

RECOMMENDED PRACTICE
DNV-RP-B401

CATHODIC PROTECTION DESIGN

OCTOBER 2010

*This document has been amended since the main revision (October 2010), most recently in April 2011.
See "Changes" on page 3.*

DET NORSKE VERITAS

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CHANGES

- **General**

As of October 2010 all DNV service documents are primarily published electronically.

In order to ensure a practical transition from the “print” scheme to the “electronic” scheme, all documents having incorporated amendments and corrections more recent than the date of the latest printed issue, have been given the date October 2010.

An overview of DNV service documents, their update status and historical “amendments and corrections” may be found through http://www.dnv.com/resources/rules_standards/.

- **Main changes October 2010**

Since the previous edition (January 2005), this document has been amended, most recently in April 2008. All changes have been incorporated and a new date (October 2010) has been given as explained under “General”.

- **Amendments April 2011**

- Item 6.5.2 has been amended and clarified concerning galvanic anode performance requirements.
- A new Guidance note has been added to item 12.4.4 (Annex C).
- The layout has been changed to one column in order to improve electronic readability.

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1. General

1.1 Introduction

1.1.1 ‘Cathodic protection’ (CP) can be defined as e.g. “electrochemical protection by decreasing the corrosion potential to a level at which the corrosion rate of the metal is significantly reduced” (ISO 8044) or “a technique to reduce corrosion of a metal surface by making that surface the cathode of an electrochemical cell” (NACE RP0176). The process of suppressing the corrosion potential to a more negative potential is referred to as ‘cathodic polarization’.

1.1.2 For galvanic anode CP systems, the anode of the electrochemical cell is a casting of an electrochemically active alloy (normally aluminium, zinc or magnesium based). This anode is also the current source for the CP system and will be consumed. Accordingly, it is often referred to as a ‘sacrificial anode’, as alternative to the term ‘galvanic anode’ consistently used in this Recommended Practice (RP). For ‘impressed current’ CP, an inert (non-consuming) anode is used and the current is supplied by a rectifier. In this RP, the cathode of the electrochemical cell (i.e. the structure, sub-system or component to receive CP) is referred to as the ‘protection object’.

1.1.3 For permanently installed offshore structures, galvanic anodes are usually preferred. The design is simple, the system is mechanically robust and no external current source is needed. In addition, inspection and maintenance during operation can largely be limited to periodic visual inspection of anode consumption and absence of visual corrosive degradation. However, due to weight and drag forces caused by galvanic anodes, impressed current CP systems are sometimes chosen for permanently installed floating structures.

1.1.4 CP is applicable for all types of metals and alloys commonly used for subsea applications. It prevents localised forms of corrosion as well as uniform corrosion attack, and eliminates the possibility for galvanic corrosion when metallic materials with different electrochemical characteristics are combined. However, CP may have certain detrimental effects, for example hydrogen related cracking of certain high-strength alloys and coating disbondment as described in 5.5.

1.1.5 CP is primarily intended for metal surfaces permanently exposed to seawater or marine sediments. Still, CP is often fully effective in preventing any severe corrosion in a tidal zone and has a corrosion reducing effect on surfaces intermittently wetted by seawater.

1.2 Scope

1.2.1 This RP has been prepared to facilitate the execution of conceptual and detailed CP design using aluminium or zinc based galvanic anodes, and specification of manufacture and installation of such anodes. Whilst the requirements and recommendations are general, this document contains advice on how amendments can be made to include project specific requirements. The RP can also easily be amended to include requirements or guidelines by a regulating authority, or to reflect Owner’s general philosophy on corrosion control by CP.

1.2.2 Some of the design recommendations and methods in Sections 5, 6 and 7 are also valid for CP systems using other current sources such as magnesium anodes and rectifiers (i.e. impressed current).

1.2.3 This RP is primarily intended for CP of permanently installed offshore structures associated with the production of oil and gas. Mobile installations for oil and gas production like semi-submersibles, jack-ups and mono-hull vessels are not included in the scope of this document. However, to the discretion of the user, relevant parts of this RP may be used for galvanic anode CP of such structures as well.

1.2.4 Detailed design of anode fastening devices for structural integrity is not included in the scope of this RP. Considerations related to safety and environmental hazards associated with galvanic anode manufacture and installation are also beyond its scope.

1.2.5 Compared to the 1993 edition of DNV-RP-B401, design considerations for impressed current CP have been deleted from the scope of the 2004 revision whilst the sections on anode manufacture and installation are made more comprehensive. CP of submarine pipelines is further excluded from the scope (see 1.5). However, this RP is applicable for CP of components of a pipeline system installed on template manifolds, riser bases and other subsea structures when such components are electrically connected to major surfaces of structural C-steel.

In this revision, guidance and explanatory notes are contained in a ‘**Guidance note**’ to the applicable paragraph in Sections 6, 7, 8 and in Annex B and C. (Most of the Guidance notes are based on queries on the 1993 revision of DNV-RP-B401 and other experience from its use. Furthermore, some informative text in the old revision has been contained in such notes).

All tables and figures associated with Sec.6 are contained in Annex A. The document has further been revised to facilitate specification of Purchaser information to Contractor, and optional requirements associated with CP design, manufacture and installation of anodes (see 1.3). Additional comments on revisions in this 2004 issue are made in the Introduction (last paragraph) of Sections 6, 7, 8 and Annex B and C.

1.3 Objectives and Use

1.3.1 This RP has two major objectives. It may be used as a guideline to Owner's or their contractors' execution of conceptual or detailed CP design, and to the specification of galvanic anode manufacture and installation. It may also be used as an attachment to an inquiry or purchase order specification for such work. If Purchaser has chosen to refer to this RP in a purchase document, then Contractor shall consider all requirements in Sections 6-9 of this document as mandatory, unless superseded by amendments and deviations in the specific contract. Referring to this document in a purchase document, reference shall also be made to the activities for which DNV-RP-B401 shall apply, i.e. CP design in Sections 6 and 7, anode manufacture in Sec.8 and/or anode installation in Sec.9.

1.3.2 CP design, anode manufacture and anode installation are typically carried out by three different parties (all referred to as 'Contractor'). Different parties issuing a contract (i.e. 'Purchaser') may also apply. The latter includes 'Owner', e.g. for CP design and qualification of galvanic anode materials. For definition of contracting parties and associated terminology, see Sec.3.

1.3.3 Specification of project specific information and optional requirements for CP detailed design, anode manufacture and anode installation are described in 7.1.2, 8.1.2 and 9.1.3, respectively.

1.4 Document Structure

1.4.1 Guidelines and requirements associated with conceptual and detailed CP design are contained in Sections 5, 6 and 7, whilst galvanic anode manufacture and installation are covered in Sec.8 and Sec.9, respectively. Tabulated data for CP design are compiled in Annex A. Annex B and C contain recommended procedures for laboratory testing of anode materials for production quality control and for documentation of long-term electrochemical performance, respectively.

1.5 Relation to Other DNV Documents

1.5.1 Cathodic protection of submarine pipelines is covered in DNV-RP-F103.

2. References

2.1 General

The following standards (2.2-2.7) are referred to in this RP. The latest editions apply.

2.2 ASTM (American Society for Testing and Materials)

ASTM G8 Test Method for Cathodic Disbonding of Pipeline Coating
ASTM D1141 Specification for Substitute Ocean Seawater

2.3 DNV (Det Norske Veritas)

DNV-RP-F103 Cathodic Protection of Submarine Pipelines by Galvanic Anodes

2.4 EN (European Standards)

EN 10204 Metallic Products – Types of Inspection Documents

2.5 Norsok

NORSOK M-501 Standard for Surface Preparation and Protective Coating

2.6 ISO (International Organization for Standardisation)

ISO 3506 Mechanical Properties of Corrosion-Resistant Stainless Steel Fasteners
ISO 8044 Corrosion of Metals and Alloys; Basic Terms and Definitions
ISO 8501-1 Preparation of Steel Substrates for Application of Paint and Related Products – Visual Assessment of Surface Cleanliness.
Part 1: Rust Grades and Preparation Grades of Uncoated Steel Substrates.
ISO 10005 Quality Management- Guidelines for Quality Plans
ISO 10474 Steel and Steel Products – Inspection Documents

2.7 NACE International

NACE RP0176	Corrosion Control of Steel Fixed Offshore Structures Associated with Petroleum Production
NACE RP0387	Metallurgical and Inspection Requirements for Cast Sacrificial Anodes for Offshore Applications

3. Terminology and Definitions

3.1 Terminology

<i>Owner</i>	Party legally responsible for design, construction and operation of the object to receive CP.
<i>Purchaser</i>	Party (Owner or main contractor) issuing inquiry or contract for CP design, anode manufacture or anode installation work, or nominated representative.
<i>Contractor</i>	Party to whom the work (i.e. CP design, anode manufacture or anode installation) has been contracted.
<i>shall</i>	indicates a mandatory requirement.
<i>should</i>	indicates a preferred course of action.
<i>may</i>	indicates a permissible course of action.
<i>agreed/agreement</i>	refers to a written arrangement between <i>Purchaser</i> and <i>Contractor</i> (e.g. as stated in a contract).
<i>report and notify</i>	refers to an action by <i>Contractor</i> in writing.
<i>accepted acceptance</i>	refers to a confirmation by <i>Purchaser</i> in writing.
<i>certificate certified</i>	refers to the confirmation of specified properties issued by <i>Contractor</i> or supplier of metallic materials according to EN 10204:3.1.B, ISO 10474:5.1-B or equivalent.
<i>purchase document(s)</i>	refers to an inquiry/tender or purchase/contract specification, as relevant.

