Cathodic Protection of Jack-up Rigs

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Abstract:

This study is based on standards/codes, available literature, and practical service experiences with cathodic protection (CP) on offshore jack-up structures as response to increasing interest in prevention of hydrogen related cracking in welds of high strength steel

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1 Summary

Hydrogen-related cracks in jack-up rigs were first observed in the UK sector in 1988. In 2022, Ptil was notified of relatively long hydrogen cracks located in the welds connecting the spudcan to the chords. Common causes for the cracking were a combination of fabrication-related flaws propagating as cracks during service under influence of weld residual stresses and service loads, and ingress of hydrogen into the steel due to cathodic protection (CP).

The present study is a follow-up of a previous report prepared for Havtil (then Petroleumstilsynet), "Hydrogen assisted cracking of jack-up installations" [1], and is based on available literature and practical service experiences with cathodic protection (CP) of jack-up rig installations.

The main conclusions from the present study are:

- Although steps can be taken in CP design to reduce the risk of hydrogen embrittlement/HISC, controlling potentials in a range close to the protection potential limit for steel in a corrosive environment is regarded as challenging.
- Strategies for control of potential involving anodes with low driving voltage or diode-controlled anodes will require that interaction with conventional CP systems (based on Al-Zn-In anodes) will have to be carefully considered in the design phase. Electrical isolation between jack-up rig and adjacent structures/pipelines will likely be required.
- Monitoring of potentials in critical areas after installation and during operation will be required.
- CP modelling is a versatile and indispensable tool in the CP design for jack-up rigs where risk of hydrogen embrittlement/HISC is identified.

The following recommendations from the previous study [1] are still regarded as relevant to reduce the risk of hydrogen embrittlement/HISC:

  - Select materials that ensure a low intrinsic susceptibility to hydrogen embrittlement, demonstrated by testing under relevant conditions. For testing under simulated (laboratory) conditions, the relevance for offshore conditions should be demonstrated.
  - Select of weld procedures, QA/QC programs and NDT methods appropriate to preventing weld flaws and other imperfections to remain undetected. For recommendations regarding areas to be inspected and relevant methods for detection of defects from fabrication, reference is made to Ref. [2].

2 Abbreviations and definitions

ABS	American Bureau of Shipping
AVG	Average
CA	Corrosion Allowance
CEN	Comité European de Normalization (European Committee for Standardization)
CF	Corrosion Fatigue
CP	Cathodic protection
CRA	Corrosion Resistant Alloy
CTOD	Crack Tip Opening Displacement
DCB	Double Cantilever Beam
DNV	Det Norske Veritas
FSA	Flame Sprayed Aluminium
GACP	Galvanic Anode Cathodic Protection Also known as SACP (Sacrificial Anode Cathodic Protection)
HACC	Hydrogen Assisted Cold Cracking
HISC	Hydrogen Induced Stress Cracking
Havtil	Havindustritilsynet (Norwegian Ocean Industry) Previously Petroleumstilsynet (Ptil/PSA)
HV	Hardness Vickers
ICCP	Impressed Current Cathodic Protection
ISO	Internation Organization for Standardization
MAX	Maximum
MIC	Microbially Initiated/Influenced Corrosion
MIN	Minimum
MPI	Magnetic Particle Inspection
MSL	Mean Sea Level
NDT	Non-Destructive Testing
OS	Offshore Standard
QA	Quality Assurance
QA	Quality Control
RP	Recommended Practice
SBR	Schottky Barrier Rectifier
SCE	Saturated Calomel Electrode
SHE	Standard Hydrogen Electrode
SMYS	Specified Minimum Yield Strength
SRB	Sulphate Reducing Bacteria
SSRT	Slow Strain Rate Testing
TSA	Thermally Sprayed Aluminium

Potentials are given in units of volts [V] vs the following reference electrodes [3]:

- Ag/AgCl/seawater = SHE – 0.250 V.
- Saturated calomel electrode (SCE) = SHE – 0.244 V.

SHE is the standard hydrogen electrode.

Stress/strength is given in units of megapascal [MPa] (1 MPa = 1 N/mm^2).

3 Introduction

3.1 Background

Jack-up rigs are a type of mobile platforms that consist of a buoyant hull fitted with a number of movable legs, capable of raising its hull above surface of the sea. The buoyant hull enables transportation of the unit and all attached machinery to a desired location. Once on the location, the hull is raised to the required elevation above the surface of the sea, supported by legs on the seabed. The legs may be designed to penetrate the seabed, fitted with spudcans (footings with enlarged sections) or attached to a bottom mat [1]. The legs of a jack-up platform are constructed from high strength steel, 690 MPa steel was introduced to obtain sufficient strength and reduce weight.

In 2022 hydrogen cracking was detected on jack-up rigs operating in the Norwegian sector of the North Sea. Cracking of 690 MPa steel was observed in the welded joints between the legs and the spudcans. All cracks had initiated in the weld metal, most cracks had propagated within the weld zones and some cracks had even propagated into the base material.

Consequently, Havtil initiated a study in 2023, «Hydrogen assisted cracking of jack-up installations» [1], identifying undetected weld defects from fabrication (hydrogen assisted cold cracking, HACC) as a likely root cause. The defects then propagated further during operation, assisted by hydrogen formed through cathodic protection (CP) of the jack-up rig (hydrogen induced stress cracking, HISC). CP is generally required to prevent corrosion of steel structures in marine environment.

In the 2023 study it was, however, concluded that it is possible to use high strength steels in the range 500 to 690 MPa without problems with hydrogen-related cracking, provided that the major classification rules, guidance notes and recommendation applicable to offshore jack-up structures are adhered to. The causes for the observed hydrogen cracking were related to deficiencies in implementation of effective QA/QC routines during fabrication, rather than deficiencies in materials or structural design.

The following recommendations were given:

1) Selection of materials and weld consumables to ensure a low intrinsic susceptibility to hydrogen embrittlement.
2) Selection of weld procedures, QA/QC programs and NDT methods appropriate to preventing weld flaws and other imperfections to remain undetected.
3) Application of a high-quality coatings to mitigate adverse effects of CP.

3.2 Scope of work

The purpose of the present study is to evaluate further the use of CP for jack-up rigs. The evaluation specifically addresses reduction in risk for HISC while maintaining adequate corrosion protection of the structure.

The study is based on the following sources:

- Standards, codes and recommended practices concerning CP.

- Available literature and previous studies on jack-up rigs and CP. A complete review of such sources will, however, not be given.
- FORCE Technology experience with CP over the past 40 years.

The current report presents the results from the work conducted from June until the end of 2024 by key personnel from FORCE Technology.

For recommendations regarding areas to be inspected and relevant methods for detection of defects from fabrication, reference is made to Ref. [2].

3.3 Objectives

The objectives and organization of the study are as follows:

- Provide advice on optimum potential for reduction in risk for HISC while maintaining adequate corrosion protection for jack-up rigs during operation.
- Provide overview of standards and recommendations that can be consulted in the CP design of jack-up rigs and to which extent these apply.
- Provide advice on how reduction in risk for HISC can be achieved in practice, considering CP design as well as monitoring of CP during the design life.

3.4 Limitations and assumptions

The main limitation is that industry stakeholders are not represented in this work.

4 Cathodic protection as source for hydrogen

4.1 Introduction

Steel structures exposed to seawater are typically protected against corrosion by a combination of coating and cathodic protection (CP) to prevent corrosion of bare steel, e.g. exposed through coating defects or damages. The coating shall be compatible with CP, resistance to cathodic disbonding at scratches/porosities shall be demonstrated under applicable protection potentials.

The main sources of hydrogen for structures under CP are therefore:

- Welding, prior to service.
- Cathodic protection (CP), during service.

Although some results suggest that there may be some hydrogen embrittlement just from free corrosion in seawater, and that the levels of hydrogen generated can be sufficient to cause hydrogen embrittlement in very high strength steels [4], this will not be relevant for structures under CP.

CP lowers the potential of the steel surface to a potential where iron is thermodynamically stable, ref. Figure 4-1, by supply of electrons from an external source, from sacrificial (galvanic) anodes and/or an impressed current CP system (ICCP).

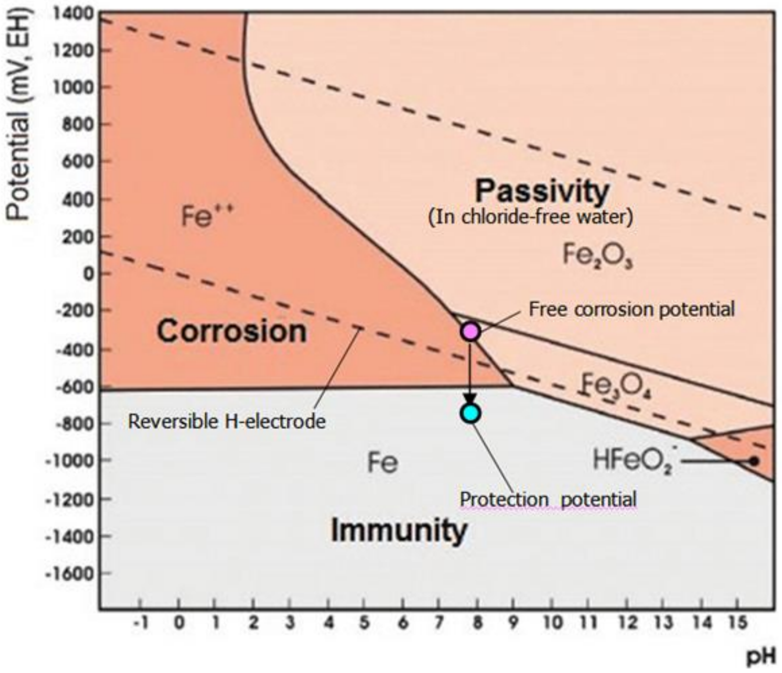

Figure 4-1 Illustration of area of protection as a function of pH and electrochemical potential – simplified Pourbaix diagram for steel in water.

The lower dashed diagonal line in Figure 4-1 represents the reversible hydrogen electrode potential (E_H), given by:

$$E_H = 0.059 \times pH \text{ (Volt)}$$

When lowering the potential to achieve CP, hydrogen evolution is thermodynamically feasible, but the rate of evolution depends on the kinetics of the reaction(s) involved.

Service-related cracks are caused by hydrogen induced stress cracking (HISC) which develop when structural steel members with residual stresses and static loads are subjected to hydrogen charging through bare (uncoated) steel surfaces under CP.

In contrast to a bare steel structure where CP leads to bulk hydrogen charging of the steel, hydrogen charging of coated structures occurs at locations of coating damages or surface breaking cracks developing from previous weld defects (point sources hydrogen charging).

As the cathodic reaction steadily produces hydrogen feeding the crack surfaces it may provide enough hydrogen for charging of a small volume of strained material ahead of the crack tip. In this small volume HISC can progress, but the crack growth rate will depend on the supply of hydrogen to the crack tip as well as the load (stress) applied.

Due to the cathode reaction taking place at the steel surface H^+ ions are consumed, causing a local increase in pH (alkalisation). In a narrow crack with restricted volume the increase in pH may be even higher, shifting the equilibrium hydrogen potential towards more negative values, ref. Figure 4-1. At the same time, the voltage (IR) drop associated with current flow in the narrow crack can increase the potential at the crack tip considerably vs the level at the crack mouth. The combined effect of IR-drop and alkalisation may reduce the hydrogen evolution considerably.

