RECOMMENDED PRACTICE

DNV-RP-B401 Edition May 2021

Cathodic protection design

DNV AS

FOREWORD

DNV recommended practices contain sound engineering practice and guidance.

Any comments may be sent by e-mail to *rules@dnv.com*

CHANGES – CURRENT

This document supersedes the June 2017 edition of DNVGL-RP-B401.

The numbering and/or title of items containing changes is highlighted in red.

Changes May 2021

Topic	*Reference*	*Description*
Document structure	Sec.1	Rewritten to align it with other DNV recommended practices, comprising the former Sec.1 to Sec.4.
	Sec.8, Sec.9 and Sec.10	App.A, App.B and App.C have been renamed Sec.8, Sec.9 and Sec.10, respectively.
Limits of cathodic protection	[2.2]	Amended to emphasize the purpose of cathodic protection for carbon and low-alloy steels.
Protection potential criterion	[2.4]	Updated to clarify the protection potential criterion and its relation to the design protective potential.
Detrimental effect of cathodic protection	[2.5.5]	The HISC susceptibility of precipitation hardening or annealed corrosion resistant alloys has been updated to no longer be related to any maximum hardness criterion.
	[2.5.8]	Updated to include a reference to DNV-RP-F112 to account for measures to prevent HISC of components in duplex stainless steel.
	[2.5.12]	Added precautions for the use of aluminium-based anodes in seawater filled compartments with limited exchange of water and/or gas.
Cathodic protection design parameters	[3.1.3]	New guidance related to structures located in water with high water current velocities has been added.
Mean design current density	[3.3.5]	Added explanatory text referring to the mean design current density.
Design current density for aluminium	[3.3.11]	Added guidance note related to the correlation between the design current density and contaminating elements in the aluminium alloy.
Current drain to reinforcing steel in concrete	[3.3.12]	Steel reinforcement for concrete structures is referred to in terms of current drain rather than cathodic protection.
Coating breakdown factors	[3.4.6]	A new coating category with new coating breakdown factors has been introduced. Subject to defined provisions, proprietary thin film coatings of anti-friction type may be accounted for as coating category II.
Determination of seawater resistivity	[3.7.1]	It has been clarified that seawater resistivity shall be based on conditions at the anode location.
Seawater resistivity	[3.7.2]	A guidance note has been added recommending that the impact that a variation in the seawater resistivity may have on the anode current output should be evaluated.

Topic	*Reference*	*Description*
Anode utilization factor	[3.8.2]	A guidance note has been added to highlight the importance of implementing the anode/anode core dimensions from the design in anode production.
Minimum anode size	[4.8.6]	The minimum ratio of net anode mass to design life has been removed.
Anode current output interference	[4.9.1]	A guidance related to anode distribution and anode current output has been added.
	[4.11.3]	The specific minimum distance between anodes has been removed. Advice to use computer modelling to quantify the reduction in anode current output due to anode interference has been added.
Provisions for electrical continuity	[4.12.2]	Provisions for electrical continuity. Description: bolted or clamped connections are included as an alternative to cable connections when full electrical continuity cannot be ensured
	[4.12.3]	New requirements for the mechanical integrity of cable connections have been added.
	[4.12.4]	The recommendation that the product of the connection resistance and current demand should not exceed 10% of the design driving voltage has been changed to a requirement and it has been added that the total resistance over the cable or the bolted and clamped connection shall be assessed and included in the anode current output calculations.
Inspection, maintenance and retrofitting	Sec.7	New section giving advice on the inspection, maintenance and retrofitting of anodes has been added.
Reference electrodes	Sec.9 and Sec.10	Updated reference electrode such that only silver/silver chloride/ saturated KCl is referred to for checking of the working reference electrode, due to restriction on the use of mercury containing ones.
Rebranding to DNV	All	This document has been revised due to the rebranding of DNV GL to DNV. The following have been updated: the company name, material and certificate designations, and references to other documents in the DNV portfolio. Some of the documents referred to may not yet have been rebranded. If so, please see the relevant DNV GL document.

Editorial corrections

In addition to the above stated changes, editorial corrections may have been made.

CONTENTS

SECTION 1 GENERAL

1.1 Introduction

Cathodic protection (CP) prevents localized forms of corrosion and uniform corrosion attacks. CP eliminates the possibility of galvanic corrosion when metallic materials with different electrochemical characteristics are in electrolytical contact with each other. CP also effectively prevents corrosion attacks on stainless steels/ corrosion resistant materials (CRA) with a low pitting resistance equivalent ($PREN_W$), e.g. UNS S31600, which can be particularly vulnerable to corrosion in seawater.

This recommended practice (RP) is primarily intended for the design of cathodic protection (CP) systems using galvanic anodes of permanently installed offshore structures associated with the production of oil and gas, including fixed platforms, permanently moored floating structures, subsea structures and oil and gas handling equipment. For CP of floating structures associated with oil and gas production, support structures for offshore wind turbines, and submarine pipelines, see DNV-RP-B101, DNV-RP-0416 and DNV-RP-F103 respectively.

Sec.2 to Sec.4 contain design aspects for cathodic protection with tabulated data given in Sec.8. The manufacture and installation of anodes are covered in Sec.5 and Sec.6, while advice on inspection, monitoring and retrofitting is given in Sec.7.

1.2 Objective

The objective of this recommended practice is to:

- facilitate the execution of conceptual and detailed CP design of marine structures for submerged service
- serve as a basis for the verification of galvanic anode cathodic protection (GACP) design
- serve as a contractual and technical reference document between the purchaser and contractor.

1.3 Scope

This recommended practice specifies requirements for the cathodic protection of permanently installed offshore structures associated with the production of oil and gas. The following topics are covered:

- procedures for the execution and documentation of marine structure GACP design using aluminium- or zinc-based galvanic anodes
- default design parameters for GACP design
- requirements for the manufacturing of galvanic anodes for marine structures with an emphasis on quality control
- requirements for the installation of anodes on marine structures
- advice on the inspection, monitoring and retrofit of GACP systems.

The document does not include:

- potential attenuation calculations related to a voltage drop in the steel structure and in the electrolyte remotely from the anodes
- the detailed design of anode fastening devices for structural integrity
- considerations related to safety and environmental hazards associated with galvanic anode manufacture and installation.

1.4 Application

CP is applicable for all types of metals and alloys commonly used in marine subsea applications, although caution and possibly specific material testing may be required for certain high strength and high hardness materials, see [2.5].

This RP may be used for the design of cathodic protection for marine structures by engineering contractors and by organizations carrying out third-party verification, and as a contractual and technical reference document between the purchaser and contractor.

If the purchaser has chosen to refer to this RP in a purchase document, the contractor shall treat all requirements in this document as mandatory, unless superseded by amendments and deviations for the specific contract.

Specific requirements for mobile installations for oil and gas production, such as semi-submersibles, jack-ups and mono-hull vessels, are not included in the scope of this document. At the discretion of the owner, parts of this RP may be applicable for the GACP of marine structures not covered in this document. The same applies to other marine structures not associated with oil and gas production. Some of the design recommendations and methods described may be valid for CP systems using other current sources, such as magnesium anodes and direct current (DC) power sources, i.e. impressed current.

1.5 References

In the context of this document, the term standard shall be understood to cover document types such as codes, guidelines and recommended practices in addition to bona fide standards.

Referenced relevant standards and recommended practice documents are given in Table 1-1 and Table 1-2. The latest valid edition of each of the DNV reference documents applies.

For other standards, the edition valid at the time of publishing this document applies, unless dated references are given.

Table 1-1 DNV references

Documet code	*Title*
DNV-RP-0416	Corrosion protection for wind turbines
DNV-RP-B101	Corrosion protection of floating production and storage units
DNV-RP-F103	Cathodic protection of submarine pipelines by galvanic anodes
DNV-RP-F112	Design of duplex stainless steel equipment exposed to cathodic protection

Table 1-2 Other references

Document code	*Title*
ASTM A193	Standard Specification for Alloy-Steel and Stainless SteelBolting for High Temperature or High Pressure Service and Other Special Purpose Applications
ASTM A320	Standard Specification for Alloy-Steel and Stainless Steel Bolting for Low-Temperature Service
ASTM D1141	Standard Practice for the Preparation of Substitute Ocean Seawater
ASTM E527	Standard Practice for Numbering Metals and Alloys (UNS)
ASTM G8	Standard Test Methods for Cathodic Disbonding of Pipeline Coating
EN 10204	Metallic Products - Types of Inspection Documents
EN 13509	Cathodic Protection Measurement Techniques
NORSOK M-501	Surface preparation and protective coating
ISO 3506-1	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners - Part 1: Bolts, screws and studs with specified grades and property classes

Document code	*Title*
ISO 3506-2	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners - Part 2: Nuts with specified grades and property classes
ISO 3506-3	Mechanical properties of corrosion-resistant stainless steel fasteners - Part 3: Set screws and similar fasteners not under tensile stress
ISO 3506-4	Mechanical properties of corrosion-resistant stainless steel fasteners - Part 4: Tapping screws
ISO 3506-6	Fasteners - Mechanical properties of corrosion-resistant stainless steel fasteners - Part 6: General rules for the selection of stainless steels and nickel alloys for fasteners
ISO 8044	Corrosion of Metals and Alloys - Vocabulary
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 8503-1	Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 1: Specifications and definitions for ISO surface profile comparators for the assessment of abrasive blast-cleaned surfaces
ISO 8503-2	Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 2: Method for grading surface profile of abrasive blast-cleaned steel - Comparator procedure
ISO 8503-3	Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 3: Method for the calibration of ISO surface profile comparators for the determination of surface profile - Focusing microscope procedure
ISO 8503-4	Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 4: Method for the calibration of ISO surface profile comparators for the determination of surface profile -Stylus instrument procedure
ISO 8503-5	Preparation of steel substrates before application of paints and related products - Surface roughness characteristics of blast-cleaned steel substrates - Part 5: Replica tape method for the determination of the surface profile
ISO 9000	Quality management systems - Fundamentals and vocabulary
ISO 9001	Quality management systems - Requirements
ISO 10005	Quality Management- Guidelines for Quality Plans
ISO 10474	Steel and Steel Products - Inspection Documents
ISO 12944	Paints and Varnishes - Corrosion Protection of Steel Structures by Protective Paint Systems
ISO 15257	Cathodic protection - Competence levels of cathodic protection persons - Basis for certification scheme
ISO 15589-1	Petroleum, petrochemical and natural gas industries - Cathodic protection of pipeline systems - Part 1: On-land pipelines
ISO 15589-2	Petroleum, petrochemical and natural gas industries - Cathodic protection of pipeline transportation systems - Part 2: Offshore pipelines
NACE SP0176	Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production

Document code	*Title*
NACE SP0387	Metallurgical and Inspection Requirements for Cast Galvanic Anodes for Offshore Applications
NACE SP0492	Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet Anodes

1.6 Definitions and abbreviations

1.6.1 Definition of verbal forms

The verbal forms defined in Table 1-3 are used in this document.

Table 1-3 Definition of verbal forms

Term	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others
may	verbal form used to indicate a course of action permissible within the limits of the document

1.6.2 Definition of terms

The terms defined in Table 1-4 are used in this document.

Table 1-4 Definition of terms

Term	*Definition*
accepted/acceptance	confirmation by purchaser/owner in writing
calcereous scale/layer	thin layer consisting primarily of calcium carbonate deposed at the metal surface when cathodically polarized
cathodic protection	electrochemical protection by decreasing the corrosion potential to a level at which the corrosion rate of the metal is significantly reduced (ISO 8044:2015)
concession request	deviation request submitted to owner for approval
contractor	party to whom the work, i.e. CP design, anode manufacture or anode installation, has been contracted
galvanic anode	casting of an electrochemically active alloy, normally aluminium (Al), zinc (Zn) or magnesium (Mg) based, which is the current source for the CP system and will be consumed
impressed current cathodic protection	electrochemical protection where an inert (insignificant consumption rate) anode is used and the current to the anode is supplied by a direct current power source
owner	party legally responsible for the design, construction and operation of the object to receive CP, in some standards also referred to as the end user
protection object	the cathode of the electrochemical cell, i.e. the structure, subsystem or component to receive CP
purchase document(s)	inquiry/tender or purchase/contract specification

Term	*Definition*
purchaser	party (owner or main contractor) issuing an inquiry or contract for CP design, anode manufacture or anode installation work, or a nominated representative
verification	confirmation, through the provision of objective evidence, that specified requirements have been fulfilled (ISO 9000:2015)

1.6.3 Abbreviations and symbols

The abbreviations described in Table 1-5 are used in this document.

Table 1-5 Abbreviations

Abbreviation	*Description*
CAD	computer aided design
CP	cathodic protection
CR	concession request [5.5.6]
CRA	corrosion resistant alloy
CTOD	crack tip opening displacement
CV	curriculum vitae
DC	direct current
DFT	dry film thickness
GACP	galvanic anode cathodic protection
HAT	highest astronomical tide
HAZ	heat affected zone
HISC	hydrogen induced stress cracking [2.5.3]
HV	Vicker's hardness
ICCP	impressed current cathodic protection
ITP	inspection and testing plan [5.4.2]
IPS	installation procedure specification [6.2]
LAT	lowest astronomical tide
MPS	manufacture procedure specification [5.2]
NDT	non-destructive testing
PQT	production qualification test [5.3]
PTFE	Polytetrafluoroethylene
PWHT	post weld heat treatment [2.5.7]
ROV	remotely operated vehicle
RP	recommended practice

Abbreviation	*Description*
SCE	standard calomel electrode [3.1.5]
SMYS	specified minimum yield strength
SRB	sulphate reducing bacteria
UNS	unified numbering system (ASTM E527)
WPS	welding procedure specification
WPQT	welding procedure qualification test
YS	yield strength

The symbols described in Table 1-6 are used in this document.

