed installations, see Annex H.

Reference electrodes used for field measurements shall be calibrated before and after use for measurements. This would normally be at the beginning and end of each day's work. Reference electrodes and their calibration are described in more details in ISO 12473.

13.4 Frequency of survey and monitoring

The number of measurements taken shall be determined by the complexity of the structure and the number, type (impressed current or galvanic) and location of the anodes. Sufficient measurements shall be taken to provide a representative view of the distribution of potential, including the likely least negative (least well protected) locations and the most negative locations (for impressed current systems, adjacent to the anodes, where over-protection is possible, causing damage to coatings and concerns regarding reduction of fatigue life).

Measurements should be repeated at the same representative locations at appropriate time intervals throughout the structure service life, so that trends in the protection level and hence CP system performance can be determined. Relative to the size of the offshore wind farms, this may be applied to a number of fixed structures combined with additional structures over a period of time, so that all turbine structures are measured over a period of 3 years to 10 years. If unexpected results are found, the number of measured structures should be increased; subject to the data first obtained, the detail and methods of survey may require revision.

For impressed current CP systems, the DC power supplies, anodes and reference electrodes shall be physically examined, in part by diver or ROV and the condition of all the above and below seawater cabling with its associated protective ducting, cable management and junction boxes shall also be assessed on a regular basis, with not more than 3 years to 5 years intervals.

Even for structures fitted with permanent CP monitoring equipment, an initial detailed structure to electrolyte potential survey (commissioning survey) shall be undertaken for a representative proportion of similar foundations, as defined in Clause 12. Thereafter, a schedule of detailed survey and checks are recommended at intervals to be agreed as part of the structure integrity management programme.

14 Retrofit cathodic protection systems

14.1 General considerations

When it is suspected that an existing CP system may need to be replaced or augmented, then as a first step, the existing performance levels e.g., potentials and potential distribution shall be determined prior to any retrofit design consideration. The starting point for such an assessment is the availability of any documented prior CP surveys and any prior knowledge of the original CP design, design criteria and as-built documentation. This study should be carried out not only for individual foundation structures but also across the windfarm development in order to determine the extent of any shortfalls in protection. For a large wind farm a study of a selection of structures can be undertaken provided the sample size ensures a realistic conclusion for the whole development.

Possible reasons for retrofitting CP systems or equipment are:

a) to augment a system installed at construction that did not achieve full polarization of the original structure;

b) to replace or augment a system that has failed in service e.g., an impressed current system that has proven unreliable, premature consumption of galvanic anodes or a galvanic anode system on a coated structure that could not maintain polarization as the coating deteriorated;

c) to provide continued protection to a structure when the original CP system has reached the end of its CP design life and the structure is required to continue operations for some time afterwards i.e. life extension.

In the case of a) and b) potential measurements collected over a period and compared in a chronological manner will indicate whether remedial measures are required after a more exhaustive, visual inspection of the installed anodes.

In the case of c) potential measurements alone will not indicate whether the CP design life of the existing CP system can be reassessed and possibly extended.

14.2 Survey before retrofit

Offshore retrofits are complex and high-cost undertakings. Any reductions in their scope that can be derived from an accurate and detailed survey and assessment of existing performance can produce considerable savings in the retrofit costs, greatly exceeding survey costs.

If an impressed current CP system has totally failed, there is little benefit in a detailed survey.

Galvanic anode systems seldom totally fail. They may be deficient in current or current distribution or restrained by failed or inadequate TP/MP or anode cage/MP bonds, or depleted and, while still operational, unable to provide the full current or likely to fail within the structure service life.

All of these different conditions require different remedial work or retrofits, and it is essential that the owner and the retrofit/remedial CP designer has sufficient survey data to fully understand why the work is needed, what its optimum extent is and what benefit can be relied upon from the original CP system. Critically, if the retrofit can be undertaken before the foundation is fully depolarized (the calcareous deposits dissolved), the design initial current density can be reduced.

On representative foundation structures across all types, sizes, depth variations and locations within the asset, a pre-retrofit survey shall be undertaken in accordance with a work instruction or specification prepared by a competent person, Clause 5.

In addition to prior survey data obtained in accordance with Clause 13 it will be advantageous to undertake a current density survey to measure cathode current density at the same location as potential measurements are obtained and also anode current densities.

NOTE The Swain Clip meter[52] or equivalent can be used for direct measurement of anode current through insert or other attachment arrangements and the Field Gradient Survey method (FiGS) or equivalent is a suitable field gradient measurement technique[40].

When it is considered that inadequate protection is being achieved, fixed reference electrodes should be installed on selected structures and potentials monitored over a period of time to determine the extent of seasonal and environmental conditions. It is recommended that a minimum of two separate structures in an asset are monitored in this way.

The extent of the survey shall be such that a competent person is able to determine the present performance of the CP system, the residual life of any components (e.g. bonds, anodes) and if possible, the causes of any deficiencies in the CP system.

All of the above work shall be closely supervised by the competent person, Clause 5 and all the equipment used shall be subject to regular calibrations at a minimum of each week and ideally every day. The calibrations shall be to a procedure prepared by the competent person and shall form part of the record of the survey.

From the survey the CP designer should be able to determine an optimum retrofit or remedial CP design.

14.3 Retrofit for inadequate protection

The design of a retrofit CP system to augment a system that has not fully polarized initially or maintained full polarization requires detailed assessment. It may be required to determine whether the original CP design was inadequate or whether there have been changes in operational parameters causing the installed system to become inadequate.

A thorough assessment of the current physical state of the existing CP system and equipment including any continuity bonds and anode attachments is essential in the design of any retrofit system being considered irrespective of the reasons for the proposed retrofit. In the case of augmentation, the design current density for retrofit CP resulting from new and existing anodes may be according to the data in Annex C unless other parameters can be justified.

14.4 Retrofit for structure life extension

The potential criterion used in the design of a retrofit CP system for structure life extension shall be in accordance with Clause 7.

A structure being considered for retrofit for structure life extension purposes may have an already well-formed calcareous layer if polarization levels at retrofit are not too positive. The demand for high initial current availability may therefore not be necessary.

If the actual operating current density is known this can be used as a basis for the retrofit. In the absence of known actual operating current density, the originally specified mean current densities can provide a margin of safety in the retrofit system leading to longer than designed CP system life in the case of galvanic anodes.

14.5 All retrofits

The existing CP system at point of retrofit may have substantial remaining life and will contribute to the combined CP system after retrofit. Due consideration of this contribution shall be taken into account when designing the additional retrofit requirements.

Depending on the circumstances of the retrofit the pre-retrofit distribution of potential is critical. In the case of structure life extension requirements this may show a general, although variable, potential levels. In the case of retrofit with inadequate potential levels, these may be confined to one or more specific locations on the structure and clear definition of this is essential if only "hot-spot" remedial measures are to be contemplated. Methods of potential measurement and potential distribution over time are discussed in Clause 13.

In either case the location of any retrofit equipment is critically dependent on the determined potential distribution.

If an impressed current system is reaching the end of its effective life, the anodes and reference electrode condition should be assessed and likely replaced. The condition of the associated protective ducting, cabling and junction boxes shall also be assessed.

For galvanic anode systems, anode mass requirements (and thus life) are an important part of the retrofit assessment. In this case not only shall the requisite additional current be supplied but the additional anodes mass to be supplied may be moderated by the already existing anode mass at the time of retrofit. It follows that a comprehensive study and calculation of the pre-retrofit state of the anodes is essential. The consumption of the existing installed anodes shall be determined to allow an assessment of their remaining current capacity over their remaining life.

Field gradient measurement techniques[40] using rotating reference electrodes provide a method of assessing actual current flows to or from structural surfaces and anodes and can allow a calculation of anode output with eventual calculation of overall current density to the structure. The measurement errors resulting from the measurement process are to be determined and conservatively taken into account in the current calculations. An estimate of addition current requirements can then be made.

The consumption to date of the anodes can be assessed from an extrapolation of the measured anode current output over the period of service. However, reliable field data are essential if sound decisions are to be made especially when calculating remaining CP system life or current availability from existing anodes.

NOTE A traditional method of assessing anode consumption is by visual and dimensional observation by divers. Estimates of the amount by which the anodes are depleted over a defined period can allow calculation of the overall average current supplied by the anodes by using the known alloy consumption rate. This requires an accurate and confident assessment by divers, but it is a subjective method of analysis based on visual conditions at the time. Different surveyors/inspectors may interpret wastage differently and can also report inconsistent evaluations of the same anode at different times.

In the case of a coated structure an assessment shall be made of the state of the coating, any coating breakdown and any physical damage which may have occurred. This may involve physical examination by ROV, or diver coupled with an assessment of current flows to the structure by field gradient measurement. Based on this assessment an estimation can be made by the CP designer (see Clause 5), possibly with support from a coating specialist, of the rate of coating breakdown until the end of the retrofit CP design life.

Once the amount of current to be supplied by the combined retrofit and existing systems has been determined, the amount of additional mass and current output (shape, spacing in the case of galvanic anodes) can be determined using conventional methods (Clause 8 in combination with Annex B and for instance data based on Annex C) to satisfy the revised CP design life. The location of additional anodes shall then be considered.

The resultant potential distribution from proposed anode locations should be subjected to computer modelling, see Annex I, which will allow a thorough assessment of the effects of the proposed retrofit solution and allow modification to optimize the location of any proposed retrofitted equipment. Modelling should inform CP current and potential distribution when replacing an original structure mounted CP system with a remote anode system.

Any retrofit CP system design should be documented in a design report see Clause 15.

Each foundation installation is unique depending on the above reasons for the retrofit which shall be considered on an individual basis and with a clear brief from the owner. However, since multiple installations in a windfarm development may be of identical design and generally of identical operational parameters, it is important to determine whether a retrofit is needed for all installations or particular individual installations at the location. The retrofit requirements, their design and implementation may possibly be considered to be the same for all installations across the project if all require remedial attention. Requirements will be different for each particular windfarm site location.

A key part of a retrofit design shall be the minimizing of offshore work boat, ROV and diver time by appropriate and possibly innovative high current anode usage, while ensuring optimum current and potential distribution. All assembly and set-up work that does not necessarily have to be carried out offshore should be carried out onshore in order to be able to save additional costs, which may amount to around 10 times the onshore costs (depending on the contractor and type of activity and work, more or less).

14.6 Equipment considerations

Monopile foundations, Figure 2 can be fitted with original CP equipment on remote cages as a retrofit operation after pile driving and TP installation. For these structures, galvanic anodes to be installed as a later retrofit will follow the same principles as for the original installation. However, it is likely that early CP designs did not adequately address anode/anode proximity and reduction in anode current output cause by this. Any retrofit using groups of galvanic anodes on cages, sleds or seabed arrays may be subject to mathematic modelling, Annex I to calculate the anode array current output as well as potential and current distribution over the structure.

Where galvanic anodes are installed pre-fitted to the TP, then retrofit anodes may be installed as remote anode assemblies on sleds or cages and cable connected to the original structure. Impressed current anodes can also be installed on remote sled assemblies.

For jacket foundation structures, see Figure 3, retrofit anode assemblies may either use remote sleds as for monopiles or galvanic anodes clamped around the tubular members at locations determined by current distribution considerations.

For retrofit applications involving mounting anodes on the foundation, the physical condition of structure for this purpose shall be inspected and assessed to confirm that the additional load can be carried, or whether remote anode locations should be considered.

When anodes are to be retrofitted either internally or externally, the original continuity bonds and their existing condition shall be reviewed and assessed in order to determine if they are, or will remain, adequate in dimension, connection integrity and electrical and physical loading capability. In this respect it is likely that the original design of these was not robust, either in respect of voltage drop or resistance to deterioration.

For internally retrofitted anodes, whether individually or in strings, they shall be individually connected together with insulated and sheathed copper cables, see Clause 11 extending above water so that secure connection can be made and anode currents correctly monitored.

Requirements for galvanic anode distribution and installation are included in Clause 9.

Impressed current anode distribution and installation considerations are included in Clause 10.

15 Documentation

15.1 General

The CP design and specifications for the materials, installation, testing, commissioning, performance verification along with recommendations for ongoing operation and maintenance of the CP system shall all be fully documented by the CP designer (see Clause 5).

The permanent records shall include as a minimum, the following documentation:

a) design report;

b) specifications for the materials and installation;

c) commissioning requirements with procedures;

d) as-built documentation including performance evaluation during commissioning;

e) operation and maintenance recommendations and procedures for performance verification during both structure service life and CP design life;

f) environmental check list (see Annex A).

These requirements shall apply to both internal and external CP designs.

15.2 Design report

15.2.1 General

The design report shall, as a minimum, document, detail and demonstrate the following:

— the basis for design.