Finally, it should be noted that not all of the hydrogen generated becomes absorbed in the steel, some recombines to molecular hydrogen that is released from the steel surface as hydrogen gas. Nevertheless, the amount of hydrogen absorbed at sufficiently negative potentials will be high enough to cause cracking if the material is simultaneously exposed to high stresses in areas with flaws or defects.

4.2 Cathodic protection design

Cathodic protection (CP) is an electrochemical process, involving reactions taking place on the surface of an electrode (metal) exposed to an electrolyte (the corrosive environment). The electrode potential establishes at the interface between the metal and electrolyte and is measured with respect to a reference electrode, ref. Section 2.

In the context of this report, CP is achieved by electrically connecting the structure to be protected (the steel in the corrosive environment) to a less noble metal which then corrodes instead of the steel and hence acts as a sacrificial anode. The rate of corrosion of the anode material, which is related to the amount of electric current flowing between anode and steel, is determined by the corrosive environment (the electrolyte), the relative areas of the steel and the sacrificial anode, and by the voltage difference between the materials. The less noble metal (the sacrificial anode) is associated with a more negative electrode potential than the nobler material (steel).

Under CP, the potential of the steel is shifted from the free-corrosion potential (i.e. the potential of steel when exposed to the corrosive environment) towards a more negative value, as illustrated in Figure 4-1. The criterion for adequate protection in terms of potential (the protection potential) depends on the material and the corrosive environment.

At the same time, the potential of the sacrificial anode is shifted away from its equilibrium potential, later referred to as the anode open-circuit potential (OCP). Here no net electric current is flowing. The potential of the sacrificial anode is shifted to a value that corresponds the amount of electric current flowing between anode and steel, later referred to as the anode closed-circuit potential.

CP systems shall be designed following a recognised standard or recommended practice, such as e.g. DNV-RP-B401 [5].

The generally accepted criterion for protection of carbon or low-alloy steels in aerated seawater is a protection potential of -0.80V (Ag/AgCl/seawater) or more negative, ref. e.g. DNV-RP-B401 [5] (which is referenced by NORSOK M-503) [6]) or EN 12495:2000 [7]. In the case of mild steel in an environment with sulphate reducing bacteria (anaerobic conditions), the design protection potential is lowered to -0.90 V (Ag/AgCl/seawater). Adverse effects of CP are noted, in DNV-RP-B401 the term over-protection is applied to potentials more negative than -1.15 V (Ag/AgCl/seawater).

Galvanic anodes for offshore applications are generally based on either aluminium or zinc. Recommendations for composition (alloying elements and impurities) are specified in design codes/standards. Aluminium alloyed with zinc (Zn) and indium (In), Al-Zn-In, is generally used in the CP design of structures (some limitations apply in closed compartments) [5].

CP design considers the closed-circuit potential of the anode material, i.e. the potential attained when the anode is connected to the object to be protected (ref. above). Design values for the common anode materials in offshore CP design are given in Table 4-1. The driving voltage of the anode is defined as the difference between the design protection potential of the steel and the closed-circuit potential of the anode. Note that a standard such as EN 12495:2000 [7] defines the requirements for CP but refers to EN 12496 [8] for the performance of galvanic anodes when used.

Table 4-1. Design parameters for sacrificial anode materials in seawater, anode surface temperature ≤30°C [5].

Anode material	Closed-circuit potential [V]	Electrochemical capacity [Ah/kg]
Aluminium (Al) based (Al-Zn-In)	-1.05	2000
Zink (Zn) based	-1.03	780

The electrochemical capacity gives the amount of electric current provided (in unit ampere-hour) when 1 kg of the of the anode material is consumed and depends on the anode material (composition/purity), current density, temperature and other environmental factors. The galvanic efficiency is given by the ratio of the amount of metal consumed in practice to that consumed theoretically for the same amount of current according to Faraday's first law of electrolysis [9]. The galvanic efficiency is reduced by self-corrosion of the anode material (i.e. consumption of material through reactions that are not related to the supply of protective current). For aluminium based anodes the galvanic efficiency is significantly affected current density (i.e. duration of testing), ref. e.g. Figure A.2 of ISO 15892:2024 [10] and Ref. [11]).

In CP design, the number of anodes to be installed is governed by the following parameters:

1) The initial anode current output, i.e. output from the anodes in their initial state, shall be sufficient to effectively polarise the structure to be protected.
2) The anodes are consumed with time to an extent determined by the amount of current supplied and the electrochemical capacity of the anode material. Anode consumption is evident through corrosion products observed on anodes that are (or have been) active. Enough anode material (anode net mass) must be installed to last the CP design life.
   A consequence of application of CP is that a calcareous layer, consisting primarily of calcium and magnesium carbonates and bicarbonates, will form on bare metal surfaces. This calcareous layer, as well as marine growth, reduces the current required for maintenance of CP.
3) The final anode current output, i.e. output from the anodes when they are consumed to their allowable utilization, shall be sufficient to re-polarise a structure if the calcareous layer/marine growth is damaged.

Calculation of the current required in the various stages of the design is based on current density requirements (initial, mean, and final) specified for different environments (geographic locations, water depth, etc.).

In CP design, coating is regarded as an electrically insulating barrier between steel and the corrosive environment, reducing the amount of current required. The coating breakdown factor (f) describes the anticipated reduction in cathodic current density [5]. For $f = 0$ the coating is 100% electrically insulating. $f = 1$ implies that the coating has no current reducing capacity.

This barrier may, however, loose some of its efficiency with time, either due to general degradation and/or due to mechanical damage. This is captured using coating breakdown constants to calculate f for the various stages of the design life (initial, mean and final). Design parameters are given for calculation of f based on type and thickness of coating and consider that f increases linearly with time.

For coated structures, the effective current density on the surface of the steel is the product of the current density on bare steel and the coating breakdown factor. This parameter is intended to be conservative, i.e. to ensure that sufficient anode current and net mass are installed. Consequently, a correctly designed CP system with sacrificial anodes will usually provide potentials in the range -0.95 to -1.05 V (Ag/AgCl/seawater) when the CP system has stabilised in the maintenance phase [5]. Towards the end of the design life, the potential may increase towards -0.80 V (Ag/AgCl/seawater), and eventually to even more positive potentials, termed under-protection [5].

Fatigue, initiation, and propagation of cracks in a material due to cyclic loading, is a failure mode to be considered in the design of steel structures. The fatigue life can be separated into five stages, i.e. development of damage through microstructural changes, initiation of microscopic cracks, growth and coalescence of microscopic flaws into dominant cracks, stable propagation of the dominant crack, and then final fracture.

When metals are exposed to both repeated stress and a corrosive environment, the fatigue behaviour is significantly different from that in air, termed corrosion fatigue (CF). Pitting is commonly identified as one corrosion mechanisms enhancing fatigue crack initiation, thereby reducing the fatigue life.

Consequently, corrosion protection should minimize not only general corrosion, but also more localised corrosion. According to DNV-RP-B401, the fatigue design calculations may even require a protection criterion more negative than -0.80 V [5].

CP is, however, known to reduce the fatigue strength compared to air, especially for high stress ranges, ref. Wormsen et al. [12]. Work cited here on low alloy steels considered for tension leg platforms (yield/tensile strength approx. 800/900 MPa), tested in artificial seawater at -0.85 and -1.05 V (Ag/AgCl/seawater, assumed), confirmed that the fatigue strength of freely corroding specimens was considerably reduced compared to air. CP improved the fatigue performance compared to free corrosion. The fracture mechanism for specimens where fatigue strength was still reduced compared to air was considered to be affected by hydrogen absorbed due to the CP.

5 Protection potential range – HISC

5.1 Review of standards and recommended practices

Several classification societies have established and maintain relevant technical standards for the construction and operation of ships and offshore facilities, e.g. the British Lloyd's Register, the American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Bureau Veritas, etc.

Also, standards are developed in Europe by Comité European de Normalization (CEN) and internationally by International Standardization Organization (ISO). CEN and ISO have an agreement for technical co-operation.

In the following, selected documents provided by ISO, CEN and by some classification societies are reviewed in terms of their requirements and recommendations regarding cathodic protection (CP) and risk for hydrogen embrittlement/HISC.

Section 5.2 provides an overview of some literature data concerning CP and risk for HISC. Note that this section does not intend to provide a comprehensive overview for testing of CP/hydrogen embrittlement.

DNV-OS-C101 (July 2023) [13] - Structural design of offshore units.

Scope: Offshore standard (OS), provides principles, technical requirements and guidance for the structural design of offshore structures.

The following is stated:

- Steel surfaces in the splash zone, below the mean sea level (MSL) for bottom fixed structures, shall be designed with CP in addition to coating.
- Design of CP systems shall be carried out according to a recognised standard, reference to DNV-RP-B401 is given in guidance note (i.e. recommendation only).
- Only anodes based on aluminium or zinc shall be used.
- The effect of CP (or exposure to anaerobic environments) of excessively strained areas of high and extra high strength steel shall be investigated for the risk of HISC. Special requirements for welding apply.

The susceptibility to HISC shall be considered, especially when the steel is used for critical applications such as jack-up legs and spudcans. The use of steels with a specified minimum yield stress (SMYS) > 550 MPa shall be subject to special considerations when anaerobic conditions may predominate.

Fatigue strength calculations shall be performed using relevant site-specific environmental data for the area(s) in which the unit will be operated and considering the corrosion protection system and time in a corrosive environment. The fatigue analysis should be based on S-N data (magnitude of alternating stress vs number of cycles to failure), determined by fatigue testing of the welded detail, or, when appropriate, be based on fracture mechanics. For detailed assessments of fatigue damage in the high cycle region ($>10^4$ cycles) reference is made to DNV-RP-C203.

DNV-RP-C203 (2024) [14] is valid for subsea applications of carbon manganese (C-Mn) steel up to yield strength 759 MPa and tensile strength 897 MPa in seawater. S-N data is provided for air, seawater with CP and seawater without CP ('free corrosion'). Protection potentials are not specified but should correspond to range -0.80 to -1.05 V (Ag/AgCl/seawater) [5]. In a referenced paper by Wormsen et al. [15] (fatigue testing in artificial seawater), a potential of -1.05 V (Ag/AgCl/seawater) simulated the most negative potential that can be obtained with Al or Zn anodes in accordance with DNV-RP-B401.

With reference to jacket structures in the splash zone area, DNV-RP-C203 states that a large part of the fatigue life is associated with initiation of a fatigue crack and growth of small cracks. For structures with a good coating, the cracks must grow to some size before the coating is broken, and until this happens the condition corresponds to that of air. The probability of having a fatigue crack of this size will then have to be considered in the analysis.

DNV-RP-B401 (May 2021) [5] - Cathodic protection design:

Scope: Recommended practice (RP) primarily intended for the design of CP systems using galvanic anodes for permanently installed offshore structures associated with the production of oil and gas, including fixed platforms.

Adverse effects of CP are noted. The term over-protection is applied to potentials more negative than -1.15 V (Ag/AgCl/seawater) but will not apply for CP systems using sacrificial anodes with normal Al or Zn anode alloys [5].

Special techniques applied to shift the CP potential to a less negative range, e.g. -0.80 V to -0.90 V (Ag/AgCl/seawater), are exemplified by use of diodes and special anode alloys. A major disadvantage is then that the individual component/system protected by this CP system needs to be electrically insulated from adjacent standard CP systems.