Table 1-6 Symbols

Symbol	*Description*
a	constant in coating breakdown factor [3.4.2]
A [m²]	anode surface area Table 8-7
A_c [m²]	cathode surface area [4.4.1]
b	constant in coating breakdown factor [3.4.2]
c [m]	anode cross sectional periphery Table 8-7
C [Ah]	current charge associated with quality control testing of anode materials [9.3.10]
C_a [Ah]	(individual) anode current capacity [4.8.3]
$C_{a\ tot}$ [Ah]	total anode current capacity [4.8.4]
E_a^0 [V]	design closed circuit anode potential [3.5.1]
E_c^0[V]	design protective potential [4.8.2]
E_p^0[V]	protection potential criterion [2.4.1]
E'_c [V]	global protection potential [3.3.4]
E'_a [V]	(actual) anode closed circuit potential [3.3.4]
ΔE^0[V]	design driving voltage [4.8.2]
f_c	coating breakdown factor [3.4.1]
f_{ci}	initial coating breakdown factor [3.4.4]
f_{cm}	mean coating breakdown factor [3.4.4]
f_{cf}	final coating breakdown factor [3.4.4]
i_c [A/m²]	design current density [3.3.1]
i_{cf} [A/m²]	design final current density [3.3.1]

Symbol	*Description*
i_{ci} [A/m²]	design initial current density [3.3.1]
i_{cm} [A/m²]	design mean current density [3.3.5]
I_a[A]	(individual) anode current output [4.8.2]
$I_{a\ tot}$ [A]	total anode current output [3.3.4]
$I_{a\ tot\ f}$ [A]	total final current output [4.8.4]
$I_{a\ tot\ i}$ [A]	total initial current output [4.8.4]
I_{af} [A]	(individual) final anode current output [4.8.2]
I_{ai} [A]	(individual) initial anode current output [4.8.2]
I_c [A]	current demand [4.4.2]
I_{cf} [A]	final current demand [4.4.2]
I_{ci} [A]	initial current demand [4.4.2]
I_{cm} [A]	mean current demand [4.4.2]
L [m]	anode length Table 8-7
m_a [kg]	(individual) net anode mass [4.8.3]
m_{ai} [kg]	(individual) initial net anode mass [4.9.3]
m_{af} [kg]	(individual) final net anode mass [4.9.3]
M_a [kg]	total net anode mass [4.7.1]
N	number of anodes [4.8.1]
r [m]	anode radius Table 8-7
R_a [Ω]	(individual) anode resistance [3.6.1]
R_{af} [Ω]	(individual) anode final resistance [4.9.2]
R_{ai} [Ω]	(individual) anode initial resistance [4.9.2]
S [m]	arithmetic mean of anode length and width Table 8-7
t_f [years]	design life [3.4.4]
u	anode utilization factor [3.8]
Δw [g]	weight loss associated with quality control testing of anode materials [9.3.10]
ϵ [Ah/kg]	anode electrochemical capacity [3.5.1]
ρ [Ω·m]	seawater/sediment resistivity [2.3.2]

SECTION 2 GENERAL CATHODIC PROTECTION DESIGN CONSIDERATIONS

2.1 General

This section addresses aspects of cathodic protection which are primarily relevant to CP conceptual design, including the compatibility of CP with metallic materials and coatings. The content of this section is informative and intended as guidelines for owners and their contractors preparing for conceptual or detailed CP design.

2.2 Limitations of cathodic protection

2.2.1

For structural components of carbon and low-alloy steels, cathodic protection should be considered as a technique for corrosion control. It follows that cathodic protection is not an alternative to corrosion resistant alloys for components with very strict dimensional tolerances, e.g. sealing assemblies associated with subsea production systems. For those lower alloy stainless steels and NiCr(Mo) alloys that are vulnerable to corrosion in seawater, GACP provides protection against localized and crevice corrosion if correctly designed.

2.2.2

For offshore structures with water filled internals such as bracings and legs of jacket structures, anodes located on external surfaces cannot be expected to provide CP of internals via holes made to facilitate flooding.

2.3 Environmental parameters affecting cathodic protection

2.3.1

The major seawater parameters affecting CP in situ are:

- dissolved oxygen content
- sea currents
- temperature
- marine growth
- salinity.

In addition, variations in seawater pH and carbonate content are factors which affect the formation of calcareous layers associated with CP and thus the current needed to achieve and maintain CP of bare metal surfaces. In seabed sediments, the major parameters are: temperature, pH, bacterial activity, salinity and sediment coarseness.

2.3.2

The above parameters are interrelated and vary with geographical location, depth and season. It is not feasible to give an exact relationship between the environmental parameters indicated above and cathodic current demands for achieving and maintaining CP. To rationalize CP design for marine applications, default design current densities, i_c (A/m^2), are defined in this document based on 1) climatic regions related to mean seawater surface temperature and 2) depth. The ambient temperature and salinity determine the specific resistivity, ρ (ohm·m), which is used to calculate the anode resistance, R_a (ohm), a controlling factor for the current output from an anode.

2.4 Protection potential criterion and design protective potential

2.4.1

A CP potential of -0.80 V relative to the Ag/AgCl/seawater reference electrode recorded without any significant voltage drop due to ohmic resistance is generally recognized as a protection potential criterion, E_p^0 for carbon and low-alloy steels.

Guidance note:

It has been argued that, to achieve efficient corrosion protection, a CP protection potential criterion of -0.90 V should apply in anaerobic environments, especially those containing sulphate reducing bacteria (SRB) as typically encountered in marine environments. DNV is not aware of any documentation that an instant-off potential, i.e. measured without ohmic resistance in the range -0.80 to -0.90 V, has led to any significant corrosion damage, including corrosion damage by bacteria. Some surface discolouration or a minor residual corrosion rate has been reported during laboratory testing. However, CP is not intended to give structural materials full immunity to any corrosion processes.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

2.4.2

In the design procedure advised in this RP, the design protective potential E_c^0 used to calculate the initial and final current output has a default value of -0.80 V and is not a variable.

2.4.3

For a correctly designed GACP system, the CP potential, i.e. as recorded without any effect of ohmic resistance, will for the main part of the design life be between -0.90 V and -1.05 V, which are also the favourable conditions for the formation of protective calcareous scale. A less negative potential will lead to enhanced anode consumption and the design life based on the mean design current densities recommended in this RP may not be achieved. Towards the end of the service life, the CP potential increases rapidly towards -0.80 V, and eventually to even less negative values, generally referred to as under-protection. The term over-protection is only applicable to protection potentials more negative than -1.15 V. Such potentials will not apply for CP by galvanic anodes based on Al or Zn.

Guidance note:

For a review of experimental data related to the formation of protective calcareous scale see e.g. /1/.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

2.5 Detrimental effects of cathodic protection

2.5.1

Cathodic protection is accompanied by the formation of hydroxyl ions and hydrogen at the surface of the protected object. These products may cause disbonding of non-metallic coatings by mechanisms including chemical dissolution and electrochemical reduction processes at the metal/coating interface, possibly including a build-up of hydrogen pressure at this interface. This process of coating deterioration is referred to as cathodic disbonding. On components containing hot fluids, the process is accelerated by heat flow to the metal/coating interface.

2.5.2

Coatings applied to machined or as-delivered surfaces are particularly prone to cathodic disbonding. However, with surface preparation to achieve an optimum surface roughness, some coating systems (e.g. those based on epoxy or polyurethane) have shown good resistance to cathodic disbonding by GACP when applied to CRAs as well as to carbon and low-alloy steel. For coating systems whose compatibility with GACP is not well documented, the owner should consider carrying out qualification testing, including laboratory testing of resistance to cathodic disbonding. The testing of marine coatings' resistance to cathodic disbonding has been standardized, e.g. in ASTM G8. Further requirements for the qualification of marine coatings are given in NORSOK M-501 and ISO 12944.

2.5.3

Cathodic protection will cause the formation of atomic hydrogen at the metal surface. Within the potential range for CP by aluminium- or zinc-based anodes (i.e. -0.80 V to -1.10 V Ag/AgCl/seawater), the production of hydrogen increases exponentially towards the negative potential limit. The hydrogen atoms can either combine to form hydrogen molecules or become absorbed in the metal matrix. In the latter case, they may interact with the microstructure of components subject to high stresses, causing the initiation and growth of hydrogen-related cracks, here referred to as hydrogen induced stress cracking (HISC). CP design will not normally take into account materials selection, so it is essential that compatibility with CP is ensured for components which may receive CP when the materials selection is being specified.

2.5.4

For all practical applications, austenitic stainless steels and nickel-based alloys are generally considered immune to HISC in the solution annealed condition. With the exceptions of UNS S30200 (AISI 302) and UNS S30400 (AISI 304) stainless steel, moderate cold work does not induce HISC sensitivity in these materials. The same applies for welding or hot forming according to an appropriate procedure. Bolts in AISI 316 stainless steel manufactured according to ISO 3506-1, grade A4, property class 80 and lower, i.e. up to SMYS 640 MPa, have proven compatibility with GACP.

2.5.5

Nickel-based alloys being annealed or precipitation hardened to enhance mechanical properties are potentially susceptible to HISC and failures of highly stressed components including bolting have been reported. This is also relevant for material with SMYS below 720 MPa. HISC failures of these materials have been observed as intergranular fractures, thus indicating grain boundary effects and not strengthening as the cause of increased sensitivity. The hardness requirement as specified for H_2S service, typically 350 HV - 400 HV maximum, may not be sufficient to prevent HISC failures and it is not proven that any hardness criteria are relevant to prevent HISC in this type of material. Similar considerations apply for the precipitation hardening of stainless steel although it appears that no CP induced failures have been reported.

2.5.6

Based on practical experience, ferritic and ferritic-pearlitic structural steels with a specified minimum yield strength (SMYS) up to at least 500 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. It is recommended that all welding is carried out according to a qualified procedure with 350 HV as an absolute upper limit. With a qualified maximum hardness in the range of 300 to 350 HV, design measures should be implemented to avoid local yielding.

2.5.7

For martensitic carbon, low-alloy and stainless steels, failures caused by CP induced HISC have been encountered involving materials with an actual YS and hardness of about 700 MPa and 350 HV respectively. It is widely recognized that untempered martensite is especially prone to HISC. The welding of materials susceptible to martensite formation should be followed by post weld heat treatment (PWHT) to reduce the heat-affected zone (HAZ) hardness and residual stresses from welding. The same recommendations for hardness limits and design measures as for ferritic steels [2.5.6] apply. Bolts in martensitic steel that have been heat treated to SMYS up to 720 MPa, e.g. ASTM A193 grade B7 and ASTM A320 grade L7, have well documented compatibility with CP. However, failures due to inadequate heat treatment have occurred, and for critical applications, batch wise testing is recommended to verify a maximum hardness of 350 HV.

2.5.8

Ferritic-austenitic (duplex) stainless steels should be regarded as potentially susceptible to HISC, independent of SMYS, typically 400 MPa to 550 MPa or a 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 therefore prove that the maximum ferrite content in the weld metal and the inner HAZ, about 0.1 mm wide, can be efficiently controlled. Ferrite contents of maximum 60% to 70% are typically specified, which excludes fillet welds and autogenous welding of pressure retaining components and other critical structural applications. Coarse microstructure is more susceptible since HISC would propagate preferentially in the ferrite phase. Cold bent uncoated pipes of small diameter with mechanical connections, i.e. without welds, have a proven record of CP compatibility when used as production control piping for subsea installations. Design precautions should include measures to avoid local plastic yielding, see DNV-RP-F112.

2.5.9

The 5000 and 6000 series aluminium alloys and copper are generally considered immune to HISC, regardless of fabrication methods. For high-strength titanium alloys, documentation is limited and special considerations (including e.g. qualification testing, see [2.5.10]) should apply.

2.5.10

There is no generally recognized test method to verify the CP compatibility of different metallic materials. Constant extension rate testing, also referred to as slow strain rate testing, is applicable to compare the 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 a constant load, and 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.

2.5.11

Special techniques have been applied to reduce the CP potential to a less negative range, e.g. -0.80 V to -0.90 V, including the use of diodes and special anode alloys. A major disadvantage of this approach is that the individual component or system needs to be electrically insulated from adjacent standard CP systems.

2.5.12

Cathodic protection in closed compartments without ventilation may cause hydrogen gas to develop to an extent that an explosive gas mixture, i.e. hydrogen/oxygen, may eventually develop. The risk is moderate with Al- and Zn-based galvanic anodes. However, at least one explosion during external welding on a water flooded platform leg containing Al-anodes has been related to this phenomenon.

Aluminium alloy anodes acidify their environment due to the hydrolysis of dissolved aluminium ions. In closed compartments, the accumulation of acidity can reach levels that cause auto-corrosion of the anodes, resulting in the enhanced production of hydrogen gas and premature anode consumption. Zinc alloy anodes are therefore recommended for use in closed compartments. Completely closed, e.g. by welding or secure valves, water flooded compartments without access to external air will not normally require CP, see [3.3.7].

2.5.13

A consequence of CP application is that a calcareous layer, consisting primarily of calcium and magnesium carbonates and bicarbonates, will form on bare metal surfaces. The thickness is typically of the order of a tenth of a millimetre, but thicker deposits may occur. The calcareous layer reduces the current demand for maintenance of CP and is therefore beneficial. A calcareous layer may, however, obstruct the mating of subsea electrical and hydraulic couplers with small tolerances. This may be prevented by applying an insulating layer consisting of a thin film coating, e.g. baked epoxy resin. An alternative measure is to electrically insulate the connectors from the CP system and use seawater resistant materials for all wetted parts. High-alloyed stainless steels, nickel-chromium-molybdenum alloys, titanium and certain copper-based alloys, e.g. nickel-aluminium bronze, have been used for this purpose.

2.5.14

Galvanic anodes may interfere with subsea operations and increase drag forces caused by flowing seawater.

2.5.15

CP eliminates the anti-fouling properties of copper-based alloys in seawater.

2.6 Galvanic anode materials

2.6.1

Galvanic anodes for offshore applications are generally based on either aluminium or zinc. The generic type of anode material, i.e. aluminium or zinc base, is typically selected by the owner and specified in the conceptual CP design report and/or in the design premises for the detailed CP design. Recommendations for max./min. contents of alloying elements and max contents of impurity elements are given in Table 8-5.

2.6.2

Aluminium alloy anodes are normally preferred due to their higher electrochemical capacity, ϵ (Ah/kg). However, the electrochemical performance of zinc alloy anodes has sometimes been considered more reliable for applications in marine sediments or internal compartments with high bacterial activity, which are both anaerobic conditions.

2.6.3

Some anode manufacturers offer proprietary anode alloys. The purchaser may require the anode manufacturer to document the electrochemical performance of its products by operational experience or by long term testing in natural seawater. A recommended testing procedure is contained in Sec.10.

2.7 Anode geometry and fastening devices

2.7.1

There are three major types of anodes for offshore structures:

- slender stand-off
- elongated, flush-mounted
- bracelet.

Stand-off and flush-mounted anodes may further be divided into short and long, based on the length to width ratio. The anode type determines the anode resistance formula [3.6] and anode utilization factor [3.8] to be applied.

2.7.2

The slender stand-off type is typically cast on a tubular insert and used for relatively large anodes on e.g. platform substructures and subsea templates. The current output, I_a (A), in relation to net anode mass, M_a (kg), is high, as is the utilization factor u.

Bracelet anodes are used primarily for pipelines but have also found some use on platform legs in the upper zone, combining a high current output to weight ratio with low drag.

The type of anodes and any special anode fastening requirements should be defined during the conceptual CP design, taking into account the forces exerted during installation phase, e.g. piling operations and operating phase, e.g. wave forces. For stand-off type anodes, special precautions may be necessary while designing and distributing anodes to avoid impeding subsea operations [4.10.2].

2.8 Use of coatings in combination with cathodic protection

2.8.1

The use of non-metallic coatings drastically reduces the CP current demand of the protection object and hence the required anode weight. For weight-sensitive structures with a long design life, the combination of a coating and CP is likely to give the most cost-effective corrosion control. For some systems with very long design lives, CP may be impractical unless combined with coatings.

2.8.2

The use of coatings should be considered for applications where the demand for CP of bare metal surfaces is known or expected to be high. This includes deep water applications for which the formation of calcareous deposits may be slow, see [3.3.2]). It should further be considered for surfaces that are partly shielded from CP by geometrical effects.

2.8.3

The application of coatings may not be suitable for parts of submerged structures requiring frequent inspection for fatigue cracks, e.g. critical welded nodes of jacket structures.

2.8.4

Metallic coatings with a zinc or aluminium basis are compatible with galvanic anode CP.

2.8.5

For material components that are sensitive to HISC, the use of a non-metallic coating system should always be considered as it will reduce hydrogen adsorption if design loads are exceeded during operation, see [2.5.6] and [2.5.7].