— The relevant standards and codes-of-practice.

— The basis of selection of the CP system (galvanic anode or impressed current system) including a risk and consequence evaluation, in 6.3.

— The CP system design life and the reasons for any diversion between this and the structure design life.

— The period of delay between installation of the foundation and the CP system being connected and operational ('set to work'). An evaluation of the consequences during the delay period shall be made including an evaluation of possible temporary corrosion protection to be applied.

— The parts of the structure to be protected with CP intended to fulfil the CP performance criteria requirements for the CP design life. This is to be linked to the corrosion protection strategy for areas not provided with effective CP corrosion protection strategy.

— Description of system including system type, system layout and anode details.

— Coating break down factors adopted.

— Details of any specific installation methods required to achieve the required CP system performance and the CP design life.

— Any assumptions and requirements, e.g. operation and maintenance, required to achieve the CP design life and performance criteria.

— The chosen steel cathode current densities (initial, mean and final) at what elevations internally (if applicable) and externally including the current density for ‘current drained’ areas which will receive CP current but which are not anticipated to meet the design CP criteria and a justification for these (see Annex B and Annex C).

— The chosen anode current density and capacity or consumption rate and a justification for these.

— Calculations demonstrating, for all elevations and zones and including both primary and secondary steel, the surface area, and current demand for all representative foundation steel dimensions/designs, including current drain to areas beyond the intended extent of the CP for initial, mean and final conditions.

— If there are electrically discontinuous elements within the structure, such as Monopile and Transition Piece, justification for the selection of cable bonds and their connections, details and calculations of contact resistances, cable resistance and overall bond resistance and current capacity. Calculations to demonstrate that these resistances do not reduce the current output from anodes to an extent not accounted for in the CP design.

— An assessment of the period between the time that the CP system is first energised (or ′put to work′) and the chosen structure to electrolyte CP criteria and any other performance characteristics will be achieved.

— A consideration of the extent to which the performance will deteriorate (the structure to electrolyte (seawater) potentials become less negative) during non-storm days in the coldest month of the year in respect of seawater temperature and during peak seawater velocities and wave heights in storms.

— Demonstration that the protection criteria will be delivered, with both the least and most negative potentials anticipated and calculations which is recommended to include mathematical modelling, see 8.9 and Annex I, showing the anticipated structure to electrolyte (seawater) potentials and current density values over the structure at 3 months after the CP system is set to work, at the mid-point in the CP design life and in the last 3 months of the CP design life.

— If CP is to be applied to the inner surfaces, the mathematical modelling if applicable shall be completed as a single unified model with the external modelling and address any current and its resultant polarization of steel due to current flowing into the internal surfaces or out of the structure internals from the anode system intended for the internal surfaces. If the inner surfaces are to free flooding compartments or to compartments with significant water flows with the tidal changes, the holes or openings between outer and inner surfaces shall be addressed in the modelling.

— An index of all documents that were used as sources of input in the design process, including any relevant standards and codes, identifying if there are conflicts between the CP design in the source documents, standards or codes along with which parts of these are used and which parts are not used, with justification for these choices.

— An index of all output documents prepared or in the process of preparation in order to document the design process.

— The CP designer’s recommendations for performance assessment of the CP systems, see Clause 13.

— A sensitivity assessment of extraneous factors which could affect the reliability of the design.

— A Designer’s risk register and any health, safety and environmental issues, including where relevant local regulations have been considered in the design.

15.2.1.1 Galvanic anode CP system

In addition to 15.2.1, the following shall be considered and documented for GACP systems

— Calculations to determine the number, distribution, size and anode capacity (mass, utilization factor and A·h capacity for the anodes.

— The assumed or measured conditions inside any flooded areas of the structure intended to receive CP or to be subject to some other corrosion protection strategy including water replenishment rates, oxygen concentration, water flow rates and internal water levels.

— Calculations and modelling to demonstrate that the steel core cast into the anodes will deliver the design utilization factor and that the calculated final or re-polarization current can be delivered at the end of the CP design life.

15.2.1.2 Impressed current CP system

In addition to 15.2.1, the following shall be considered and documented for impressed current CP systems.

— Selected anode material and geometry, selected power supply type, method of protecting cables, the extent of remote (from onshore) monitoring and control.

— The selected cable materials and sizes. Calculations of cable current capacities and voltage drops demonstrating, for all anodes and peak current output that the designed cable cross section allows uniform anode current output at a common power supply voltage, i.e. with a <10 % variation.

— The selected dielectric shield materials and dimensions and a justification for these. The justification shall include a detailed assessment of the reliability of the selected items for full CP design life without offshore interventions.

— Calculations to determine the power supply current and voltage outputs and the necessary characteristics of AC ripple on the DC output along with the requirements for surge (electrical fault and lightening) protection on all input and output circuits.

— Calculations to determine the number, distribution, size, composition, wear rate and life for anodes.

— The chosen performance monitoring sensors, which may include but not limited to reference electrodes for structure to electrolyte potential measurements, coupons or monitored anodes for current density or current measurement or coupons for corrosion rate or confirmation of corrosion protection and locations for these.

— Due to the considerable operation and maintenance demands of impressed current CP systems, the operation and performance data should be available in real time at a central monitoring location, anticipated to be onshore and linked to the turbine performance central monitoring location and should generate out of optimal performance alarms. The operating procedures and personnel requirements for operation and seeking specialist advice, where necessary, shall be documented.

15.3 Material specification requirements

15.3.1 General

The specifications shall comprehensively describe all CP materials, in sufficient detail to issue for purchasing, which will ensure the design requirements are met. Further requirements are detailed in Clause 9 and 10.

The specification shall detail installation procedure including all details of the works necessary to carry out the works.

The specification shall include the requirements for quality plan and quality control documentation with inspection and test results.

15.3.2 Galvanic anodes

The anode specifications and drawings shall ensure that, for galvanic anodes, the designed anode casting and core dimensions determined to deliver the CP performance shall not be varied by the construction contractor or the anode supplier. The anode cores and their welding details to the structure shall be subject to structural assessment.

Specification for the galvanic anodes shall detail, as a minimum, the following:

— conformity with EN 12496;

— conformity with the CP design anode dimensions, with the minimum nett mass (of alloy) for each anode and the minimum anode length for each anode being not less than the anode design mass and dimensions;

— core dimensions and material in conformity with the CP design anode core dimensions and material;

— requirements for manufacturer's drawing of anode construction, inspection and test plans and approval mechanism for these;

— composition of the anode alloy being close to the composition upon which the design A·Hr capacity is based; this may require closer compositional limits than permitted in EN 12496;

— number of anodes of each size within the design to be destructively tested in order to demonstrate the core location, any voids and/or porosity of the casting are in accordance with EN 12496;

— number of samples from the furnace(s) for chemical analysis and for electrochemical testing and the acceptance criteria for these tests;

— inspection requirements and access for inspection by or on behalf of the owner;

— documentation required;

— packaging instructions to protect the anodes during transportation and handling.

15.3.3 Impressed current CP materials

15.3.3.1 Anodes

Specification for the impressed current anodes shall detail the following:

— type of anodes, the active element (e.g. mixed metal oxide) composition or type, coating, loading, wear rate, life and material substrate (e.g. titanium);

— anode design life to be achieved at the current rating required by the CP design;

— requirements for accelerated testing data to demonstrate performance of the anode active element on its substrate, if there is a substrate;

— requirements for testing to demonstrate the coating loading on the substrate and adhesion between the coating and the substrate, if there is a substrate;

— track record requirements of the selected anodes in marine environment;

— dimensions and tolerances;

— requirements for manufacturer's specifications and drawings of the cable-anode connections including the testing procedure and acceptance criteria for electrical continuity, chemical resistance and mechanical integrity;

— requirements for manufacturer's drawing of overall anode assembly construction and inspection and test plans and approval mechanism for these;

— inspection requirements and access for inspection by or on behalf of the owner;

— documentation required;

— packaging instructions to protect the anodes during transportation and handling.

15.3.3.2 Cable materials

For the DC current and monitoring cables specifications shall include as a minimum:

— type of formation, conductor material, cross section;

— longitudinal resistance;

— insulation material and minimum thickness and colour;

— sheath material and minimum thickness and colour;

— rated voltages;

— mechanical shielding or armouring if needed;

— requirements for manufacturer's drawings of cable construction and testing regime and approval mechanism for these;

— any inspection requirements and access for inspection by or on behalf of the owner;

— documentation required;

— packaging instructions to protect the cables during transportation and handling.

The cables shall be in accordance with the relevant IEC Standards which shall be defined in the specifications.

15.3.3.3 DC power supplies

Specification for the DC power supplies shall detail the following:

— CP system design life and the requirement for the DC power supply to meet this;

— environment of the installation site, including temperature, relative humidity and exposure to chlorides or other corrosive elements;

— type (e.g. transformer rectifier or switch mode);

— power supply design life without significant component replacement;

— AC input, phases, frequency and voltage;

— DC output current and voltage and DC output control;

— required over-voltage and over-current protections, lightning protection (for all circuits, input and output including monitoring);

— transformer construction characteristics and class (if applicable);

— rectifier construction characteristics;

— maximum DC. ripple and frequency;

— cooling and temperature control;

— enclosure material, IP protection degree and any requirements for coating maintenance during DC power supply design life;

— auxiliaries and accessories: controls, alarms, signals and measurements, terminals, nameplates, safety tags;

- requirements for manufacturer's drawing of DC power supply construction, circuit diagrams and inspection and test plans and approval mechanism for these;
- interface with data acquisition system;
- spare parts for commissioning, 2 years operation, 5 years operations;
- inspection and Factory Acceptance Test (FAT) requirements and access for inspection by or on behalf of the owner;
- documentation required;
- packaging instructions to protect the DC power supplies during transportation and handling.

15.3.3.4 Junction boxes

Specification for the junction boxes shall detail the following

- environment of the installation site;
- IP protection degree;
- materials of the enclosure and of internal equipment;
- colour;
- terminals of the DC positive, negative (if applicable), monitoring and data acquisition system junction boxes;
- labelling to identify all terminals;
- requirements for manufacturer's drawing of junction box construction and approval mechanism for these;
- any inspection requirements and access for inspection by or on behalf of the owner;
- documentation required;
- packaging instructions to protect the junction boxes during transportation and handling.

15.3.3.5 Reference electrodes

Specification for the reference cells shall detail the following:

- type of electrode or reference electrode (e.g., Zn, Ag/AgCl/seawater, Ag/AgCl/0,5 M KCl; single or dual);
- composition, mass and form of electrode elements;
- enclosure material and form of electrode casing;
- cable details (e.g., conductor form, material, resistance, insulation, sheath, number of cores, form of construction, filling, shield, armour, sheath, diameter, colour) length;
- requirements for manufacturer's drawings of reference electrode construction, inspection and test plans and approval mechanism for these;
- manufacture's calibration test;
- identification or labelling of individual electrodes;
- any inspection requirements and access for inspection by or on behalf of the owner;
- documentation required;

— packaging instructions to protect the junction boxes during transportation and handling.

15.3.3.6 Data recording equipment

For the data acquisition system and/or data logger:

— parameters to be acquired and recorded;

— hardware and software specifications;

— data acquisition system requirements: number of acquisition channels, type of interfaces, type of clock and acceptable error, accuracy of the acquisition channels, operating temperature and thermal drifts, acquisition interval, data storage capacity, autonomy of the battery, digital filters, alarm set points, AC input type;

— software requirements: input signals and interfaces, output data required and their organization, compatibility of data with software for data export and analysis;

— environment;

— enclosure;

— protections;

— auxiliaries and accessories: nameplates;

— spare parts for commissioning and for 5-year operations;

— specifications for acceptance tests;

— inspection and Factory Acceptance Test (FAT) requirements and access for inspection by or on behalf of the owner;

— documentation required;

— packaging instructions to protect the DC power supplies during transportation and handling.

15.4 Installation drawings and specifications

The overall CP system shall be detailed on the structure drawings.

These shall detail the locations of all CP materials including all anodes, power supplies, bond cables, monitoring or data logging systems, junction boxes, reference electrodes, cables, cable management systems, ducts, conduits, penetrations and shall detail the fixings of all these CP components to the structure. All these locations shall be in accordance with the CP design.

Detailed drawings shall be provided for all cable routes, the cable management systems for them and location of galvanic anodes.

Where appropriate, specific installation specifications shall be prepared.