NORSOK M-503:2016 [6] – Cathodic protection:

Scope: NORSOK standard giving requirements for CP design of e.g. submerged installations.

The CP design methodology shall be in accordance with DNV RP-B401 for structures. The CP system shall have sufficient capacity to polarise carbon steel exposed to seawater to a potential more negative than -0.80 V (Ag/AgCl/seawater).

For design limitations for candidate materials, reference is made to NORSOK M-001.

Requirements for HISC evaluation are given for martensitic and duplex stainless steels, 13Cr and 22Cr/25Cr. In the earlier edition, Ref. [16] (2007), a special evaluation was required with respect to HISC for high-strength carbon steel materials (SMYS > 550 MPa and maximum actual yield strength 750 MPa).

Lloyds Register of Shipping, Recommended practice for fixed offshore installations, July 2023 [17] (replacing Rules and regulations for the classification of fixed offshore installations, 1989 (amendments 2000):

Scope: Recommended practice (RP) applicable to offshore installations engaged in offshore operations, including e.g. drilling and oil/gas production and storage. This RP is applicable to fixed offshore installations/platforms (a structure that is bottom founded and transfers all actions on it to the seabed) and operate at a fixed geographic location for their entire service life.

Specific reference is made to jack-ups under 'General geotechnical requirements' (Section 2.4.3).

Criteria for CP are stated as follows (Chapter 6, Section 2), all potentials given vs the Ag/AgCl/seawater reference electrode:

- CP systems are to comply with EN 12495 unless local legislation dictates otherwise.
- The CP system shall be capable of polarising the steelwork to:
    - -0.80 to -1.10 V for aerobic conditions.
    - -0.90 to -1.10 for anaerobic conditions.
- Potentials more negative than -1.10 V must be avoided to minimise any damage due to hydrogen absorption and reduction in the fatigue life.
- For steel with a tensile strength exceeding 700 MPa the maximum negative potential should be limited to -0.95 V.
- Where the steel is prone to hydrogen assisted cracking the potential should not be more negative than -0.83 V. No further details are, however, given on how to identify these materials.

ISO 19902 (2nd Edition 2020 [18]) Petroleum and natural gas Industries – fixed offshore structures:

Scope: International standard covering fixed offshore structures, including jack-ups.

CP is identified as one of the main options for corrosion control. The design shall ensure a protection potential within the range -0.80 to -1.10 V (Ag/AgCl/seawater).

Owing to risk for HISC, steels with a SMYS exceeding 720 MPa shall not be used for critical components under CP without special considerations. Applicable CP codes are identified, e.g. EN 12473, EN 12495, NACE RP0176, DNV-RP-B401 and NORSOK M-503.

EN 12473 (2nd Edition, February 2014 [19] (1st Edition, January 2000)) – General principles for cathodic protection in seawater:

Scope: European standard covering the general principles of CP and intended as an introduction to other European standards in the general series "Cathodic protection of steel structures in sea water", e.g. EN 12495:2000 for CP of fixed offshore structures [7] and prEN 12496:1997 (later EN 12496:2013) for galvanic anodes.

A risk of cathodic disbonding and HISC of high strength steels is identified as potentials become more negative. For carbon-manganese and low alloy steels with SMYS ≤ 550 MPa, a negative limit of -1.10 (Ag/AgCl/seawater) prevents these risks. This limit is achieved on structures protected by zinc or aluminum galvanic anodes.

For steels with SMYS >550 MPa, a negative limit of potential in the range -0.83 V to -0.95 V (Ag/AgCl/seawater) is generally specified. In the previous edition of this standard (year 2000), this requirement was given for materials with SMYS > 700 MPa, and the negative limit of the potential was given in the range -0.80 V to -0.95 V (Ag/AgCl/seawater)).

For a given material, this standard requires that the specific negative potential limit shall be determined by testing. Ref. [20] is cited.

EN 12495 (1st February, January 2000 [7]) – Cathodic protection for fixed steel offshore structures:

Scope: European standard defining requirements for CP of fixed offshore structures, covering external surfaces in contact with seawater or seabed for steels with a specified minimum yield strength (SMYS) not exceeding 500 MPa.

Risks associated with 'over-polarisation' (hydrogen embrittlement of the steel structure and of cathodic disbonding) are addressed. Generally, the higher the tensile properties, the greater the risk of hydrogen induced damage. However, material hardness and microstructure are also important.

Hydrogen embrittlement can occur on conventional steels used for offshore fixed structures (grade S355 as per EN 10025) at potentials more negative than -1.10 V (Ag/AgCl/seawater). Relevant tests should be performed for the use of CP outside these limits.

It is stated that polarisation of the structure to potential more negative than -0.8 V (Ag/AgCl/seawater) can result in the evolution of hydrogen gas at the steel surface. The associated risk identified is, however, related to risk of explosion in confined air spaces.

BS 7361-1:1991 [21] (withdrawn August 2013, superseded by EN 15112:2006 (External cathodic protection of well casing) and EN 13636:2004 (Cathodic protection of buried metallic tanks and related piping)):

Scope: This part of withdrawn British Standard BS 7361 covered the applications of CP of buried or immersed metalwork and the internal protection of containers for aqueous liquids, i.e. did not cover CP of offshore structures.

The adverse effects of hydrogen on high strength steels and steels subjected to high stress levels were, however, noted. Reference was made e.g. to the then 'Recommended Practice B401' by Det Norske Veritas for acceptable protective potentials and strength levels for steels immersed in seawater. CP was stated to be 'inappropriate for highly stressed high tensile steel' (clause 5.5.8 of Ref. [21]). Also, achieving protection of steel exposed in deep cracks ('deeply embedded steel') could be restricted by the need to ensure that any steel closer to the surface also remains within the potential limit and are not exposed to potentials that are too negative. This is due to the voltage drop associated with flow of protection current to depth of the crack. To overcome this voltage drop, a more negative potential will be required where the crack breaks the outer surface.

NACE (AMPP) SP0176-2007 [22] - Corrosion control of submerged areas of permanently installed steel offshore structures associated with petroleum production:

Scope: This standard provides guidelines for establishing minimum requirements for corrosion control on steel fixed offshore structures associated with petroleum production. The potential at which corrosion is controlled is stated to be a function of temperature and environment. In waters exposed to air and at typical ambient temperatures, potentials more negative than -0.80 V (Ag/AgCl/seawater) have proved to be satisfactory. For other circumstances, the potential to control corrosion can be estimated.

Risk of hydrogen embrittlement is not addressed, except in context of use of very active magnesium anodes.

Table 5-1 provides a summary of the requirements/recommendations regarding negative limit potential for high strength steel. As can be seen, not all relevant documents specifically address this issue, and there is also some variation in the threshold strength for when risk of hydrogen embrittlement shall be addressed.

Table 5-1. Summary – potential limit for hydrogen embrittlement (vs Ag/AgCl/seawater reference electrode).

Standard/code	Year	Strength	Comment
DNV-OS-C101 [13]	2023	SMYS > 550 MPa	Special considerations under anaerobic conditions, none for CP
DNV-RP-B401 [5]	2021	-	No specific requirements
Lloyds [17]	2023	Tensile strength > 700 MPa	Negative limit potential -0.95 V, -0.83 V if prone to hydrogen embrittlement
ISO 19902 [18]	2020	SMYS > 720 MPa	Not used for critical components under CP without special considerations
EN 12473 [19]	2014	SMYS > 550 MPa	Negative limit potential range -0.83 to -0.95 V
EN 12495 [7]	2000	SMYS < 500 MPa	No specific requirements
NACE SP0176 [22]	2007	-	No specific requirements

5.2 Review of selected literature

5.2.1 Protection potential

To select the optimum protection potential for a given material/environment, the risk for corrosion must be balanced against the risk for hydrogen damage/embrittlement [23].

According to the general CP design criteria, ref. Section 4.2, the protection potential for carbon or low-alloy steel in seawater is -0.80 V (Ag/AgCl/seawater). This is adopted by all standards/codes referenced in Section 5.1, and appears to have been established early, e.g. is referenced in Ref. [24] from 1984. It is noted that NACE SP0176 [22] allows for estimation of other values but provides limited guidance on how this can be done.

The following parameters have been identified to be significant for corrosion of steel in ocean waters, all affected by water depth [24]:

- Temperature.
- Salinity.
- Oxygen content.
- Seawater currents.
- Marine growth.

Seawater currents enhance the transport of oxygen to the surface, while presence of marine growth may have a limiting effect. Also, impact of time has been noted, as growing layers of rust on the steel surface reduced the corrosion rate.

Generally, CP design codes and standards do not relate the protection potential criterion to a specific corrosion rate. ISO 15589-1 (CP design of on-land pipelines) [25] states, however, the protection potential is the metal-to-electrolyte potential at which the corrosion rate is less than 0.01 mm/year. This rate is stated to be sufficiently low so that corrosion will be within acceptable limits for the design life.

This report does not intend to give a full overview of the basis for -0.80 V (Ag/AgCl/ seawater) as protection potential for carbon steel in seawater. Some examples of testing encountered as part of this study are, however, given in the following.

As part of a study of hydrogen embrittlement, Batt and Robinson established values for the protection potential of a quenched and tempered high strength steel, Weldox 700, with SMYS 700 MPa [26]. The chemical composition of this steel, originally developed for submarine hulls but similar to steels of equivalent strength for offshore applications, is summarised in Table 5-2.

Table 5-2. High strength steel Weldox 700 – chemical composition (weight-%) [27].

C	Si	Mn	Cr	Mo	Ni	Al	B	Cu	Fe
0.17	0.22	0.91	0.51	0.5	1.35	0.075	0.002	0.19	Rem.

Some results are given in Figure 5-1, illustrating corrosion rate vs protection level after 6 months testing. Considering 0.001 mm/year to represent an acceptable rate of metal loss, protection potentials of -0.77 and -0.79 V (SCE) were derived for natural and sterile seawater, respectively [27] (potentials vs Ag/AgCl/seawater are approx. the same, ref. Section 2). Freely cording conditions corresponded to approx. -0.675 V (SCE). Reference was made to test results reported by others ranging from -0.74 to -0.86 V (SCE), depending on material and environmental conditions (corresponding corrosion rate 0.001 mm/year). These potentials were then considered appropriate to protect the steel adequately, in general agreement with the design requirement of e.g. DNV-RP-401 [5].