2.9 Electrical insulation

Provisions for electrical insulation are only necessary if certain components or units need to be electrically insulated to avoid CP or to control the CP potential by special means, see [2.5.11].

SECTION 3 CATHODIC PROTECTION DESIGN PARAMETERS

3.1 General

3.1.1

This section describes design parameters to be used for the conceptual and detailed design of GACP systems and gives guidance on the selection of such parameters. With the exception of the design life, see [3.2] and possibly also coating breakdown factors, see [3.4.3], the actual design values to be applied for a specific project are normally selected by the contractor from Sec.8, based on environmental conditions and other parameters identified in the project design basis. However, sometimes certain or all CP design parameters have already been defined by the purchaser in a project document, e.g. the project design basis or material selection philosophy.

3.1.2

If reference is made to this RP in a purchase document, and unless otherwise specified or agreed with owner, the default design values referred to in this section shall apply.

3.1.3

The design values recommended in this section are consistently selected using a conservative approach. Adherence to these values is therefore likely to provide a service life that exceeds the design life of the CP system. For CP of support structures associated with offshore wind turbines, see DNV-RP-0416.

Guidance note:

The default values for initial/final design current densities recommended in Sec.3 have been developed for structures relatively far from shore, and may not be conservative in water with high sea water current velocities, such as shallow water with a large difference between HAT and LAT. When DNV-RP-B401 is specified for CP design for structures located in such waters, it should be considered whether to increase the initial design current densities for all initially bare steel surfaces to account for the effect of high sea water currents, see DNV-RP-0416 [5.2.2].

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.1.4

The contractor may propose the use of alternative design values, but any such data is then subject to the acceptance of the owner, e.g. in response to a concession request, preferably before the CP design work has started.

3.1.5

All electrochemical potentials associated with CP in this section refer to the Ag/AgCl/seawater reference electrode. The potential of this reference electrode is virtually equal to that of the saturated calomel electrode (SCE). The Ag/AgCl/saturated KCl reference electrode has a potential -50 mV vs the SCE, see EN 13509, Annex A.

Guidance note:

The Ag/AgCl/0.5M KCl reference electrode potential is virtually equal to that of the SCE. However, it should be noted that these anodes may not be stable in seawater, especially for long-term use.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.2 Design life

3.2.1

The design life of a CP system is specified by the owner [3.1.1], and shall take into account the CP requirements in structural design standards, design life of the protection object, likelihood of the design life being extended, and any period of time when the CP system will be active prior to start of the operating phase of the protection object.

Guidance note:

The maintenance and repair of CP systems for fixed offshore structures are generally very costly and sometimes impractical. It is therefore normal practice to apply at least the same anode design life as for the protection object. However, in certain circumstances the planned retrofitting of galvanic anodes may be an economically viable alternative to the installation of very large anodes initially. This alternative should then be planned such that necessary provisions for retrofitting are made during the initial design and fabrication.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3 Design current densities

3.3.1

In this document, current density, i_c , refers to the cathodic protection current per unit surface area (in A/m^2). The initial and final design current densities, i_{ci} (initial) and i_{cf} (final), respectively, give a measure of the anticipated cathodic current density demand to achieve cathodic protection of a bare metal surface within a reasonably short period. They are used to calculate the initial and final current demands which determine the number and sizing of anodes. The effect of any coating on current demand is taken into account applying a coating breakdown factor, see [3.4].

3.3.2

The initial design current density refers to the cathodic current density that is required to effectively polarize a bare metal surface, typically for structural steel surfaces with some rusting and/or mill scale.

Guidance note:

The initial design cathodic current density is necessarily higher than the final design current density because the calcareous scale, see [2.5.13], and possibly marine fouling layer developed during this initial phase reduce the subsequent current demand, i.e. the polarization to more negative potentials is facilitated. A sufficient initial design current density enables rapid formation of protective calcareous scale and hence efficient polarization.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.3

The final design current density refers to metal surfaces with established calcareous scale and marine growth. It takes into account the current density required to re-polarize a structure if such layers are partly damaged, e.g. by periodic removal of marine growth.

Guidance note:

An appropriate final design current density (and hence CP polarizing capacity) will further ensure that the protection object remains polarized to a potential of -0.95 V to -1.05 V throughout the design life. In this potential range, the current density demand for maintenance of CP is lowest.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.4

The initial and final current densities are used to calculate the required number of anodes of a specific type [4.8] to achieve a sufficient polarizing capacity by use of Ohm's law based on the following requirements, see [5.4.2]:

1) the anode potential is in accordance with the design closed circuit potential [3.5.3] and
2) the current demand shall be supplied with the potential of the protection object (i.e. cathode) at the design protective potential for C-steel and low-alloy steel, i.e. -0.80 V [2.4.2].

Guidance note:

It follows from the above relationship that the anode current and hence the cathodic current density decreases linearly when the cathode is polarized towards the closed circuit anode potential, reducing the driving voltage for the galvanic cell.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.5

The tabulated mean (or maintenance) design current density, i_{cm} (A/m^2) in Table 8-2, is a measure of the anticipated cathodic current density once the CP system has attained its steady-state protection potential. This is typically 0.15 V to 0.20 V more negative than the design protective potential. The values recommended in Table 8-2 contain a certain conservatism to take into consideration that retrofitting of anodes may not be practical and that the design life of a structure is frequently exceeded by 20% or more. A reduction of the recommended mean design current densities may therefore be justified. However, such design shall be specified or approved by the owner.

Guidance note:

The decrease in cathode potential (i.e. cathodic polarization) reduces the anode current so that the mean design current density becomes about 50% of the initial/final design current density. As the initial polarization period preceding the steady-state condition is normally short compared to the design life, the time-weighted cathodic current density to be used to calculate the required anode net mass becomes very close to the steady-state cathodic current density.

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3.3.6

Cathodic current densities to achieve and maintain CP are dependent on factors that vary with geographical location and operational depth. Recommendations for initial/final and mean design current densities are given in Table 8-1 and Table 8-2 respectively, based on climatic regions and depth. These design current densities have been selected in a conservative manner to account for harsh weather conditions, including waves and sea currents, but not erosive effects on calcareous layers caused by silt or ice. They further assume that the seawater at the surface is saturated with air, i.e. at 0.2 bar oxygen partial pressure.

Guidance note:

The data in Table 8-1 and Table 8-2 reflect the expected influence of seawater temperature and depth on the properties of a calcareous scale formed by cathodic protection and of the content of dissolved oxygen. The properties of such layers are dependent on the seawater ambient temperature and, moreover, on certain depth dependent parameters other than temperature, see [2.3.1]. Oxygen is dissolved from the air or generated by microorganisms in the seawater close to the surface through photosynthesis such that the oxygen content at a large depth in a tropical region is likely to be substantially lower than in temperate or Arctic surface waters of the same ambient seawater temperature. The higher design current densities in the uppermost zone are a result of wave forces and marine growth degrading calcareous scales and convective mass transfer of oxygen. In certain areas, the decomposition of organic material may reduce and ultimately consume all oxygen in the seawater. No such reduction in oxygen content is accounted for in Table 8-1 and Table 8-2. See also [3.1.3], higher current densities may be required in locations of high seawater velocity or particularly high tides.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.7

For CP of freely flooded compartments and for closed compartments with free access to air, design current densities for depths of 30-100 m given in Table 8-1 and Table 8-2 are recommended. However, lower values than those in Table 8-2 may be considered for compartments that can readily be retrofitted with anodes or where very similar conditions have been demonstrated to require lower current densities. For CP in seawater filled compartments, the use of zinc anodes should be considered if sufficient exchange of seawater cannot be ensured, see also [2.5.12]. Permanently closed and sealed flooded compartments do not normally need CP.

3.3.8

For bare steel surfaces buried in sediments, an initial, mean and final design current density of 0.020 A/m^2 is recommended irrespective of geographical location and depth.

3.3.9

For piping and other components heated by an internal fluid, the design current densities as specified in Table 8-1, Table 8-2 and [3.3.8] shall be increased by 0.001 A/m^2 for each °C that the metal/environment interface is assumed to exceed 25°C. For single wall conduits this temperature shall be assumed to be equal to the temperature of the internal fluid.

Guidance note:

The additional CP current density is to account for the increased convective and diffusive mass transfer of oxygen induced by heat transfer.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.10

The design current densities in Table 8-1 and Table 8-2 shall also apply for surfaces of any stainless steel or non-ferrous components of a CP system which includes components in C-steel or low-alloy steel. To calculate the anode current output according to [4.8.2], a design protective potential of -0.80 V shall then also apply for these materials.

3.3.11

For aluminium components, or those coated with either metallic aluminium or zinc, a design current density of 0.010 A/m^2 is recommended for the initial/final as well as mean values. For internally heated components, the design current density shall be increased by 0.0002 A/m^2 for each °C that the metal/seawater is assumed to exceed 25°C.

Guidance note:

The current demand for aluminium components may be higher than 0.010 A/m^2. In a recent study it was found that the current demand varied significantly with the type of alloy, apparently depending on the Cu and Fe content.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.12

For the current drain to reinforcing steel and other concrete embedded steel components associated with offshore structures, the design current densities in Table 8-3 are recommended. For the external current drain to reinforcing steel in shafts that are normally empty, the design current densities in Table 8-3 should be multiplied by a factor of 1.5.

Guidance note:

This RP does not account for any cathodic protection of reinforcement steel in concrete structures. However, CP systems for external steel components attached to such structures can experience some current drain from the reinforcement. The reinforcement is expected to be embedded in a concrete quality giving sufficient corrosion protection for the service life. The cathodic current density of steel embedded in concrete is mainly controlled by a reduction of oxygen. In the splash zone and in internal dry compartments, oxygen is transported by capillary action of pore water, driven by evaporation at the atmospheric surface. Hence, the cathodic current density depends on the exposure conditions (i.e. distance to atmospheric exposure of concrete) and ambient temperature.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.3.13

When the ratio of the actual reinforcing steel surface area in m^2 to the reinforced concrete volume in m^3, ratio B, exceeds 5, an adjustment factor of 5/B may be applied to the design current densities in Table 8-3.

3.4 Coating breakdown factors for cathodic protection design

3.4.1

The coating breakdown factor, f_c , describes the anticipated reduction in cathodic current density due to the application of an electrically insulating coating. When $f_c = 0$, the coating is 100% electrically insulating, thus decreasing the cathodic current density to zero. $f_c = 1$ means that the coating has no current reducing properties.

Guidance note:

The coating breakdown factor should not be confused with coating degradation that is apparent during a visual examination. A coating showing extensive blistering may still retain good electrically insulating properties. Conversely, an apparently perfect coated surface may still allow a significant passage of current.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.4.2

The coating breakdown factor is a function of coating properties, environmental parameters and time. As a simple engineering approach, f_c shall be expressed as:

$$f_c = a + bt$$

where t (years) is the design life and a and b are constants that are dependent on coating properties and the environment.

Guidance note:

The effect of marine growth is highest in the upper 30 metres where wave forces may further contribute to coating degradation. Another factor is periodic cleaning of marine growth in this zone.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.4.3

The owner should preferably specify constants a and b for the calculation of coating breakdown factors based on its own practical experience of specific coating systems in a particular environment. When the owner has not specified any such data, the default values in Table 8-4 shall be used. The coating breakdown factors as established in Sec.8 are based on considerations addressed in [2.8.3].

3.4.4

Once a and b are defined, the mean and final coating breakdown factors, f_{cm} and f_{cf}, respectively, to be used for CP design purposes shall be calculated by introducing the CP design life, t_f (years):

$$f_{cm} = a + b\frac{t_f}{2} \qquad (3.1)$$

$$f_{ci} = a \qquad (3.2)$$

$$f_{cf} = a + bt_f \qquad (3.3)$$

3.4.5

If the calculated value, f_{cf}, according to [3.4.4] exceeds 1, $f_{cf} = 1$ shall be applied in the design. When the design life of the CP system exceeds the actual calculated life of the coating system according to [3.4.2], f_{cm} may be calculated as:

$$f_{cm} = 1 - \frac{(1-a)^2}{2bt} \qquad (3.4)$$

3.4.6

To account for the effect of a coating system on coating breakdown factors, four coating categories have been defined for inclusion in Table 8-4:

Category I	One layer of epoxy paint coating, minimum 20 μm nominal DFT.
Category II	One or more layers of marine paint coating (epoxy-, polyurethane- or vinyl-based), total nominal DFT minimum 250 μm.
Category III	Two or more layers of marine epoxy-based paint coating total nominal DFT min. 350 μm.
Category IV	Two or more layers of epoxy-based coatings according to NORSOK M-501 systems 3B or 7, with total nominal DFT of minimum 350 μm or the equivalent and meeting all requirements for coating system qualification, coating application, inspection and repairs given in the same standard. The purchaser is further required to be involved in quality control by accepting the coating application procedure and carrying out quality surveillance during coating work.

Category I includes shop primer type coatings. It is assumed for categories II, III and IV that the manufacturer-specific coating materials to be applied have been qualified by documented performance in service, or by relevant testing. It is further assumed for all categories that all coating work has been carried out according to the manufacturer’s recommendations and that surface preparation has included blast cleaning to minimum Sa 2½ in accordance with ISO 8501. The surface roughness shall be in accordance with ISO 8503 series and the coating manufacturer's recommendation.

Manufacturer-specific thin-layer coating systems of the anti-friction coating type, typically containing PTFE with a heat cured polymeric binder, may be defined as category I or category II coating, subject to the following provisions: the substrate has been prepared by blasting to a defined surface roughness, the prepared surface has been phosphatized according to a defined procedure, coating has been applied by spraying to a minimum DFT of 50 μm (category II) and 20 μm (category I) and subsequently heat cured at controlled conditions, and the resistance to cathodic disbonding according to ISO 12944-9 has been qualified at the max operating temperature of the steel substrate.

For any other paint coatings applied without blast cleaning to a defined surface roughness, including machined, ground, brushed and as-rolled surfaces, a coating breakdown factor of f_{cm} = f_{cf} = 1 shall be applied, while the initial current demand may be calculated as for category I.

Guidance note:

For any coating systems not covered by categories I to IV and with a major potential effect on the overall current demand, the applicable values for a and b may be found in other codes/standards, e.g. DNV-RP-F103 or ISO 15589-2 or the owner should specify or accept applicable values for a and b.

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3.4.7

The values for the a and b constants for a depth of 30-100 m in Table 8-4 are applicable for calculating the current demands of flooded compartments and of closed compartments with free access to air.

3.4.8

The constant a in Table 8-4 does not account for significant damage to paint coatings during fabrication and installation or surfaces deliberately left bare at e.g. welds. If such damage or uncoated surfaces are anticipated, the affected surface area shall be estimated and included in the design calculations as bare metal surface.

3.5 Galvanic anode material design parameters

3.5.1

Unless otherwise specified or accepted by the owner, the compositional limits for alloying and impurity elements for Al- and Zn-based anodes in Table 8-5 shall apply. If the manufacturer is able to demonstrate and assure better performance with these alloys, a broader range of compositions than those given in Table 8-5 may be used. The CP design parameters related to anode material performance are:

- design electrochemical capacity, ϵ (Ah/kg)
- design closed circuit anode potential, E_a^0 (V).

The design electrochemical capacity, ϵ (Ah/kg), design closed circuit anode potential, E_a^0 (V) and utilization factor, u, are used to calculate:

- the design anode current output
- the required net anode mass

using Ohm’s and Faraday’s laws, respectively.