15.5 As-built installation and commissioning report requirements

An as-built installation and commissioning report for the CP system shall be prepared and shall incorporate as a minimum the following:

a) A general description of the system, parties associated with the system (e.g., owner, CP designer, contractor, specialist sub-contractor, vendor etc) and the key personnel responsible for the design, supervision and commissioning of the CP system and their respective responsibilities.

b) A copy of the method statements and/or specifications and drawings in accordance with which the CP system was installed and commissioned, indicating all deviations or variations there from.

c) A detailed description of the installation and commissioning works including key data.

d) As-built drawings detailing the installation and its components in sufficient detail to facilitate all future requirements for inspection, maintenance and reconstruction of the system and its major components.

e) All measurements and test data taken before or during commissioning.

f) A record of the "as-left" operating conditions of the system.

g) All test instrumentation shall have valid calibration certificates following ISO 17025 traceable to national or European Standards of calibration. The documentation shall constitute part of the permanent records for the works.

The as-built installation report shall record any changes from the design parameters not known or envisaged at the time of the design. Any subsequent changes to materials, their location or anticipated life shall be highlighted with justification for such changes.

Commissioning data should include the results of surveys conducted after energizing (setting to work) each CP system in order to assess if it satisfies the CP design criteria and operates effectively, including structure to electrolyte potential measurements to demonstrate that the CP protection criteria are achieved over the entire structure intended to be protected by CP.

15.6 Operation and maintenance requirements

An operational and maintenance manual for the CP system shall be prepared and shall incorporate as a minimum the following:

a) Reference to a detailed description of the system (design report), initial performance documentation and a set of "as-built" drawings and documentation.

b) Reference to commissioning data, documenting adequate performance at time of first polarization.

c) Details of recommended maintenance and inspection intervals and procedures.

d) Templates for data sheets for all recommended maintenance, inspection and performance assessment activities.

e) For impressed current systems, operating procedures for the DC power supplies and performance monitoring systems, including error finding procedures and remedial actions as appropriate. Due to the operation and maintenance demands of impressed current CP systems, the operation and performance data should be available in real time enabling the CP specialist to respond to out of optimal performance alarms. The operating procedures and personnel requirements for operation and seeking specialist advice, where necessary, shall be documented.

f) A list of the major components of the CP system with data sheets and the source(s) of spare parts and/or maintenance for these components and for the overall system.

Other documents can also be included as considered necessary.

Each stage of the installation, commissioning and operation shall be either the subject to appropriate visual, mechanical or electrical testing, or all and all testing shall be documented.

16 Safety and cathodic protection

16.1 Objectives

The CP system shall comply with all safety standards and regulations related to electrical equipment that may apply to offshore wind installations.

This Clause deals with safety hazards due to CP systems and related to diving personnel during their underwater operations. Safety aspects of diving operations are outside the scope of this document. Reference should be made to appropriate statutory regulations.

The galvanic anodes system and the impressed current system are considered, in association with the following main dangers: physical obstruction, electric shock, and evolution of dangerous gases.

16.2 Physical obstructions

The major risk from anodes is the entanglement of the diver's umbilical or lifeline around the anodes or the anode supports, and the mechanical damage to the equipment due to chafing. Thus, the following galvanic anode and anode assembly characteristics are recommended:

a) galvanic anodes with bent-shaped cylindrical stand-off supports, protruding from anode ends

b) flush mounted anodes

Similarly, for example, anode cable conduits and junction boxes should be designed to exclude any sharp edges or corners or protruding ends.

For particular situations where anodes are installed in areas where gas can collect, explosion hazard can arise unless measures are taken. This could be a risk aspect inside a monopile, see 8.2.3.

16.3 Protection against electric shock

Depending on the field gradient around the impressed current anodes, divers may be adversely affected and impaired. The safety risk is related to the operating voltage and the AC ripple. See IMCA document[31]. In the event that an impressed current CP system equipment is defective, or the diver inadvertently makes direct contact with the active anode element, the diver might suffer an electric shock.

During diving operations whether related or not directly related to CP system, and any diving inspection carried out close to impressed current anodes, it may be required that the DC supply to CP anodes is switched off.

Collection of cathodic protection performance data shall not be undertaken with the CP system switched off because the data will be invalid.

NOTE 1 Despite the advice in the IMCA document[31], many diving contractors will refuse to dive when impressed current systems are switched on. Thus, it may not be possible to survey the performance of impressed current CP systems using divers. ROV's should not be affected and should not require the CP system to be switched off.

NOTE 2 It is possible to design impressed current systems that are safe for proximate diver operation and that can be proven to be so. This involves the secure limiting of AC ripple in the DC current output of the CP system and limiting the power supply and anode operating voltage. Proof of safety can be by DC and AC field gradient measurement ahead of diver approach to CP anodes. See Reference [31].

If the CP system is switched OFF for any reason, particular attention should be given to ensuring that any CP system that has been switched off is turned on again and its performance confirmed before personnel leave the structure.

16.4 Gas evolution

16.4.1 Hydrogen evolution

Polarization of the structure to potential more negative than −0,80 V wrt. Ag/AgCl/seawater reference electrode can result in the evolution of hydrogen gas at the steel surface. If the gas is allowed to collect in confined air spaces, such as monopiles that are only part full of seawater, it may present a risk of explosion.

To avoid this hazard, the following measures should be taken:

a) all designs to include an adequate venting to prevent the build-up of hydrogen,

b) the structure to electrolyte potential to be kept at values less negative than the threshold value at which hydrogen evolution is not significant.

16.4.2 Chlorine evolution

Electrochemical reactions at the surfaces of impressed current anodes in seawater invariably result in the evolution of chlorine gas, which is highly toxic and corrosive. If this is allowed to collect in confined air spaces above the water line, it may present a hazard to personnel and materials.

To avoid this hazard, all designs shall prevent the build-up of gas, e.g., by installing a ventilation system, with a recommendation that the ventilation is powered and monitored in case of power failure. Also, it is recommended to monitor that gas levels are within safe limits.

Annex A
(informative)

Environmental checklist

Document number (if available):	Title of standard: **Cathodic protection of offshore wind turbine structures**	**ISO TC156, WG10**
	Version of the environmental checklist: **First draft**	Date of last modification of the environmental checklist:

Environmental Issue	**Stages of the CP system life cycle**										**All stages**
	Acquisition		**Production**		**Use**			**End-of-Life**			
	Raw materials and energy	**Pre-manufactured materials and components**	**Production**	**Packaging**	**Use**	**Maintenance and repair**	**Use of additional products**	**Reuse/Material and Energy Recovery**	**Incineration without energy recovery**	**Final disposal**	**Transportation**
Inputs											
Materials											
Water											
Energy											
Land											
Outputs											
Emissions of dangerous gases											
Release of hydrogen gas											
Chlorine evolution											
Waste											
Noise, vibration, radiation, heat											
Other relevant aspects											
Risk to the environment from accidents or unintended use											
Customer information											

NOTE 1 The stage of packaging refers to the primary packaging of the manufactured product. Secondary or tertiary packaging for transportation, occurring at some or all stages of the CP system life cycle, is included in the stage of transportation.

NOTE 2 Transportation can be dealt with as being a part of all stages (see checklist) or as separate sub-stage. To accommodate specific issues relating to product transportation and packaging, new columns can be included and/or comments can be added.

<table>
<tr><td colspan="3">Document number (if available):</td><td colspan="5">Title of standard:
Cathodic protection of offshore wind turbine structures</td><td colspan="4">ISO TC156, WG10</td></tr>
<tr><td colspan="3"></td><td colspan="5">Version of the environmental checklist:
First draft</td><td colspan="4">Date of last modification of the environmental checklist:</td></tr>
<tr><td>Environmental Issue</td><td colspan="10">Stages of the CP system life cycle</td><td rowspan="2">All stages</td></tr>
<tr><td rowspan="2"></td><td colspan="2">Acquisition</td><td colspan="2">Production</td><td colspan="3">Use</td><td colspan="3">End-of-Life</td></tr>
<tr><td>Raw materials and energy</td><td>Pre-manufactured materials and components</td><td>Production</td><td>Packaging</td><td>Use</td><td>Maintenance and repair</td><td>Use of additional products</td><td>Reuse/Material and Energy Recovery</td><td>Incineration without energy recovery</td><td>Final disposal</td><td>Transportation</td></tr>
<tr><td colspan="12">Comments:</td></tr>
<tr><td colspan="12">NOTE 1 The stage of packaging refers to the primary packaging of the manufactured product. Secondary or tertiary packaging for transportation, occurring at some or all stages of the CP system life cycle, is included in the stage of transportation.

NOTE 2 Transportation can be dealt with as being a part of all stages (see checklist) or as separate sub-stage. To accommodate specific issues relating to product transportation and packaging, new columns can be included and/or comments can be added.</td></tr>
</table>

Annex B
(normative)

Method of using metocean data to calculate marked-up seawater flow velocity

B.1 Abbreviations

Abreviations are given in Table B.1.

Table B.1 — Abbreviations used in Annex B

Abbreviation	Unit	Description
CD	Deg.	Current speed direction (going towards)
CS	m/s	Current speed (depth averaged)
FWZ	m	Frequently wetted zone
h	m	Water depth (distance from seabed to still water level)
HAT	m	Highest Astronomical tide
H_{m0}	m	Significant wave height (based on hydrodynamic modelling)
H_{rms}	m	Root mean square wave height
k	m^{-1}	Wave number
L	m	Wavelength
L_0	m	Deep-water wavelength
LAT	m	Lowest astronomical tide
MWD	Deg.	Mean wave direction (coming from)
SWL	m	Still water level (excluding water surface variations due to waves)
t_{m-1}	s	Wave period (based on −1st moment of wave spectrum)
t_p	s	Peak wave period
$U(z)$	m/s	Current velocity at level z above applied datum
WL	m	Water level or still water level (SWL) excluding water surface variations due to waves
z	m	Vertical upward coordinate
σ_u	m/s	Standard deviation of wave orbital motion

B.2 Introduction

For CP design a methodology to derive a long-term time averaged velocity profile of combined waves and currents is presented.

NOTE 1 The actual data presented in this Annex relates to a specific site location and is for illustrative purposes only.

Metocean data (water levels, waves, seawater currents, wind, and water- and air properties) are in offshore wind applied for a large variety of purposes - including design conditions for corrosion protection.

The metocean data handling is to be done as described in this annex and used as described in 8.6 using also input from for instance Annex C.

For corrosion and CP, the relevance of seawater flow relates to frequently occurring conditions of structure wetting and seawater flow velocity:

a) Frequently wetted zone;.variations in water level and wave conditions result in parts of the structure being permanently immersed, other parts frequently wetted and other part only splashed/sprayed or rarely wetted. The part of the structure frequently wetted due to water level variations and wave passage will drain electric currents from the CP system.

   For CP design a FWZ is defined representing the frequently wetted part of the structure.

b) Seawater flow velocity; the seawater flow velocity from combined waves and seawater currents influence the required CP cathodic current density to protect the structure. The higher the water flow velocity the higher the required current density to protect the structure. The water flow velocity influences and normally delays CP polarization/calcareous deposit development.

The variation in seawater flow velocity and seawater level is complex. Both in regard to the instantaneous flow patterns around a foundation and further in terms of the current velocity, water levels and wave conditions changing due to astronomical tides and passage of meteorological weather systems.

Metocean data can typically be provided as long-term time series with hourly values of relevant properties. The data are derived combining meteorological and hydrodynamic modelling, calibrated, validated and sometimes assimilated to measured properties. Available or dedicated metocean studies can provide hindcasted data dating back to late 1970s for most wind farm sites undergoing maturation.

Wave height of a surface wave is defined as the difference between the elevation of a crest and a neighbouring trough. For consistency with Metocean terminology, the term “current speed” is in this Annex used for the water flow currents present in the sea due to tide and wind forcing. The current speed together with the water motion due to waves makes up the water flow rate.

B.3 Metocean conditions

The sea state parameters of metocean modelling are typically defined by:

— water level (WL) (sometimes named still water level (SWL));

— depth average current speed (CS);

— significant wave height (H_{m0});

— peak wave period (t_p).

An example of these parameters is shown in scatter plots below in Figure B.1. The water level is shown relative to mean sea level (MSL).