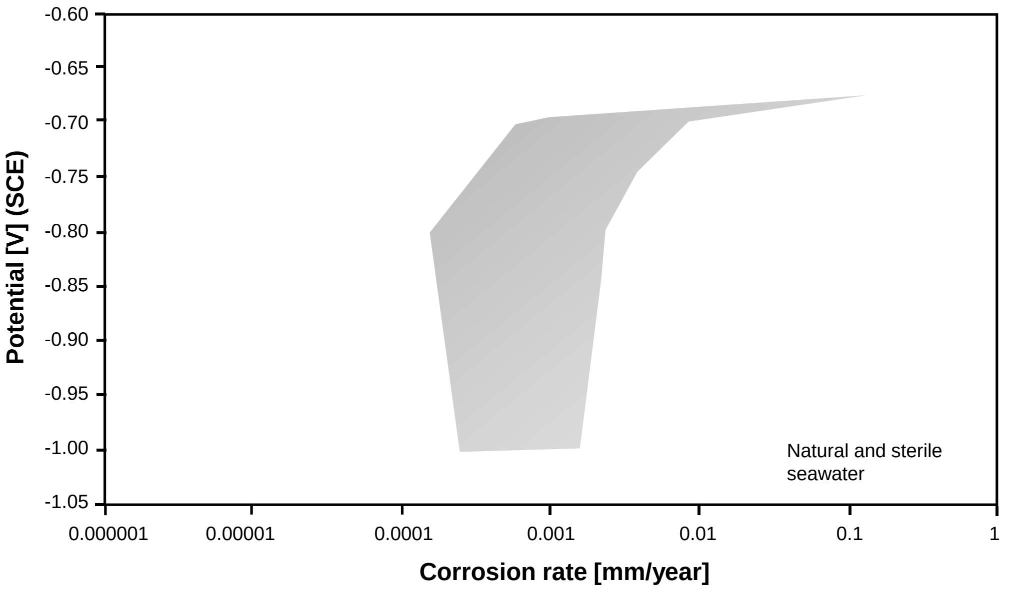

Figure 5-1. Range of average corrosion rates vs potential, Weldox 700 in sterile artificial seawater (laboratory) and natural seawater (coastal site), 6 months test period, potentiostatic weight loss measurements, adapted from Ref. [27].

Limited information is given regarding the surface of the samples after testing [28]:

- Specimens exposed under conditions of free corrosion were covered by corrosion products, the surface underneath showed evidence of differential aeration cells (localised corrosion).
- Specimens exposed at -0.70 V (SCE) showed evidence of corrosion products.
- Specimens exposed at more negative potentials (-0.75 V (SCE) and more negative) displayed what was described as calcareous scale. Underneath, the steel was described as bright and uncorroded, but it is not clear whether this applies to all specimens or only those exposed at -0.95 V (SCE).

As part of testing of candidate materials for low-driving voltage anodes, Pautasso et al. [29] tested high-strength Ni-alloyed steel with yield strength >930 MPa), and a low-alloy carbon (C-Mn) steel, ref. Table 5-3.

Table 5-3. Typical composition of steel grades tested in Ref. [29].

	C	Si	Mn	Cr	Mo	Ni	P (max.)	S (max.)	Fe
Ni alloy[1)]	0.12-0.18	0.10-0.40	0.30-0.60	1.00-1.50	0.30-0.50	3.70-4.20	0.035	0.035	Rem.
C-Mn[2)]	<0.2	<0.4	<1.4	-	-	-	0.040	0.040	Rem.

Note 1. Similar to HY-130, yield strength 130 ksi (896 MPa).
Note 2. S275 according to EN1025, yield strength >235 MPa.

The free-corrosion potential depended on exposure conditions in laboratory (natural seawater, with or without oxygen, under non-flowing (stagnant) or flowing conditions). For the Ni alloy steel, the more negative potentials were observed for the non-flowing (stagnant) conditions, approx. -0.70 V (SCE), while potentials closer to -0.65 V (SCE) were measured under the conditions with flowing seawater (potentials vs Ag/AgCl/seawater are approx. the same, ref. Section 2). The C-Mn steel was measured under non-flowing (stagnant) conditions only and returned potentials between -0.745 and -0.78 V (SCE), depending on the oxygen level.

Regarding a corrosion rate of 0.01 mm/year as 'negligible', uniform corrosion was stated to be limited at -0.73 V (SCE), while full protection was achieved at -0.85 V (SCE) for the high strength steel in natural seawater [29].

The above can be summarised as follows:

The free corrosion potential and corresponding corrosion rate for steel clearly depends on material composition and environmental conditions. Especially, results are expected to differ between tests performed in the laboratory (which allows for detailed control of the experimental conditions, but where it may be difficult to reproduce relevant condition) and tests performed in the field (were conditions will be representative, but where e.g. seasonal variations may complicate the interpretation of the results). Exposure time will also have impact on the results.

The same considerations apply for testing performed to demonstrate adequate protection against corrosion. Here, an additional complicating factor will be the composition and density of the calcareous layers formed on the steel surface under CP. These will depend on the environmental conditions, but also on the polarisation history of test samples.

There appears to be no generally accepted criterion for what can be regarded as adequate protection. The sources cited above range from 0.01 mm/year [25] [29] to 0.001 mm/year [27]. Uniform corrosion rate appears to be the main parameter of interest, limited information is given about the distribution of corrosion over the surface, i.e. the tendency for localised corrosion.

Consequently, it is possible that steels can be sufficiently protected at potentials less negative than -0.80 V (Ag/AgCl/seawater), but this will have to be verified by testing under relevant conditions. Specifically, impact of protection potential on the risk of corrosion fatigue must be addressed.

5.2.2 Potential limit for hydrogen embrittlement

Concerning the risk of hydrogen damage/embrittlement, it is noted that there is no generally accepted test method to verify material compatibility with CP [5]. Slow strain rate testing (SSRT) is applicable for material comparison ('screening') but does not accurately represent the conditions found offshore [30]. For quantitative testing under controlled CP conditions, DNV-RP-B401 refers to uniaxially loaded tensile specimens (constant load), 4-point bend specimens (constant displacement), and crack tip opening displacement (CTOD) specimens.

Assessing the effect of hydrogen on fracture performance requires measures of stress intensity [23]. A normal Charpy test is too fast for the hydrogen to diffuse through to the crack tip, hence hydrogen will not have much effect on the test results. However, hydrogen embrittlement (sub-critical crack growth), might still occur if there is more time available. Crack growth then takes place when the stress intensity at a flaw exceeds a threshold value, K_{th} (or K_{ISCC}), and it is usually substantially less than the fracture toughness value. In practice, K_{th} depends on the hydrogen content of the steel, and will vary with the CP potential.

Generally, the recommended practices/standards cited in Section 5.1 do not provide references for their requirements/recommendations. EN 12473 [19], however, cites Ref. [20] (1993). Here it was established by SSRT that hydrogen damage to steel was insignificant provided that cathodic potentials were not more negative than -0.830 V (Ag/AgCl/seawater) (-0.825 V (SCE)). The following materials were tested, ref. Table 5-4:

- Type A – tubular high strength steel (specified yield stress 700 MPa, actual range 704-746 MPa), used in several jack-up rigs operating on the United Kingdom continental shelf.
- Type B - high strength steel, rolled plate, used in the jack-up chords of the rig from which Type A samples had been obtained.

Table 5-4. Chemical specification for steel grades tested in Ref. [20].

Type	C	Si	Mn	Cr	Mo	Ni	P	S	Al (tot)	Fe
A	0.05-0.10	0.10-0.40	1.70-2.30	-	0.20-0.40	2.50-3.50	<0.020	<0.012	0.01-0.05	Rem.
B	<0.19	0.15-0.5	0.8-1.5	≤1.25	≤0.45	≤1.2	≤0.03	≤0.025	-	Rem.

SSRT was considered the most suitable method to produce the required results within a short period. Round (un-notched) tensile specimens were loaded slowly at constant strain rate, with the gauge area exposed to the test environment. Time to failure, reduction in cross-sectional area and sample elongation were reported and the fracture surface examined.

Billingham et al. [30] summarises some of the work on CP potential values for high strength steels available at the time (2003). The following is cited from this summary:

- Hydrogen will be produced at potentials more negative than -0.710 V (Ag/AgCl/seawater) for North Sea seawater (pH 8.3 and 10 °C).
- The amount of hydrogen produced (and therefore absorbed by the steel) increases as the potential becomes more negative. Even small concentrations of sulphide can significantly increase the amount of hydrogen absorbed by steel.
- For steels with yield strength >700 MPa, the potentials should generally be within the range -0.80 to -0.95 V (Ag/AgCl/seawater).
- For steels with yield strength >800 MPa, the potential should not be more negative than -0.80 V (Ag/AgCl/seawater).

The work of Batt et al. Ref. [30] involved double cantilever beam (DCB) testing of Steel 900 (quenched and tempered high strength steel used in marine applications, SMYS 900 MPa). Chemical composition is given in Table 5-5. The yield and tensile strength were 1038 and 1080 MPa, respectively, hardness 372±6 HV1.

Table 5-5. High strength steel (‘Steel 900’) – chemical composition (weight-%) [27].

C	Si	Mn	Cr	Mo	Ni	P	S	B	Cu	V	Fe
0.11	0.21	0.66	0.5	0.51	5.02	0.006	0.005	<0.001	0.1	0.05	Rem.

The threshold stress intensity for hydrogen embrittlement was measured in tests performed for up to approx. 1 year under the following conditions [27] (potentials vs Ag/AgCl/seawater are approx. the same, ref. Section 2):

- Sterile artificial seawater and filtered natural seawater, potentials controlled potentiostatically between -0.8 and -1.10 V (SCE).
- Natural seawater, potentials controlled by coupling to zinc anodes, to -1.02 V (SCE).
- Seabed sediments, potentials controlled by coupled to zinc anodes or to Al-0.1 wt% Ga low-voltage anodes.

Neither of the specimens tested at -0.8 V (SCE) displayed any crack growth, while the more protected specimens showed the highest crack velocities. With reference to previous corrosion testing [28], it was recommended to control potential at -0.77 and -0.79 V (SCE) in natural and sterile seawater, respectively, to provide adequate corrosion protection and minimise the risk for HISC.

All specimens buried in seabed sediments showed crack branching, indicating a much greater susceptibility to embrittlement and demonstrating the effect of sulphides in promoting hydrogen uptake. Here, even potentials in the range -0.77 to -0.79 V (SCE) would be too negative for the material tested.

Noting that high strength steels differ significantly in terms of crack tip stress intensity, it was recommended that the risk of embrittlement of a particular grade of steel should be addressed individually [28] (especially for exposure to marine sediments). This is in line with statement given by Billingham et al in 2003 [30], that although yield strength and hardness give some indication of the susceptibility to hydrogen embrittlement of a particular steel, the significance of microstructure implies that these measures can only give an approximate guide.

To summarize, there appears to be no generally accepted test method to verify material compatibility with CP. SSRT provides results within a reasonably short period of time but is applicable for 'screening'. Measuring fracture performance under relevant conditions (environment, level of CP, load), is more complicated and time consuming. Recommended practices/standards appear to be based on a relatively limited number of tests performed under relevant conditions, at least with regards to potential for which risk of hydrogen embrittlement can be regarded as minimised (the negative limit potential).

Citing Billingham et al. [30] (2003), standardisation of test methods (SSRT in particular) with respect to conditions most applicable to offshore use was requested, to allow for comparison and assessment of scatter. Establishing relationships (if any) between SSRT and fracture mechanics test results would also be useful. In this context, reference can be made to the joint industry project (JIP) resulting in the development of recommended practice DNV-RP-F112, design against hydrogen induced stress cracking for duplex stainless steel [31].

6 Strategies for control of protection potential

6.1 Introduction

As shown in the previous sections, the risk for hydrogen embrittlement is related to the protection potential. The risk of HISC for components under CP is therefore reduced if potentials on critical component/parts are shifted to less negative values.

Table 5-1 of Section 5.1 provides a summary of the requirements/recommendations identified regarding negative limit potential for high strength steel. There is some variation in the recommendations given, but where negative limit potential is specified, it ranges from -0.83 to -0.95 V (Ag/AgCl/seawater) depending on strength.

Considering that a protection potential for steel in seawater of -0.80 V (Ag/AgCl/seawater) is commonly agreed, the potential range for which CP needs to be controlled will be relatively tight. If a less negative protection potential is to be used in design, extensive testing will be required to verify that corresponding corrosion rates are within design limits for the structure. Also, implications for corrosion fatigue must be addressed.