3.5.2

The design values for electrochemical capacity, ϵ (Ah/kg), in Table 8-6 shall be used for the design unless otherwise specified by the owner. For zinc anode surface temperatures exceeding the limits given in Table 8-6, it is recommended to qualify the anode material for the project-specific maximum temperature according to Sec.10 (free-running test).

Guidance note:

This RP strongly recommends that the inherent conservatism of using the default values in Table 8-6 is utilized for the design, also if an anode manufacturer claims that its product is capable or achieving a higher performance. Data on anode electrochemical efficiency from short-term laboratory examinations of galvanic anode materials will typically result in values close to the theoretical limit (e.g. ≥ 2,500 Ah/kg for Al-Zn-In material). This is due to the relatively high anodic current densities that are utilized for testing. Such data should not replace the recommended design values for electrochemical capacity. Even long-term testing according to Sec.10 will tend to result in slightly non-conservative values as the testing time is still relatively short and the anodic current density relatively high compared to the working conditions for real anodes. If the anode manufacturer’s data based on such testing is still used for the for design, it should be ensured that the casting conditions and composition of alloying and impurity element limits for all the anode production are very close to the composition of the alloy originally tested. This will mean the composition being within a smaller range than in Table 8-5 for both alloying and impurity limits, see [10.2.2].

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3.5.3

The design values for closed circuit anode potential, E_a^0 (V), in Table 8-6 shall be used for the design.

3.6 Anode resistance formulas

3.6.1

The anode resistance, R_a (ohm), shall be calculated using the formula in Table 8-7 that is applicable to the actual anode shape. Calculations shall be performed for the initial anode dimensions and for the estimated dimensions when the anode has been consumed to its utilization factor [4.8].

3.7 Seawater and sediment resistivity

3.7.1

The seawater resistivity, ρ (ohm·m), is a function of the seawater salinity and temperature. In the open sea, the salinity does not vary significantly and temperature is the main factor. The relationship between resistivity and temperature at a salinity of 30‰ to 40‰ (parts per thousand) is shown in Figure 8-1. Local seawater temperature and salinity at the anode location shall be used to determine the seawater resistivity according to Figure 8-1.

3.7.2

In coastal areas, particularly at river outlets and in enclosed bays, the salinity will vary significantly. It is recommended that the design of CP systems in such locations is based on resistivity measurements reflecting the annual mean value and the variation of resistivity with depth.

Guidance note:

The impact of periods of time during which the resistivity is above the annual mean should be assessed, and during these periods when the anode current output may be reduced, it should be evaluated if sufficient current can be delivered to maintain the mean current density and required polarization level.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.7.3

Compared to seawater, the resistivity of marine sediments is higher by a factor ranging from about 2 for very soft clays to approximately 5 for sand. Unless sediment data for the location are available, the highest factor (5) shall be assumed when calculating the resistance of any buried anodes.

3.7.4

In temperate regions (annual average surface water temperature of 7°C to 12°C), resistivities of 0.30 ohm·m in seawater and 1.5 ohm·m in marine sediments are recommended as reasonably conservative estimates for the calculation of anode resistance in seawater and marine sediments, respectively, irrespective of depth. Lower values shall be documented by actual measurements, taking into account any seasonal variations in temperature.

3.8 Anode utilization factor

3.8.1

The anode utilization factor, u, is the fraction of anode material of an anode with a specific design that may be utilized when calculating the net anode mass required to sustain protection throughout the design life of a CP system, see [4.7.1]. When an anode is consumed to its utilization factor, the polarizing capacity (as determined by the anode current output) becomes unpredictable due to the loss of support of the anode material, or rapid increase in anode resistance due to other factors, see [4.10].

3.8.2

The utilization factor depends on the anode design, particularly the anode dimensions and location of anode cores [4.10.4]. Unless otherwise specified by the owner, the anode utilization factors in Table 8-8 shall be used for design calculations.

Guidance note:

If the anode design dimensions and anode core design used in the design are not implemented in the purchase of anodes, the anode design performance may not be delivered.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.9 Current drain and contingency

3.9.1

The CP current drain to components that are electrically connected to the protection object shall be considered during the design. This may include e.g. components in alloys that are regarded as fully resistant to corrosion in seawater and components that do not need corrosion protection for structural purposes due to high wall thickness relative to expected corrosion rates (e.g. piles and casings installed in the seabed).

3.9.2

The design current densities and coating breakdown factors in [3.3] and [3.4], respectively, are applicable when calculating the current drains to components that are not considered to need CP, but will be (or may possibly become) electrically connected to the CP system being designed.

3.9.3

For buried surfaces of mud mats, skirts, piles and suction anchors, a current drain (i.e. 0.020 A/m^2) in accordance with [3.3.8]) shall be accounted for, based on the outer (sediment exposed) external surface area. For open pile ends, the top internal surface shall be included for a distance of 5 times the diameter and shall be regarded as seawater exposed unless potential attenuation calculations justify a lower current drain. Internal surfaces of closed piles filled with sediments do not have to be included.

3.9.4

Unless otherwise specified or accepted by the owner, a current drain of 5 A per well casing, sediment buried section, shall be included in current drain calculations. Current demands of conductors freely exposed to seawater shall be calculated as for structural components.

Guidance note:

A current of 5 A might not be sufficient to account for the current drain to multilateral well completions. A conservative approach to include additional current drain to a multilateral well is to add 5 A for each lateral branch and up to 15 A for three or more lateral branches.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

3.9.5

It is recommended that the current drain to anchor chains is accounted for by 30 m of seawater exposed chain below mean seawater level (MSL).

3.9.6

Any current drain to steel armouring of flexible pipelines should be calculated using a design current density of 0.0005 A/m^2, based on the circumferential surface of the outer steel reinforcement layer.

SECTION 4 CATHODIC PROTECTION CALCULATION AND DESIGN PROCEDURES

4.1 General

4.1.1

For large protection objects such as platform substructures, the detailed design of a CP system is normally preceded by conceptual design activity. During this conceptual design phase, the type of anodes and fastening devices should be selected, taking into account forces exerted on anodes during installation and operation. Moreover, any coating systems to be applied to specific areas or components should also normally be specified, allowing for a preliminary calculation of current demands for cathodic protection and the associated total net mass of anode material required. If no CP conceptual report has been prepared, then the premises and basic concepts for detailed CP design shall be defined by the purchaser in some other reference document(s) to be included in an inquiry for a CP detailed design. The personnel who are to carry out the CP design or its verification should have adequate competence and experience as documented by a CV accepted by the purchaser or a certification scheme, e.g. ISO 15257.

4.1.2

Besides any reference to this RP in a purchase document, see [1.2], the following information and any optional requirements (intended as a check-list) shall be provided by the purchaser:

Information:

- conceptual CP design report, if completed [4.1.1]
- design life of the CP system to be installed [3.2]
- relevant information from the project design basis [4.1.1], e.g. salinity and temperature as a function of depth calculating the anode resistance, location of seawater level and mud line for platform substructures, and the environmental and installation parameters affecting forces exerted on anodes
- structural drawings and information on coating systems as required to calculate the surface areas to be protected, including components which may exert temporary or permanent current drain [4.1.3]
- identification of any interfaces with electrically connected components/systems with self-supporting CP systems, e.g. pipelines.

Requirements (optional):

- requirements for documentation and 3rd party verification, including a supply schedule [4.13]
- any specific requirement for the CP design parameters to be applied, e.g. coating breakdown factors [3.4.3]
- any specific requirements for the anode material [3.5] and anode design [4.6]
- any further amendments and deviations to this RP applicable to the CP design.

4.1.3

The purchaser shall ensure that valid revisions of drawings and specifications affecting the calculation of the current demand for CP and location of anodes are available to the contractor during the design work. It shall be ensured that all necessary information is provided for the contractor to calculate the overall current demand.

4.2 Subdivision of cathodic protection object

4.2.1

In the design of CP systems for large and/or complex objects, it is always convenient to divide the protection object into separate units to be protected.

4.2.2

The division into units may be based on e.g. depth zones or physical interfaces of the protection object, such as retrievable units within a subsea production system.

4.3 Surface area calculations

4.3.1

For each CP unit [4.2], surface areas to receive CP shall be calculated separately for surfaces with and without a coating, see coating categories in [3.4.6], and for surfaces affected by other parameters, e.g. surface temperatures which influence the CP current demand. For surfaces located in more shallow waters, i.e. depth < 50 m, the current demand [3.3] should be calculated based on the surface area wetted at HAT.

4.3.2

It is practical to apply some simplification when the calculating surface areas of objects with complex geometries. However, it shall be ensured that the overall result of any such simplification is conservative.

Guidance note:

For major surface areas, an accuracy of -5/+10% is adequate. For smaller components, the required accuracy may be lower depending on whether or not a coating will be applied to such items and to the major surfaces, respectively.

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4.3.3

Surface area calculations for each unit shall be based on drawings or computer aided design (CAD) models and documented in the CP design report, see [4.13].

4.3.4

The contractor shall make sure that all items affecting CP current demand are included in the surface area calculations. This may include various types of outfitting to be installed by different contractors.

Guidance note:

For subsea production systems, production control equipment is typically manufactured from uncoated stainless steel (piping components, couplings, connectors, cable trays, etc.) which constitutes a significant current demand. ROV override components are also often manufactured from stainless steel without a coating. Moreover, some components like valve blocks and hydraulic cylinders may have coating applied directly to machined surfaces, increasing the coating breakdown factor to be used for the design [3.4.6].

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4.4 Current demand calculations

4.4.1

To calculate the current demand, I_c (A), to provide adequate polarizing capacity, see [3.3.1] to [3.3.4], and to maintain cathodic protection during the design life [3.3.5], the individual surface areas, A_c (m^2), of each CP unit shall be calculated according to [4.2] and multiplied by the relevant design current density, i_c (A/m^2), and by the coating breakdown factor, f_c , if applicable:

$$I_c = A_c i_c f_c \qquad (4.1)$$

i_c and f_c are then to be selected according to [3.3] and [3.4], respectively.

4.4.2

For items with major surfaces of uncoated metal, the CP current demands for both initial polarization and polarization at the end of the design life, I_{ci} (A) and I_{cf} (A), respectively, shall be calculated, together with the mean current demand required to maintain cathodic protection throughout the design period, I_{cm} (A). For protection objects with current demand primarily associated with coated surfaces, the initial current demand may be deleted in the design calculations. For future reference, all calculated data shall be documented in the design report.

4.5 Current drain calculations

4.5.1

All items which are expected to, or may, become electrically connected to a CP system shall be considered in current drain calculations.

Guidance note:

Complex offshore structures often include temporary or permanent components which are not considered to require CP but will drain current from the CP system, e.g. mooring systems for floating installations or secondary structural components, e.g. piles and skirts, which can readily tolerate some corrosive wear. Also, metallic materials with intrinsic resistance to corrosion in seawater will still drain current from a CP system.

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4.5.2

Calculations of current drain shall use the design current densities [3.3] and coating breakdown factors [3.4] for items requiring CP. Calculations of surface areas and current demands shall be carried out according to [4.3] and [4.4], respectively.

4.5.3

For calculations of the current drain to mud mats, skirts, piles, well casings and steel anchor chains, see [3.9.3], [3.9.4] and [3.9.5].

4.6 Selection of anode type

4.6.1

For certain structures, anode types may be specified by the owner/purchaser, taking into account the effects of e.g. sea current drag and interference with subsea interventions [4.1].

4.6.2

If no anode type has been specified by the owner/purchaser, the contractor shall select the anode type taking into account e.g. the net anode mass to be installed and available space for the location of anodes. The selection of the anode type is primarily determined by the size and geometrical configuration of the protection object, in addition to forces exerted on anodes during installation and operation. The anode type further affects the anode utilization factor and the anode current output in relation to weight. For general considerations regarding the anode type selection, see [2.7].

Guidance note:

Long stand-off type anodes are usually preferred for relatively large anodes, about 100 kg and more to be installed on platform substructures and subsea templates. A flush-mounted anode with the same net anode mass will have a lower anode current output and lower utilization factor.

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4.7 Anode mass calculations

4.7.1

The total net anode mass, M_a (kg), required to maintain cathodic protection throughout the design life, t_f (years), shall be calculated from I_{cm} (A) for each unit of the protection object, including any current drain:

$$M_a = \frac{I_{cm} t_f 8760}{u \epsilon} \qquad (4.2)$$

8760 refers to hours per year. u and ϵ (Ah/kg) shall be selected based on [3.8] and [3.5], respectively.

4.8 Calculation of number of anodes

4.8.1

From the anode type selected [4.6], the number of anodes, (N), anode dimensions and anode net mass, m_a (kg), shall be defined to meet the requirements for:

1) initial/final current output, I_{ai}/ I_{af} (A), and
2) anode current capacity C_a (Ah)

which relate to the CP current demand, I_c (A), of the protection object.

Guidance note:

The preliminary sizing of anodes should be based on commercially available products, requiring liaison with potential anode vendors.

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4.8.2

The individual anode current output, I_a (A), required to meet the current demand, I_c (A), is calculated using Ohm's law:

$$I_c = I_a N = \frac{N\left(E_c^0 - E_a^0\right)}{R_a} = \frac{N\Delta E^0}{R_a} \qquad (4.3)$$

where E_a^0 (V) is the design closed circuit potential of the anode material, see [3.5], and R_a (ohm) is the anode resistance, see [3.6]. The initial and final current output, I_{ai} and I_{af}, shall be calculated using the initial and final anode resistance, R_{ai} and R_{af}, respectively. To calculate the anode resistance, see [4.9]. E_c^0 (V) is the design protective potential which is -0.80 V, see [2.4]. This means that it shall always be used for calculations according to equation (4.3) in combination with this potential, even if a more negative protection potential, e.g. ≤ -0.90 V, is aimed for, see [3.3]. ΔE^0 (V) is the design driving voltage.

Guidance note:

As the design driving voltage in equation (4.3) is defined using the design protective potential for C-steel, the driving voltage refers to the required anode current output at the design protective potential. Hence, the initial/final design current densities given in Table 8-3 are based on a design protection potential of -0.80 V. .

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

4.8.3

The individual anode current capacity, C_a (A·h), is given by:

$$C_a = m_a \epsilon u \qquad (4.4)$$

where m_a (kg) is the net mass per anode. The total current capacity for a CP unit with N anodes thus becomes NC_a (Ah).

4.8.4

Calculations shall be carried out to demonstrate that the following requirements are met:

$$C_{a\ tot} = N \cdot C_a \geq 8760 \cdot I_{cm} \cdot t_f \qquad (4.5)$$

$$I_{a\ tot\ i} = N \cdot I_{ai} \geq I_{ci} \qquad (4.6)$$

$$I_{a\ tot\ f} = N \cdot I_{af} \geq I_{cf} \qquad (4.7)$$

$C_{a\ tot}$ in equation (4.5) is the total anode current capacity. I_{cm}/ I_{ci}/ I_{cf} in equations (4.5), (4.6) and (4.7) are the current demands of a CP unit, including any current drain. 8760 is the number of hours per year. I_{ai} and I_{af} in equations (4.6) and (4.7) are the initial and final current output for the individual anodes. If anodes with a different size and hence different anode current capacity C_a (Ah), and current output, I_a (A), are utilized for a CP unit, then NC_a and NI_{ai} / NI_{af} shall be calculated for each individual size and added to calculate the total anode current capacity, $C_{a\ tot}$, and total anode current output, $I_{a\ tot\ i}$ / $I_{a\ tot\ f}$.