3.2 Definitions

For the following technical items below, definitions in the text apply:

cathodic protection (1.1.1), galvanic anode (1.1.2), protection object (1.1.2), polarization (1.1.1), calcareous scale/layer (5.5.13), cathodic disbondment (5.5.1).

References within parentheses refer to the applicable paragraph.

For items applicable to quality control and CP design parameters, reference to the applicable paragraph is made in the list of abbreviations (4.1) and symbols (4.2).

4. Abbreviations and Symbols

4.1 Abbreviations

CP	cathodic protection
CR	concession request (8.5.6)
CRA	corrosion resistant alloy
CTOD	crack tip opening displacement
DC	direct current
DFT	dry film thickness
HAZ	heat affected zone
HISC	hydrogen induced stress cracking (5.5.3)
HV	Vicker's hardness
ITP	inspection and testing plan (8.4.2)
IPS	installation procedure specification (9.2)
MIP	manufacture and inspection plan (8.4.2)
MPS	manufacture procedure specification (8.2)
NDT	non-destructive testing
PQT	production qualification test (8.3)
PWHT	post weld heat treatment (5.5.7)
ROV	remotely operated vehicle
RP	recommended practice
SCE	standard calomel electrode (6.1.5)
SMYS	specified minimum yield strength
UNS	unified numbering system
WPS	welding procedure specification
WPQT	welding procedure qualification test
YS	yield strength

4.2 Symbols

A (m ²)	anode surface area (Table 10-7)
A_c (m ²)	cathode surface area (7.4.1)
a	constant in coating breakdown factor (6.4.2)
b	constant in coating breakdown factor (6.4.2)
C (Ah)	current charge associated with quality control testing of anode materials (11.3.10)
c (m)	anode cross sectional periphery (Table 10-7)
C_a (Ah)	(individual) anode current capacity (7.8.2)
$C_{a\text{ tot}}$ (Ah)	total anode current capacity (7.8.2)
E_a° (V)	design closed circuit anode potential (6.5.1)
E_c° (V)	design protective potential (7.8.2)
E_c' (V)	global protection potential (6.3.4)
E_a' (V)	(actual) anode closed circuit potential (6.3.4)
ΔE° (V)	design driving voltage (7.8.2)
ε (Ah/kg)	anode electrochemical capacity (6.5.1)
f_c	coating breakdown factor (6.4.1)
f_{ci}	initial coating breakdown factor (6.4.4)
f_{cm}	mean coating breakdown factor (6.4.4)
f_{cf}	final coating breakdown factor (6.4.4)
I_a (A)	(individual) anode current output (7.8.2)
I_{ai} (A)	(individual) initial anode current output (7.8.2)
I_{af} (A)	(individual) final anode current output (7.8.2)
$I_{a\text{ tot}}$ (A)	total anode current output (6.3.4)
$I_{a\text{ tot }i}$ (A)	total initial current output (7.8.4)

$I_{a\ tot\ f}$ (A)	total final current output (7.8.4)
I_c (A)	current demand (7.4.2)
I_{ci} (A)	initial current demand (7.4.2, 6.3.1)
I_{cm} (A)	mean current demand (7.4.2)
I_{cf} (A)	final current demand (7.4.2)
i_c (A/m ²)	design current density (6.3.1)
i_{ci} (A/m ²)	design initial current density (6.3.1)
i_{cm} (A/m ²)	design mean current density (6.3.5)
i_{cf} (A/m ²)	design final current density (6.3.1)
L (m)	anode length (Table 10-7)
M_a (kg)	total net anode mass (7.7.1)
m_a (kg)	(individual) net anode mass (7.8.3)
m_{ai} (kg)	(individual) initial net anode mass (7.9.3)
m_{af} (kg)	(individual) final net anode mass (7.9.3)
N	number of anodes (7.8.1)
r (m)	anode radius (Table 10-7)
R_a (ohm)	(individual) anode resistance (6.6.1)
R_{ai} (ohm)	(individual) anode initial resistance (7.9.2)
R_{af} (ohm)	(individual) anode final resistance (7.9.2)
$R_{a\ tot}$ (ohm)	total anode resistance (6.3.4)
S (m)	arithmetic mean of anode length and width (Table 10-7)
ρ (ohm·m)	seawater/sediment resistivity (6.7.1)
t_f (years)	design life (6.4.4)
u	anode utilisation factor (6.8)
Δw (g)	weight loss associated with quality control testing of anode materials (11.3.10)

5. General CP Design Considerations (Informative)

5.1 General

5.1.1 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 in nature and intended as guidelines for Owners and their contractors preparing for conceptual or detailed CP design. Nothing in this section shall be considered as mandatory if this RP has been referred to in a purchase document.

5.1.2 Compared to the 1993 revision of this RP, the major revisions of this 2004 revision are contained in 5.5.

5.2 Limitations of CP

5.2.1 For carbon and low-alloy steels, cathodic protection should be considered as a technique for corrosion control, rather than to provide immunity (1.1.1). It follows that cathodic protection is not an alternative to corrosion resistant alloys for components with very high dimensional tolerances, e.g. sealing assemblies associated with subsea production systems.

5.3 Environmental Parameters Affecting CP

5.3.1 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 considered factors which affect the formation of calcareous layers associated with CP and thus the current needed to achieve and to maintain CP of bare metal surfaces. In seabed sediments, the major parameters are: temperature, bacterial growth, salinity and sediment coarseness.

5.3.2 The above parameters are interrelated and vary with geographical location, depth and season. It is not feasible to give an exact relation between the seawater environmental parameters indicated above and cathodic current demands to achieve and to maintain CP. To rationalise CP design for marine applications, default design current densities, i_c (A/m²), are defined in this document based on 1) climatic regions (related to mean seawater surface temperature) and 2) depth. The ambient seawater temperature and salinity determine the specific seawater 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.

5.4 Protective Potentials

5.4.1 A potential of - 0.80 V relative to the Ag/AgCl/seawater reference electrode is generally accepted as the design protective potential E_c° (V) for carbon and low-alloy steels. It has been argued that a design protective potential of - 0.90 V should apply in anaerobic environments, including typical seawater sediments. However, in the design procedure advised in this RP, the protective potential is not a variable.

5.4.2 For a correctly designed galvanic anode CP system, the protection potential will for the main part of the design life be in the range - 0.90 to - 1.05 (V). Towards the end of the service life, the potential increases rapidly towards - 0.80 (V), and eventually to even less negative values, 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.

5.5 Detrimental effects of CP

5.5.1 Cathodic protection will be 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 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.

5.5.2 Coatings applied to machined or as-delivered surfaces of corrosion resistant alloys (CRAs) 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 galvanic anode CP, when applied to CRAs as well as to carbon and low-alloy steel. For coating systems whose compatibility with galvanic anode CP is not well documented, Owner should consider carrying out qualification testing, including laboratory testing of resistance to cathodic disbondment. Testing of marine coatings’ resistance to cathodic disbondment has been standardised, e.g. in ASTM G8.

5.5.3 Cathodic protection will cause formation of atomic hydrogen at the metal surface. Within the potential range for CP by aluminium or zinc based anodes (i.e. - 0.80 to - 1.10 V Ag/AgCl/seawater), the production of hydrogen increases exponentially towards the negative potential limit. The hydrogen atoms can either combine forming 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 initiation and growth of hydrogen-related cracks, here referred to as ‘hydrogen induced stress cracking’ (HISC).

5.5.4 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 of 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, part 1, grade A4, property class 80 and lower (up to SMYS 640 MPa) have proven compatibility with galvanic anode CP.

5.5.5 For certain nickel based alloys (i.e. austenitic alloys including e.g. UNS N05500 and N07750), precipitation hardening may induce high sensitivity to HISC. For precipitation hardened austenitic stainless steels, the susceptibility is lower and a hardness of max. 300 HV may be considered a reasonably safe limit, whilst materials with hardness higher than 350 HV should generally be avoided for any components to receive CP. In the intermediate hardness range (i.e. 300 to 350 HV), precautions should be applied during design to avoid local yielding and/or to specify a qualified coating system as a barrier to hydrogen absorption by CP. The qualification of coatings for this purpose should include documentation of resistance to disbonding in service by environmental effects, including CP and any internal heating.

5.5.6 Based on practical experience, ferritic and ferritic-pearlitic structural steels with specified minimum yield strength (SMYS) up to at least 500 MPa have proven compatibility with marine CP systems. (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 300 to 350 HV, design measures should be implemented to avoid local yielding and to apply a reliable coating system as a barrier to CP induced hydrogen absorption.