Strategies for achieving less negative potentials are discussed in the following sections:

- Distribution of conventional Al-Zn-In anodes – optimisation by CP modelling.
- Changing the chemical composition of the anode material – anodes with low driving voltage.
- Use of diode-controlled anodes.
- Use of coating.

Examples of projects utilising the various strategies are given in Section 7.

The following is noted:

Impressed current CP (ICCP) or hybrid ICCP/GACP systems have the advantage that the potential can be controlled, provided that the potential monitoring is effective [30]. The inherent risk of these systems is, however, that poor management or system failure could lead to extreme over-protection or no protection. Also to be noted is the need for robust reference electrodes which should be located as close to critical areas as possible.

ICCP as method for controlling potential on jack-ups is not considered further, the discussing will be limited to the use of sacrificial (galvanic) anodes (GACP).

Offshore structures (and pipelines) are typically in electrical contact with other (metallic) objects. These are designed with their own CP systems (GACP or ICCP) or designed to not require CP (through selection of corrosion resistant materials (CRAs), or the use of corrosion allowance (CA), or due to low corrosivity (for deeply buried parts)).

Even though not requiring CP themselves, such object(s) may impose an additional load on the CP system in question, but it is also possible that current may be supplied by the 'external' CP systems. This is typically observed when electrically connecting systems protected by GACP and ICCP together, whereby the ICCP system may render the sacrificial anodes less active or in some cases inactive (or cathodic).

This can also be observed when connecting GACP systems using on Al and Zn based anodes, respectively. The somewhat larger driving voltage of the Al based anodes will have to be counteracted by a correspondingly lower resistance of the Zn based anodes for the current output from the two systems to be equivalent. Otherwise, the Zn based anodes may be rendered less active.

As noted in DNV-RP-B401 [5], the use of methods for control of potential on jack-up rigs will require electrical isolation of the structure to avoid connection with conventional ('unregulated') CP systems. The 'unregulated' CP system would dominate the protection potential on the jack-up rig, causing the critical parts of the structure to become exposed to normal (i.e. more negative) potentials, i.e. not in accordance with the design requirements.

Even if electrical isolation has been installed, this may fail during operation. Also, the risk of short-circuiting of the electrical isolation needs to be addressed, hence monitoring of potentials will be required.

6.2 Anode distribution – CP modelling

The potential distribution on a structure where CP is provided by sacrificial anodes is determined by the following factors:

- The anode material, which determines the anode potential (i.e. the closed-circuit potential with anode connected to steel).
- The anode geometry, which determines the anode resistance.
- The number and distribution of anodes.
- The anode current output, which together with the anode resistance determines the voltage (IR) drop associated with current flow from the anode. The anode current output is governed by the current demand of the structure, i.e. the current density requirement of steel exposed to seawater and/or to sediments, but also by the amount of current supplied elsewhere (as drain).

CP modelling is typically used to verify the performance of a CP system, i.e. that the distribution of anodes is such that the entire structure is adequately protected. For materials that are not susceptible to hydrogen embrittlement, this implies demonstrating that potentials are more negative than -0.80 V (Ag/AgCl/seawater) over the entire structure (-0.90 V (Ag/AgCl/seawater may apply for buried parts with risk of MIC [5]).

To be noted is that the potential will be more negative in the vicinity of the sacrificial anodes, the level, again depending on the amount of current supplied by the anodes. When CP is provided by conventional Al-Zn-In or Zn alloys, the potential next to the anodes can be considerably more negative than the potentials regarded as 'safe' with regards to HISC, ref. Section 5.

Dielectric shields are used in ICCP systems to limit potentials close to the anodes. However, for use with sacrificial anodes the area of shield required is very large and hence not regarded as practical [23].

For materials that are susceptible to HISC, CP modelling can be used to shift anodes away from highly stressed areas and/or from areas where flaws from manufacturing is difficult to detect/repair. Anodes can also be grouped together to reduce their current output through encouraging the interference between closely spaced anodes (i.e. by increasing the overall anode resistance), or installed remotely, e.g. on sleds/pods or on electrically connected adjacent structures.

One difficulty with this approach, and in fact for all the strategies considered for potential control, is that the CP design input parameters are intended to be conservative, i.e. shall ensure that sufficient current is installed to achieve initial polarisation, and that installed anode net mass will cover the entire design life. This conservatism is generally confirmed by later CP inspections, especially for well-protected structure. Not only are the current densities for bare (uncoated) steel found to be much lower than the design values, see e.g. Ref. [32], but the design coating breakdown factors can also be too high.

Knudsen and Steinsmo measured the long-term current demand for coated and uncoated samples cathodically protected under the same conditions [33]. Coatings according to DNV-RP-B401 (1993) categories 1, 2 and 4 were tested, as well as NORSOK M-501 (1994) System 7. The two degradation mechanisms identified, cathodic disbonding around coating holidays and random blistering, appeared to have limited long-term effect on the current demand. Irrespective of type/thickness of coating, the coating breakdown factors were significantly lower than given by DNV-RP-B401 (1993)/NORSOK M-CR-503 (1994).

In Ref. [34], the visual appearance of the coating on several subsea installations were used to assess coating damage/degradation. Again, the design coating breakdown factors were very conservative, by a factor of 4-5 for one of the structures after 25 years.

Consequently, unless more realistic design parameters are used, the potential distribution on a structure will be significantly more negative than the design protection potential.

Jack-up rigs are used in a variety of locations and the maintenance current density will depend on environmental parameters (temperature, oxygen content, flow rate) and the previous polarisation history of the steel. The actual current demand will therefore not be known in the design phase when the number and distribution of anodes are defined. It may therefore be difficult to reconcile the requirements of the CP design calculations with a need for maintaining a less negative potentials on parts of the structure due to risk of HISC.

The following should also be noted:

For fully coated structures, the small amount of steel exposed to the corrosive environment through a coating damage (e.g., associated with a surface breaking crack) will experience relatively negative potentials, i.e. more negative than the limit defined to minimise the risk of HISC. This coating damage/crack may then act as a point source capable of introducing locally high hydrogen concentrations at a crack tip. In terms of risk of hydrogen embrittlement, the worst-case scenario would be narrow cracks in an otherwise coated structure. Defining the acceptance criteria for potentials associated with such cracks is regarded as challenging.

The use of coatings is discussed further in Section 6.5

The pros and cons of anode distribution/CP modelling as a tool to minimise risk of HISC are summarised as follows:

- Pros:
    - Conventional anodes/anode materials can be used, i.e. materials specified in CP design standards.
- Cons:
    - Conservatism in CP design must be reduced without risking under-protection.
    - Detailed CP modelling is required.
    - Interaction with other CP system must be minimised/controlled, i.e. through electrical isolation.
    - Regular monitoring is required to verify that potentials remain within strict potential limits.

6.3 Anode design - galvanic anodes with low driving voltage

Materials to be used as galvanic (sacrificial) anodes must meet the following requirements [9]:

- The equilibrium potential (open-circuit potential, OCP) must be sufficiently negative with respect to the protection potential of the object to be protected so that the driving voltage is adequate.
- The tendency to passivation, i.e. to form insoluble surface compounds, should be as low as possible.
- The polarisability should be limited, i.e. the anode should be able to supply relatively large amounts of current without a too large (positive) shift in the closed-circuit potential. This shift affects the anode's capability of supplying current.
- The electrochemical (or current) capacity (i.e. the usable current per unit mass of anode material) should be as close to the theoretical value as possible, i.e. self-corrosion (consumption of anode material not related to supply of protective current) should be limited.
- Anode consumption should be uniform, i.e. the microstructure should be fine-grained.

Galvanic anodes for offshore applications are generally based on either aluminium or zinc, ref. Section 4.2. Recommendations for maximum/minimum contents of alloying elements and maximum contents of impurity elements are specified for generic type materials in the CP design standards/recommendations such as DNV-RP-B401 [5]. Here, design values for anode closed-circuit potential and electrochemical capacity are given, ref. Table 4-1.

One option for changing the protection potential on structures is the use of materials with a less negative equilibrium (open circuit) potential (and consequently lower driving voltage). In Ref. [29] (1998) several candidate materials were tested with reference to a previously assessed protection range, ref. results cited in Section 5.2.1:

- Pure cadmium (Cd): satisfactory open-circuit potential (around -0.80 V (Ag/AgCl/seawater)), but significant polarisation under current transfer. Alloying with zinc (Zn), indium (In) or mercury (Hg) did not improve performance.

- Pure aluminum (Al): open-circuit potential not stable, significant polarisation under current transfer.
- Aluminium alloyed with zinc (Zn) or indium (In): Resulted in a too negative open-circuit potential vs the target (Zn) or activation with non-stable open-circuit potential (In).
- Aluminium alloyed with gallium (Ga) or cadmium (Cd): Moderate activating effect, satisfactory steady-state (closed-circuit) potentials under current transfer.

Anodic performance testing in cold seawater (2 °C) was then performed for two alloys, Al-0.1% Ga (AG2, ref. Table 6-1) and Al-0.1% Cd. Acceptable performance was demonstrated for alloy AG2, full-scale marine testing was then performed for this material only.

Table 6-1. Chemical composition for alloy AG2 in % [29], remainder aluminium (Al)

Ga	Zn	In	Hg	Cu	Fe	Si	Ni	Mg	Mn	Other
≥0.092 ≤0.110	≤0.15	≤0.005	≤0.005	≤0.005	≤0.08	≤0.1	≤0.005	≤0.01	≤0.01	≤0.005

Anode potentials under various current output values (5 to 200 mA) ranged from -0.83 to -0.80 V (Ag/AgCl/seawater). An average galvanic efficiency of 50% was reported, corresponding to an electrochemical capacity of approx. 1500 Ah/kg [29] (the theoretical electrochemical capacity for pure (unalloyed) aluminium is 2981 Ah/kg [9]).The weight loss was approx. 12% after 2 years operation under medium current density.

Relevant specifications covering alloys for low driving voltage applications are now e.g.:

- EN 12496:2013 [8][1] – alloy A4.
- US.S. Military Specification MIL-DTL-24779D (SH) [35] – low voltage aluminium.

Table 6-2 specifies chemical composition of these alloys while Table 6-3 provides typical values based on normal operating conditions. It should be noted values given for other alloys (e.g. alloy A2) in Ref. [8] are consistently higher than values provided for the equivalent aluminium-based material in DNV-RP-B401, ref. Table 4-1.

Table 6-2. Chemical composition for aluminium anodes given as mass fraction in % [8], [35].

Alloy	Zn	In	Ga	Fe	Si	Cu	Cd	Al
A4 [8]	0.15 (max.)	0.005 (max.)	0.092-0.110	0.08 (max.)	0.10 (max.)	0.005 (max.)	-	Rem.

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[1] Standard ISO/FDIS 9351 under development is based upon revised and updated EN 12496:2013.

Table 6-3. Typical properties of aluminium anodes in normal operating conditions in seawater [8].

Alloy	Closed-circuit potential [V] (Ag/AgCl/seawater)	Electrochemical (current) capacity [Ah/kg] (seawater)
A4	-0.83	1500
A2	-1.09	2500

The electrochemical capacity is significantly lower than for the conventional Al-Zn-In alloys to be replaced. This must be accounted for in the CP design, significantly increasing the number anodes required installed (i.e. the anode net mass) to last the entire design life. Also, the time dependence of capacity noted for other sacrificial anodes (and typically accounted for in the design values recommended) needs to be addressed [36].