4.8.5

If the above criteria cannot be fulfilled for the anode dimensions and net mass initially selected, another anode size shall be selected and the calculations repeated until the criteria are fulfilled.

Guidance note:

Optimizing the requirements in equations (4.5), (4.6) and (4.7) is an iterative process where a simple computer spreadsheet may be helpful. In general, if equation (4.5) is fulfilled, but not (4.6) and/or (4.7), a higher number of smaller anodes, or the same number of more elongated anodes should be used. On the other hand, if NI_a in equations (4.6) and (4.7) is much larger than I_{ci} and I_{cf}, fewer and/or more compact anodes may be applied.

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4.8.6

Unless a high initial current capacity is deliberately aimed for, e.g. in the case of protection objects consisting primarily of uncoated metal surfaces, the anodes to be installed should have a similar anode current output (I_a) to net anode mass (m_a) ratio. Small anodes with high anode current output to net mass ratio can be more rapidly consumed than large anodes with a lower ratio, which could result in an insufficient total anode current capacity towards the end of the design life. For any specific protection object or CP unit, see [4.2.1], the highest anode current output to net anode mass ratio should not exceed that of any other anode by more than 50%.

Guidance note:

When anodes have the same anode resistance and hence same anode current output, but a major difference in net anode mass, i.e. due to different anode geometry, the anode with the lowest net anode mass is consumed first. Similarly, when anodes have the same net anode mass but a major difference in anode resistance and hence anode current output, the anode with the lowest anode resistance is consumed first.

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4.8.7

For all anodes to be utilized for the full design life, the ratio between the net anode mass (kg) and design life (years) should be at least 0.2 and 0.5 for Al-based and Zn-based anodes, respectively.

Guidance note:

For very small protection objects to be designed with a self-supporting CP system although being electrically connected to larger objects with CP, this ratio may not be practical.

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4.9 Calculation of anode resistance

4.9.1

The anode resistance, R_a (ohm), to be used in equation (4.3) shall be based on the applicable formulas in Table 8-7 using the actual anode dimensions and specific resistivity of the surrounding environment. Specific resistivities of the surrounding environment shall be selected according to [3.7]. The use of formulas in Table 8-7 presumes that anodes can be distributed such that interference between anodes does not cause a significant reduction in their current output. If anodes have to be arranged in arrays where significant interference effects may be expected, see [4.11.3], a numerical model analysis should be carried out to determine a reduction factor for the current output as calculated without any interference according to [4.8.2].

4.9.2

To calculate the initial anode resistance, R_{ai} (ohm), the initial anode dimensions are inserted in the relevant anode resistance formula in Table 8-7. The final anode resistance, R_{af} (ohm), is calculated based on the expected dimensions when the anode has been consumed to its utilization factor, u, see [3.8] Table 8-7.

4.9.3

When the anode has been consumed to its utilization factor, u, at the end of the design life, t_f (years), the remaining net anode mass, m_{af} (kg), is given by:

$$m_{af} = m_{ai}\left(1 - u\right) \qquad (4.8)$$

The final volume of the anode to be used when calculating R_{af} can be calculated from the remaining net anode mass, m_{af}(kg), specific density of anode material and volume of insert materials. When details of anode inserts are not available, their volume should either be neglected or estimated to give a conservative approach.

4.9.4

For long and short slender stand-off anodes consumed to their utilization factor, a length reduction of 10% shall be assumed. Furthermore, assuming that the final anode shape is cylindrical, the final radius shall be calculated based on this length reduction and the final anode mass/volume as explained in [4.9.3].

4.9.5

For long flush-mounted anodes, the final shape shall be assumed to be a semi-cylinder and the final length and radius (= width/2) shall be calculated as in [4.9.4].

4.9.6

For short flush-mounted anodes, bracelet anodes and other shapes mounted flush with the protection object, the final exposed area shall be assumed to be equivalent to the initial area facing the surface to be protected.

4.10 Anode design

4.10.1

The contractor shall specify in the CP design report the tentative dimensions and net mass of the anodes to be used.

4.10.2

For anodes that may become subject to significant forces during installation and operation, the design of anode fastening devices shall be addressed in the design report. Special considerations apply for large anodes to be installed on structural members subject to fatigue loads during pile driving operations. Doubler and/or gusset plates may be required for large anodes.

4.10.3

When using the anode resistance formula in Table 8-7 for stand-off type anodes, the distance from the anode to the protection object shall be minimum 300 mm. However, for distances down to 150 mm, the formula may still be used by multiplying the anode resistance with a factor of 1.3.

4.10.4

The detailed anode design shall ensure that the utilization factor assumed during calculations of the required anode net mass according to [4.7] is met. Hence, it shall be ensured that the anode inserts are still likely to support the remaining anode mass when the anode has been consumed to its design utilization factor. Unless otherwise agreed, anode cores of stand-off type anodes shall protrude through the end faces.

4.10.5

Except for stand-off type anodes, the application of a marine grade paint coating, typically epoxy coating, minimum 100 μm DFT shall be specified for anode surfaces facing the protection object. This is to avoid build-up of anode corrosion products that could cause the distortion and eventually fracture of anode fastening devices.

4.11 Distribution of anodes

4.11.1

The calculated number of anodes, N, for a CP unit shall be distributed to provide a uniform current distribution, taking into account the current demand of individual members due to different surface areas and any coatings used. On platform substructures, special areas to be considered when distributing anodes are e.g. nodes, pile guides and conductor bundles. The location of all individual anodes shall be shown on drawings.

4.11.2

Whenever practical, anodes dedicated to CP of surfaces buried in sediments shall be located freely exposed to the sea.

4.11.3

For platform substructures extending through the splash zone, all anodes should be located minimum 2 m below LAT. Anodes should further be located with sufficient spacing between each other to avoid interaction effects that reduce the useful current output. As far as practical, an anode shall be located so that those of its surfaces intended for current output are not in close proximity to structural members as this will reduce the current output. On jacket legs, anodes should face the centre of the structure. On diagonals and bracings, anodes should be located alternatingly on the upper and lower surfaces except on the uppermost horizontal bracing where all anodes should be located facing downwards. Anodes dedicated for conductor bundles should be located as close as practical to bundles and support frames. On subsea production systems, anodes for current drain may be located on the template protection structure if they have a reliable electrical connection to the valve tree.

Guidance note:

Interference effects are most significant for long anodes mounted in parallel on a flat surface or a surface with low curvature. If two anodes are located opposite each other on a tubular member, anode interference can be neglected. The minimum anode spacing to avoid significant interaction effects depends on e.g. the anode size and number of parallel anodes. It is therefore recommended to consider the effect of anode interference for parallel anodes on a flat or low curvature surface. A conservative approach to calculate the anode current output may be to consider two or more adjacent anodes as one long anode, or as one wide anode, depending on their location in relation to each other. An alternative approach to account for interference between adjacent anodes is to use computer modelling to quantify the anode interference. Computer modelling of the electrolytic voltage drop away from the anodes using the design current densities in Table 8-2 might result in excessively high electrolytic voltage drops, indicating marginal or even insufficient cathodic protection in terms of the estimated protection potential.

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4.11.4

No anodes shall be welded to pressure containing components or areas with high fatigue loads. For main structural components, the minimum distance from anode fastening welds to structural welds shall be 150 mm. On jacket structures, no anodes shall be located closer than 600 mm to nodes.

4.11.5

The location of anodes shall take into account restrictions imposed by the fabrication, installation and operation of the protection object. For large and/or complicated objects, early liaison with other engineering disciplines, as well as with fabrication and installation contractors, is advised.

4.12 Provisions for electrical continuity

4.12.1

Besides welded connections, full electrical continuity may be assumed for cold forged connections, metallic seals and threaded connections, i.e. across the mated threads without insulating coating, e.g. anti-friction type.

4.12.2

For anodes attached to the protection object by means other than welding, and for components of a CP unit without a reliable electrical connection as defined above, electrical continuity shall be ensured by a cable connection or a bolted or clamped connection, see [4.12.4]. Cables for electrical continuity shall be of stranded copper wire having a minimum cross section of 16 mm^2. Coating on contact surfaces between the bolt head and the metal surface beneath the bolt head shall be removed and the components shall be assembled before any flash rust appears at the bolting surface. To prevent any loss of bolt pretension, the stacking of cables at one connection is not allowed. The cables shall be attached by brazing, friction or explosion welding, or by a mechanical connection using e.g. serrated washers to provide a reliable electrical connection at bolt heads or washers. In case of anode sleds, at least two cables per anode sled shall be installed in order to guarantee the electrical safety of the system if one cable is lost/damaged.

Guidance note:

Cable dimension having a cross section of 16 mm^2 may not be practical for providing electrical continuity to small objects and other types of continuity cables may be considered, including small diameter stainless steel wire. The maximum voltage drop in the cable should be calculated based on requirements in [4.12.4].

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4.12.3

The mechanical integrity of connections using cables shall be ensured. Any cable shoes shall have a brazed or crimped connection to the cable. The full connection, including the cable shoe connection to the cable, shall be tested during installation as specified in [6.6.3].

4.12.4

If the CP design includes the use of cables or bolted or clamped connections for electrical continuity, requirements for the verification of electrical continuity shall be specified in the CP design report. The product of the connection resistance and the current demand or current output for a non-welded anode shall not exceed 10% of the design driving voltage, e.g. 25 mV for Al-Zn-In anodes in seawater. In no case shall the resistance across a continuity cable exceed 0.1 ohm. The total resistance over the cable, and the bolted and clamped connections shall be assessed and included in the anode current output calculations.

4.13 Documentation

4.13.1

The detailed engineering documentation, CP detailed design report, shall contain the following items:

- design premises, including all relevant CP design parameters

  incl. reference to all relevant project specifications, codes and standards
- surface area calculations

  incl. reference to all relevant drawings, incl. revision numbers or the date/revision of CAD drawings
- current demand calculations

  initial/final and mean
- current drain calculations, if applicable

  initial/final and mean
- calculations of the minimum required net anode mass
- anode resistance calculations

  initial and/or final, as relevant
- calculations of the minimum number of anodes required

  incl. anode current output and anode capacity for the initial and final life of the system
- calculation of net anode mass based on the required number of anodes, if higher than the required net anode mass
- calculation of total current output based on the number and type/size of anodes to be installed
- tentative anode design including any special provisions for structural integrity and electrical continuity. Any requirement for utilization factors higher than the default values in Table 8-8 shall be highlighted.
- anode distribution drawings
- evaluation of anode interference if applicable
- provisions for electrical continuity, including verification by testing if applicable
- anode manufacturing requirements, e.g. by reference to Sec.5 of this RP.

All relevant CP design parameters and all results of calculations shall be contained in the main report. Any print-outs from calculation sheets shall be contained in an appendix together with drawings and shall not replace a CP design report.

4.13.2

The scope of any (a) conceptual CP design report shall be agreed. The same applies to the detailed CP design of protection objects involving only a few anodes.

4.13.3

The documentation shall be sufficiently well organized and detailed to allow third-party verification and possible future calculations for a life extension or retrofit.

SECTION 5 ANODE MANUFACTURE

5.1 General

5.1.1

This section covers the manufacture of galvanic anodes, including the preparation of anode cores prior to casting. The requirements in this section comply with those in NACE SP0387, and give some amendments, primarily related to quality control.

5.1.2

Besides any reference to this RP in a purchase document, see [1.2], the following information and any optional requirements, intended as a check-list, shall be enclosed by the purchaser:

Information:

— anode material type, i.e. aluminium or zinc-base and any special requirements for the chemical composition, i.e. other than those specified in [3.5.1], and for the qualification of anode material [2.6.3]

— tentative anode dimensions and net anode mass for each anode type and any special requirements for anode fastening devices [4.10].

Requirements (optional):

— any special requirements for the anode utilization factor [3.8]

— any special requirements for pre-production qualification testing (PQT), including a schedule for notification and the supply of documentation [5.3.2] to [5.3.4]

— any special requirements for the manufacturing procedure specification (MPS) [5.2] or inspection and testing plan (ITP) [5.4.2], including a schedule for the supply of documentation

— any special requirements for the frequency of dimensional testing [5.6.2], destructive testing [5.6.5] and electrochemical testing [5.6.6] during production

— any specific requirements for the contractor's management of non-conformities [5.6.10] and concession requests [5.5.6]

— any reduced requirements for traceability [5.5.1] and [5.5.10]

— any requirements for retaining anode material specimens [5.6.1]

— any special requirements for the marking of anodes [5.7.1]

— any special requirements for the handling, storage and shipping of anodes [5.8.1]

— any special requirements for the final documentation, including a schedule for supply [5.7.4]

— any further amendments and deviations to this RP.

5.1.3

Unless otherwise agreed, electrochemical testing of galvanic anode materials for quality control shall be carried out according to Sec.9.

5.1.4

The testing procedure for documenting long-term performance in Sec.10 is non-mandatory and shall be specified by the purchaser in the purchase document if applicable.

5.2 Manufacturing procedure specification

5.2.1

Unless otherwise agreed, a manufacturing procedure specification (MPS) shall be prepared for purchase orders of 15,000 kg net alloy or more. However, the purchaser may also specify an MPS for smaller orders. The MPS shall include as a minimum:

- specification of anode core materials
- receipt, handling and storage of materials
- maximum and/or minimum contents of anode material alloying elements and maximum contents of impurity elements
- detailed anode drawing, with anode inserts, including gross/net weight and dimensional/weight tolerances, see the comment below in this paragraph
- welding procedure specification and reference to the qualification test (WPQT) for any welding of anode cores, and qualification requirements for welders
- preparation of anode cores prior to casting
- anode casting, including control of temperature and addition of alloying elements
- inspection and testing of anodes
- coating of surfaces facing the protection object, except for stand-off type anodes
- handling, storage and shipping of anodes
- marking, traceability and documentation.

The detailed anode design shall ensure that anode internal cores are not significantly exposed and support the remaining anode mass when the anode is consumed to the utilization factor specified in Table 8-8, or any less conservative, i.e. higher, factor specified by the purchaser.

5.2.2

The purchaser may specify that detailed procedures for testing/inspection and other information relevant to quality control are also to be included in the MPS, e.g. detailed procedures for inspection and testing, and the handling of non-conformances and concession requests. The purchaser may further specify that the MPS shall be submitted for review and acceptance before the anode manufacturing starts.

5.3 Pre-production qualification testing

5.3.1

The primary objective of pre-production qualification testing (PQT) is to verify that the MPS is adequate to achieve the specified anode properties. Of particular interest are those aspects that require destructive testing and hence cannot be frequently verified during regular production. The PQT shall use the same specific materials and equipment as for regular production.

5.3.2

Unless otherwise agreed, a PQT shall be prepared for a purchase order of 15,000 kg net alloy or more. However, the purchaser may also specify a PQT for smaller orders.

5.3.3

Specific requirements for the PQT, including e.g. the number of anodes to be inspected for each mould, including those for destructive examination, and a schedule for notification and reporting, shall be specified in the purchase documents.

5.3.4

An MPS and an inspection and test plan ITP, see [5.4.2], specific for the PQT, together with a detailed schedule for anode casting, inspection and/or testing, and reporting shall be submitted to the purchaser in a timely manner as per the purchase document, prior to the start-up of the qualification activities.