5.5.7 For martensitic carbon, low-alloy and stainless steels, failures 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 recognised that untempered martensite is especially prone to HISC. Welding of materials susceptible to martensite formation should be followed by post weld heat treatment (PWHT) to reduce heat-affected zone (HAZ) hardness and residual stresses from welding. The same recommendations for hardness limits and design measures as for ferritic steels (5.5.6) apply. Bolts in martensitic steel 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.

5.5.8 Ferritic-austenitic ('duplex') stainless steels should be regarded as potentially susceptible to HISC, independent of SMYS (typically 400 to 550 MPa) or specified maximum hardness. Welding may cause increased HISC susceptibility in the weld metal and in the HAZ adjacent to the fusion line. This is related to an increased ferrite content rather than hardness. Qualification of welding should therefore prove that the maximum ferrite content in the weld metal and the inner HAZ (about 0.1 mm wide) can be efficiently controlled; contents of maximum 60 to 70% are typically specified. Forgings are more prone to HISC than wrought materials due to the coarse microstructure allowing HISC to propagate preferentially in the ferrite phase. Cold bent pipes of small diameter (uncoated and with mechanical connections, i.e. no welding) have proven records for CP compatibility when used as production control piping for subsea installations. Design precautions should include 1) measures to avoid local plastic yielding and 2) use of coating systems qualified for e.g. resistance to disbondment by mechanical and physical/chemical effects.

5.5.9 Copper and aluminium based alloys are generally considered immune to HISC, regardless of fabrication modes. For high-strength titanium alloys, documentation is limited and special considerations (including e.g. qualification testing, see 5.5.10) should apply.

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

5.5.11 Special techniques have been applied to control the CP protective potential to a less negative range (e.g. - 0.80 to - 0.90 V), including the use of diodes and special anode alloys, but practical experience is limited. A major disadvantage of this approach is that the individual component or system needs to be electrically insulated from adjacent "normal" CP systems.

5.5.12 Cathodic protection in closed compartments without ventilation may cause development of hydrogen gas to an extent that an explosive gas mixture (i.e. hydrogen/oxygen) may eventually develop. The risk is moderate with Al and Zn-base galvanic anodes but at least one explosion during external welding on a water flooded platform leg containing such anodes has been related to this phenomenon. (Closed water flooded compartments will not normally require CP, see 6.3.7).

5.5.13 A consequence of CP application is that a calcareous layer (consisting primarily of calcium carbonate) 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 mating of subsea electrical and hydraulic couplers with small tolerances. This may be prevented by applying an insulating layer 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.

5.5.14 Galvanic anodes may interfere with subsea operations and increase drag forces by flowing seawater (see 5.7.3).

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

5.6 Galvanic Anode Materials

5.6.1 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 Owner and specified in the conceptual CP design report and/or in the design premises for detailed CP design.

5.6.2 Aluminium based anodes are normally preferred due to their higher electrochemical capacity, ε (A·h/kg). However, zinc based anodes have sometimes been considered more reliable (i.e. with respect to electrochemical performance) for applications in marine sediments or internal compartments with high bacterial activity, both environments representing anaerobic conditions.

5.6.3 Some manufacturers offer proprietary anode alloys. Purchaser may require that the anode manufacturer shall document the electrochemical performance of their products by operational experience or by long term testing in natural seawater. (A recommended testing procedure is contained in Annex C).

5.7 Anode Geometry and Fastening Devices

5.7.1 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 (6.6) and anode utilisation factor (6.8) to be applied.

5.7.2 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 utilisation factor u .

Stand-off anodes are manufactured up to a net anode mass of several hundred kilograms. In surface waters, drag forces exerted by sea currents are significant.

Bracelet anodes are used primarily for pipelines but have also found some use on platform legs in the upper zone, combining high current output to weight ratio with low drag. All flush mounted anodes should have a suitable coating system applied on the surface facing the protection object. This is to avoid build-up of anode corrosion products that could cause distortion and eventually fracture of anode fastening devices.

5.7.3 Type of anodes and any special requirements to anode fastening should be defined during conceptual CP design, taking into account forces exerted during installation (e.g. piling operations) and operation (e.g. wave forces). For stand-off type anodes, special precautions may be necessary during anode design and distribution of anodes to avoid impeding subsea operations (7.10.2).

5.8 Use of Coatings in Combination with CP

5.8.1 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.

5.8.2 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 6.3.2). It should further be considered for surfaces that are partly shielded from CP by geometrical effects.

5.8.3 For large and complex structures like e.g. multi-well subsea production units, extensive use of coating is required to limit the overall current demand and to ensure adequate current distribution. The CP design procedure in this document does not account for a voltage drop in the seawater remotely from anodes.

To compensate for this, the design coating breakdown factors to be used for CP design are deliberately selected in a conservative manner to ensure that a sufficient total final current output capacity is installed. As a consequence, any calculations of the electrolytic voltage drop away from the anodes (e.g. by means of finite or boundary element analyses) and using these coating breakdown factors may result in excessively high electrolytic voltage drops, indicating marginal or even insufficient cathodic protection in terms of the estimated protection potential.

This will primarily apply to relatively long design lives when the calculated coating breakdown, and hence current demands and electrolytic voltage drop increase exponentially.

5.8.4 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.

5.8.5 Metallic coatings on zinc or aluminium basis are compatible with galvanic anode CP. However, compared to organic coatings, they have not been considered to afford any advantage in decreasing the current demand for CP. Zinc rich primers have been considered unsuitable for application with CP due to either susceptibility to cathodic disbondment (5.5.1) or low electrical resistivity, leading to high CP current demand.

5.8.6 For components in materials sensitive to HISC by CP, a non-metallic coating system should always be considered as a barrier to hydrogen adsorption (5.5.6-5.5.7).

5.9 Electrical Continuity and Current Drain

5.9.1 Provisions for electrical insulation are only necessary if certain components or sub-systems are to be electrically insulated to avoid CP or to control the CP potential by special means (see 5.5.11 and 5.5.12).

5.9.2 CP current drain to components that are electrically connected to the protection object will have to 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 sea bed).

6. CP Design Parameters

6.1 General

6.1.1 This section describes design parameters to be used for conceptual and detailed design of galvanic anode CP systems and gives guidance on the selection of such parameters. With the exception of the design life (see 6.2) and possible also coating breakdown factors (see 6.4.3), the actual design values to be applied for a specific project are normally selected by Contractor, based on environmental and other parameters identified in the project design basis. However, sometimes certain or all CP design parameters have already been defined by Purchaser in a project document.

6.1.2 If reference is given to this RP in a purchase document, and unless otherwise agreed, the default design values referred to in this section shall apply.

6.1.3 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.

6.1.4 Owners of offshore structures may specify a less, or in certain cases a more conservative design data, based on their own experience or other special considerations. Contractor (i.e. other than Owner) may further propose use of alternative design data, however, any such data shall then be accepted by Owner, preferably before the CP design work has started.

6.1.5 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 equivalent to that of the standard calomel electrode (SCE).

6.1.6 Compared to the 1993 revision of this RP, the major revisions of this 2004 revision are that the number of depth zones for design current densities have been extended from 2 to 4 (3 only for CP of concrete reinforcing steel) whilst the number of ‘coating categories’ are reduced from 4 to 3. Revisions of the actual design parameters (contained in Annex A in this revision) are otherwise marginal.

6.2 Design Life

6.2.1 The design life of a CP system is normally specified by Owner, taking into account the likelihood of the design life of the protection object being extended. The design life shall further take into account any period of time when the CP system will be active prior to operation of the protection object.

Guidance note:

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 planned retrofitting of sacrificial 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.

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6.3 Design Current Densities

6.3.1 In this document ‘current density’, i_c , refers to cathodic protection current per unit surface area (in A/m²). 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 of time. 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 by application of a ‘coating breakdown factor’, see 6.4.

6.3.2 The initial design current density refers to the cathodic current density that is required to effect polarization of an initially 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 5.5.13) and possibly marine fouling layer developed during this initial phase reduce the subsequent current demand (i.e. the ‘polarization resistance’ is reduced). A sufficient initial design current density enables rapid formation of protective calcareous scale and hence efficient polarization.

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6.3.3 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 to - 1.05 V throughout the design life. In this potential range, the current density demand for maintenance of CP is lowest.

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6.3.4 The initial and final current densities are used to calculate the required number of anodes of a specific type (7.7) to achieve a sufficient polarizing capacity by use of Ohm's law and assuming that

- 1) the anode potential is in accordance with the design closed circuit potential (6.5.3) and
- 2) the potential of the protection object (i.e. cathode) is at the design protective potential for C-steel and low-alloy steel, i.e. - 0.80 V.

Guidance note:

It follows from the above relationship that the anode current and hence the cathodic current density decreases linearly when the cathode is polarised towards the closed circuit anode potential, reducing the driving voltage for the galvanic cell. According to 7.8.3, the total CP current for a CP unit, I_{tot} (A), becomes:

$$I_{tot} = \frac{(E'_c - E'_a)}{R_{atot}}$$

Where $R_{a\ tot}$ (ohm) is the total anode resistance, E'_c (V) is the global protection potential and E'_a (V) is the actual anode (closed circuit) potential.