When purchasing anode manufacturers' proprietary alloys, see e.g. Ref. [37], the purchaser should require the anode manufacturer to document the electrochemical performance of their products by operational experience or by long term testing. A recommended testing procedure is contained in Sec. 10 of Ref. [5], 'Laboratory Testing of Galvanic Anode Materials for Qualification of the Electrochemical Performance'. To be noted is that data on anode electrochemical capacity from short-term laboratory examinations will typically result in values close to the theoretical value. Even long-term testing (12 months) will tend to result in somewhat non-conservative results and should not be used in design.

The pros and cons of use of low driving voltage anodes as a tool to minimise risk of HISC are summarised as follows:

- Pros:
    - Can control potential in the desired range (if properly designed).
    - Relatively simple installation (same as for conventional anodes).
    - Robust system (if compatible with connected conventional CP system(s). Otherwise, electrical isolation is required.
- Cons:
    - Limited driving anode voltage may increase time to achieve adequate polarisation.
    - Lower electrochemical capacity than conventional Al based anodes (more anode net mass required).
    - Detailed CP modelling required.
    - Conservatism in CP design must be reduced without risking under-protection, testing may be required to establish/confirm design parameters.
    - Interaction with other CP system must be minimised/controlled.
    - Limited track record (behaviour over time when connected to conventional CP system (Al based anodes).
    - Regular monitoring is required to verify that potentials remain within strict potential limits.

6.4 Anode design – galvanic anodes with voltage limit devices

Ref. [20] (1993) concluded that the only practical way of ensuring that the potential limit for hydrogen damage to steel was not exceeded on site was by use of Schottky barrier diodes to separate the anodes from the structure being protected. Potentials indicating correct operation of these systems, or their failure, were stated to be quite definite, and easily measured by conventional techniques:

- Open circuit at anode: -0.70 V (SCE) (potentials vs Ag/AgCl/seawater are approx. the same, ref. Section 2).
- Correct operation: -0.825 V (SCE).
- Short circuit of diode or contact with another system: -0.95 V (SCE), or more negative.

In 1997, modifications already performed on jack-ups experiencing hydrogen-assisted cracking included removal of anodes from affected areas (inside of spudcans) and voltage-limited anodes being connected on the legs [38]. Reference is also made to the case described in Section 7.1.5.

Ref. [30] (2003) stated that diodes had been employed for some offshore production jack-ups, as well as for drilling units. In general, partial removal of coating on the structure was required for the diodes to correctly manage the CP levels. There was no information on the failure rate of diodes used to control CP, but failure of one or several diodes was not expected to cause a severe problem. Problems encountered with CP/diode systems were in some cases explained by the lack of the correct coating and/or poor modelling. The fact that under-protection had been observed raised concern over the risk of pitting corrosion and the effect of such potentials on fatigue crack growth rates. Overall, the experience with long-term effects of CP potentials close to the free corrosion potential (i.e. less negative than -0.80 V (Ag/AgCl/seawater, but values not given) was concluded to be limited at this time.

Ref. [23] (2001) gives one example on use of diodes, the BP Harding jack-up (TPG 500 design), installed in 110 m of water, in 1996. A triangular hull is supported by three 125 m high legs on a fixed concrete base. The highest strength steel (700 MPa) was employed in the racks. Voltage limiting diodes were retrofitted to minimise excessively negative CP levels. It is understood that these have led to more positive potentials in practice than intended, around -0.70 V (Ag/AgCl/seawater), but this may have been due diodes being installed in a partial replacement of the original anode systems and not as part of the original anode installation.

CP of the Elgin-Franklin production jack-up (TPG500 design), installed in 92 m of water with production start-up in 2001, was eventually based on use of conventional anodes. Use of voltage limiting diodes was investigated initially [23], ref. the case described in Section 7.1.1.

To further highlight some of the issues related to the use of diode-controlled anodes, the CP design of a buried 13Cr flowline in the Norwegian sector [39] is described in some detail in Section 7.1.2. Conventional sacrificial anodes were used.

It should be noted that a diode installed between the sacrificial anode and the structure (cathode) shall ensure a sufficient potential drop between the anode and the cathode to minimise risk of HISC while maintaining adequate protection against corrosion. The operation of the diode will require passage of a certain amount of current through it. A low current demand on individual anodes, e.g. due to inherent conservatism in the CP design, will give a potential drop over the diode close to zero, resulting in a potential close to that of the anode without the diode. It should also be noted that the diode characteristics may be temperature dependent, i.e. temperature is a factor to be considered in the CP design with diodes.

In the design of a CP system with diodes, the actual current in the system must be known to be able to predict the actual potential on the structure. The most negative potential is defined by the minimum amount of current required to adequately protect the structure and ensure that there is no risk for under-protection.

Additional measures to ensure to ensure a minimum current through the diode should be considered, e.g. leaving areas without coating.

Like any other components, diodes can fail, i.e. their reliability must be considered in the design. Relevant failure modes should be identified, noting that closed-circuit and open-circuit failure modes will have different impact on CP, open circuit may be regarded as fail safe in terms of avoiding too negative potentials. In addition, the diode housing must be designed to mitigate mechanical damage during installation or operation.

Measurements after installation are required to demonstrate that the diode-controlled CP system work as intended. Also, regular monitoring is required to capture failure of diodes, impact of degradation may, however, be more difficult to diagnose.

The pros and cons of diode-controlled anodes as a tool to minimise risk of HISC are summarised as follows:

- Pros:
    - Can control potential within the desired potential range (if properly designed).
- Cons:
    - Limited driving anode voltage may increase time to achieve adequate polarisation.
    - More complex CP design, extensive testing required to establish design parameters. CP modelling required.
    - Track record limited for used when connected to conventional CP system(s).
    - Increased cost vs conventional anodes.
    - Not possible to control the potential once diodes are installed.
    - Diodes may fail, regular monitoring required to verify that diodes operate satisfactorily and that potentials remain within strict potential limits.

It must be stressed that for diode-controlled CP systems to work properly, they must be electrically isolated from other CP systems, ref. Section 6.1.

6.5 Coating

According to NORSOK M-001 [40] applicable to fixed offshore installations, a coating system in accordance with NORSOK M-501 [41] coating system 7 shall be applied on carbon steel submerged in seawater. A coating system corresponding to system 7B is recommended for areas exposed to seawater at ambient temperature, such as jack-up legs and spudcan.

These coatings are primarily applied to reduce the CP current demand, i.e. to reduce the number of sacrificial anodes required. These coatings are not expected to act as 100% effective barriers against hydrogen charging and HISC, ref. the use of coating breakdown parameters outlined in Section 4.2.

A high quality, thick insulation coating may reduce the risk for HISC, e.g. in highly stressed areas where even narrow cracks/small coating damages can lead to significant local hydrogen uptake. At the same time, this may reduce the possibility of detecting cracks/crack propagation. According to DNV-RP-F112 [31], applicable for duplex stainless steels, coating shall not be used as the only means of preventing HISC by CP (unless agreed by the end user). The combined materials selection and design with respect to maximum allowable stress/strain shall be such that HISC will not occur even if the coating is damaged or removed.

One option is to leave highly stressed areas uncoated. For high strength steels, however, also the bulk hydrogen charging through uncoated surfaces increases the risk of HISC [1]. Consequently, control of protection potential is also required for the uncoated steel.

This may be counteracted by metallising the surface.

Ref. [20] (1993) stated that flame sprayed aluminium (FSA) coatings had been used for the protection of steel offshore for several years, both sealed and unsealed. FSA coatings could be useful for the protection of high strength steels as potentials in the range -0.80 to -0.90 V (SCE) could be expected [42] (potentials vs Ag/AgCl/seawater are approx. the same, ref. Section 2). Applied at sufficient thickness they could ensure a sufficient operating life in terms of corrosion protection. Although these potentials are somewhat on the negative side of -0.83 V (Ag/AgCl/seawater), FSA coatings might be worth further study for high strength steel applications. According to Ref. [30] (2003), however, the potentials associated with these coatings were too negative, between -0.90 and -1.0 V (Ag/AgCl/ seawater).

The outer surface of the legs of the Siri jack-up platform, installed in 60 m water depth in 1998, was coated with hot sprayed aluminium [43]. The lower 27 m of the legs are without holes for the jacking system and was made of 390 MPa steel. The remaining parts of the legs have jacking holes and were made of high strength steel (minimum yield strength 690 MPA, actual yield strength 800 MPa [30]). Difficulties with access for inspection were noted [43]. Even if it in principle would be possible to inspect the legs with traditional MPI, the practical problems of access, weld location and surface protection would make it virtually impossible to inspect the legs by traditionally accepted methods to a high standard of quality.

The Siri installation includes a large oil storage tank to which the legs are connected. All sacrificial anodes are mounted on the storage tank, i.e. 'remotely' vs the legs, ref. Section 6.2. With reference to Ref. [1] and references herein, the potential ranged from -0.95 V to -1.03 V (Ag/AgCl/seawater) after 20 years (-0.90 to -1.0 V (Ag/AgCl/seawater) on the legs), with no reports of any HISC related issues.

In a literature review from 2020, Syrek-Gerstenkorn et al. [44] state that TSA has proven its capability to successfully protect steel in harsh marine environments from corrosion when applied properly. Some of the conclusions relevant for corrosion protection of high strength steels can be summarised as follows:

- Coating thickness is an important parameter that influences performance, the application of sealants can prolong the life of the coating.
- The self-corrosion of the coatings must be distinguished from their ability to protect steel, when the coating is damaged or when connection is made to bare steel. If a large area of steel is exposed, the consumption of TSA can be significantly higher due to the coating providing CP of the exposed steel.
- Simulated laboratory tests should be conducted under intended service conditions. Testing of the coatings in NaCl solutions is not representative of in-service conditions and should be avoided.
- TSA has mostly been used in offshore structures with some form of CP system in place. Recently, TSA has been applied on offshore wind turbines as a stand-alone corrosion control method. However, no standards cover the suitability of using TSA as a primary CP system.

DNV-RP-B401 for example specifies design current densities for components coated with either metallic aluminium or zinc to be used with external CP [5]. Thermally sprayed Zinc (TSZ) shall not be used in seawater immersion service if exposed to a CP system based on aluminium anodes [41]. Sealers recommended by coating manufacturers shall be used to seal the inherent porosity of TSA.

Some gaps in knowledge about TSA have also been identified [44], e.g.:

- The performance of damaged TSA coatings in cold seawater, especially when without external CP (e.g. as a stand-alone CP system).
- The suitability of using TSA coatings for the protection of high strength steels where hydrogen embrittlement is a concern.

The pros and cons of coating/metallisation as a tool for minimising the risk of HISC are summarised as follows:

- Pros:
    - Reduces the number of sacrificial anodes required, depending on type and thickness of coating.
- Cons:
    - Reduces availability for inspection for flaws (fabrication) or cracks (operation).
    - Potential range on the negative side (TSA), depends on method of application and alloy composition.
    - Uncertainties regarding use of TSA as stand-alone CP system.

7 FORCE Technology Experience

7.1.1 Case 1 – Conceptual CP design of jack-up rig (1997)

CP modelling was performed for a jack-up rig of TGP 500 design to demonstrate that the solution selected for CP would maintain potentials between -0.78 and -0.83 V (Ag/AgCl/seawater) for the entire seawater exposed structure and for the parts of high strength steel for a design life of 35 years.