5.3.5

Data sheets and calibration certificates for instruments essential to quality control, e.g. temperature sensors, shall be available for the purchaser’s review during the PQT.

5.3.6

The results of all the inspections, tests and calibrations during qualification, recordings of essential operational parameters for casting, and material certificates shall be compiled in a PQT report. Unless otherwise agreed, the report shall be accepted by the purchaser before production starts.

5.4 Quality control of production

5.4.1

Prior to the start-up of regular production (i.e. for purchase orders of 15,000 kg net alloy or more, or for higher/lower quantities as agreed on, see [5.2.1]), the contractor shall submit the following documents to the purchaser for acceptance:

- a project-specific MPS, updated to reflect the process parameters used during the completed and approved PQT [5.3]
- a project-specific inspection and testing plan (ITP), updated to reflect the process parameters used during the completed and approved PQT
- a daily log format, see [5.6.11]
- a description of the responsibilities of personnel involved in quality control.

5.4.2

The ITP shall meet the general requirements of ISO 10005, Sec.5.10. It shall be in tabular form, defining all quality control activities associated with the receipt of materials, preparation of anode cores, and casting, inspection, testing and marking of anodes. The activities shall be listed in consecutive order, with each activity assigned a unique number and with reference to the applicable codes, standards and contractor’s procedures or work instructions applicable to the specific project. Furthermore, the frequency and/or extent of inspection and testing, acceptance criteria and actions in the case of non-conformances shall be defined in the plan. The ITP shall further contain a column for inspection codes, e.g. inspection, witnessing and hold points indicating the involvement of the contractor, purchaser and any 3rd party. It is good practice to include a reference to the applicable reporting form or document, and to refer to the specific equipment or tools to be used for verification.

5.4.3

The MPS, ITP, and daily log shall be in English, unless otherwise agreed.

5.4.4

Procedures and work instructions referenced in the ITP, and applicable acceptance criteria, shall be available to all persons concerned with the associated work in their native language.

5.4.5

The purchaser shall have the right to inspect any activity associated with the work throughout production and to carry out audits of the contractor's QA / QC system. The purchaser shall identify any hold points for witnessing in the ITP and inform the contractor accordingly.

5.5 Materials, fabrication of anode inserts and casting of anodes

5.5.1

Anode insert materials shall meet all the requirements in NACE SP0387 and, unless otherwise agreed, inserts for welding to the protection object shall be traceable to a certificate according to EN 10204, 3.1 or ISO 10474, 3.1.

5.5.2

The contractor shall verify that all materials received for anode manufacture are in accordance with the specified requirements. The verification may include actual testing or a review of the supplier's certificates. A review of the certificates and any verification testing to be performed by the contractor shall be included in the ITP. Any materials checked and found non-conforming shall be marked and quarantined.

5.5.3

Materials to be used for surface preparation and coating shall be contained in their original packing until use and shall be adequately marked, including the following information:

— manufacturer's name and location of manufacture
— material type and product designation
— batch/lot number
— date of manufacturing and shelf life, if applicable
— the manufacturing standard, if applicable
— instructions for storage and handling, including health and safety notes.

5.5.4

The contractor shall ensure that any materials for coating and surface preparation are stored and handled so as to avoid damage by the environment or other effects. The supplier's recommendations for storage and use shall be readily available for the purchaser's review.

5.5.5

All fabrication welding of steel inserts and surface preparation before casting shall meet the requirements in NACE SP0387 and shall be subject to visual inspection just prior to casting.

5.5.6

All work associated with the preparation of anode cores and casting of anodes shall be carried out according to the qualified MPS, if applicable, describing the equipment and procedures to be used. Once the MPS has been qualified, any changes shall be formally accepted by the purchaser through a concession request (CR).

5.5.7

Equipment for monitoring process parameters critical to quality, e.g. temperature sensors, spectrometers or other analysis equipment and scales, shall be calibrated at scheduled intervals as specified in the ITP.

5.5.8

Galvanic anodes of zinc or aluminium-zinc-indium type may not be subjected to heat treatment.

5.5.9

Flush mounted type anodes shall be coated according to a coating procedure and after completion of a visual inspection for surface defects.

5.5.10

Unless otherwise agreed, all anodes produced shall be traceable to certificates for coating materials, if applicable.

5.6 Inspection and testing of anodes

5.6.1

Sampling for chemical analysis purposes shall be carried out according to NACE SP0387 and for each anode heat, i.e. after all alloying and homogenization work is completed, except that, for aluminium-based anodes, two samples shall be collected for all heats exceeding 500 kg, unless otherwise agreed. For spectrometric analyses of the anode chemical composition, reference standards with a known chemical composition, i.e. for the specified contents of all alloying and impurity elements certified by an independent party, shall be used. The purchaser shall have the right to require anode sample material for verification testing in an independent laboratory, or to deliver samples with a known composition for testing. This is to verify the equipment and procedures for chemical analysis used by the manufacturer. The purchaser may further specify that the contractor shall retain sample material for any additional chemical analyses and/or electrochemical testing. All anodes produced from a testing lot not meeting the specified composition shall be rejected.

5.6.2

The anode weight and dimensions shall be verified using the frequency and acceptance criteria specified in NACE SP0387. The positions of protruding inserts shall comply with tolerances in the manufacturer’s drawing and shall be checked for a minimum of 10% of the anodes of a specific design. The purchaser may specify extended inspection of anode dimensional tolerances.

5.6.3

Inspections for cracks and other surface irregularities shall be carried out on all anodes using the acceptance criteria specified in NACE SP0387, with the following amendments:

- for zinc-based anodes, no cracks visible to the naked eye are acceptable
- cracks that are seen to penetrate to anode inserts are not permitted
- within the section fully supported by anode inserts, cracks wider than 2 mm are only permitted if the crack length is maximum 100 mm.

Guidance note:

Cracks within sections fully supported by anode inserts are defined in NACE SP0492 as 'cracks that would intersect with the core if they propagate indefinitely'.

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5.6.4

Any coating applied shall be visually inspected on all anodes. Any coating spill on surfaces not intended for coating shall be removed.

5.6.5

Unless otherwise agreed, a minimum of two anodes of each size shall be subject to destructive testing to verify the absence of internal defects and adequate location of anode inserts. The cutting procedure and acceptance criteria in NACE SP0387 shall apply. Such testing shall be carried out as part of the PQT, if applicable. If no PQT is performed, testing should be carried out during the first day of production. The owner/purchaser shall have the right to select anodes for testing. Any batch-wise destructive testing of anodes during production shall be specified in the purchase order.

5.6.6

As a minimum, electrochemical testing shall be performed as part of a PQT or first day production test for purchase orders exceeding 15,000 kg of net anode material and for each further 15,000 kg of net anode material produced. The owner/purchaser may specify extended testing and/or 3rd party testing.

5.6.7

When electrochemical testing applies, sampling for testing shall be carried out for each heat produced, see [9.2.1]. For a definition of heat, see [5.6.1]. Unless otherwise agreed, the testing shall be carried out according to the procedure in Sec.9 and the following acceptance criteria shall apply:

Aluminium-based anodes:

- electrochemical capacity: minimum 2,500 Ah/kg,
  closed circuit potential: ≤ -1.05 V at the end of the 4th testing period.

Zinc-based anodes:

- electrochemical capacity: minimum 780 Ah/kg,
  closed circuit potential: ≤ -1.00 V at end of the 4th testing period.

In the case of failure to meet specified electrochemical properties, contractor shall immediately issue a non-conformance report.

5.6.8

Failures during testing which are obviously due to defective sampling or operational faults in testing equipment may be disregarded and testing repeated on the same anode (sample).

5.6.9

In case of failure during the fractional testing of properties other than electrochemical performance, e.g. destructive testing of one per 50 anodes, the preceding and following anodes shall be tested individually until at least 3 successive anodes are acceptable.

5.6.10

In case of repeated non-conformity with specified properties, i.e. other than electrochemical performance, production shall be discontinued, the anode manufacturer shall issue a non-conformance report and the cause of the failure shall be determined. Non-conforming anodes, either individual or lots, shall be marked and quarantined. For failures during electrochemical testing, see [9.4.3].

5.6.11

All data from the inspection and testing of anodes and calibration of testing and monitoring equipment shall be noted in the daily log. For anode-specific data, reference shall be made to the unique anode number or heat [5.7.2]. The log shall be updated daily and be available for the purchaser's review at any time during manufacture.

5.7 Documentation and marking

5.7.1

As a minimum, each anode shall be marked with the manufacturer's name or symbol, anode material, e.g. A for aluminium, Z for zinc, heat number and serial number. Any further marking requirements shall be specified in the purchase document.

5.7.2

All results of the inspection and testing during PQT, if applicable, and production shall be documented and traceable to a unique anode number or batch of anodes, as applicable, and certificates for anode core materials and coating materials, if applicable. For specific requirements for a daily log, see [5.6.11].

5.7.3

The contractor shall issue an inspection document according to EN 10204 or ISO 10474 and an inspection certificate 3.1.

5.7.4

The purchaser may specify requirements for the final documentation in additional to those in NACE SP0387, e.g. documentation to be supplied to the purchaser, including the format and schedule and that the contractor is to retain documentation for more than the two-year minimum requirement in NACE SP0387.

5.8 Handling, storage and shipping of anodes

5.8.1

Any requirements in addition to those in NACE SP0387 shall be specified in the purchase document.

SECTION 6 INSTALLATION OF ANODES

6.1 General

6.1.1

The installation of galvanic anodes on offshore structures will normally involve welding or another connection ensuring full electrical continuity as described in [4.12.1], and sometimes also the clamping of anode supports to structural steel components. In the latter case, electrical continuity shall be provided by a cable, attached to the anode support and the protection object by brazing, or by some special mechanical connection designed to ensure reliable electrical continuity. Electrical continuity cables may also be installed to provide electrical continuity to components of a CP unit that has no reliable electrical connection to anodes. The design requirements for such connections stated in [4.12] shall apply.

6.1.2

Considerations of the mechanical integrity of anode fastening devices during the installation and operation of the applicable structures and any special requirements shall be included in the CP detailed design report. For large anodes, the design may include the use of doubler and/or gusset plates. No welding or brazing to pressure-containing components shall be performed. Thermite welding is not recommended for CRAs. Alternative methods like pin brazing or soft soldering may be considered.

6.1.3

Besides any reference to this RP in a purchase document, see [1.2], the following information and any optional requirements intended as a checklist shall be enclosed by the purchaser:

Information:

- anode drawings from the detailed CP design, or prepared by the anode manufacturer if completed
- drawings from the detailed CP design showing the location of individual anodes.

Requirements (optional):

- any requirement for preparation of an IPS [6.2]
- any special requirements for documentation [6.7.2]
- any further amendments to and deviations from this RP.

6.2 Installation procedure specification

6.2.1

The contractor may specify that all work related to the anode installation shall be described in an installation procedure specification (IPS). If applicable, this document shall include, as a minimum:

- specification of the materials and equipment to be used, including certificates and material data sheets
- receipt, handling and storage of anodes and materials for anode installation
- reference to welding and/or brazing procedure specifications and qualification of personnel carrying out welding/brazing
- inspection and testing of anode fastening
- documentation of materials and inspection records.

6.3 Qualification of the installation

6.3.1

All welding associated with anode installation shall be qualified according to a recognzsed standard. Only qualified welders and/or operators of brazing equipment shall be used.

6.4 Receipt and handling of anodes

6.4.1

All anodes supplied by the purchaser shall be inspected by the contractor to confirm compliance with the CP design and anode drawings and to confirm no significant damage or other adverse effects. Non-conforming anodes and other materials shall be quarantined.

6.4.2

The contractor shall ensure that anodes and other materials for anode installation are stored and handled so as to avoid damage by the environment or other effects.

6.5 Anode installation

6.5.1

Anodes shall be installed according to drawings approved for construction, showing the locations of individual anodes and any other relevant specifications for fabrication of the protection object. All welding associated with anode installation shall be carried out according to the qualified WPS and by qualified welders.

6.5.2

Any significant changes to the anode installation compared to approved drawings are subject to the approval of the purchaser. However, for ease of installation, stand-off anodes to be mounted on structural components may be displaced laterally by no more than one anode length and circumferentially by a maximum of 30°.

Guidance note:

For some CP designs, the detailed location of the anodes is so crucial, e.g. due to significant interference between the anodes and/or in restricted spaces where the anode current output may be hindered. that any changes to the anode location are considered significant. See also the guidance note in [4.11.3].

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6.5.3

When welding anodes to components subject to high external loads, welded connections shall be placed at least 150 mm away from other welds, and minimum 600 mm away from structural nodes of jacket structures.

6.5.4

Installed anodes shall be adequately protected during any subsequent coating work. Any spill of coating on anodes shall be removed. Exposed anode cores shall be coated to the same standard as the rest of the coated object.

6.6 Inspection of anode installation

6.6.1

Anode installation inspections shall, as a minimum, include a visual examination of welds and any brazed connections. For welding to structural components, further NDT may apply in accordance with the applicable fabrication specification.

6.6.2

Subsequent to completed anode installation, compliance with the anode installation drawings shall be confirmed.

6.6.3

For brazed and mechanical connections to ensure electrical continuity, measurements shall be carried out according to a documented procedure and using an instrument capable of verifying a maximum electrical resistance of 0.1 ohm or such lower value as required by the CP design. The mechanical integrity of the cable-to-cable lug connection shall be qualified and documented.

6.7 Documentation

6.7.1

The final location of anodes shall be documented on as-built drawings.

6.7.2

Measurements to verify electrical continuity shall be documented.

6.7.3

The purchaser may specify further requirements for the anode installation documentation.

SECTION 7 INSPECTION, MAINTENANCE AND RETROFITTING

7.1 General

7.1.1

A primary advantage of GACP systems is that they require a minimum of inspection and maintenance to ensure reliable corrosion control for the overall design life. Still, with a typical design life in the range of 10-30 years and in some cases up to 50 years, some efforts are pertinent to ensure that the GACP system functions as expected for the overall design of the protection object. In addition, an initial survey is sometimes required by the owner or a regulating authority to confirm that the design, manufacturing and installation of the GACP are adequate. In some cases it has been found necessary to retrofit a CP to compensate for deficient design and manufacturing, or damage during installation, or to extend the life of the GACP system beyond the initial design life. With the life of offshore structures increasing, the need for CP inspection and possibly also retrofitting is likely to be enhanced.

7.1.2

The need to inspect, maintain and retrofit a GACP, both initially and while operating, is dictated by the actual function of the protection object, any regulatory requirements and the owner's corrosion control philosophy. For steel substructures for oil and gas platforms, the fatigue design calculations may be based on a protection criterion more negative than -0.80 V, see [5.4], may be a prerequisite for the fatigue calculations used for the design.

7.2 Inspection of galvanic anode cathodic protection

7.2.1

The purpose of GACP inspection may be to:

- confirm that design, manufacturing and installation procedures have been adequate to provide an initial corrosion control function, in compliance with the requirements of the owner and/or a regulating authority
- verify adequate CP throughout operation and assess any need for maintenance or retrofitting according to the owner’s and any regulatory authority's requirements for CP
- collect data to verify and optimize the CP design for future applications.

7.2.2

The following inspection techniques are commonly used in GACP inspections:

- recordings of CP potentials of protection objects that are remote from galvanic anodes and typically also closed-circuit potentials of some selected anodes
- visual inspection by ROV operated cameras or possibly by divers in shallow and calm waters.