The sea state properties can be detailed further:

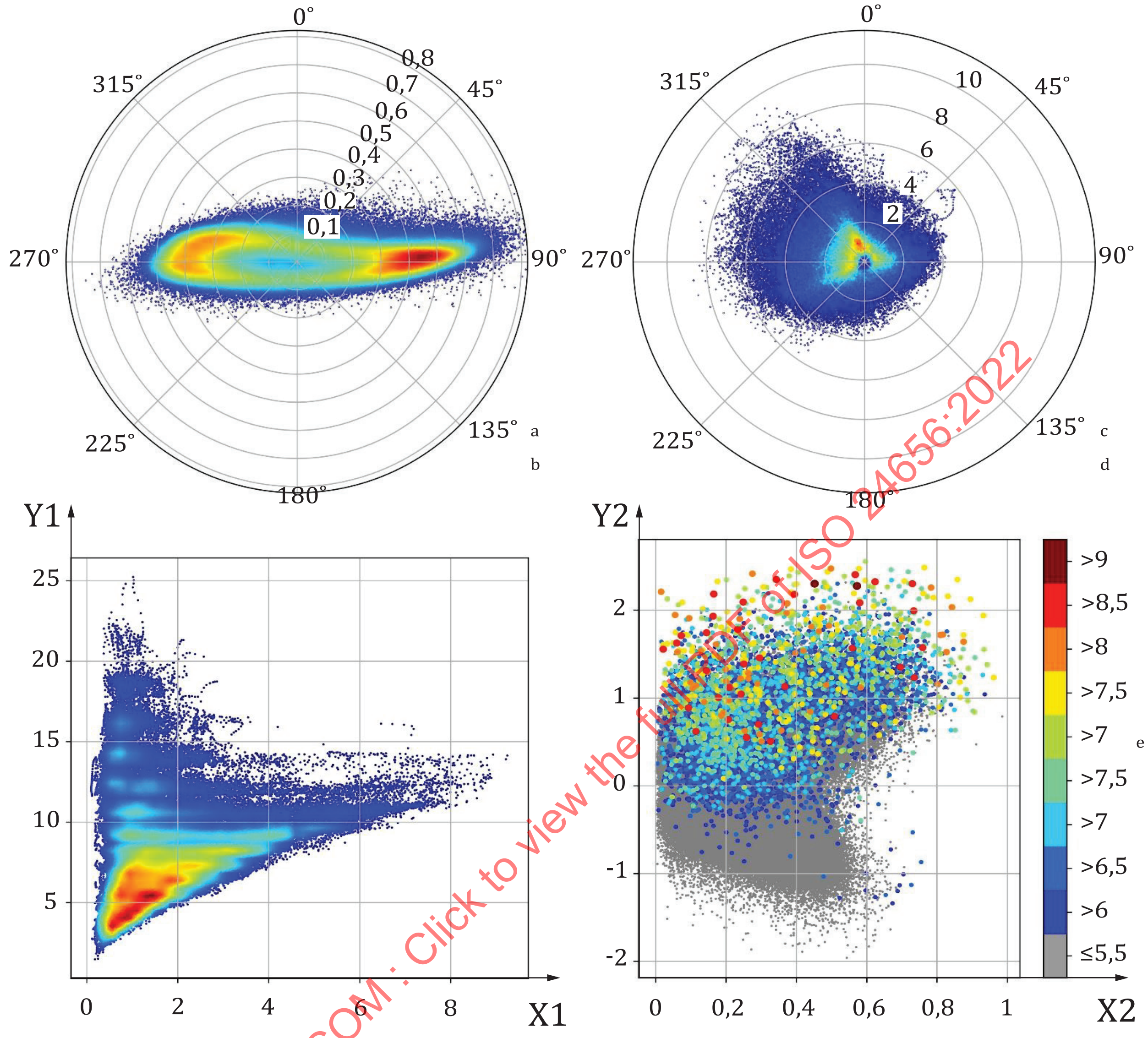
— The water level can be split into tidal and surge components.

— The current speed can be detailed with a velocity profile.

— The wave conditions can be detailed with wave spectrum information (the wave spectrum describes how the irregular waves observed in the seas can be decomposed (analysed) into a combination or regular waves of varying height and period).

Water column stratification can be observed in enclosed basins such as the Baltic Sea. In stratified water columns, the top layer is typically warm and low saline, while the lower layer will be colder and has a higher salinity. The stratification can be seasonal or permanent.

An example of site data showing metocean data can be seen in Figure B.1.



Key

X1 Significant wave height, H_{m0}, [m]

Y1 Peak wave period, t_p, [s]

X2 depth averaged current speed, *CS*, [m/s]

Y2 water level, WL, here given relative to Mean Sea Level (MSL) [mMSL]

a Current direction, CD, going towards [deg.].

b Depth averaged current speed, *CS*, [m/s].

c Mean wave direction, MWD, [deg.].

d Significant wave height, H_{m0}, [m].

e Significant wave height, H_{m0}, [m].

NOTE Site example. Hourly data 1979-2015.

Figure B.1 — Metocean conditions

B.4 Frequently wetted zone

The FWZ is the part of the structure that intermittently is immersed in water due to water level variations and passage of waves. A good estimate for the Frequently Wetted Zone can be obtained by coupling the water level and wave height time series.

Waves are nonlinear having higher crests than troughs. Wave run-up (increase in height at the structure) occurs on the front and back of the structure. The effect of nonlinearity and run-up will increase structure wetting.

The significant wave height, H_{m0} will in open seas be approximately equivalent to the mean of the third largest waves and can be taken as a good proxy for the wave height resulting in structure immersion due to waves. A simple expression for the Immersion Zone can be obtained from Formula (B.1):

$$\mathrm{FWZ}(t) = \mathrm{WL}(t) + H_{\mathrm{m0}}(t) \tag{B.1}$$

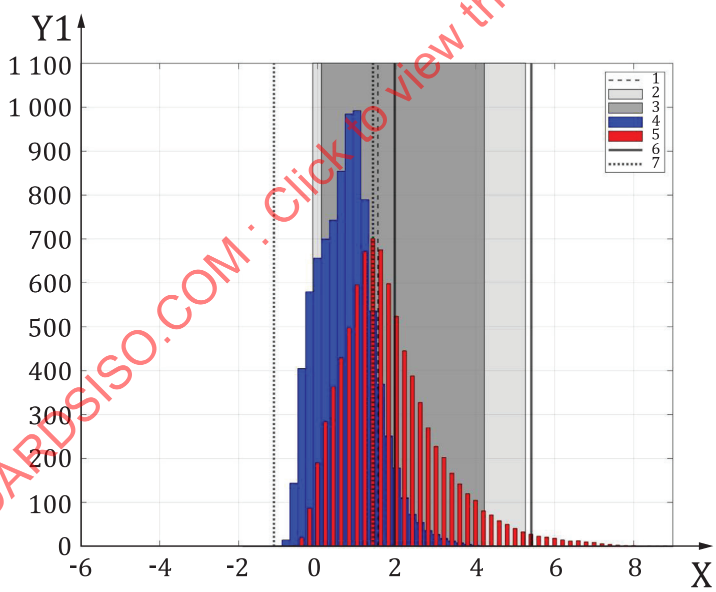
where t is time. For floating structures WL(t) should be replaced with FBL(t), where FBL(t) is free board level of the floating structure.

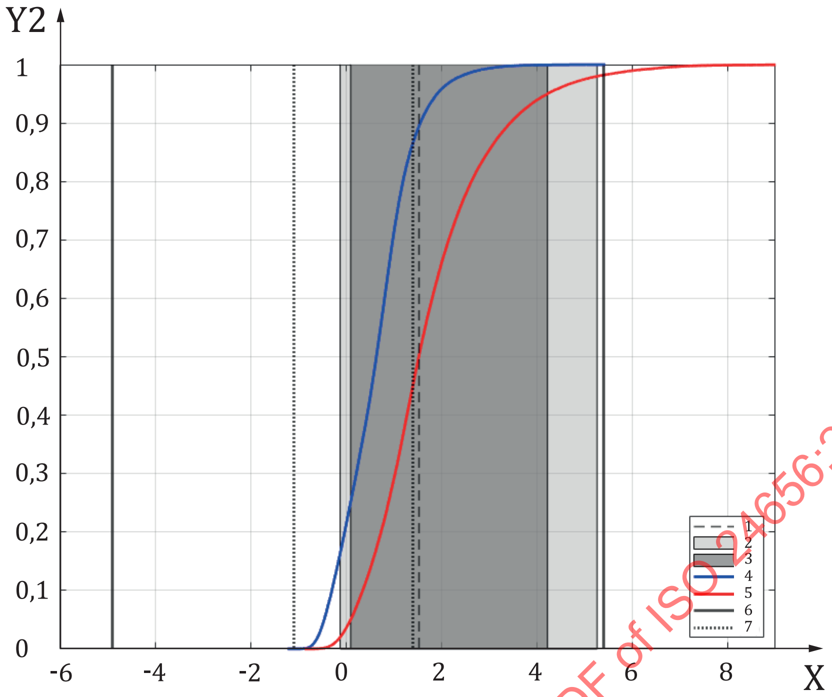
Quantiles of the frequently wetted zone can then be applied for the CP design:

— $\mathrm{FWZ}_{50\,\%}$: The 50 percent quantile of the frequently wetted zone can be taken as a good estimate of the level to which the structure impacts the mean anode drain.

Applied to the example site location, the calculated frequently wetted zone is in Figure B.2 compared to a more complex approach considering the individual waves in the sea for individual wave run-up (IWR). The simple approach is noted to conservatively give a slightly higher located frequently wetted zone than the individual wave run-up (IWR) analysis. Details of the individual wave analysis are given at the end of this annex.

Included in Table B.2 is also the IEC 61400-3-1[13], splash zone (SZ), defined from one-year return period values of still water level and significant wave height.





Key

X [m MSL]

Y1 [hours/year]

Y2 $1-P_x$

1 $FWZ_{50\ \%}$

2 $FWZ_{2-98\ \%}$

3 $FWZ_{5-95\ \%}$

4 FWZ : IWR

5 FWZ : SWL + H_{m0}

6 SZ (IEC 61400-3-1)

7 LAT / HAT

NOTE Site example. Hourly data 1979-2015. P_x is the exceedance probability.

Figure B.2 — Frequently wetted zone and splash zone

Table B.2 — Example comparison of the frequently wetted zone and splash zone

	Frequently wetted zone [m MSL]			Splash zone [m MSL]	
Method	$FWZ_{5\ \%}$	$FWZ_{50\ \%}$	$FWZ_{95\ \%}$	Lower level	Upper level
WL + H_{m0}	0,1	1,5	4,2	-	-
IEC 61400-3-1:2019[13]	-	-	-	−4,9	5,4

B.5 Seawater flow velocity

B.5.1 General

For CP design a long-term average seawater flow velocity profile can be derived representing mean water flow rates across the water depth from seabed to a given frequently wetted zone quantile e.g. $FWZ_{50\,\%}$ and $FWZ_{95\,\%}$. The average velocity profile can be split into contributions from current speed, wave motion and local flow patterns and turbulence caused by the structure.

B.5.2 Current speed

Current speed is driven in part by wind forcing and in part by tide and surge. The tide and surge driven current, $U_c(z)$, has a logarithmic velocity profile, often simplified with the power law profile[25], shown by Formula (B.2):

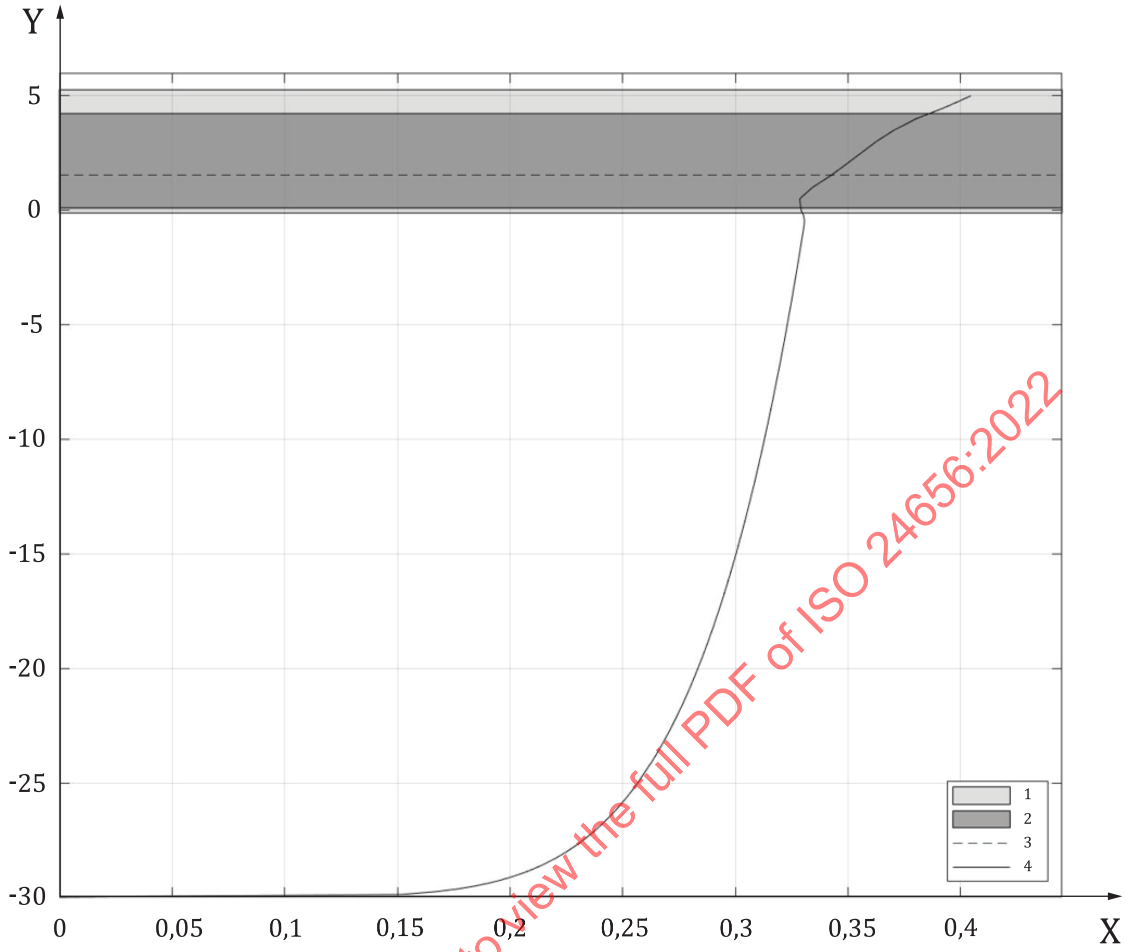
$$U_c(z) = \frac{8}{7} CS \left(\frac{z+h}{h} \right)^{1/7} \tag{B.2}$$

In addition to this, the wind forcing generates a surface friction driven triangular shaped velocity profile extending 10 m to 20 m down into the water column.