The original coating philosophy considered glass flake epoxy on tubulars and shop primer on leg chords while the rack was to be left uncoated.

Conventional aluminium-based anodes with diode control were considered. The CP models developed considered the impact of temperature on the diode response, based on measurements and/or manufacturer’s data.

Different diodes and diode configurations were tested, results for two parallel diodes per anode are shown in Figure 7-1. The leg chords were coated in accordance with the coating philosophy, and as can be seen this gave too negative potentials initially. This could be resolved by leaving the leg chords uncoated, see results in Figure 7-2. For reference, without the diodes and with coating in accordance with coating philosophy, the average potential on the high strength steel was -1.027 V (Ag/AgCl/seawater) initially and -0.983 V (Ag/AgCl/seawater) after 35 years.

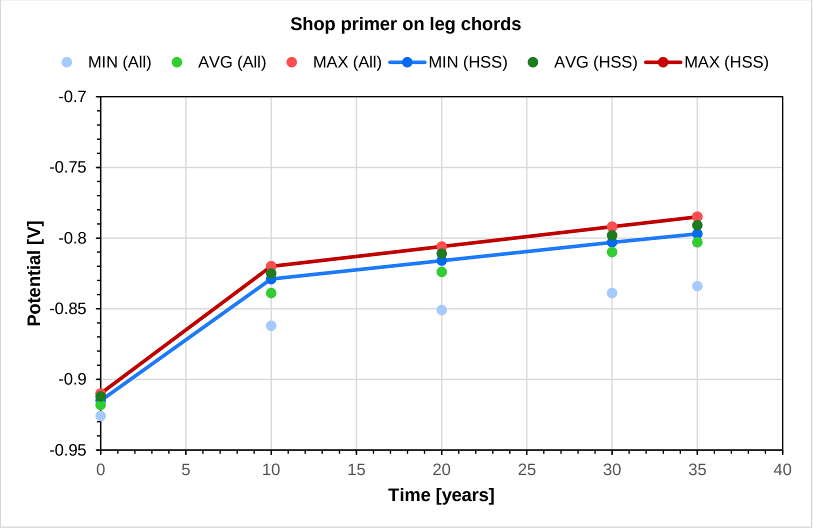

Figure 7-1. CP model result - potential vs time – all steel ('All') vs high strength steel ('HSS') – maximum (MAX), average (AVG) and minimum (MIN) values. Shop primer on leg chords, with diodes.

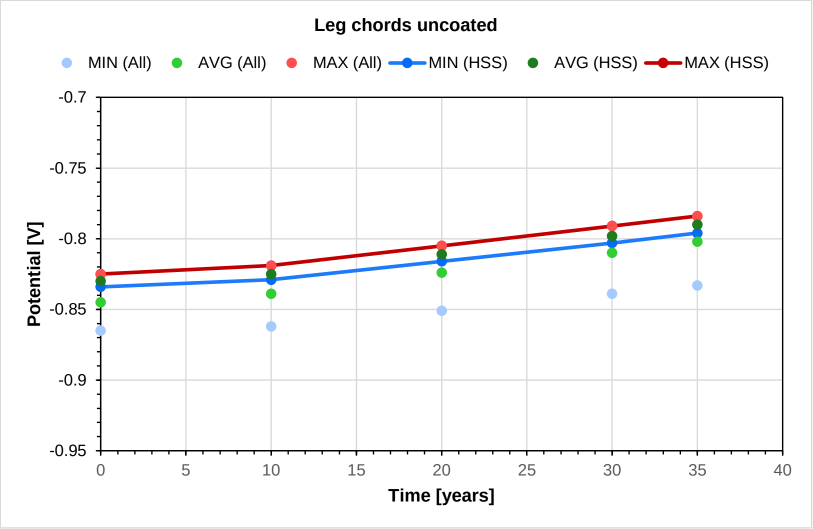

Figure 7-2. CP model result - potential vs time – all steel ('All') vs high strength steel ('HSS') – maximum (MAX), average (AVG) and minimum (MIN) values. Leg chords uncoated, with diodes.

The eventual CP design philosophy selected for this jack-up rig was not based on the use of diode-controlled anodes, mainly because of difficulties related to the bridge linking to a nearby platform (i.e. issues with electrical continuity). Further details are not known.

7.1.2 Case 2 – CP design of 13Cr flowline (2004)

The corrosion protection design of a buried 13Cr flowline in the Norwegian sector was modified with the aim of eliminating production of hydrogen from CP system [39]. Noting that hydrogen would enter the material where coating was damaged, or not applied in the first place, the number and size of such areas were minimised, by improving the quality of the coating and by reducing the number of required penetrations. Conventional sacrificial anodes were used, connected to the pipeline via diodes.

In the design of a CP system with diodes, the actual current in the system must be known to be able to predict the actual potential on the pipeline. The most negative potential is defined by the minimum amount of current required by the pipeline. Extensive testing was performed to estimate the current density requirement for the buried pipeline. Minimum values for the design coating breakdown factors were used in the design.

Stainless steel plates were installed in series with the anode/diode assembly to ensure a minimum current through the diode. Without the cathode plates, a low pipeline current demand, e.g. due to intact coating, would give a potential drop over the diode close to zero, resulting in potentials close to that of the anode without the diode.

The design was based on protection range of -0.60 to -0.75 V (Ag/AgCl/seawater). As the actual current demand of the flowline were not known, the voltage drop over the diode could not be determined with accuracy in the CP design. Consequently, the acceptable potential range was extended, from -0.55 to -0.80 V (Ag/AgCl/ seawater).

Measurements performed on the 13Cr flowline after installation showed that the diode-controlled CP system worked as intended. The potential was shifted towards less negative values and stabilised around -0.70 V (Ag/AgCl/seawater) after approx. a month. This flowline/CP system is still in satisfactory operation. A later CP survey confirmed that approx. 75% of the diode-controlled anodes remained active and that potentials remained within the protection range.

7.1.3 Case 3 – CP design of jack-up rig (2004)

CP design was performed of jack-up platform consisting of 3 truss leg structures on top of skirt foundations, to be installed at approx. 100 m water depth. The CP design was performed in accordance with DNV-RP-B401 (1993) and NACE RP0176 (2003). The structure was to be coated, except for the chords and the welds between the chords.

Hydrogen embrittlement was not considered in the CP design. The negative potential limit was given at -1.10 V (Ag/AgCl/seawater), and conventional Al-Zn-In anodes were used. To be noted is that DNV-RP-B401 (1993) advised to carry out qualification testing whenever materials with SMYS in excess of 550 MPa were to be used for ‘specially critical applications’, or in ‘excessively severe conditions’ for which practical experience was lacking. Further details were not given, except that such applications might involve plastic strain (particularly when combined with cyclic loads) or protection potentials more negative than -1.10 V (Ag/AgCl/seawater).

The jack-up platform is still in operation. Further details are not known.

7.1.4 Case 4 – CP design and modelling for jack-up rig (2019)

The legs of the jack-up in question are made of high strength steel (690 MPa yield strength) and risk of HISC was therefore considered. Potential less negative than -0.83 V (Ag/AgCl/seawater) was regarded as safe CP level, defining the negative limit potential at the start of the project.

Phase 1 of the work involved CP modelling of jack-up and electrically connected structures (with their own sacrificial anodes), to investigate whether safe CP levels on jack-up could be achieved without electrically isolating the jack-up from the rest of the structures:

- Determine potential level of jack-up without any anodes fitted to this structure ('remote' CP).
- Optimise anode distribution on all structures, to maintain adequate protection while minimising the polarisation of the high-strength steel parts.
- Investigate options of leaving parts uncoated.

Preliminary CP simulations showed that a limited potential range of -0.77 to -0.83 V (Ag/AgCl/seawater) could be achieved by a conventional CP system on adjacent structures, but only if the coating on jack-up legs was removed. There would, however, not be sufficient initial current to achieve the polarisation required to develop dense calcareous deposits. Consequently, the current requirement would remain high throughout the design life, and the mean (maintenance) phase would not be achieved.

The following remedial options were then examined, in order of priority:

1. Low-voltage (Al-Ga) anodes.
2. Schottky barrier rectifier (SBR) anodes.
3. Additional anode sleds (installed on seabed (remotely) and electrically connected to structure by continuity cables), connected for as short time as possible to supply the current required to ensure adequate initial polarisation and build-up of good calcareous deposits. The sleds were to be disconnection once this was achieved. If done prior to installation of the jack-up this could minimise the risk of exposing high-strength steel parts to too negative potentials.
4. TSA coating on legs and spudcan. The number of anodes required for the legs would be reduced, but potentials outside of the desired range, from -0.90 to -1.03 V (Ag/AgCl/seawater), were anticipated.

Only option 1 was subject to detailed CP modelling. Figure 7-3 shows results for potential distribution and anode wastage 2 years after installation. CP model boundary conditions were selected in accordance with DNV-RP-B401. Structures with conventional Al-Zn-In anodes are indicated, low-voltage Ga-Al anodes were included on the remaining structures. The structures have reached full polarisation and entered the maintenance (mean) phase. Further development in potential after this time is determined by increased current requirement due to coating breakdown and increased anode resistance due to anode depletion. Figure 7-4 shows potential distribution after 30 years. As can be seen, although large parts of the structures remain adequately protected, some parts of the structures with Al-Ga anodes exhibit potentials less negative than the design protection potential, -0.80 V (Ag/AgCl/seawater).

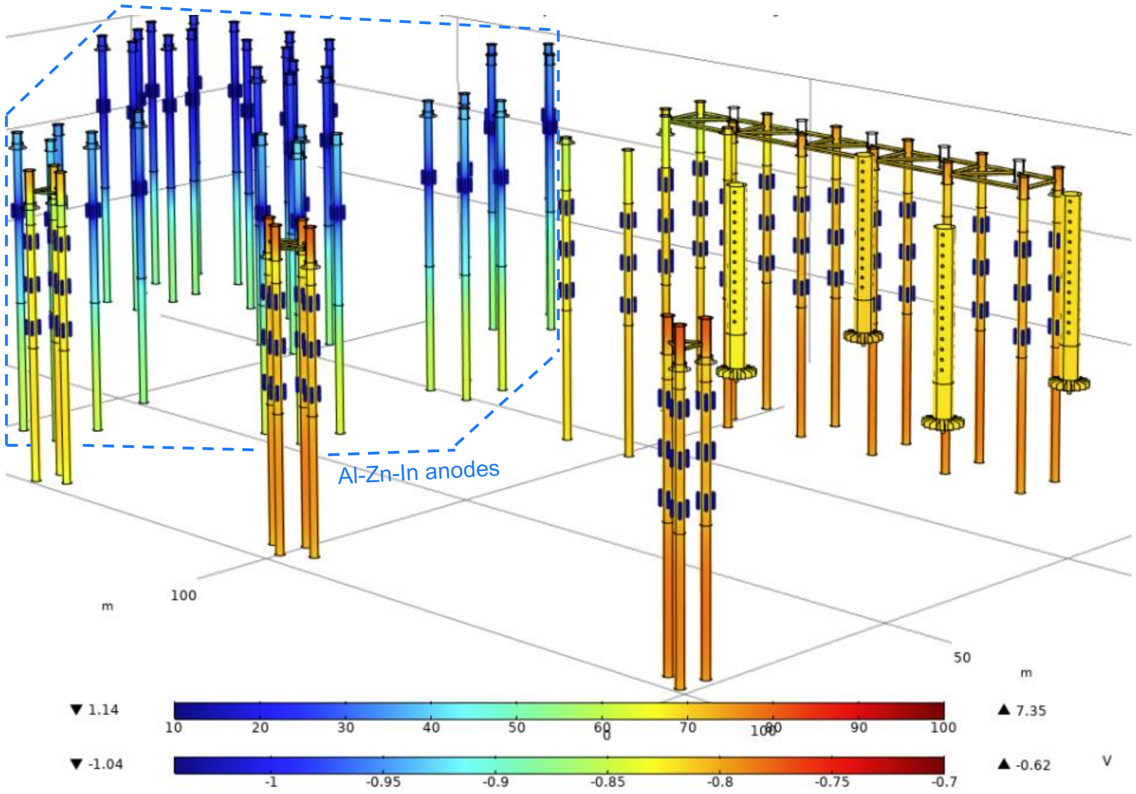

Figure 7-3. Potential distribution (V) and anode wastage (%) after 2 years – locations for Al-Zn-In anodes indicated.