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6.3.5 The mean (or 'maintenance') design current density, i_{cm} (A/m²), 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 to 0.20 V more negative than the design protective potential.

Guidance note:

The decrease in cathode potential (i.e. 'cathodic polarization') reduces the anode current as stated in the Guidance note to 6.3.4 so that the average design current density becomes about 50% of the initial/final design current density. As the initial polarization period proceeding steady-state condition is normally short compared to the design life, the time-weighted cathodic current density becomes very close to the steady-state cathodic current density.

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6.3.6 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 average design current densities are given in Tables 10-1 and 10-2 of Annex A, 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 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 Tables 10-1 and 10-2 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 content. The properties of such layers are dependant on the seawater ambient temperature and moreover, on certain depth dependant parameters other than temperature (see 5.3.1). Oxygen is dissolved in the surface layer (by dissolution from air and photo synthesis) 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 on degradation of calcareous scales and convective mass transfer of oxygen. In certain areas, decomposition of organic material may reduce and ultimately consume all oxygen in the seawater. No such reduction in oxygen content is accounted for in Tables 10-1 and 10-2.

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6.3.7 For freely flooded compartments and for closed compartments with free access to air, design current densities for 30-100 m given in Tables 10-1 and 10-2 are recommended. Closed and sealed flooded compartments do not normally need CP.

6.3.8 For bare steel surfaces buried in sediments, a design current density (initial/final and average) of 0.020 A/m² is recommended irrespective of geographical location and depth.

Guidance note:

In the uppermost layer of seabed sediments, bacterial activity may be the primary factor determining the CP current demand. Further down into sediments, the current will be related to hydrogen evolution.

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6.3.9 For piping and other components heated by an internal fluid, the design current densities as specified in Tables 10-1 and 10-2 shall be increased by 0.001 A/m² 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 increased convective and diffusive mass transfer of oxygen induced by heat transfer.

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6.3.10 The design current densities in Tables 10-1 and 10-2 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. For calculation of anode current output according to 7.8.2, a protective potential of -0.80 V shall then also apply for these materials.

6.3.11 For aluminium components, or those coated with either aluminium or zinc, a design current density of 0.010 A/m² is recommended for initial/final as well as mean values. For internally heated components, the design current density shall be increased by 0.0002 A/m² for each °C that the metal /seawater is assumed to exceed 25°C.

6.3.12 For cathodic protection of concrete reinforcing steel and other concrete embedded steel components associated with offshore structures, the design current densities in Table 10-3 of Annex A are recommended. For seawater filled concrete shafts, cathodic protection should be provided from both sides. For external protection of shafts that are normally empty, the design current densities in Table 10-3 shall be multiplied with a factor of 1.5.

Guidance note:

The cathodic current density of steel embedded in concrete is mainly controlled by 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 will be dependent on the exposure conditions (i.e. distance to atmospheric exposure of concrete) and ambient temperature.

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6.3.13 When the actual reinforcing steel surface area (in m²) to reinforced concrete volume (in m³) ratio B exceeds 5, an adjustment factor 5/B may be applied to the design current densities in Table 10-3

6.4 Coating Breakdown Factors for CP Design

6.4.1 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 as apparent by visual examination. A coating showing extensive blistering may still retain good electrically insulating properties. Conversely, an apparently perfect coated surface may allow a significant passage of current.

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

$$f_c = a + b \cdot t$$

where t (years) is the coating age 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 meters where wave forces may further contribute to coating degradation. Another factor is periodic cleaning of marine growth in this zone.

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6.4.3 Owner should preferably specify constants a and b for calculation of coating breakdown factors based on his own practical experience of specific coating systems in a particular environment. When Owner has not specified any such data, the default values in Table 10-4 of Annex A shall be used. The coating breakdown factors as established in Annex A are based on considerations addressed in 5.8.3.

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

$$f_{cm} = a + b \cdot \frac{t_f}{2}$$

$$f_{cf} = a + b \cdot t_f$$

For certain protection objects, with large uncoated surfaces, the initial coating breakdown factor, $f_{ci} = a$, may be applied to calculate the initial current demand to include coated surfaces.

6.4.5 If the calculated value according to 6.4.4 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 (6.4.2), f_{cm} may be calculated as:

$$f_{cm} = 1 - \frac{(1-a)^2}{2 \cdot b \cdot t_f}$$

6.4.6 To account for the effect of a coating system on coating breakdown factors, three ‘coating categories’ have been defined for inclusion in Table 10-4:

- Category I** One layer of epoxy paint coating, min. 20 μm nominal DFT
- Category II** One or more layers of marine paint coating (epoxy, polyurethane or vinyl based), total nominal DFT min. 250 μm .
- Category III** Two or more layers of marine paint coating (epoxy, polyurethane or vinyl based), total nominal DFT min. 350 μm .

Category I includes shop primer type of coatings. It is assumed for Categories II and III that the supplier-specific coating materials to be applied have been qualified by documented performance in service, or by relevant testing. It is further assumed for all three categories that all coating work has been carried out according to manufacturer’s recommendations and that surface preparation has included blast cleaning to minimum SA 2.5 in accordance with ISO 8501. The surface roughness shall be controlled according to manufacturer’s recommendation. For any coatings applied without blast cleaning (including machined, ground, brushed and as-rolled surfaces), a coating break-down factor of $f_{cm} = f_{cf} = 1$ shall be applied, while the initial current demand may be calculated as for Category I.

Guidance note:

Published data on the performance of coatings on cathodically protected structures are scarce, in particular for long service lives. The data in Table 10-4 should therefore be regarded as rather course but conservative engineering judgements. For any coating system not covered by the three coating categories above and with major potential effect on the overall current demand, Owner should specify or accept the applicable constants a and b.

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6.4.7 NORSOK M-501 Systems no. 3B and 7 meet the requirements of Category III.

6.4.8 a and b values for a depth 30-100 m in Table 10-4 are applicable to calculations of current demands of flooded compartments and of closed compartments with free access to air.

6.4.9 The constants in Table 10-4 do not account for significant damage to paint coatings during fabrication and installation. If such damage is anticipated, the affected surface area is to be estimated and included in the design calculations as bare metal surface.

6.5 Galvanic Anode Material Design Parameters

6.5.1 Unless otherwise specified or accepted by Owner, the compositional limits for alloying and impurity elements for Al and Zn-based anodes in Table 10-5 shall apply. 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), and design closed circuit anode potential, E_a^0 (V) are used to calculate

- 1) the design anode current output and
- 2) the required net anode mass using Ohm’s and Faraday’s laws, respectively.

6.5.2 The design values for electrochemical capacity, ε (Ah /kg), in Table 10-6 of Annex A shall be used for design unless otherwise specified by Owner. The data are applicable for ambient temperature seawater (i.e. up to 30°C as a yearly mean value).

Guidance note:

It is DNV's strong recommendation that the inherent conservatism of using the default values in Table 10-6 shall be utilised for design, also if an anode manufacturer claims that his product is capable to achieve 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. $\geq 2,500$ Ah/kg for Al-Zn-In material). This is due to the relatively high anodic current densities that are utilized for testing. Such data shall not replace the recommended design values for electrochemical capacity. Even long term testing according to Annex C 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. When using anode manufacturer's testing data for design, it should further be ensured that the composition of alloying and impurity elements of the material tested and the casting conditions are representative for normal, and preferably also "worst case" production (see 12.2.2 of Annex C).

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6.5.3 The design values for closed circuit anode potential, E_a^o (V), in Table 10-6 of Annex A shall be used for design. The data are applicable for all ambient seawater temperatures (i.e. max 30°C yearly average).

Guidance note:

Higher anode temperatures may apply if anodes are heated by an internal medium and buried in seabed sediments and the data in Table 10-6 are then not applicable. However, such conditions are only relevant for CP of pipelines which is not covered by this document.

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6.6 Anode Resistance Formulas

6.6.1 Unless otherwise agreed, the anode resistance, R_a (ohm), shall be calculated using the formula in Table 10-7 of Annex A 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 utilisation factor (7.8).

6.7 Seawater and Sediment Resistivity

6.7.1 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 Fig. 10-1 of Annex A.

6.7.2 In shore 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.

6.7.3 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 shall be assumed for calculation of the resistance of any buried anodes.

6.7.4 In temperate regions (annual average surface water temperature 7 to 12°C), resistivities of 0.30 and 1.3 ohm·m are recommended as reasonably conservative estimates for the calculation of anode resistance in seawater and marine sediments, respectively, and independent of depth. Lower values are to be documented by actual measurements, taking into account any seasonal variations in temperature.

6.8 Anode Utilization Factor

6.8.1 The anode utilisation factor, u , is the fraction of anode material of an anode with a specific design that may be utilised for calculation of the net anode mass required to sustain protection throughout the design life of a CP system (see 7.7.1). When an anode is consumed to its utilisation factor, the polarizing capacity (as determined by the anode current output) becomes unpredictable due to loss of support of anode material, or rapid increase of anode resistance due to other factors (see 7.9)

6.8.2 The utilisation factor is dependant on the anode design, particularly its dimensions and the location of anode cores (7.10.4). Unless otherwise agreed, the anode utilisation factors in Table 10-8 of Annex A shall be used for design calculations.