The wind friction driven current will in hydrodynamic modelling be included in the depth averaged current velocity. For simplicity, the power profile can be taken to represent both tide, surge and wind component of the current profile.

Long term average current velocity profile is exemplified in Figure B.3 based on hourly values of the 36-year long metocean modelling time series.

Within the Frequently Wetted Zone, the averaging current velocity profile covers only the period of time, in which the water level has reached this height. For example, for z = $FWZ_{95\,\%}$, the averaging is based on the 5 percent of the time in the data time series that this level is exceeded, i.e., when water level in a time step of the hydrodynamic modelling is below $FWZ_{95\,\%}$, the time step is not included in the averaging for the current speed for this level.



Key

X $U_c(z)$ [m/s]

Y z [mMSL]

1 $FWZ_{2-98\ \%}$

2 $FWZ_{5-95\ \%}$

3 $FWZ_{50\ \%}$

4 $U_c(z)$

NOTE Site example - 30 m water depth. Hourly data 1979-2015.

Figure B.3 — Long term time average current velocity profile

B.6 Wave motion

Wave motion generates elliptical shaped flow circulation in the water column – so-called orbital velocities. This wave motion decays fast towards the seabed. The velocity amplitude of the orbital velocity follows a hyperbolic profile, defined by wave height, wave period and water depth. The wave orbital velocity amplitude of irregular waves can be described by the standard deviation (σ_u) of the wave orbital motion.

An approximate vertical profile of the standard deviation of the wave orbital velocity can be derived as Reference [41] by the use of the following Formula (B.3):

$$\sqrt{2}\sigma_u(z) = \frac{\pi H_{\rm rms}}{T_{m-1}} \frac{\cosh[k(z+h)]}{\sinh(kh)} \tag{B.3}$$

NOTE Reference [41] only contains the expression in its reduced form as it looks when evaluated at seabed (z = -h), where the denominator for the hyperbolic decay of wave motion equals 1. For evaluation of the velocity profile across the water depth we simply replace "1" with "$\cosh[k(z+h)]$".

$\sqrt{2}$ factor applied on the left-hand side in the expression is included to make the equation consistent with regular waves. I.e., for a regular wave the velocity amplitude is equal to $\sqrt{2}\sigma_u$. The root-mean-square wave height, $H_{\rm rms}$, in the expression can be taken as given by Formula (B.4):

$$H_{\rm rms} = \frac{H_{m0}}{\sqrt{2}} \tag{B.4}$$

The wave period $t_{\rm m\text{-}1}$ can be approximated by:

$$t_{m-1} = \frac{\rm t_p}{1{,}1} \tag{B.5}$$

The wave number, k, is defined from the wavelength as:

$$k = \frac{2\pi}{L} \tag{B.6}$$

where L is the iteratively determined water depth dependent wavelength:

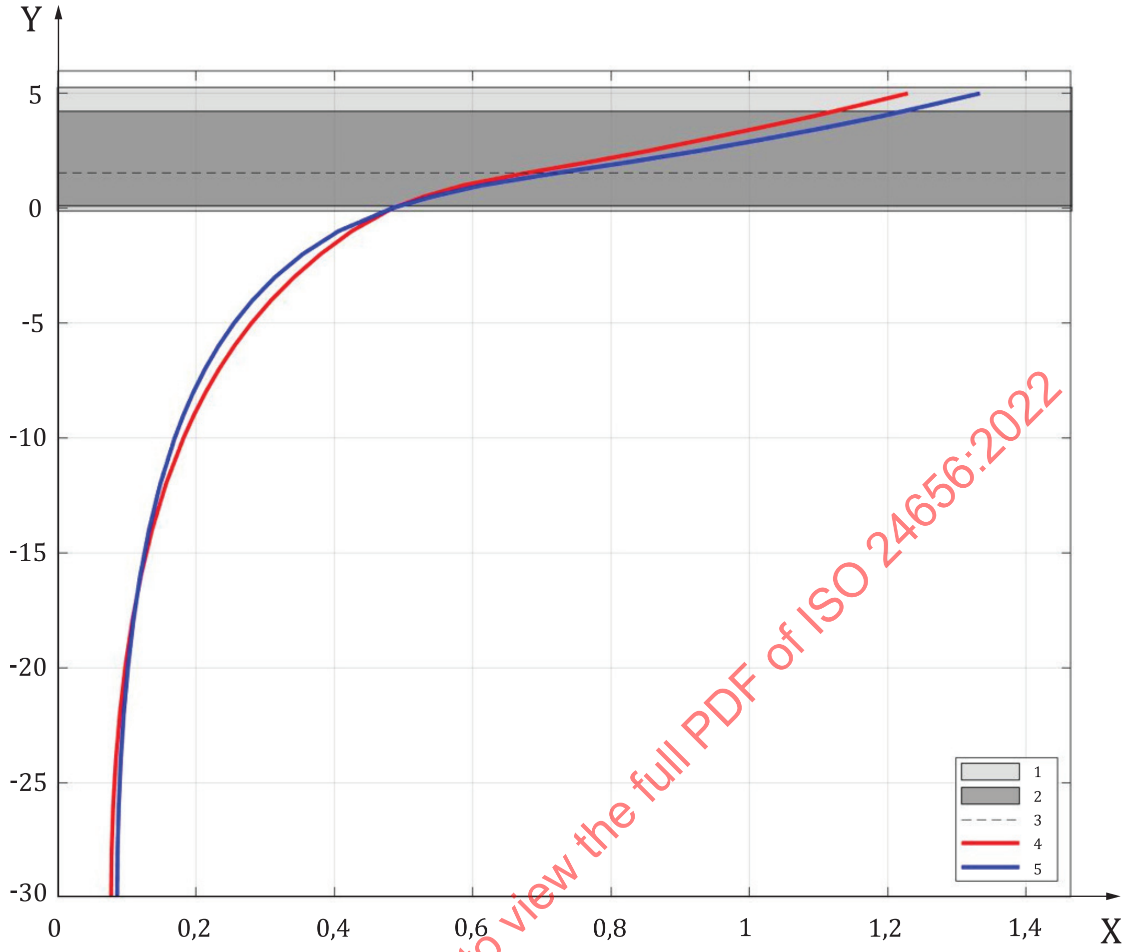
$$L = L_0 \ \tanh(kh) \tag{B.7}$$

and L_0 is the deep-water wavelength:

$$L_0 = 1{,}56 \ T_{m-1}^2 \tag{B.8}$$

Long term average wave orbital velocity profile is exemplified in Figure B.4, based on hourly values of the 36-year long metocean modelling time series. Within the frequently wetted zone, the averaged velocity is representative of the time the Frequently Wetted zone level is exceeded. For example, for z = FWZ$_{95\ \%}$, the averaging is based on the 5 percent of the time in the data time series that this level is exceeded.

The calculated wave orbital velocity profile is in Figure B.2 compared to a more complex approach considering the individual waves in the sea. The simple approach is noted to give a consistent comparison to the individual wave analysis. Details of the individual wave analysis is given at the end of this annex.



Key

X $U_m(z)$ [m/s]

Y z [mMSL]

1 $FWZ_{2-98\ \%}$

2 $FWZ_{5-95\ \%}$

3 $FWZ_{50\ \%}$

4 $\sqrt{2}\sigma_u(z)$

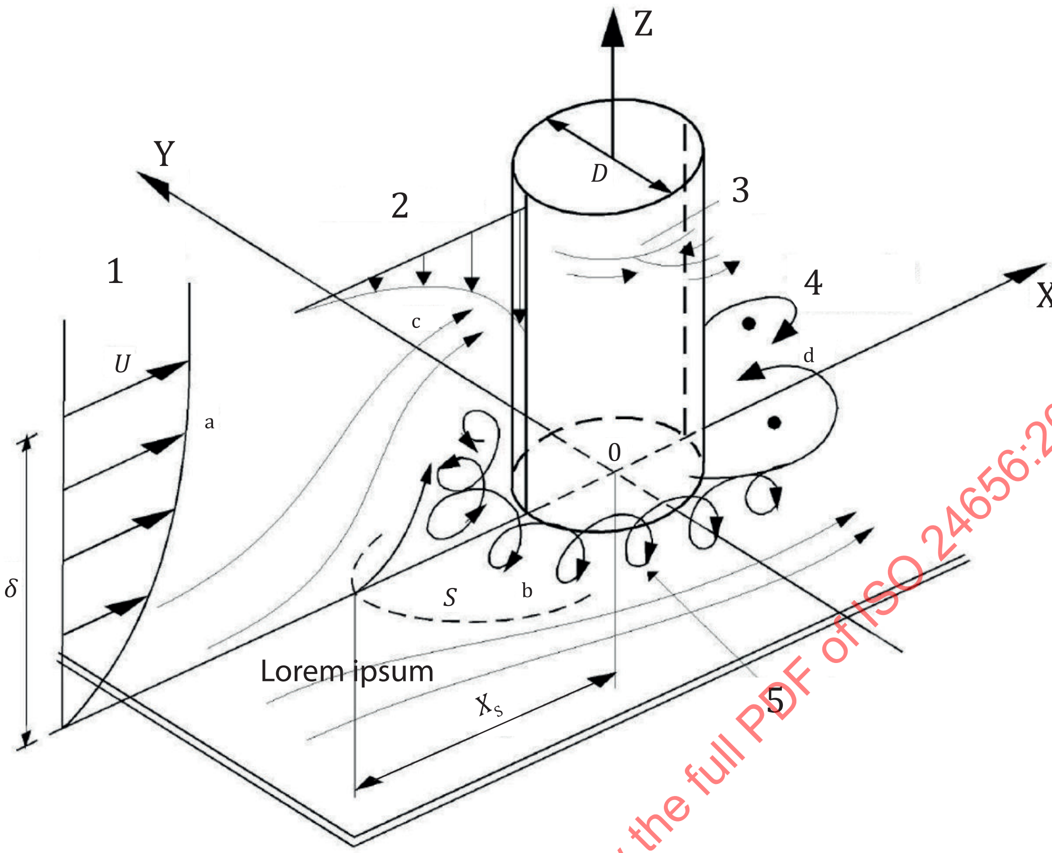
5 IWR

NOTE Site example −30 m water depth. Hourly data 1979-2015.

Figure B.4 — Long term time averaged wave orbital velocity profile with depth

B.7 Structure generated flow amplification and turbulence

A conceptual sketch of the complex flow from current flowing past a vertical pile is shown in Figure B.5. Very high turbulence levels are generated at the bed by the so-called horseshoe vortex, while the convergence of streamlines at the side of the pile leads to locally increased current speeds.



Key

1 approach flow
2 down flow
3 separation
4 lee-wake vortices
5 horseshoe vortex
D pile diameter
S separation line (The location where the incoming flow reverses due to adverse pressure gradient caused by stagnation pression built up at the pile. The S-line equivalently marks the boundary of the horseshoe vortex footprint)
U velocity
X_s Separation distance (Distance from pile centre to separation line. X_s is a measure of the size of the horseshoe vortex.)
δ boundary layer thickness (Often taken equal to the water depth.)
[a] Steady seawater velocity profile.
[b] Horseshoe vortex in front of pile.
[c] Vortex flow pattern at the lee side of the pile.
[d] Streamlines at the side of the pile.