Other techniques may be relevant for collecting data from a CP system, e.g. measurements of electric field gradients at anodes for assessments of the current output from individual anodes. Also, for the same purpose, fixed monitoring systems for on-line recording of the protection potential and anode current output have been developed.

7.2.3

For the purpose of bullet point 1 in [7.2.1], an initial inspection is mostly performed within a year of the installation of the GACP system. For structures with major surfaces in bare steel, the initial polarization may be sluggish and steady state conditions with respect to CP potentials may not have been reached within one year. However, with a correct design, a protection potential criterion of -0.80 V should be obtained within this period of time. For platform substructures, visual inspection is of secondary importance during an initial survey except to confirm that anodes have not been damaged during installation. However, for subsea production systems with bare components in CRAs with poor resistance to seawater, e.g. UNS 31600 components for production control systems, early visual inspection is recommended to disclose any components installed without electrical continuity to anodes. For the purpose of bullet point 2 in [7.2.1], inspections are typically performed at five-year intervals unless a previous inspection has disclosed a marginal cathodic protection, whilst for the purpose of bullet point 3 in [7.2.1], steady state conditions should have been established prior to inspection.

7.2.4

The party to be contracted to deliver the CP survey should document adequate experience from the execution of similar work. It is essential that the scope and objectives of a GACP survey with a purpose according to [7.2.1] are defined in detail by the owner/purchaser, which should further ensure that the contractor has access to relevant information on the CP design, e.g. drawings showing the locations and initial dimensions of anodes and results of any previous survey. Any preferred locations for inspection, e.g. specific steel jacket nodes with high cyclic loads, should furthermore be advised.

7.2.5

The contractor should subsequently prepare a detailed inspection procedure that as a minimum addresses:

- capabilities of ROV tools that are relevant for the GACP inspection
- qualification of personnel to plan, supervise and evaluate the inspection
- description of the equipment to be used in the GACP inspection, including data acquisition/recording and considerations of contingency needs for equipment to be brought offshore
- detailed procedure for verifying reference electrodes to be used for a CP potential survey
- pre-determined locations for CP potential recordings, other recordings, selected anodes for visual inspection and potential recordings, taking into account the locations, results of potential recordings, other recordings and anode consumption estimates from any previous surveys of the protection structure
- pre-determined locations for CP potential recordings and other recordings and selected anodes for visual inspection and potential recordings, taking into account the locations and results of potential recordings and other recordings and the anode consumption estimates from any previous surveys of the protection object
- reporting format and index, including extent of photographic documentation of anodes.

7.3 Cathodic protection potential survey

7.3.1

CP potential surveys can either be surface deployed or ROV or diver assisted. In both cases the potential measuring unit contains one or two Ag/AgCl/seawater cells of the type 'open-electrolyte', i.e. direct access by seawater.

7.3.2

A surface-deployed potential survey, also referred to as a drop cell survey, uses a reference electrode unit attached to a sinker weight suspended by a polymeric rope and with an electrically insulated grounding wire attached topside to the steel structure via a voltmeter. This technique is primarily applicable in relatively shallow and calm waters, allowing the reference to be located within one or a few metres from the protection object. It is primarily intended to record variations in the global protection level vertically along an offshore substructure, from splash zone to seabed. Depending on the location of the probe in relation to anodes and the size/geometry of the structure, application of coating, and properties of the calcareous layer and marine growth, the local protection potential, i.e. without the effect of an ohmic voltage drop, may be 10 mV to 50 mV less negative. Still, the recording of a potential more negative than -0.85 V should indicate that the protection potential criterion of -0.80 V is fulfilled also at more remote locations at the same horizontal level. To confirm an adequate protection level in steady state conditions, an average potential value of < -0.90 V should be recorded since less negative values indicate that the anodes are operating with a higher driving voltage than designed for and this may potentially lead to premature anode consumption.

7.3.3

In principle, an ROV or diver assisted potential survey may utilize a grounding wire attached to the topside. A contact probe that typically has a small stainless steel tip, referred to as, e.g., a tip contact probe or stabbing probe, may also be used to establish direct metallic contact subsea and to define the distance between the reference cell and the steel surface for accurate and reproducible recordings of potentials without any significant effect from ohmic resistance. For ROV assisted surveys, the voltmeter and data acquisition may be contained in the ROV. For diver assisted surveys, the voltmeter may be installed in a hand-held tool with a digital display for recording by the diver. CP potential recordings should be supervised by a competent person to ensure that data being recorded manually or automatically are free from deficiencies due to defective equipment or the faulty execution of recording procedures.

7.3.4

Immediately prior to a CP potential survey and following its completion, the reference electrode(s) used for in-situ recordings should be checked according to an approved procedure. It is good practice to undertake reference electrode and instrument calibration checks offshore daily, to avoid the need to repeat several days of surveys if excessive errors in equipment are detected. This may be carried out in a plastic container filled with fresh seawater and using one or more master electrodes calibrated and certified in an accredited laboratory. In the following, the offshore checking of a working reference electrode is referred to as calibration. Results from offshore calibrations should be included in the survey report. Accurate calibration and use of a tip contact probe defining the distance to the object should allow CP potentials to be recorded with an accuracy of well within ± 10 mV. Potential values recorded will to some extent be affected by variations in ambient seawater temperature and salinity. Any insulation damage to grounding or lead wires that exposes metallic copper to seawater can severely disturb potential recordings and can be detected during calibrations topside if wires are submerged in seawater during the offshore calibration. ROV tools are preferably to contain two reference electrodes to allow internal calibrations during operation so as to exclude faulty recordings, whilst a diver held tool can be checked in-situ against a small piece of pure zinc. In case faulty readings due to poor metallic contact are suspected, a new stabbing with the spike tip should be performed.

7.3.5

The CP potential measurements should be carried out at pre-determined locations of the protection object [7.2.4]. The number of measurements to be performed depends on the size and geometry of the object and the purpose of the survey [7.2.1]. For a platform substructure, measurements should be performed all the way from the splash zone down to the sediment line and should include some locations remotely located from anodes but still accessible with the ROV or diver. Additional measurements should be considered at locations where anomalies are seen during the survey. Measurements should further be performed on some representative anodes whilst steel potentials in the immediate vicinity of anodes are of limited interest.

7.4 Visual surveys

7.4.1

A visual CP survey may be carried out in combination with a CP potential survey or a survey with another main purpose which does not include potential recordings. For subsea production systems, the absence of ferric rust on carbon and low alloy steel surfaces as confirmed by a visual survey may be sufficient to conclude that a GACP system provides adequate protection. During the survey, some pre-determined anodes should be checked for the degree of consumption as evidenced by photographic documentation. Any anodes noticed to have especially small or high consumption should also be documented by photos and location. If anodes are found to be covered by thick deposits, water blasting should be performed on some anodes to allow for a more accurate estimate of their consumption. If corrosion products are blasted off, the anode can be measured using photogrametry or lasers and the measured dimensions used to calculate the remaining anode mass. A factor could be applied to compensate for irregular corrosion patterns, cavities etc. When estimating the percentage anode consumption, an accuracy of ± 10% should be aimed for and this requires knowledge of the initial anode dimensions.

7.4.2

The extent of any marine growth on the protection object should be documented during the survey and observations of rust deposits or other anomalies relevant to corrosion control should also be documented. The absence of ferric rust deposits is of particular importance for subsea production systems where deficient electrical continuity to one or more anodes is by far the most common failure mode and is difficult to disclose using potential recordings alone. Special attention should then be paid to any rust accumulations at pressure containing components of the production control system. Any degradation of paint coating including excessive blistering or general flaking should furthermore be documented.

7.5 Maintenance and retrofitting of galvanic anode cathodic protection

7.5.1

For GACP systems of protection objects permanently installed subsea, maintenance is not practical. For units retrieved to the surface, and fitted with CP, e.g. valve tree modules, the replacement of largely or completely consumed anodes and rectification of faulty electrical connections may be considered as maintenance. During retrieval of components with self-supporting CP systems, it is recommended to carry out photographic documentation of anodes and any degradation of coatings.

7.5.2

Once the need to retrofit CP has been identified, two alternative approaches may apply. For offshore structures with a continuous AC source available, impressed current cathodic protection (ICCP) is in principle an alternative to the use of additional galvanic anodes. Proprietary systems have been developed, typically based on inert ICCP anodes being suspended by wire ropes within a structure or at buoys anchored on the seabed around the structure. However, the application of such systems appears to have been hampered primarily by the vulnerability of cables to anodes and reference electrodes being damaged by physical effects and the uncertain long-term performance of anodes and reference electrodes. It is therefore recommended that the management of any retrofitted subsea cables should be considered in the design to avoid the failure of such systems. Retrofitting using galvanic anodes has utilized stand-off or bracelet type anodes with special hinges for attachment to jacket bracings. Other concepts include arrays of galvanic anodes placed on sledges on the seabed with cable attachment to the protection object and electrical continuity provided by e.g. friction welding.

7.5.3

The design of GACP retrofitting should take into account historical data, e.g. potential measurements and other measurements, the estimated capacity of any remaining anodes and the condition of the steel surfaces, remaining coating, calcareous layers and marine growth in addition to the remaining life of the structure to be retrofitted. Circuit resistance in any cable connections and anode interference effects shall be considered if multiple anodes are placed on sledges for installation on the seabed. In any case, the design of CP retrofit systems requires advanced knowledge of CP design and offshore installation procedures. It is recommended that verification of the design documentation should be performed by a competent third party.

SECTION 8 TABLES AND FIGURES

8.1 Tables and figures

Table 8-1 Recommended initial and final design current densities (A/m^2) for seawater exposed bare metal surfaces, as a function of depth and climatic region based on surface water temperature, see [3.3]

Depth *[m]*	*Tropical* *(> 20 °C)*		*Sub-tropical* *(12- 20 °C)*		*Temperate* *(7-11 °C)*		*Arctic* *(< 7 °C)*	
	initial	*final*	*initial*	*final*	*initial*	*final*	*initial*	*final*
0-30	0.150	0.100	0.170	0.110	0.200	0.130	0.250	0.170
>30-100	0.120	0.080	0.140	0.090	0.170	0.110	0.200	0.130
>100-300	0.140	0.090	0.160	0.110	0.190	0.140	0.220	0.170
>300	0.180	0.130	0.200	0.150	0.220	0.170	0.220	0.170

Table 8-2 Recommended mean design current densities (A/m^2) for seawater exposed bare metal surfaces, as a function of depth and climatic region based on surface water temperature, see [3.3]

Depth *(m)*	*Tropical* *(> 20 °C)*	*Sub-tropical* *(12- 20 °C)*	*Temperate* *(7-12 °C)*	*Arctic* *(< 7 °C)*
0-30	0.070	0.080	0.100	0.120
>30-100	0.060	0.070	0.080	0.100
>100-300	0.070	0.080	0.090	0.110
>300	0.090	0.100	0.110	0.110

Table 8-3 Recommended mean design current densities for current drain of reinforcing steel (i.e. in concrete structures) as a function of depth and climatic region based on surface water temperature, see [3.3.12])

Depth *[m]*	*Tropical* *(> 20 °C)*	*Sub-tropical* *(12- 20 °C)*	*Temperate* *(7-12 °C)*	*Arctic* *(< 7 °C)*
0-30	0.0025	0.0015	0.0010	0.0008
>30-100	0.0020	0.0010	0.0008	0.0006
>100	0.0010	0.0008	0.0006	0.0006
1) The current densities in A/m^2 refer to the steel reinforcement surface area, not the surface area of concrete.				

Table 8-4 Recommended values for a and b constants for calculation of paint coating breakdown factors (coating categories are defined in [3.4.6])

Depth *[m]*	*Recommended values for a and b constants for coating categories I, II, III and IV, see [3.4.7]*			
	I *(a = 0.10)*	*II* *(a = 0.05)*	*III* *(a = 0.02)*	*IV* *(a = 0.02)*
0-30	b = 0.10	b = 0.025	b = 0.012	b = 0.008
>30	b = 0.05	b = 0.015	b = 0.008	b = 0.005

Table 8-5 Recommended compositional limits for Al-based and Zn-based anode materials, see [3.5]

Alloying/impurity element	*Zn-base*	*Al-base*
Zn	rem.	2.5-5.75
Al	0.10-0.50	rem.
In	na	0.015-0.040
Cd	0.025-0.07	≤ 0.002
Si	na	≤ 0.12
Fe	≤ 0.005	≤ 0.09
Cu	≤ 0.005	≤ 0.003
Pb	≤ 0.006	na

Table 8-6 Recommended design electrochemical capacity and design closed circuit potential for anode materials at seawater ambient temperatures, see [3.5]

Anode material	*Anode surface temperature ([°C]*	*Seawater exposure*		*Sediment exposure*	
		Closed circuit potential [V]	*Electrochemical capacity [Ah/kg]*	*Closed circuit potential [V]*	*Electrochemical capacity [Ah/kg]*
Al-Zn-In	≤30	-1.050	2,000	-1.000	1,500
	60	-1.050	1,500	-1.000	680
	80	-1.000	720	-1.000	320
Zn	≤30	-1.030	780	-0.980	750
	> 30 to 50			-0.980	580

1) For zinc anode surface temperatures exceeding 50°C, it is recommended to qualify the anode material for the project-specific maximum temperature according to Sec.10 (free-running test).

Table 8-7 Recommended anode resistance formulae for cathodic protection design calculations

Anode type	*Resistance formula*
Long slender stand-off 1) 2) $L \geq 4r$	$R_a = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{r} - 1\right)$
Short slender stand-off 1) 2) $L < 4r$	$R_a = \frac{\rho}{2\pi L}\left[\ln\left\{\frac{2L}{r}\left(1 + \sqrt{1 + \left(\frac{r}{2L}\right)^2}\right)\right\} + \frac{r}{2L} - \sqrt{1 + \left(\frac{r}{2L}\right)^2}\right]$
Long flush-mounted 2)3) $L \geq 4 \cdot$ width and $L \geq 4 \cdot$ thickness	$R_a = \frac{\rho}{2S}$
Short flush-mounted, bracelet and other types	$R_a = \frac{0.315\rho}{\sqrt{A}}$

1) The equation is valid for anodes with a minimum distance of 0.30 m from the protection object. For anode-to-object distances of less than 0.30 m but minimum 0.15 m the same equation may be applied with a correction factor of 1.3.

2) For non-cylindrical anodes: $r = c/2\pi$ where c (m) is the anode cross-sectional periphery.

3) S [m] is the arithmetic mean of the anode length and width.