6.9 Current Drain Design Parameters

6.9.1 The design current densities and coating breakdown factors in 6.3 and 6.4, respectively, are applicable for calculation of 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.

6.9.2 For buried surfaces of mud mats, skirts and piles, a current drain (i.e. 0.020 A/m^2 in accordance with 6.3.8) 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. Internal surfaces of piles filled with sediments do not have to be included.

6.9.3 Unless otherwise specified or accepted by Owner, a current drain of 5 A per well casing shall be included in current drain calculations.

Guidance note:

Casings for subsea wells are typically cemented which reduces the current drain compared to platform wells which are normally not cemented. However, subsea wells may become exposed to significant current drain by e.g. installation and work-over equipment during subsea installations and interventions.

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6.9.4 Current drain to anchor chains shall be accounted for by 30 m of chain for systems with mooring point topside only. For systems with mooring point below the water level, the seawater exposed section above this point shall also be included. A current drain of 30 m of chain shall also be included for CP of anchoring arrangements using chains. For any current drain to the steel armouring of flexible pipelines, 0.0005 A/m^2 (based on the external pipe surface) is recommended.

7. CP Calculation and Design Procedures

7.1 General

7.1.1 For large protection objects such as platform sub-structures, the detailed design of a CP system is normally preceded by a conceptual design activity. During this conceptual design, 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 would 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 Purchaser in some other reference document(s) to be included in an inquiry for CP detailed design.

7.1.2 Besides any reference to this RP in a 'purchase document' (see 1.3), the following information and any optional requirements (intended as a check-list) shall be provided by Purchaser:

Information:

- conceptual CP design report, if completed (7.1.1)
- design life of CP system to be installed (6.2)
- relevant information from the project design basis (7.1.1); e.g. salinity and temperature as a function of depth for calculation of anode resistance, location of seawater level and mud line for platform substructures, environmental and installation parameters affecting forces exerted on anodes
- structural drawings and information of coating systems as required for calculation of surface areas to be protected, including components which may exert temporary or permanent current drain (7.1.3)
- identification of any interfaces to electrically connected components/systems with self-sufficient CP systems, e.g. pipelines.

Requirements (optional):

- requirements to documentation and 3rd party verification, including schedule for supply (7.13)
- any specific requirement to CP design parameters to be applied, e.g. coating breakdown factors (6.4.3) and current drain to wells (6.9.3)
- any specific requirements to anode material (6.5) and anode design (7.6)
- any further amendments and deviations to this RP applicable to CP design.

7.1.3 Purchaser shall ensure that valid revisions of drawings and specifications affecting calculation of current demand for CP and location of anodes are available to Contractor during the design work. It shall be ensured that all necessary information is provided for Contractor to calculate the overall current demand, e.g. conductors for production platform sub-structures and production control system for subsea valve trees.

7.1.4 The CP calculation procedure in this 2004 revision is the same as in the 1993 issue of this RP and revisions in the text are primarily for clarification. However, a note on the use of anodes with large difference in size has been added in 7.8.6.

7.2 Subdivision of CP Object

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

7.2.2 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.

7.3 Surface Area Calculations

7.3.1 For each CP unit (7.2), surface areas to receive CP shall be calculated separately for surfaces with and without a coating system (see Coating Categories in 6.4.6) and for surfaces affected by other parameters (e.g. surface temperature) which influence the CP current demand.

7.3.2 It is practical to apply some simplification when calculating surface areas for 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.

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7.3.3 Surface area calculations for each unit shall be documented in the CP design report. Reference shall be made to drawings, including revision numbers.

7.3.4 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 design (6.4.6).

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7.4 Current Demand Calculations

7.4.1 To calculate the current demand, I_c (A), to provide adequate polarizing capacity (6.3.1-6.3.4) and to maintain cathodic protection during the design life (6.3.5), the individual surface areas, A_c (m²), of each CP unit shall be calculated according to (7.2) and multiplied by the relevant design current density, i_c (A/m²), and the coating breakdown factor, f_c , if applicable:

$$I_c = A_c \cdot i_c \cdot f_c \quad (1)$$

i_c and f_c are then to be selected according to (6.3) and (6.4), respectively.

7.4.2 For items with major surfaces of uncoated metal, the CP current demands for both initial polarization and for 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 can be deleted in the design calculations. For future reference, all calculated data shall be documented in the design report.

7.5 Current Drain Calculations

7.5.1 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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7.5.2 Calculations of current drain shall use the design current densities (6.3) and coating breakdown factors (6.4) for items requiring CP. Calculations of surface areas and current demands shall be carried out according to (7.3) and (7.4), respectively.

7.5.3 For calculation of current drain to mud mats, skirts, piles, well casings and steel anchor chains, see 6.9.2, 6.9.3 and 6.9.4.

7.6 Selection of Anode Type

7.6.1 For certain structures, anode types (i.e. stand-off, flush mounted or bracelet anodes) may be specified by Owner/Purchaser, taking into account effects of e.g. sea current drag and interference with subsea interventions (7.1).

7.6.2 If anode type has not been specified by Owner/Purchaser, then Contractor shall select anode type taking into account e.g. net anode mass to be installed and available space for location of anodes. Selection of 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 utilisation factor and the anode current output in relation to weight. (For general considerations of anode type selection, see 5.7).

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 utilisation factor.

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7.7 Anode Mass Calculations

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

$$M_a = \frac{I_{cm} \cdot t_f \cdot 8760}{u \cdot \varepsilon} \quad (2)$$

In (2), 8760 refers to hours per year. u and ε (Ah/kg) are to be selected based on (6.8) and (6.5), respectively.

7.8 Calculation of Number of Anodes

7.8.1 From the anode type selected (7.6), 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_{ci}/I_{cf} (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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7.8.2 The individual anode current output, I_a (A), required to meet the current demand, I_c (A), is calculated from Ohm's law:

$$I_c = N \cdot I_a = \frac{N(E_c^\circ - E_a^\circ)}{R_a} = \frac{N \cdot \Delta E^\circ}{R_a} \quad (3)$$

where E_a° (V) is the design closed circuit potential of the anode material (6.5) and R_a (ohm) is the anode resistance (6.6). The initial and final current output, I_{ai} and I_{af} , are to be calculated using the initial and final anode resistance, R_{ai} and R_{af} , respectively. For calculation of anode resistance, see 7.9. E_c° (V) is the design protective potential which is - 0.80 V (5.4). ΔE° (V) is termed the design driving voltage.

Guidance note:

As the design driving voltage in (3) is defined using the design protective potential for C-steel, the initial/final design current densities that define the anode current output capacity, and hence the driving voltage, refer to the required anode current output at this potential. Hence, the initial/final design current densities given in Table 10-3 are based on a protection potential of - 0.80 V. This means that they shall always be used for calculations according to (3) in combination with this potential, also if a more negative protection potential (e.g. $\leq - 0.90$ V) is aimed for, see 6.3.

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

$$C_a = m_a \cdot \varepsilon \cdot u \quad (4)$$

where m_a (kg) is the net mass per anode. The total current capacity for a CP unit with N anodes thus becomes $N \cdot C_a$ (A·h)

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

$$C_{a \text{ tot}} = N \cdot C_a \geq I_{cm} \cdot t_f \cdot 8760 \quad (5)$$

$$I_{a \text{ tot i}} = N \cdot I_{ai} \geq I_{ci} \quad (6)$$

$$I_{a \text{ tot f}} = N \cdot I_{af} \geq I_{cf} \quad (7)$$

$C_{a \text{ tot}}$ in (5) is the total anode current capacity. $I_{cm}/I_{ci}/I_{cf}$ in (5, 6, 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 (6) and (7) are the initial and final current output for the individual anodes.

Guidance note:

If anodes with different size and hence, anode current capacity, C_a (Ah), and current output, I_a (A), are utilised for a CP unit,

$N \cdot C_a$ and $N \cdot I_{ai}/N \cdot I_{af}$ will have to be calculated for each individual size and then added for calculation of the total anode current capacity ($C_{a \text{ tot}}$) and total anode current output

($I_{a \text{ tot i}}/I_{a \text{ tot f}}$).

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7.8.5 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:

Optimising the requirements in (5), (6) and (7) is an iterative process where a simple computer spreadsheet may be helpful. In general, if (5) is fulfilled, but not (6) and/or (7), a higher number of smaller anodes, or the same number of more elongated anodes are to be used. On the other hand, if $N \cdot I_a$ in (6, 7) is much larger than I_{ci} and I_{cf} , fewer and/or more compact anodes may be applied.

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7.8.6 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 will be more rapidly consumed than large anodes with a higher 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, ref. 7.2.1) the highest anode current output to net anode mass ratio should not exceed that of any other anode by more than 50 %. For all anodes to be utilised for the full design life, the ratio between net anode mass (kg) and design life (yrs) should be minimum 0.5 and 1.0 for Al-based and Zn-based anodes, respectively.