NOTE From Roulund, Sumer, Fredsøe and Michelsen, 2005[42].

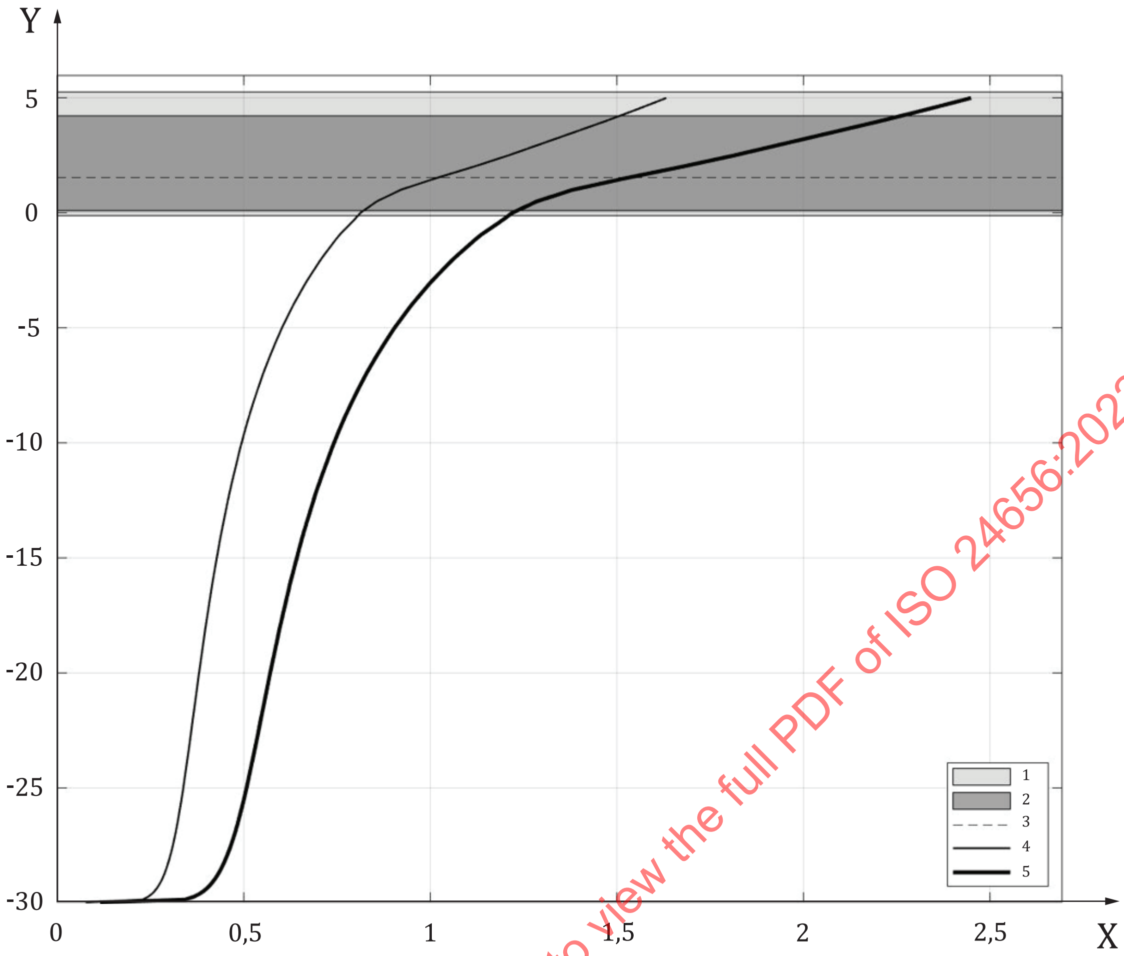
Figure B.5 — Seawater velocity past a vertical pile

The complex flow patterns around a pile in steady current is further complicated by presence of waves. The detailed flow patterns will primarily vary with the flow being either wave or current dominated and further with wave stroke to pile diameter ratio of the flow. These details are outside the scope of the present annex. Reference is made to [43] for details.

The convergence of streamlines at the side of the pile approximately doubles the flow velocities. Measurements of the so-called bed shear stresses under the horseshoe vortex at the base of the pile have shown up to around a factor 10 increase in the bed shears stress, equivalent to a local tripling of the near bed flow velocities.

Above flow amplification are localized to the sides and base of the foundation it will likely be overly conservative to apply these amplifications across the entire pile surface. Still it is evident that the presence of the pile increases flow speed and turbulence. The height of near bed turbulence scales with structure size but is limited to a relatively shallow zone close to the seabed. As an engineering approach, an area and time average of the flow speed amplification is suggested to be taken as 1,5.

Combined current and wave velocities profiles are shown as top figure in Figure B.6 with the Figure marked up by factor 1,5 at the bottom to be applied for corrosion design.



Key

X $U(z)$ [m/s]

Y z [mMSL]

1 $FWZ_{2-98\ \%}$

2 $FWZ_{5-95\ \%}$

3 $FWZ_{50\ \%}$

4 $U_m(z)+U_c(z)$

5 $1{,}5 \cdot (U_m(z)+U_c(z))$

Figure B.6 — Combined seawater flow velocity profile from combination of current and wave velocities as figure marked legend 6 and with a marked up factor on 1,5 as figure marked legend 7

B.8 Individual wave run-up (IWR) analysis

Hourly sea states from hydrodynamic modelling can be converted into time series of surface elevation of irregular waves. In the example a JONSWAP (Joint North Sea Wave Observation Project) representative of North Sea irregular wave condition spectrum has been applied for this conversion. The individual waves (height and period) are derived from so-called zero-crossing analysis of the irregular surface elevation wave time series. Crest elevation of each wave and the horizontal wave orbital velocity at the crest is calculated from 2nd order wave theory to capture nonlinearity in the wave. Wave run-up is calculated converting the kinetic energy of the orbital velocity into a potential energy-based run-up height. Finally, the still water level, wave crest level and run-up height are added to obtain frequently wetted zone based on individual wave analysis. Reference for run-up description is made in Reference [44].

B.9 Irregular wave orbital velocity profile

Hourly sea states from hydrodynamic modelling can be converted into time series of wave orbital velocities as function of time and vertical coordinates. Velocities above still water level can either be obtained through profile stretching or by higher order wave theory. In the example so-called Wheeler stretching has been applied. The wave orbital velocity amplitude profile of the irregular waves is derived as $\sqrt{2}$ times the standard deviation (σ_u) of the wave orbital motion time series.

B.10 Data to be provided by metocean specialists to CP designers

This document does not require the CP designer to be expert in metocean data; it gives guidance on what data should be available from metocean specialists and is required in the CP design process.

Based on metocean data that will necessarily be available for use in the structural design of foundations, metocean specialists will be able to provide the following data to the CP designer (Clause 5). They should be requested from the project metocean team by the CP designer:

— $FWZ_{50\ \%}$: The 50 percent quantile of the frequently wetted zone can be taken as a good estimate of the level to which the structure impacts the mean anode drain [See B.4 and 8.6.2].

— $FWZ_{5\ \%}$: The 5 percent quantile of the frequently wetted zone [See Figure 6].

— The combined (water) current [as B.5] and wave velocity profile [as B.6] with the ×1,5 mark-up factor [See B.7] at the elevations as detailed in Figure 6 and are the ‘marked-up seawater velocities’. They will vary with water depth.

These data, derived from existing data, from the metocean specialists, are key items for the CP design. They are used as follows:

— The 50 and 5 percent quantiles of the frequently wetted zone are used as detailed in 8.6.2.

— The marked-up seawater velocity is used to find basis for current density for instance as in Annex C (in particular Table C.2).

Annex C
(informative)

Guidance on cathodic protection current density requirement for cathodic protection of wind offshore structures

C.1 General

The selection of the current density design parameters is one of the most important parts of the CP design.

Environmental parameters as described in 8.5 can affect design current densities required for initial polarization and its maintenance and also the properties of the calcareous scale formed by the CP current. The most significant of these environmental parameters in offshore wind turbine foundation locations is the variable seawater flow velocity and this is detailed in Annex B.

This document recognizes that the CP current densities within Standards and Codes developed and proven competent for deep water oil and gas applications have proven inadequate for inshore wind foundations since these standards have either ignored or under-estimated the effects of sea water velocity and have generally proved very conservative in their recommendations.

While this annex presents some guidance for the selection of current density, specific locations will require specific and particular current density parameters for successful design and the guidance data in this Annex should not be used as a substitute for detailed consideration of current density requirements by a competent and experienced CP designer (see Clause 5).

The informative guidance in this Annex is based upon a review of the available data. It can be used, in conjunction with metocean data, Annex B for external seawater immersed surfaces and internal immersed surfaces with a high degree of expectation of successful CP performance if all other aspect of the CP design is undertaken in accordance with this document

The CP designer should determine if additional safety factors should be used to increase the CP current densities provided in guidance below, or in particular cases, if these can be reduced.

In respect of buried or driven elements of the foundations and steel in concrete elements, it is considered that the informative guidance in this annex represents safe values, for which actual measurements are very difficult or impossible to collect and, as it will normally represent a smaller part of the total CP current design, it is suggested that it can be used without modification.

Any deviations from the suggested values in this Annex should be documented in the CP design report and justified therein with a sensitivity analysis if appropriate.

When coating/paint systems are used, in conjunction with the determined bare steel CP current density requirement, coating breakdown factors shall be applied to determine the CP current demands, see guidance in Annex D.

The CP designer (see Clause 5) should determine, with as much accuracy as is possible, the appropriate Initial, mean and final CP current densities that are appropriate for the location's environmental conditions. Some safety margins may reasonably be added to any estimation, including those based on data from nearby, or from field data from locations considered to be approximately similar or from laboratory data. In a situation where, for example, measured CP surveyed and monitored (data logged fixed sensor) performance values from nearby similar structures or retrofit cases have been determined, and where full conformity with appropriate protection criteria has been delivered for a minimum of 12 months with data covering cold winter storm conditions, the use of such data or the same design data may be justified for new structures in the same or nearby locations. The assumption that past design parameters were successful solely on the basis of potential surveys using divers, ROVs or drop cells, without monitored (data logged fixed sensor) performance data is not sufficiently robust.

In estuarine conditions, with brackish waters, the current densities for CP of steel in shallow waters provided may be applicable for resistivity of up to 2 Ωm. Where the resistivity is greater than 2 Ωm, it may be necessary to undertake current drainage tests or laboratory investigations to determine current density requirements in waters for which there is no established CP historical data. While it might be anticipated that current density requirements will reduce with increasing electrical resistivity, the variations are complex and depend upon the ability of the estuarine waters, which may be subject to contamination, to produce calcareous deposits at design CP potentials. Thus, current density requirements in estuarine conditions may be greater than in undiluted, clean, seawater.

The CP designer should assess the entirety of the environmental conditions at the site of the installation and shall determine appropriate current density and electrical resistivity values. This assessment shall be fully documented and presented as part of a detailed CP Design Report for the structures.

C.2 Indicative design CP current densities for the protection of bare steel in external immersed and frequently wetted zones

The guidance in Table C.1 below is provided on the basis that seawater flow velocity has been assessed in accordance with Annex B and that a marked-up seawater flow velocity profile has been made. Any assessment using a partial estimate of seawater flow velocity will be inadequate and will render the guidance below inaccurate.

For externally immersed steel it may be assumed that the dissolved oxygen content of the seawater is constant with increasing depth, at least for water depths up to 100 m relative to MSL. There will be variations in temperature with time, whereby the highest current demand is expected during colder temperature water situations, due to higher dissolved oxygen and less protective calcareous deposits, see References [39] and [45].

In the data below, the primary variable is seawater flow velocity and for bare, non-corroded steel, but some 'coarse' temperature influences are given below and reflect the established variances in the existing standards for steel in seawater.