Table 8-8 Recommended anode utilization factors for cathodic protection design calculations

Anode type	*Anode utilization factor*
Long slender stand-off $L \geq 4r$	0.90
Short slender stand-off $L < 4r$	0.85
Long flush-mounted $L \geq 4$ width and $L \geq 4$ thickness	0.85
Short flush-mounted, bracelet and other types	0.80

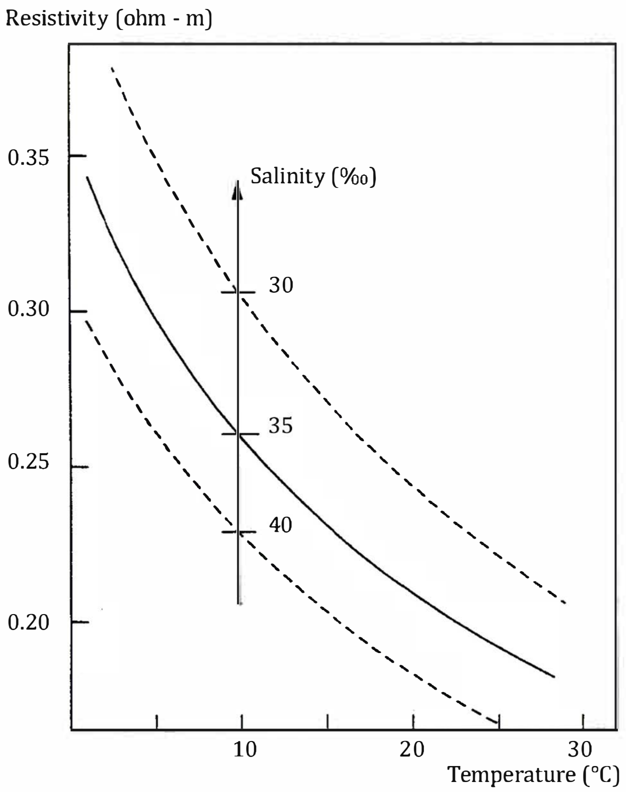

Figure 8-1 Seawater resistivity as a function of temperature for salinity of 30‰ to 40‰.

SECTION 9 LABORATORY TESTING OF GALVANIC ANODE MATERIALS FOR QUALITY CONTROL

9.1 General

9.1.1

This laboratory test procedure is intended for quality control of Al-base and Zn-base anode materials during manufacture of galvanic anodes.

Guidance note:

The results of testing according to this procedure are not applicable to cathodic protection design because electrochemical data from short-term testing, typically using high anodic current densities, will tend to be non-conservative with respect to the actual long-term performance in the field. The primary quality control measures in anode production are composition, by rigorous analysis of the alloy during production, dimensions, weights and casting quality. However, even very small contaminant levels of elements not normally analysed during production or listed in Table 8-5 can cause a serious reduction in anode quality and performance. These short, accelerated, laboratory electrochemical tests are recommended in order to detect any such contaminants and prevent the use of such defective anodes.

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9.1.2

The testing shall be performed according to a detailed procedure describing all relevant steps. The owner/ purchaser shall have the right to witness any testing at the contractor's premises.

9.1.3

All these procedure's requirements shall be considered mandatory, unless deviations have been agreed, see [5.1.3]. The owner/purchaser may, however, choose to specify an alternative test procedure.

9.2 Sampling and preparation of test specimens

9.2.1

Unless otherwise specified, the quality control of electrochemical properties, i.e. electrochemical efficiency and closed-circuit anode potential, shall be carried out for each 15,000 kg of anodes produced. Sampling for potential testing by separate mini-castings shall, however, be performed for each heat of anode material produced. All samples for testing shall have adequate marking. For retention of samples, see [5.6.1]. The owner/purchaser shall have the right to select the sample for testing, e.g. based on a review of the chemical composition of the individual heats.

Guidance note:

The individual heats are sometimes much smaller than 15,000 kg and it is then essential that the testing is performed on a heat that is representative of all those produced. Hence, the heat selected should have contents of alloying and/or impurity elements in the lower and upper ranges, respectively.

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9.2.2

Cylindrical test specimens with a diameter of 10 mm ± 1 mm and a length of 50 mm ± 5 mm shall be prepared by machining samples. A hole of about 3 mm in diameter shall be drilled and tapped on one end for connection of a titanium or stainless steel support rod. The specimen shall subsequently be rinsed in tap water followed by ethanol, then dried and weighed to an accuracy of ± 0.1 mg.

9.2.3

The specimens shall be adequately marked throughout all stages of the preparation, storage and testing.

9.3 Equipment and experimental procedure

9.3.1

After mounting the support rod, the specimen ends and the part of the rod exposed to the test solution shall be coated with a suitable sealing compound such as polychloroprene glue or silicon rubber.

9.3.2

The testing solution shall be natural seawater of adequate purity and a salinity of minimum 30‰ or synthetic seawater according to ASTM D1141.

Guidance note:

Seawater constituents other than chloride, sulphate, bicarbonate/carbonate, sodium, calcium and magnesium ions have no effect on the electrochemical performance of galvanic anodes and may be omitted when preparing synthetic seawater. Tap water is acceptable for preparation of the solution.

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9.3.3

A minimum of 10 litres per test specimen shall be used. The solution shall be continuously purged with air and shall not be exchanged during the test period. The temperature shall be maintained at 20 ± 3 °C.

9.3.4

Each specimen shall be suspended in the centre of an uncoated cylindrical steel container, e.g. made of a pipe section, the wetted surface area of which shall be minimum 20 times the exposed anode specimen area, i.e. minimum 400 cm^2, approximately. The general arrangement is shown in Figure 9-1.

9.3.5

Galvanostatic control shall be effected by means of a DC constant current source, capable of controlling the current according to [9.3.7]. The specimen and cathode shall be coupled to the positive and negative rectifier terminals, respectively. Multiple testing cells may be connected in series to one DC source.

9.3.6

A current integrator, e.g. a copper coulometer or an electronic device capable of determining the total discharged current to an accuracy of ± 2%, shall be inserted into the circuit containing one or more test cells in circuit.

9.3.7

The current through the cell(s) shall be adjusted to provide anodic current densities, based on the initially exposed surface area, in accordance with the following scheme:

Day 1	1.5 mA/cm^2
Day 2	0.4 mA/cm^2
Day 3	4.0 mA/cm^2
Day 4	1.5 mA/cm^2.

The current density shall be controlled to an accuracy of 0.1 mA/cm^2 and shall be maintained for a period of 24 hours ± 1 hour. The total testing time shall be 96 hours ± 4 hours.

9.3.8

At the end of each testing period, the anode potential shall be measured at three positions per specimen. A standard reference electrode (silver/silver chloride/saturated KCl) with an electrolyte bridge, e.g. a Luggin capillary, shall be used. The tip of the bridge shall be positioned within 1 mm from the specimen surface, but without disturbing any corrosion products formed on the anode specimen. Reference electrodes shall be checked against a certified, max 1, year reference electrode at intervals not exceeding one week. Potential recordings using a silver/silver chloride/saturated KCl reference electrode shall be converted to potential recordings using Ag/AgCl/seawater [3.1.5].

9.3.9

After completion of the full test period, the support rod and sealing compound shall be removed and the specimen cleaned of corrosion products. Aluminium-based specimens shall be cleaned for 10 min at 80°C in a solution of 20 g chromium trioxide and 30 ml phosphoric acid per litre water. Zinc-based specimens shall be immersed for 2 hours in a saturated ammonium chloride solution at ambient temperature. Specimens shall subsequently be rinsed in tap water, thereafter in ethanol and weighed to an accuracy of ± 0.1 mg.

9.3.10

The electrochemical efficiency, ε (Ah/kg), shall be calculated from

$$\varepsilon = (1000C)/\mathit{\Delta} w$$

where C is the total current charge in Ah and $\mathit{\Delta}$w is the weight loss in grams.

9.4 Acceptance criteria and re-testing

9.4.1

The acceptance criteria in [5.6.7] apply.

9.4.2

Failures during testing which are obviously due to operational errors may be disregarded and testing repeated on a new specimen of the same sample, see [5.6.8], or a specimen cut from an anode of the same heat.

9.4.3

If the specified requirements cannot be met, re-tests may be carried out on 3 specimens from each heat of the testing lot normally representing up to 15,000 kg of anode material. Failure of any specimen of a heat shall lead to rejection of all anodes from that heat.

9.5 Documentation

9.5.1

The test report shall contain relevant data for the anode material(s) tested, including the heat number, chemical composition and casting date. The specimen preparation, test equipment and testing procedure shall be outlined.

9.5.2

All recorded potentials, i.e. 3 per specimen, shall be presented in tabular form, as-recorded and converted to Ag/AgCl/seawater, if applicable. The specimen weight loss and total current charge shall be given in addition to the calculated electrochemical efficiency. A photograph of the cleaned specimen shall be included in the report.

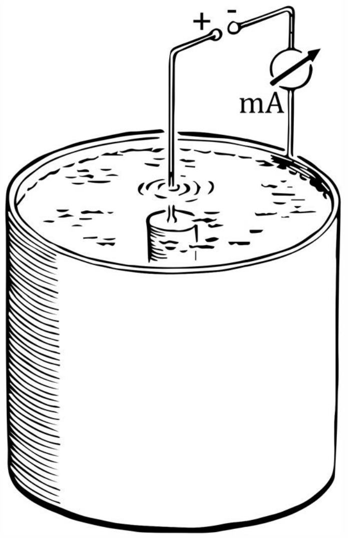

Figure 9-1 General arrangement for quality control testing of galvanic anode materials

SECTION 10 LABORATORY TESTING OF GALVANIC ANODE MATERIALS FOR QUALIFICATION OF THE ELECTROCHEMICAL PERFORMANCE

10.1 General

10.1.1

This section gives a recommended procedure for documenting the electrochemical performance of galvanic anode materials in natural seawater of ambient temperature. The procedure may be modified to include testing in hot or cold seawater.

> **Guidance note:**
>
> The performance of anodes is best documented by field testing of full-size anodes. However, such testing is elaborate and often not practical.
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

10.1.2

Qualification testing should preferably be performed by, or at least witnessed by, a party independent of the anode manufacturer.

10.1.3

Testing according to this procedure is non-mandatory and shall be specified by the purchaser, see [5.1.3]. Modifications of the test parameters may be agreed.

10.2 Sampling and preparation of test specimens

10.2.1

Specimens for testing shall be cut from full-scale anodes using the same type of raw materials, smelting and casting practices as for normal production. The net mass of the anode shall be minimum 30% of the maximum anode net mass of anodes to which the documentation shall apply.

> **Guidance note:**
>
> The performance of an anode material may be affected by solidification and cooling such that specimens from smaller anodes, or separately cast specimens, may not be fully representative of larger anodes.
>
> ---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

10.2.2

The chemical composition of the anode(s) to be used for documentation shall reflect the compositional limits that shall apply during the manufacturer's normal production, see [3.5.2]. This will normally require preparation of a special heat, combining the maximum specified contents of impurity elements and minimum contents of the actual alloying elements. No heat treatment of the casting is allowed for Zn and Al-Zn-In anode materials.

Guidance note:

To justify the compositional limits specified by the manufacturer, testing of more than one heat may be required.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

10.2.3

Minimum 5 specimens of each heat to be documented shall be tested. Cylindrical specimens with a diameter of minimum 25 mm and a length of 100 mm shall be prepared. A hole of about 4 mm in diameter shall be drilled and tapped on one end for connection of a titanium support rod. The specimen shall subsequently be rinsed in tap water followed by ethanol, then dried and weighed to an accuracy of ± 0.1 mg

10.2.4

The specimens shall be adequately marked throughout all stages of preparation, storage and testing. Anode material from the anode casting should be retained for any additional testing later on.

10.3 Equipment and experimental procedure

10.3.1

After mounting the support rod, the specimen ends and the part of the rod exposed to the test solution shall be coated with a suitable sealing compound such as polychloroprene glue or silicon rubber.

10.3.2

The testing environment shall be clean natural seawater with a salinity of ≥ 30 ‰. The temperature may be allowed to vary in the range + 7°C to + 20°C. The temperature and salinity of the seawater shall be recorded at least once per week. The test shall be configured as outlined in Sec.9, however, there shall be a continuous exchange of seawater in the cell, minimum 1 l/min. The seawater shall be continuously purged with air.

Guidance note:

Seawater temperature variations in the range above are not considered to affect the electrochemical performance of anode materials significantly. However, lower temperatures are sometimes believed to reduce the performance, and purchasers of the anodes may require documentation of the anode materials' performance at such temperatures.

---e-n-d---o-f---g-u-i-d-a-n-c-e---n-o-t-e---

10.3.3

Testing may be performed either with galvanostatic control or as a free-running test. The testing time shall be minimum 12 months.

Guidance note:

A free-running test, which means that the anode/cathode assembly is allowed to polarize spontaneously during the test. The driving voltage and hence the anodic current density will thus vary during the test. For a galvanostatic test, the anode potential is controlled throughout the testing period.

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10.3.4

With galvanostatic control, the anodic current density shall be maximum 1 mA/cm^2 based on the initial exposed anode surface area. The integrated current, i.e. for minimum 12 months, may be determined as for [9.3.6] but manual readings minimum once per day and five days per week for the first two weeks, thereafter once per week, will suffice. Recordings of the anode potential, see [9.3.8], shall be performed with the same minimum frequency as for manual current readings.

10.3.5

For a free-running test, the anode and cathode shall be connected over a 10 ohm ± 1 ohm precision resistance. The actual resistance is to be recorded with an accuracy of ± 0.2 ohm. The inner uncoated cathode surface area shall be approximately 30 times the exposed anode surface area. The outer surface shall be coated to achieve a defined surface area of about 1:30.

The current shall be calculated from measurements of the voltage drop across the precision resistance using a high impedance (≥ 107 ohm) voltmeter. Measurements of the anode potential, cathode potential and cell current shall be carried out at the maximum intervals specified above.

10.3.6

Reference electrodes used for recording anode potential shall be checked against a certified reference electrode at regular intervals, minimum once per month. The reference electrode shall not be more than one year old. After the test is completed, the specimens shall be cleaned and the electrochemical efficiency calculated as in [9.3.9] and [9.3.10].

10.4 Documentation

10.4.1

The test report shall contain relevant data on the smelting and casting of anodes and location of test specimens. The contents of alloying and impurity elements shall be specified with nominal and guaranteed contents as a reference.

10.4.2

The average and maximum/minimum salinity and temperature of seawater shall be reported.

10.4.3

Sampling, specimen preparation, marking, testing equipment, calibrations and recordings of data shall be described in the report. Anode potentials (versus Ag/AgCl/seawater) shall be displayed graphically as a function of time. For free-running tests, the calculated anodic current density based on the original exposed surface area and the cathode potential shall also be given in graphical form.

10.4.4

Data from measurements of the anode weight loss shall be included in the report in addition to the calculated electrochemical efficiency (in Ah/kg). The mean value and standard deviation shall be reported. Photographs of anode specimens prior to and after cleaning shall be included.

Guidance note:

A steady state electrochemical potential of ≤ -1.07 V and an electrochemical efficiency of minimium 2,250 Ah/kg are considered adequate to verify the performance of an Al-based material that has been tested and justify the use of the default values in Table 8-6, see the guidance note to [3.5.2].

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SECTION 11 BIBLIOGRAPHY

11.1 Bibliography

Table 11-1 Bibliography list

Reference no.	*Source*
/1/	Hartt WH, 2012 Frank Newman Speller Award: Cathodic Protection of Offshore Structures—History and Current Status, CORROSION. 2012;68(12):1063-1075.

CHANGES – HISTORIC

June 2017 edition

This document supersedes the October 2010 edition of DNV-RP-B401.

The purpose of the revision of this service document is to comply with the new DNV GL document reference code system and profile requirements following the merger between DNV and GL in 2013. Changes mainly consists of updated company name and references to other documents within the DNV GL portfolio.

Some references in this service document may refer to documents in the DNV GL portfolio not yet published (planned published within 2017). In such cases please see the relevant legacy DNV or GL document. References to external documents (non-DNV GL) have not been updated.