Guidance note:

For anodes with 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 will be consumed first. Similarly, for anodes with the same net anode mass but with major difference in anode resistance and hence, anode current output, the anode with the lowest anode resistance will be consumed first.

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7.9 Calculation of Anode Resistance

7.9.1 The anode resistance, R_a (ohm), to be used in (3) shall be based on the applicable formulas in Table 10-7 of Annex A, using the actual anode dimensions and specific resistivity of the surrounding environment. Specific resistivities of the surrounding environment shall be selected according to (6.7).

7.9.2 To calculate the initial anode resistance, R_{ai} (ohm), the initial anode dimensions are inserted in the relevant anode resistance formula in Table 10-7. The final anode resistance, R_{af} (ohm), is calculated based on the expected dimensions when the anode has been consumed to its utilisation factor, u , (see 6.8) as explained below.

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

$$m_{af} = m_{ai} \cdot (1 - u) \quad (8)$$

The final volume of the anode to be used for calculation of R_{af} can be calculated from the remaining net anode mass, m_{af} (kg), specific density of anode material and the 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.

7.9.4 For long and short slender stand-off anodes consumed to their utilisation 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 (7.9.3).

7.9.5 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 above.

7.9.6 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.

7.10 Anode Design

7.10.1 Contractor shall specify in CP design report tentative dimensions and/or net mass for anodes to be used.

7.10.2 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.

7.10.3 For use of the anode resistance formula in Table 10-7 for stand-off type anodes, the minimum distance from anode to protection object shall be minimum 300 mm. However, for distances down to 150 mm, the formula can still be used by multiplying the anode resistance with a factor of 1.3.

7.10.4 The detailed anode design shall ensure that the utilisation factor assumed during calculations of required anode net mass according to 7.7 is met. Hence, it shall be ensured that the anode inserts are still likely to support the remaining anode material when the anode has been consumed to its design utilisation factor. Unless otherwise agreed, anode cores of stand-off type anodes shall protrude through the end faces.

7.10.5 With the exception of stand-off type anodes, a marine grade paint coating (min. 100 μm DFT) shall be specified for anode surfaces facing the protection object.

7.11 Distribution of Anodes

7.11.1 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.

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

7.11.3 Anodes should be located with sufficient spacing between each other to avoid interaction effects that reduce the useful current output. As far as practical, anodes shall be located so that those of its surfaces intended for current output are not in close proximity to structural members, reducing the current output.

Guidance note:

With the exception of very large anodes, shielding and interference effects become insignificant at a distance of about 0.5 meter or more. If anodes are suspected to interfere, a conservative approach may be to consider two adjacent anodes as one long anode, or as one wide anode, depending on their location in relation to each other.

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7.11.4 No anodes shall be located for welding 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.

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

7.12 Provisions for Electrical Continuity

7.12.1 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 coating.

7.12.2 For anodes attached to the protection object by other means than welding, and for components of a CP unit without a reliable electrical connection as defined above, electrical continuity shall be ensured by a stranded cable (typically copper). Cables for electrical continuity shall have a minimum cross section of 16 mm² and are to 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. Any cable shoes shall have

a brazed connection to the cable. Use of cable connections apply both for any anodes attached to the protection object by means other than welding and to individual components to receive CP, but without a reliable electrical connection to the CP unit as defined in (7.12.1).

7.12.3 If the CP design includes use of cables for electrical continuity, requirements to verification of electrical continuity shall be specified in the CP design report. It is recommended that the product of the connection resistance and the current demand (or current output for a non-welded anode) does not exceed 10% of the design driving voltage. In no case shall the resistance across a continuity cable exceed 0.1 ohm.

7.12.4 For anodes intended for cathodic protection of concrete rebar, special provisions are required to ensure electrical continuity.

7.13 Documentation

7.13.1 The detailed engineering documentation ('CP detailed design report') shall contain the following items:

- Design premises
(incl. reference to all relevant project specifications, codes and standards)
- Surface area calculations
(incl. reference to all relevant drawings, incl. revision numbers)
- Current demand calculations
(initial/final and mean)
- Current drain calculations (if applicable),
(initial/final and mean)
- Calculations of minimum required net anode mass
- Anode resistance calculations
(initial and/or final, as relevant)
- Calculations of minimum number of anodes required
(incl. anode current output and anode capacity for initial and final life of system)
- Calculation of net anode mass based on required number of anodes (if higher than required net anode mass)
- Calculation of total current output based on number and type/size of anodes to be installed
- Tentative anode design (incl. any special provisions for structural integrity and electrical continuity. Any requirement for utilisation factors higher than the default values in Table 10-8 shall be highlighted)
- Anode distribution drawings
- Provisions for electrical continuity, including verification by testing (if applicable).

7.13.2 For a conceptual CP design report, the scope shall be agreed.

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

8. Anode Manufacture

8.1 General

8.1.1 This section covers the manufacture of galvanic anodes, including preparation of anode cores prior to casting. The requirements in this section comply with those in NACE RP0387, giving some amendments, primary related to quality control.

8.1.2 Besides any reference to this RP in a 'purchase document' (see 1.3.1), the following information and any optional requirements (intended as a check-list) shall be enclosed by Purchaser:

Information:

- anode material type (i.e. aluminium or zinc-base) and any special requirements to chemical composition (i.e. other than specified in 6.5.1) and to qualification of anode material (5.6.3)
- tentative anode dimensions and net anode mass for each anode type and any special requirements to anode fastening devices (7.10)

Requirements (optional):

- any special requirements for anode utilisation factor (6.8)
- any special requirements for pre-production qualification testing (PQT), including schedule for notification and supply of documentation (8.3.2-8.3.4)
- any special requirements for 'manufacturing procedure specification' (MPS) (8.2) or 'inspection and testing plan' (ITP) (8.4.2), including schedule for supply of documentation.
- any special requirements for frequency of dimensional testing (8.6.2), destructive testing (8.6.5) and electrochemical testing (8.6.6) during production
- any specific requirements for Contractor's management of non-conformities (8.6.10) and concession

- requests (8.5.6)
- any reduced requirements for traceability (8.5.1, 8.5.10)
- any requirements for retaining of anode material specimens (8.6.1)
- any special requirements for marking of anodes (8.7.1)
- any special requirements for handling, storage and shipping of anodes (8.8.1)
- any special requirements for final documentation, including schedule for supply (8.7.4)
- any further amendments and deviations to this RP.

8.1.3 Unless otherwise agreed, electrochemical testing of galvanic anode materials for quality control shall be carried out according to Annex B. The testing procedure for documentation of long-term performance in Annex C is, however, non-mandatory and shall be specified by Purchaser in the purchase document, if applicable.

8.1.4 Compared to the 1993 revision of this RP, the requirements to quality control associated with anode manufacture, both mandatory and optional to Purchaser, have been extended.

8.2 Manufacturing Procedure Specification

8.2.1 Unless otherwise agreed, a ‘manufacturing procedure specification’ (MPS) shall be prepared for purchase orders of 15,000 kg net alloy or more. However, 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 comment below in this paragraph)
- welding procedure specification and reference to 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 protection object (not 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 utilisation factor as specified in Table 10-8, or any less conservative (i.e. higher) factor specified by Purchaser.

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

8.3 Pre-Production Qualification Testing

8.3.1 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.

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

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

8.3.4 An MPS and an ‘inspection and test plan’ (ITP, see 8.4.2) specific for the PQT, together with a detailed schedule for anode casting, inspection and/or testing, and reporting shall be submitted to Purchaser in a timely manner (as per the purchase document) prior to start-up of the qualification activities.

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

8.3.6 Results from all inspection, testing 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 Purchaser prior to start of production.

8.4 Quality Control of Production

8.4.1 Prior to 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 8.2.1), Contractor shall submit the following documents to Purchaser for acceptance:

- a project specific MPS, updated to reflect the process parameters used during the completed and accepted PQT (8.3)
- a project specific ‘inspection and testing plan’ (ITP) updated to reflect the process parameters used during the completed and accepted PQT
- a ‘daily log’ format (see 8.6.11)
- a description of responsibilities of personnel involved in quality control.

8.4.2 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 receipt of materials, preparation of anode cores, 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, 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 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.

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

8.4.4 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.

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

8.5 Materials, Fabrication of Anode Inserts and Casting of Anodes

8.5.1 Anode insert materials shall meet all requirements in NACE RP0387 and unless otherwise agreed, inserts for welding to the protection object shall be traceable to a certificate according to EN 10204, 3.1.B or ISO 10474, 5.1.B.

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

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

- manufacturer’s name and location of manufacture
- material type and product designation
- batch/lot number
- date of manufacturing (and shelf life, if applicable)
- manufacture standard (if applicable)
- instruction for storage and handling (including health and safety notes).

8.5.4 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. Supplier’s recommendations for storage and use shall be readily available for Purchaser’s review.

8.5.5 All fabrication welding of steel inserts and surface preparation before casting shall meet the requirements in NACE RP0387 and shall be subject to visual inspection just prior to casting.