Table C.1 — Indicative CP design current densities (Initial/Mean/Final) mA/m^2 for bare steel in seawater external immersed and frequently wetted zones

Region	Tropical 20 °C to 25 °C (note 7)	Sub-tropical 12 °C to 20 °C	Temperate 7 °C to 11 °C	Arctic <7 °C
Marked-up seawater flow velocity m/s Based on Annex B (Note 1)				
0,3	160/45/95	185/55/110	210/60/120	250/75/150
0,5	175/50/100	205/60/120	230/65/130	275/80/160
0,75	200/55/105	240/65/128	265/70/170	320/85/170
1,0	225/60/110	270/70/135	300/75/180	360/90/180
1,5	265/70/145	315/85/170	350/95/190	420/115/230
2,0	315/80/160	380/95/190	420/105/210	505/130/250
2,5	354/85/165	460/100/200	460/110/220	550/130/265
3,0	390/100/195	470/120/240	520/130/260	625/155/310

NOTE 1 The marked-up factor is 1,5 on the derived depth seawater flow velocity curve and represents the seawater flow velocity as experienced by the structure. The method of calculating the 'sea water velocity' based on metocean data can be found in Annex B and should be used in the application of the data in Table C.1. This means that a seawater flow velocity on 0,5 m/s will be experienced as 0,75 m/s at the structure steel/ seawater interface.

NOTE 2 As these seawater velocities should be applied at incremental depths, the above table applies to all depths to 100m below MSL.

NOTE 3 At extreme depth, typically > 100 m relative to MSL, there is some evidence that CP current density can increase due to sea water chemistry changes. The CP Designer should, in such circumstances which are normally not encountered in offshore wind foundations applications, obtain detailed oceanographic and seawater chemistry data, review the available literature from deep water oil and gas CP applications, determine and document any increase in current densities that are appropriate for that location.

NOTE 4 The values in Table C.1 assume that current and potential distribution are uniform over the entire immersed structure intended to be protected by CP. If this is not achieved either by uniform distribution of anodes or by the use of remote anodes, all of the above figures should be increased by a factor related to the extent of non-uniformity. Modelling see Annex I is a useful tool to verify adequate protection where anodes are distributed in an inhomogeneous manner.

NOTE 5 The values in Table C.1 assume that the extent of polarization within 12 months will reach between −0,90 and −1,05 V Ag/AgCl/seawater. At polarized potentials outside this range, the Mean current densities can be expected to be higher[46].

NOTE 6 The Initial current densities above do not reflect the higher values in the first hours and days of CP, but they are suitable for galvanic anode CP design using the process in 8.6. Using this calculation process, the Initial current density that will be delivered by galvanic anode CP will be significantly greater than the calculated value from 8.6, due to the higher anode/steel driving voltage as the steel is polarized from its natural potential (ca. −0,60 V) through partial protection (−0,70 V) and then to the protected range, typically more negative than −0,90 V. Initially, the current delivered will be at least 50 % greater than calculated in 8.6, due to the higher driving voltage.

NOTE 7 The values in Table C.1 are based on published literature, see References [35][39][45] and [46].

C.3 Indicative design CP current densities for the protection of bare steel in internal immersed wetted zones

Some guidance data for initial CP current of low carbon steel, carbon manganese steel or cast iron in North Sea water at 7 °C as a function of oxygen content and seawater flow velocity is reproduced below in Table C.2 from Table B.1 in EN 17243.

Where the dissolved oxygen content is reduced (e.g. due to consumption of the oxygen by the cathodic reaction in a poorly renewed water system) the initial current density may also be reduced.

NOTE 1 Long term performance data of internal CP systems for the interior of wind turbine monopiles are not yet available.

In the case of deoxygenated systems with a residual dissolved oxygen content <1 ppm, CP is not normally required.

Table C.2 — Estimated initial maximum current density required to protect clean carbon steel in North Sea water at 7 °C. — (from EN 17243)

CP initial current density mA/m^2					
Linear flowrate m/s (see Note 2)	O_2 content				
	6 ppm	7 ppm	8 ppm	9 ppm	10 ppm
0	68	80	91	102	114

Table C.2 *(continued)*

0,3	78	91	105	118	131
0,4	82	85	109	123	136
0,6	89	103	118	133	148
1	102	119	136	153	170
2	136	159	182	205	227
4	205	239	273	307	341

NOTE 2 Flow inside a monopile highly depends on tides, access from external seawater meaning number and location of holes in the monopile. In order to evaluate the velocity, flow calculations are needed.

It is the responsibility of the CP designer to establish the design current density required to achieve protection. This can be achieved by reviewing previous validated designs and published data. The basis on which the current density requirements are established shall be documented.

Mean current density requirement depends on the degree to which the water is replaced within the system and the extent to which calcareous deposits have been allowed to form.

For "once through" systems or where the water is renewed regularly, such that high oxygen level is maintained; or for low temperature systems (<5 °C), which limits formation of calcareous deposit, then the maintenance current density may be similar to the initial design current density indicated in Table C.2.

For systems where the water is replenished, the mean current density can be taken as 0,2 to 0,3 of the initial current density subject to calcareous deposits being formed. However, in a closed system, with oxygen depletion, the current density requirement may be reduced even more.

NOTE 3 In closed compartments with limited water replenishment and risk of acidification, it may be considered appropriate to reduce the current density applied to the structure.

In offshore wind MPs it is expected that if CP criteria are met and seawater chemistry is not significantly changed by CP calcareous deposits will form, and the Mean current densities will decrease. However, significant seawater chemistry changes are likely with limited or no seawater replenishment, if Aluminium alloy galvanic anodes or impressed current CP are used.

In respect of offshore wind MP foundations that are flooded there are three general conditions that may apply, some by design and some by the change of characteristics in service. These are summarized as:

a) MP internals that are intentionally flooded, typically by way of substantial seawater ingress/egress holes in the MP at more than one elevation, with the internal water level being at the external water level and there being no or minimal time lag between the inner and outer water levels:

   These systems will have a minimum water replenishment of the volume between the lowest seawater ingress/egress holes and the varying high tide level at every tide. These MPs may exhibit internal water velocities, generally, related to the daily high water to low water distance divided by the time between tides; in addition, there may be localized higher velocities and possible turbulence in the vicinity of the ingress/egress holes.

   In this situation the internal seawater dissolved oxygen content (DO) can be expected to be maintained at around that of the external seawater. However, caution and detailed assessment should be applied if there is any significant depth of water below the lowest ingress/egress hole, such as where a 'sump' has been caused by drilling during piling. In such situations it may be necessary to model the water flow within the MPs.

b) MP internals that are flooded intentionally or unintentionally by way of limited seawater ingress and egress that may be via leaking cable or J-tube seals or other unplanned water transmittal and/

or may be enhanced by the intentional provision of small seawater ingress or egress in order to avoid changes in sea water chemistry during the use of internal CP:

In this situation the DO may be somewhat depleted. In applications where CP is being installed internally, the CP Designer should assess the appropriate CP current densities taking into account the known DO and temperature, along with an assessment of the risk of increase in DO due to unintentional leakage of seawater into the MP.

c) Sealed, with no water ingress and egress:

In this situation the DO may be significantly depleted. If any reliance is taken of DO depletion in respect of corrosion mitigation, the level of DO and temperature should be regularly surveyed through the full depth of water within the MP and the corrosion rate both above and below the water should be assessed by coupons or corrosion rate monitoring (ER) probes. As an alternative continuous water level measurement may be applied reflecting if water level is static. In applications where CP is being installed internally, the CP Designer should assess the appropriate CP current densities taking into account the DO and temperature along with an assessment of the risk of increase in DO due to unintentional leakage of seawater into the MP.

From this background and both laboratory and field studies[47] and [39], indicative current densities can be proposed as shown in Table C.3. For internal CP of offshore wind foundations, the final or re-polarization current density (intended for re-polarization after storm conditions) has no meaning and is not applicable in the table.

An assessment should be made of the water flow rates, dissolved oxygen, anticipated changes in water chemistry during CP design life, stratification and their impact on CP current density throughout the CP design life to determine the optimum initial and mean steel (cathode) current densities for the structure internal surfaces. If appropriate, different current densities may be applied to different depths in sea water.

If the internal water level can exceed the elevation of any internal working platform, ladders or other internal metallic items, their surface areas shall be included in the cathodic area calculation.

The mean current density figures are given under the assumption that anodes are distributed to where the current demand is, hence providing a uniform distribution of current and potential in the water column. It is to be noted that the constrained electrolyte within monopiles limits the current distribution in the vertical direction with a built-in risk of inadequate current distribution; this is different to the external situation.

Table C.3 — Indicative CP design current densities (Initial/Mean) mA/m^2 for bare steel in seawater internal immersed (see Note 1)

Region	Tropical		Sub-tropical		Temperate		Arctic	
	20 °C to 25 °C		12 °C to 20 °C		7 °C to 11 °C		<7 °C	
All with Zero Flow	Initial	Mean	Initial	Mean	Initial	Mean	Initial	Mean
Dissolved Oxygen ppm								
1	9	3	10	4	11	4	14	5
2	17	5	21	6	23	7	27	8
3	26	8	31	9	34	10	41	12
4	34	11	41	13	46	14	54	17
5	43	13	52	15	57	17	68	20
6	51	15	62	18	68	20	81	24
7	60	17	73	21	80	23	95	27
8	68	20	83	25	91	27	109	32

Table C.3 *(continued)*

Region	Tropical		Sub-tropical		Temperate		Arctic	
	20 °C to 25 °C		12 °C to 20 °C		7 °C to 11 °C		<7 °C	
All with Zero Flow	Initial	Mean	Initial	Mean	Initial	Mean	Initial	Mean
Dissolved Oxygen ppm								
9	77	24	95	30	102	30	125	38

NOTE 4 The above values assume calcareous deposits will form.

NOTE 5 The assumed dissolved Oxygen (DO) in open seawater is 8 ppm to 9 ppm in temperate regions.

NOTE 6 If the internal seawater flow velocity exceeds 0,3 m/s; use the data in **Table C.1**

NOTE 7 The conversion of current density from one region to another is based on published literature see bibliography.

NOTE 8 The values in Table C.3 assume that the extent of polarization within 12 months will reach between −0,90 and −1,05 V Ag/AgCl/seawater. At polarized potentials outside this range, the Mean current densities can be expected to be higher[46].

NOTE 9 The Initial current densities above do not reflect the higher values in the first hours and days of CP, but they are suitable for galvanic anode CP design using the process in 8.6. Using this calculation process, the Initial current density that will be delivered by galvanic anode CP will be significantly greater than the calculated value from 8.6, due to the higher anode/steel driving voltage as the steel is polarized from its natural potential (ca. −0,60 V) through partial polarisation (−0,70 V) and then to the protected range, typically more negative than −0,90 V. Initially, the current delivered will be at least 50 % greater than calculated in 8.6, due to the higher driving voltage.

C.4 Indicative design current densities for the protection of bare steel in seabed (ambient temperature)

Externally, CP current will flow to buried/driven pile external surfaces to a considerable depth. The extent or depth to which ‘full’ CP (polarization to the selected protection criterion) can be applied will be determined by attenuation of current and potential controlled by the current density, the soil/seabed electrical resistivity and the electrical resistance of the pile. Coating the pile external surface for some length will increase the depth to which ‘full’ CP can be provided.

Internal CP current will flow to buried or driven piles to a limited depth. In addition to the attenuation factors affecting external CP current distribution, internally the constrained cross section of electrolyte contained within the MP or driven tubular pile will further constrain current flow. Effectively the electrical resistance of the column of seabed within the MP or pile reduces the current and presents volt drops in the electrolyte. With uncoated steel it may be impossible to achieve ‘full’ CP for more than a few metres below seabed.

Corrosion rates for driven piles in marine seabed environments are generally assumed to be low, EN 1993-5[16] with an assumed evenly distributed corrosion rate of (0,01 to 0,04) mm/side/year where no CP is applied.

NOTE 1 A correlation between EN 1993-5[16], corrosion rate and corrosivity in the marine seabed environment has not been found. Some studies can be found in Reference [48].

If required, an evaluation of corrosion risk of bare steel in undisturbed seabed environment, based on parameters as chloride, sulfate, pH, soil resistivity etc. may be used and evaluated based on, for instance, DIN 50929-3[27]. It is to be noted that these evaluations do not take the risk of microbial induced corrosion (MIC) into account, and a corrosion rate based on any of these are likely to be underestimated in case MIC is or will be active.

NOTE 2 There is no known published evidence of active MIC affecting piles at more than 2 m below seabed, irrespective of the presence of organic content, sulfates and sulfate reducing bacteria (known to result in highest corrosion rates compared with other bacteria). The number of available data sets are low, and the CP designer will need to make an engineering judgement on the risk of MIC below this indicative depth. Externally, due to the large volume of electrolyte, it is possible to polarise the steel to significant depth below seabed. However, internally, for example within monopiles, attenuation of cathodic protection current and potential can be significant, due to the restricted electrolyte, and it may not be possible to provide adequate polarisation to any significant depth below seabed.