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

8.5.7 Equipment for monitoring of process parameters critical to quality (e.g. temperature sensors) shall be calibrated at scheduled intervals as specified in the ITP.

8.5.8 No heat treatment is allowed for galvanic anodes of zinc or aluminium-zinc-indium type.

8.5.9 Coating of flush mounted type anodes shall be applied according to a coating procedure and after visual

inspection for surface defects has been completed.

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

8.6 Inspection and Testing of Anodes

8.6.1 Sampling for chemical analyses shall be carried out according to NACE RP0387 and for each ‘anode heat’ (i.e. after all alloying and homogenisation 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 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. Purchaser shall have the right to require anode sample material for verification testing in an independent laboratory, or to present samples for testing by Purchaser. Purchaser may further specify that 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.

8.6.2 Verification of anode weight and dimensions shall be carried out with the frequency and acceptance criteria specified in NACE RP0387. Positions of protruding inserts shall comply with tolerances in manufacturer’s drawing and shall be checked for a minimum of 10% of the anodes of a specific design. Purchaser may specify extended inspection of anode dimensional tolerances.

8.6.3 Inspection for cracks and other surface irregularities shall be carried out on all anodes with the acceptance criteria as specified in NACE RP0387, 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 accepted
- within the section fully supported by anode inserts, cracks of a width greater than 2 mm are only accepted if the length is maximum 100 mm.

8.6.4 Any coating applied shall be visually inspected on all anodes concerned. Spill of coating on surfaces not intended for coating shall be removed.

8.6.5 Unless otherwise agreed, a minimum of two anodes of each size shall be subject to destructive testing to verify absence of internal defects and adequate location of anode inserts. The cutting procedure and acceptance criteria in NACE RP0387 shall apply. Such testing shall be carried out as a part of the PQT, if applicable. If no PQT is to be performed, testing should be carried out during the first day of production. Owner/purchaser shall have the right to select anodes for testing. Any batchwise destructive testing of anodes during production shall be specified in the purchase order.

8.6.6 As a minimum, electrochemical testing shall be performed as a 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 production. Owner/purchaser may specify extended testing and/or 3rd party testing.

8.6.7 When electrochemical testing applies, sampling for testing shall be carried out for each heat produced, ref. 11.2.1, Annex B. (For definition of heat, see 8.6.1). Unless otherwise agreed, the testing shall be carried out according to the procedure in Annex B and the following acceptance criteria shall apply:

Aluminium based anodes:

electrochemical capacity: minimum 2,500 Ah/kg,
closed circuit potential: ≤ -1.05 V at 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.

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

8.6.9 In case of failure during fractional testing of other properties 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.

8.6.10 In case of repeated failures to meet specified properties (i.e. other than electrochemical performance), production shall be discontinued and Contractor shall issue a ‘non-conformance report’ and the cause of the failure shall be determined. Non-conforming anodes (individual or lots) shall be marked and quarantined. For failures during electrochemical testing, see 11.4.3, Annex B.

8.6.11 All data from 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 (8.7.2). The log shall be updated on a daily basis and shall be available for Purchaser’s review at any time during manufacture.

8.7 Documentation and Marking

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

8.7.2 All results from inspection and testing during PQT (if applicable) and production shall be documented and shall be traceable to a unique anode number (or batch of anodes, as applicable), certificates for anode core materials and coating materials, if applicable. For specific requirements to a ‘daily log’, see 8.6.11.

8.7.3 Contractor shall issue an inspection document according to EN 10204 or ISO 10474, inspection certificate 3.1.B.

8.7.4 Purchaser may specify requirements to final documentation, additional to those in NACE RP0387; e.g. documentation to be supplied to Purchaser (including format and schedule) and Contractor’s retaining of documentation exceeding 2 years (minimum requirement in NACE RP0387).

8.8 Handling, Storage and Shipping of Anodes

8.8.1 Any additional requirements to those in NACE RP0387 shall be specified in the purchase document.

9. Installation of Anodes

9.1 General

9.1.1 Installation of galvanic anodes on offshore structures will normally involve welding and sometimes also clamping of anode supports to structural steel components. In the latter case, electrical continuity is typically provided by a copper cable, attached to the anode support and the protection object by brazing, or by some special mechanical connection designed to ensure a reliable electrical continuity. Electrical continuity cables may also be installed to provide electrical continuity to components of a CP unit without reliable electrical connection to anodes by welds, metallic seals or threaded couplings. The design requirements for such connections in 7.12 shall apply.

9.1.2 Considerations of the mechanical integrity of anode fastening devices during 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 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.

9.1.3 Besides any reference to this RP in a ‘purchase document’ (see 1.3.1), the following information and any optional requirements (intended as a check-list) shall be enclosed by Purchaser:

Information:

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

Requirements (optional):

- any requirement for preparation of an IPS (9.2)
- any special requirements for documentation (9.7.2)
- any further amendments to and deviations from this RP.

9.2 Installation Procedure Specification

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

- specification of 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.

9.3 Qualification of installation

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

9.4 Receipt and Handling of Anodes

9.4.1 All anodes supplied by Purchaser shall be inspected by Contractor to confirm compliance with anode drawings and to confirm no significant damage or other adverse effects. Non-conforming anodes and other materials shall be quarantined.

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

9.5 Anode Installation and Provisions for Electrical Continuity

9.5.1 Installation of anodes shall be carried out according to drawings approved for construction, showing 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.

9.5.2 Any significant changes of anode installation from approved drawings shall be approved by Purchaser. However, for ease of installation, stand-off anodes to be mounted on structural components may be displaced laterally not more than one anode length and circumferentially max. 30°.

9.5.3 For welding of 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.

9.5.4 Installed anodes shall be adequately protected during any subsequent coating work. Any spill of coating on anodes shall be removed. For coated objects, exposed anode cores shall be coated to the same standard.

9.6 Inspection of Anode Installation

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

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

9.6.3 For brazed and mechanical connections for electrical continuity, measurements shall be carried out according to a documented procedure and with an instrument capable of verifying an electrical resistance of 0.1 ohm maximum.

9.7 Documentation

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

9.7.2 Measurements for verification of electrical continuity shall be documented.

9.7.3 Purchaser may specify further requirements to the anode installation documentation.

10. Annex A – Tables and Figures

10.1 Tables and Figures

Table 10-1 Recommended initial and final design current densities (A/m²) for seawater exposed bare metal surfaces, as a function of depth and ‘climatic region’ based on surface water temperature (ref. 6.3).

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 10-2 Recommended mean design current densities (A/m²) for seawater exposed bare metal surfaces, as a function of depth and ‘climatic region’ based on surface water temperature (ref. 6.3).

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 10-3 Recommended mean design current densities for protection of reinforcing steel (i.e. in concrete structures) as a function of depth and ‘climatic region’ based on surface water temperature (ref. 6.3.12). The current densities in A/m² refer to the steel reinforcement surface area, not surface area of concrete.

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

Table 10-4 Recommended constants a and b for calculation of paint coating breakdown factors. (Coating Categories are defined in 6.4.6).

Depth (m)	Recommended a and b values for Coating Categories I, II and III (see 6.4.7)		
	I (a = 0.10)	II (a = 0.05)	III (a = 0.02)
0-30	b = 0.10	b = 0.025	b = 0.012
>30	b = 0.05	b = 0.015	b = 0.008

Table 10-5 Recommended compositional limits for Al-based and Zn-based anode materials (ref. 6.5).

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	≤ 0.07	≤ 0.002
Si	na	≤ 0.12
Fe	≤ 0.005	≤ 0.09
Cu	≤ 0.005	≤ 0.003
Pb	≤ 0.006	na

<i>Anode Material Type</i>	<i>Environment</i>	<i>Electrochemical Capacity (Ah/kg)</i>	<i>Closed Circuit Potential (V)</i>
Al-based	seawater	2,000	-1.05
	sediments	1,500	-0.95
Zn-based	seawater	780	-1.00
	sediments	700	-0.95

<i>Anode Type</i>	<i>Resistance Formula</i>
Long slender stand-off ^{1) 2)} $L \geq 4r$	$R_a = \frac{\rho}{2 \cdot \pi \cdot L} \left(\ln \frac{4 \cdot L}{r} - 1 \right)$
Short slender stand-off ^{1) 2)} $L < 4r$	$R_a = \frac{\rho}{2 \cdot \pi \cdot L} \left[\ln \left\{ \frac{2L}{r} \left(1 + \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right) \right\} + \frac{r}{2L} - \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right]$
Long flush mounted ²⁾ $L \geq 4 \cdot \text{width}$ and $L \geq 4 \cdot \text{thickness}$	$R_a = \frac{\rho}{2 \cdot S}$
Short flush-mounted, bracelet and other types	$R_a = \frac{0.315 \cdot \rho}{\sqrt{A}}$
<p>1) The equation is valid for anodes with minimum distance 0.30 m from protection object. For anode-to-object distance less than 0.30 m but minimum 0.15 m the same equation may be applied with a correction factor of 1.3</p> <p>2) For non-cylindrical anodes: $r = c / 2 \pi$ where c (m) is the anode cross sectional periphery</p>	

<i>Anode Type</i>	<i>Anode Utilisation Factor</i>
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

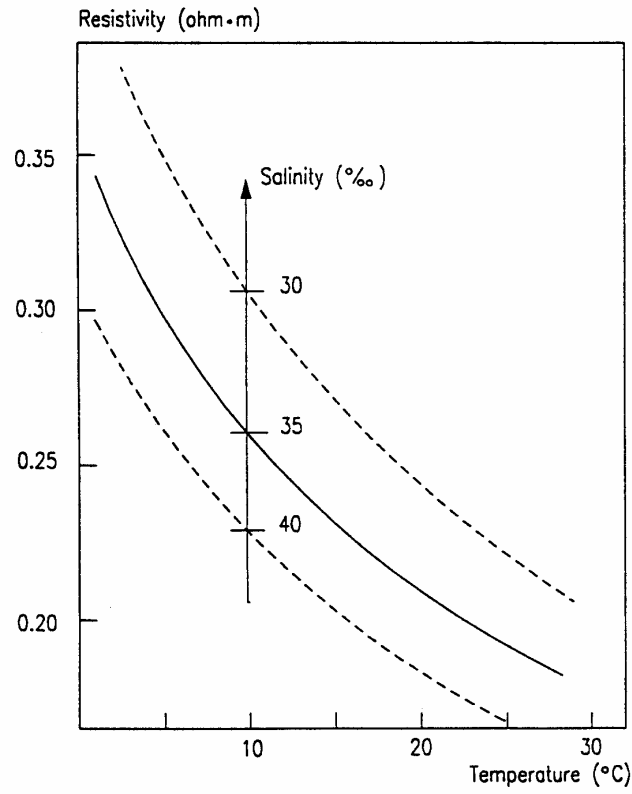


Figure 10-1
Seawater resistivity as a function of temperature for salinity 30 to 40 ‰.

11. Annex B – Laboratory Testing of Galvanic Anode Materials for Quality Control

11.1 General

11.1.1 This laboratory test procedure is intended for quality control of Al-base and Zn-base anode materials during manufacture of galvanic anodes. In this Annex, the definitions of Owner, Purchaser and Contractor (i.e. anode manufacturer) in 3.1 apply.

Guidance note:

The results from 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.

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11.1.2 The testing shall be performed according to a detailed procedure describing all relevant steps. For testing at the premises of Contractor, Owner/Purchaser shall have the right to witness the testing.

11.1.3 All requirements of this procedure shall be considered as mandatory, unless deviations have been agreed, see 8.1.3. Owner/Purchaser may, however, choose to specify an alternative test procedure.

11.1.4 Compared to the 1993 revision of this document, some amendments have been made, primarily regarding sampling of testing material. Moreover, a detailed testing procedure is required for quality control purposes. Use of 3 % NaCl solution as alternative to natural or synthetic seawater is not allowed in the 2004 revision. Acceptance criteria have further been included in 8.6.6. Other revisions are for clarification or simplification only.

11.2 Sampling and Preparation of Test Specimens.

11.2.1 Unless otherwise specified, 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 retainment of samples, see 8.6.1. Owner/Purchaser shall have the right to select sample for testing, e.g. based on a review of 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 for 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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11.2.2 Cylindrical test specimens with a diameter of 10 mm ± 1 mm and a length of 50 mm ± 5 mm shall be prepared by machining of samples. A hole of about 2 mm 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, dried and weighed to an accuracy of ± 0.1 mg

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

11.3 Equipment and Experimental Procedure

11.3.1 After mounting of 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.

11.3.2 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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11.3.3 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.

11.3.4 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 cm², approximately. The general arrangement is shown in Fig. 11-1

11.3.5 Galvanostatic control shall be affected by means of a DC constant current source, capable of controlling the current according to 11.3.7 below. The specimen and the cathode shall be coupled to the positive and negative rectifier terminals, respectively. Multiple testing cells may be connected in series to one DC source.

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

11.3.7 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/cm²

Day 2: 0.4 mA/cm²

Day 3: 4.0 mA/cm²

Day 4: 1.5 mA/cm²

The current density shall be controlled to an accuracy of 0.1 mA/cm² and shall be maintained for a period of 24 hours \pm 1 hour. The total testing time shall be 96 hours \pm 4 hours.

11.3.8 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 or calomel) 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, however, without disturbing any corrosion products formed on the anode specimen. Reference electrodes shall be calibrated at intervals not exceeding one week. Potential recordings using a reference electrode other than 'Ag/AgCl/seawater' (e.g. a SCE) shall be converted to this reference.

11.3.9 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.

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

$$\varepsilon = (C \cdot 1000) / \Delta w$$

where C is the total current charge in Ah and Δw is the weight loss in grams.

11.4 Acceptance Criteria and Re-Testing

11.4.1 The acceptance criteria in 8.6.7 apply.

11.4.2 Failures during testing which are obviously due to operational errors may be disregarded and testing repeated on a new specimen of the same sample (ref. 8.6.8) or a specimen cut from an anode of the same heat.

11.4.3 In the case of failure to meet the specified requirements, 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.

11.5 Documentation

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

11.5.2 All recorded potentials (i.e. 3 per specimen) shall be presented in tabular form, as-recorded and converted to Ag/AgCl/seawater, if applicable. 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.

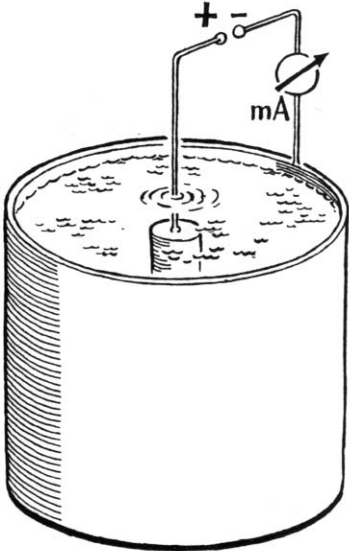


Figure 11-1
General arrangement for quality control testing of galvanic anode materials

12. Annex C – Laboratory Testing of Galvanic Anode Materials for Qualification of Electrochemical Performance

12.1 General

12.1.1 This Annex gives a recommended procedure for documentation of the electrochemical performance of galvanic anode materials in natural seawater of ambient temperature. (The procedure can 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.

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

12.1.3 Testing according to this procedure is non-mandatory and shall be specified by Purchaser, see 8.1.3. Modifications of the test parameters may be agreed.

12.1.4 Compared to the 1993 revision of this document, some amendments have been made, primarily regarding sampling of testing material. The recommended size of the testing specimen has further been increased as experience has shown that the specimen may become consumed before a test period of 12 months has been completed. Some further amendments are made in 12.2.3 and 12.3.5. Other revisions are for clarification or simplification only.

12.2 Sampling and Preparation of Test Specimens.

12.2.1 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 for 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 for larger anodes.

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12.2.2 The chemical composition of the anode(s) to be used for documentation shall reflect the compositional limits that shall apply during manufacturer's normal production (see 6.5.2). This will normally require preparation of a special heat, combining 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.

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12.2.3 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 2 mm 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, dried and weighed to an accuracy of ± 0.1 mg

12.2.4 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.

12.3 Equipment and Experimental Procedure

12.3.1 After mounting of 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.

12.3.2 The testing environment shall be clean natural seawater with salinity ≥ 30 ‰. Temperature may be allowed to vary in the range $+7^{\circ}\text{C}$ to $+20^{\circ}\text{C}$. Temperature and salinity of seawater shall be recorded at least once per week.

The test shall be configured as outlined in Annex B, 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:

Variations in seawater temperature 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 anodes may require documentation of anode materials' performance at such temperatures.

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

Guidance note:

'Free-running', implies 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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12.3.4 With galvanostatic control, the anodic current density shall be maximum 1 mA/cm² based on the initial exposed anode surface area. The integrated current (i.e. for minimum 12 months) may be determined as for 11.3.6 in Annex B but manual readings minimum once per day and 5 days per week for the first two weeks, thereafter once per week, will suffice. Recordings of anode potential (see 11.3.8, Annex B) shall be performed with a minimum frequency as for manual current readings.

12.3.5 For a free-running test, the anode and cathode shall be connected over a 10 ohm ± 1 ohm precision resistance (Actual resistance 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 anode potential, cathode potential and cell current shall be carried out at maximum intervals as specified above.

12.3.6 Reference electrodes used for recordings of anode potential shall be calibrated at regular intervals (minimum once per month). After completed test, the specimens shall be cleaned and the electrochemical efficiency calculated as in 11.3.9 and 11.3.10, Annex B.

12.4 Documentation

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

12.4.2 Average, and maximum/minimum salinity and temperature of seawater shall be reported.

12.4.3 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 original exposed surface area) and the cathode potential shall also be given in graphical form.

12.4.4 Data from measurements of anode weight loss shall be included in the report in addition to the calculated electrochemical efficiency (in Ah/kg). 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 minimum 2,250 Ah/kg are considered adequate to verify the performance of an Al-based material tested and justifies the use of the default values in Table 10-6' (see Guidance note to 6.5.2).

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