On this basis, taking into account the relative ease of passing current to some depth externally and the relative difficulty of doing this internally, it is suggested that the immersed CP design should anticipate 'full' CP for only a few metres below the seabed and that the CP modelling, both externally and internally should use the design parameters in Table C.4 below to indicate the extent of protection. This will dictate what is possible, without any additional particular attempts to fully protect to an identified depth.

Table C.4 — Indicative design current densities below seabed for CP and 'current drain' below a depth at which CP is determined not necessary

Current density mA/m²			
	Initial value	Maintenance value	Re-polarization
For levels where, protective potential is to be achieved[a]	20	20	Not applicable
Drainage for depth from where full protection is needed[a] to −10 m below seabed	10	10	
Drainage for depth −10 m below seabed to pile toe	5	5	

[a] The level below seabed to achieve full protection from a CP system should be evaluated on a case-by-case basis, taking risk of corrosion into account

NOTE For internal monopile applications attenuation within the electrolyte contained within the monopile may prevent the above values being achieved.

C.5 Indicative design current densities (mA/m² reinforcement surface area) for the protection of reinforcing steel in gravity base foundations

The current density required for CP of steel embedded in water saturated concrete will be significantly below that for steel embedded in concrete above the water. The current density for CP of steel in atmospherically exposed concrete, before corrosion has initiated, will be significantly below that required for CP of corroding steel in atmospherically exposed concrete. ISO 12696 provides guidance which has been proven, in practice, to be generous (normally in excess of the actual requirements). This is evidenced by the fact that, after the application of CP current for some time, the maintenance current density is generally approximately half that required for initial polarization.

The current density recommendations for CP of steel in water saturated concrete are from ISO 12696.

"A.4 Cathodic protection for steel in buried or immersed concrete structures

Cathodic protection for steel in buried or immersed concrete follows the same basic principles as for atmospherically exposed concrete described in A.3. The principal difference is that the concrete is likely to become water saturated, which will result in reduction in oxygen content at the steel surface under normal exposure conditions, which will be accelerated under the application of cathodic protection. Where oxygen depletion occurs, the potential will become very negative and the current required for cathodic protection will be reduced.

Hence, the current density required for steel in concrete that is buried or immersed for protection may be, if the concrete is fully water saturated, considerably less than that required for atmospherically exposed concrete. Typical current densities range from 0,2 mA/m² to 2,0 mA/m² for new structures (before corrosion initiation) in water saturated conditions. For structures that are not fully water saturated and are corroding before the application of cathodic protection, current densities may be as high as those for atmospherically exposed concrete, up to 20 mA/m².

The current density is also dependent on whether the concrete is fully immersed or whether one face is exposed to air (e.g. as for tunnels, portions of diaphragm walls, underground storage tanks and where the thickness of the concrete structure is typically less than 0,5 m to 1 m). If this is the case, then a differential concentration (differential oxygen) cell can be created between the fully immersed face and the air exposed face. Where such conditions occur, a higher current density will be required on the immersed portion."

It is considered that these values are appropriate for use in offshore wind foundations, both for CP and for current drain from a CP system. Based upon these figures the current densities shown in Table C.5 may be used:

Table C.5 — Indicative design current densities (mA/m² of steel reinforcement surface area) for the protection of reinforcing steel in gravity base foundations or current drain allowance for composite structures

	'Tropical'	**'Sub-tropical'**	**'Temperate'**	**'Arctic'**
Typical seawater surface temperatures / **Depth**	**>20 °C**	**12 °C to 20 °C**	**7 °C to 11 °C**	**<7 °C**
MSL to upper splash zone level and above, where chloride contamination of concrete surface is likely If chlorides are present at steel depth sufficient to initiate corrosion	25	20	20	15
MSL to upper splash zone level and above, where chloride contamination of concrete surface is likely If chlorides are not present at steel depth sufficient to initiate corrosion, and corrosion has not initiated	2,5	2	2	1,5
MSL to −30 m LAT if element is not water saturated from both sides, e.g. hollow column not water filled inside	10	10	5	5
MSL to −30 m LAT if element is water saturated from both sides, e.g. if hollow column is water filled inside	2,5	2	2	1,5

NOTE CP of steel in concrete from anodes immersed in the seawater (internally or externally) is expected to protect the reinforcement to a level up to where it is frequently wetted, $FWZ_{50\,\%}$. However, if some of part of the frequently wetted zone has chloride contamination of concrete at steel depth sufficient to initiate corrosion, impressed current CP of the steel in concrete, using embedded anodes (mesh, ribbon or discrete) can be required.

Annex D
(informative)

Coatings and coating breakdown for CP design

D.1 General: coating systems

Coating systems for offshore structures are generally epoxy based although other base coatings are also used for special applications. Coating systems are described in NORSOK M-501[29] and ISO 12944[4][5] describes various coating types and describes mandatory pre-qualification and testing of both coating material and applicators in addition to surface preparation and inspection and testing requirements. ISO 12944 is a multi-part standard covering all aspects of materials, testing, surface preparation, application and inspection and resting. There is a dedicated part (see ISO 12944-9[5]) which covers paint systems and performance testing for offshore and related structures.

Suitable coating systems for offshore wind turbine foundation structures are described in NORSOK M-501 as coating system 7B and in ISO 12944-9 [5] as appropriate for various environments which are described in ISO 12944-2[4] as CX (offshore), Im4 (immersed) and CX and Im4 (tidal and splash zone). DNVGL-RP-B401[23], further classifies coating systems for the purposes of coating breakdown for CP design into three categories of performance for different epoxy, polyurethane or vinyl-based systems. The coating systems described in NORSOK M-501 as systems 3B and 7 meet the requirements of Category III with NORSOK M-501 system 7B commonly used for offshore immersion purposes.

This annex includes the above coating systems as appropriate for offshore wind turbine foundation structures as determined by appropriately qualified coating specialists. It is assumed that they are optimally applied, to optimally prepared surfaces and that these processes are independently inspected. Table D.1 categorises five separate coating systems with categories I, II and III being identical to the same categories in DNVGL-RP-B401 although all relate to epoxy-based coatings. A further two categories are included in this annex to cover the increasing use offshore of more durable, higher performance coating systems. Category IV is effectively NORSOK M-501 System 7A and Category V is a glass flake filled coating system.

Table D.1 — Coating categories

Coating Category	I	II	III	IV	V
Related Standard and Code categories	N/A	N/A	ISO 12944-9[5] Im4	ISO 12944-9[5] CX Im4	N/A
			NORSOK M-501 7B	NORSOK M-501 7A	N/A
	DNVGL RPB401 Cat I	DNVGL RPB401 Cat II	DNVGL RPB401 Cat III	N/A	N/A
Coating system	2 component epoxy based	2 component epoxy based	2 component epoxy based	2 component epoxy based	2 component glass flake epoxy or polyester. Lamellar glass flake, non-micronised > 20 % in mass
Minimum number of coats	1	1	2	2	2

Table D.1 *(continued)*

Coating Category	I	II	III	IV	V
Nominal Dry Film Thickness (NDFT) (µm)	≥ 20	≥ 250	≥ 350	≥ 600	≥ 1 000

Some of the codes and standards referenced in Table D.1 allow the use of zinc-rich primers. In this document, zinc rich primers are not recommended for use in the immersed, tidal and splash zones.

NOTE The coating systems in Table D.1 assume that surface preparation, application, inspection and testing has been carried out in full accordance with all relevant parts of the referenced related codes and standards.

D.2 Coating breakdown

Even with a well applied and inspected thin film coating, an initial amount of coating defect may be expected and some damage occurring during installation is likely to occur. Both these features are taken into account under the broad title of “initial coating breakdown” in this document.

During immersion service there may be some blistering and coating disbondment leading to general coating degradation which will be visually apparent. The term coating breakdown describes the progressive loss of film electrical resistance occurring over the period of service of the coating system and which will not be visually apparent.

NOTE 1 Coating breakdown should not be confused with coating degradation as apparent by visual examination. A blistered coating can remain electrically resistive whilst a coating with water absorption after time can allow significant passage of CP current even when still appearing visually sound.

The progressive loss of coating electrical performance due to coating breakdown can be taken into account by the use of numerical factors inserted into the CP current demand calculations (see 8.6.2). Breakdown factors may be quoted as percentages or as decimalised fractions.

Table D.2 has factors for both initial damage and annual breakdown rate for the coatings described in Table D.1. However, caution is required when using these values since they are indicative only and should not be used as default values without due consideration formed by specialist knowledge and experience. The values quoted in Table D.2 can be regarded as conservative and the owner of the asset should either specify the factors to be used or accept the factors proposed by the CP designer. It is expected that the CP designer will determine the breakdown factors in conjunction with an expert coating specialist.

Table D.2 — Coating breakdown factors expressed as percentages

Coating category			I	II	III	IV	V	I	II	III	IV	V
Zone	Initial after coating a %	Initial after installation b %	Annual breakdown rate for surfaces exposed to free-flowing seawater c %/year					Annual breakdown rate for surfaces within confined spaces not exposed to free-flowing seawater c %/year				
$FWZ_{50\ \%}$ to $FWZ_{5\ \%}$	Cat. III 1,0 Cat. IV: 0,75 Cat. V 0,5	Cat. III 1,0 Cat. IV: 0,75 Cat. V 0,5	NA	NA	1,5	0,8	0,6	NA	NA	1,5	0,8	0,6
From $FWZ_{5\ \%}$ to −30 mLAT	Cat. I: 5,0 Cat. II: 2,5 Cat. III: 1,0 Cat. IV: 0,75 Cat. V: 0,5	Cat. I 5,0 Cat. II 2,5 Cat. III 1,0 Cat. IV: 0,75 Cat. V 0,5	10	2,5	1,2	0,6	0,4	5	1,5	0,8	0,4	0,3

Table D.2 *(continued)*

Coating category			**I**	**II**	**III**	**IV**	**V**	**I**	**II**	**III**	**IV**	**V**
Zone	Initial after coating a %	Initial after installation b %	Annual breakdown rate for surfaces exposed to free-flowing seawater c %/year					Annual breakdown rate for surfaces within confined spaces not exposed to free-flowing seawater c %/year				
From −30 mLAT to scour	Cat. I: 5,0 Cat. II: 2,5 Cat. III: 1,0 Cat. IV: 0,75 Cat. V: 0,5	Cat. I 5,0 Cat. II 2,5 Cat. III 1,0 Cat. IV: 0,75 Cat. V 0,5	5	1,5	0,8	0,6	0,4	5	1,5	0,8	0,4	0,3
From scour to pile toe	Cat. I: 5 Cat. II: 2,5 Cat. III: 1,0 Cat. IV: 0,75 Cat. V: 0,5	10 to 25 % Low in fine sands and Clay. Higher in gravels and boulders	1	1	0,5	0,2	0,1	1	1	0,5	0,2	0,1

NOTE 2 There is no splash zone for internal surfaces but there can be a tidal zone.

NOTE 3 Coating breakdown for coatings below seabed/scour level will depend on among other the seabed material.

NOTE 4 Category V coatings can contain different loadings of glass flake and be of thicker or thinner DFT from that in Table D.2. Micronised glass is not as effective as flake glass in improving performance. Values for c can therefore be reduced or increased accordingly if justified.

For initial coating breakdown, values a and b shall be added together.

Coating performance is significantly affected by the quality of the surface, both cleanliness and roughness, the conditions in the paint shop at the time of application and subsequent curing, the quality and rigour of the inspection and the extent of post coating handling damages and the quality of any repair or damages. The extent of secure data on coating breakdown is small and the coatings available today have not previously been in service for 20 years plus. As stated in the text before Table D.2, caution should be applied when using these values since they are indicative only and should not be used as default values without due consideration formed by specialist knowledge and experience.

NOTE 5 The integrated coating and cathodic protection design can permit areas intentionally bare (uncoated or damaged and un-repaired). Any such areas will be in addition to those values in Table D.2.

The calculation of coating breakdown for insertion into the current demand Formulae (see 8.6.2) is as follows.

$$\text{Initial coating breakdown \%: } f_{\text{cinitial}} = \text{a}\left(f_{\text{cinitial after coating}}\right) + \text{b}\left(f_{\text{cinitial after installation}}\right) \quad \text{(D.1)}$$

$$\text{Mean coating breakdown \%: } f_{\text{cmean}} = f_{\text{cinitial}} + \text{t c}/2 \quad \text{(D.2)}$$

$$\text{Final coating breakdown \%: } f_{\text{cfinal}} = f_{\text{cinitial}} + \text{t c} \quad \text{(D.3)}$$

where

a, b and c are as described in Table D.2

t is the design life of the CP system

For uncoated parts of the structure: $f_{c\ \text{initial}} = f_{c\ \text{mean}} = f_{c\ \text{final}} = 1$ (100 %)