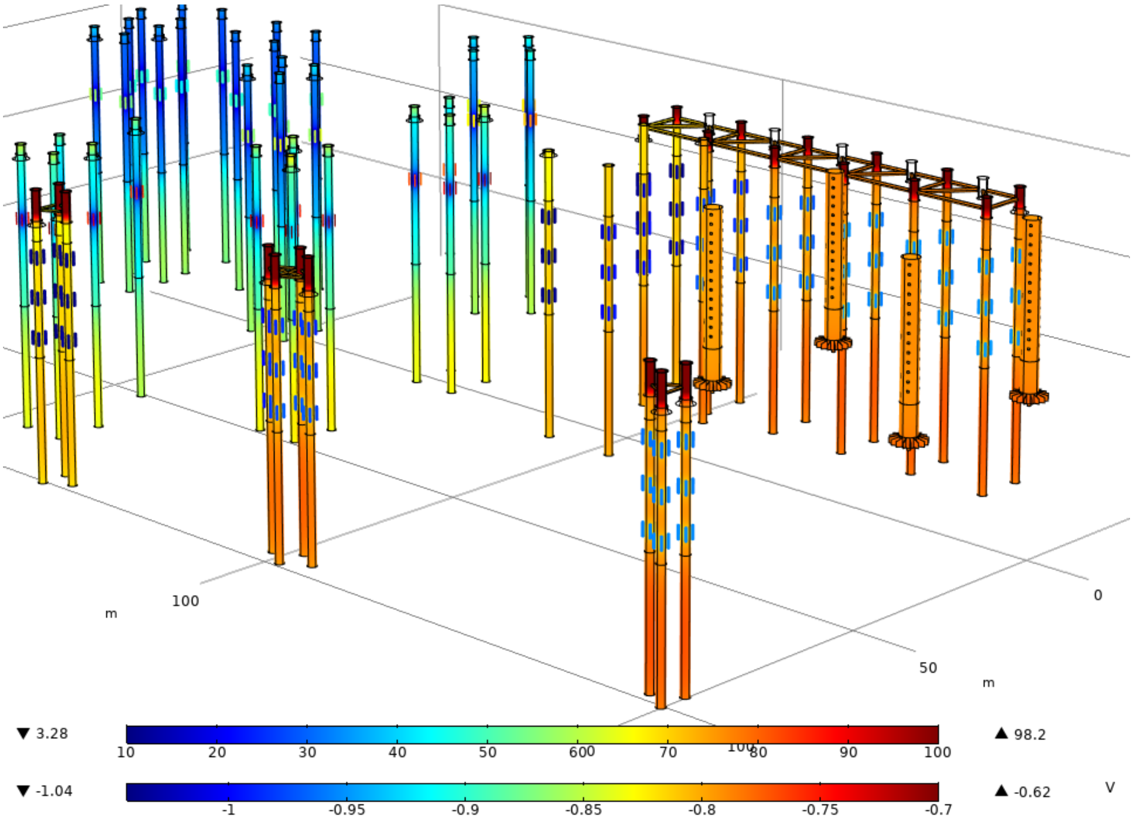

Figure 7-4. Potential distribution (V) and anode wastage (%) after 30 years.

The low voltage Al-Ga anodes, combined with the conventional CP system, were concluded to be most promising of the options considered. The development of under-protection on parts of the structures towards the end of the design life was, however, noted if CP design was based on design input parameters. Also, the low-voltage anodes were regarded as a relatively novel technology, and it was concluded that the use of these anodes in a 'hybrid' CP system would require further evaluation.

In phase 2 of this work, risk of HISC was still a concern, but the negative limit potential had been shifted to -1.05 V (Ag/AgCl/seawater) [26]. The basis for this shift is not known. The jack-up CP design was now based on DNV-RP-B401, with conventional Al-Zn-In sacrificial anodes installed on the spudcans for external CP. All external surfaces were to be coated according to DNV-RP-B401 coating category III.

7.1.5 Case 5 – CP modelling of jack-up rig (2023)

A CP model previously developed for a jack-up drill rig was modified to examine effect of removing anodes from the spudcan due to suspected problems with HISC. The model boundary conditions were verified based on CP inspection data, providing a potential profile for the jack-up when located at a water depth of 110 m.

The purpose of the simulations was to demonstrate that the jack-up would remain protected for water depths ranging from 50 to 110 m, i.e. that anodes remaining on the legs and bracings would be able to adequately protect the structure for the entire design life.

The impact of removing anodes from the spudcan on potentials are summarised in Table 7-1. The potential distribution is shown in Figure 7-5. Removing the anodes from the spudcan had significant impact on the most negative (MIN) potential experienced here, but potentials remained more negative than -0.90 V (Ag/AgCl/seawater).

Table 7-1. CP model of jack-up – potential [V] (Ag/AgCl/seawater), with or without anodes on coated spudcan.

Anodes on spudcan	Spudcan AVG	Spudcan MIN	Legs AVG	Legs MIN
Yes	-0.953	-0.982	-0.958	-0.977
No (removed)	-0.936	-0.944	-0.946	-0.970

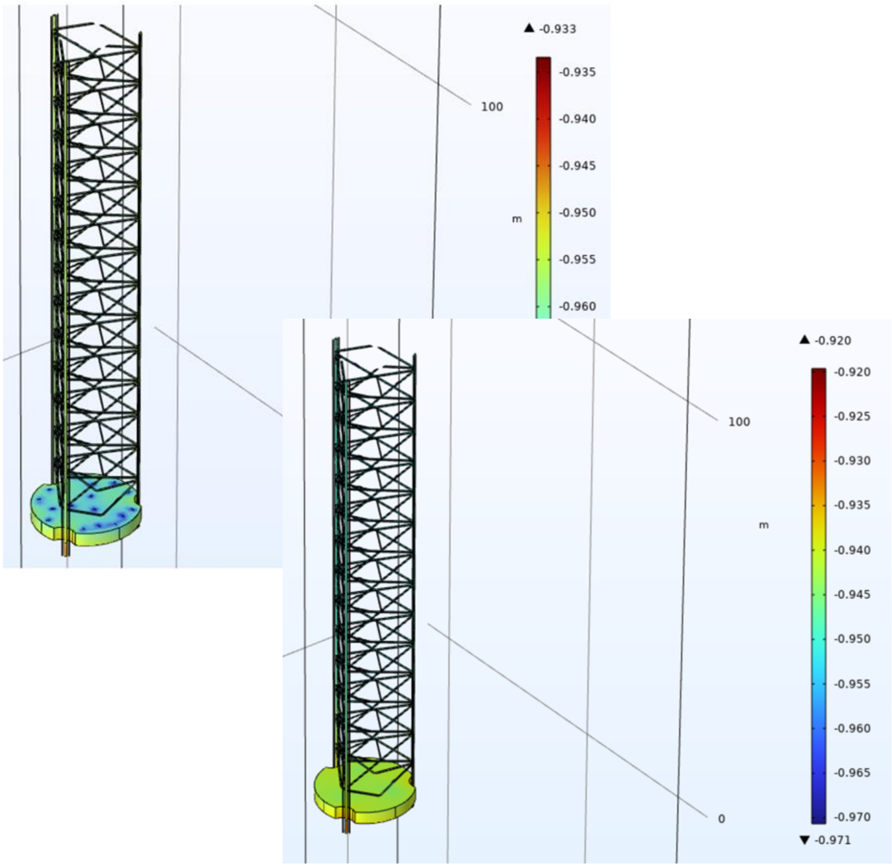

Figure 7-5. Potential distribution (V) – with anodes on spudcan (upper left figure) and without anodes on spudcan (lower right figure).

The subsequent CP model simulation results indicated a slight increase in potential in more shallow waters, i.e. as the ratio between the number of seawater exposed anodes on legs and bracings and the seawater exposed steel surface area was reduced. In very shallow waters (water depth 10 m), the seawater exposed parts of the structure could not be fully protected. Additional CP provided by anodes located on anode sleds (installed on seabed (remotely) and electrically connected to structure by continuity cables) would then be required.

8 Conclusions and Further Work

Testing performed to demonstrate adequate corrosion protection of steel in seawater clearly depends on material composition and environmental conditions. There appears to be no generally accepted criterion for what can be regarded as adequate protection. Rate of uniform corrosion is of interest, but also the distribution of corrosion over the surface, i.e. the tendency for localised corrosion.

Although, it is possible that steels can be sufficiently protected at potentials less negative than -0.80 V (Ag/agCl/seawater), this will have to be verified by testing under relevant conditions. Specifically, the risk of corrosion fatigue must be addressed.

Requirements/recommendations regarding high strength steel and CP, where given, vary somewhat in terms the threshold strength for when risk of hydrogen embrittlement shall be addressed. The negative potential limit for high strength steel is given as -0.83 V (Ag/AgCl/seawater) for steel with SMYS > 550 MPa [19] or for steel with tensile strength > 700 MPa 'if prone to hydrogen embrittlement' [17] (-0.95 V (Ag/AgCl/seawater) if not). This variation may reflect differences in tests performed to demonstrate hydrogen embrittlement/ HISC (or lack thereof). There appears to be no generally accepted test method/ protocol to verify material compatibility with CP. Results from short-term screening tests may not be relevant for actual conditions, while testing fracture performance under relevant conditions is comparatively complicated and time consuming.

Considering -0.83 V (Ag/AgCl/seawater) as a 'safe' negative potential limit with respect to hydrogen embrittlement/HISC, the allowed potential range of potential of the CP design will be very limited. Even if it can be demonstrated by testing that the protection potential required for a given material under specific environmental conditions could be shifted by some mV towards a less negative value, the potential range for which CP needs to be controlled remains tight.

Several strategies for control of protection potential have been outlined in Section 6. One major issue for all these strategies is the fact that conservatism in CP design (which is intended) will result in actual potentials more negative than the design protection potential. A properly executed CP design based on conventional Al-Zn-In anodes and a protection potential limit of -0.80 V (Ag/AgCl/seawater) generally results in potentials of -0.95 V (Ag/AgCl/seawater) or more negative. The most negative potential is limited by the closed-circuit potential of the anode material.

Consequently, designing for a less negative actual potential range by use of conventional anode materials will be difficult as the 'minimum' requirement of the structure will not be known in the design phase. Also, detailed CP modelling is required to distribute the anodes.

Use of anode materials with low driving voltage, i.e. Al-Ga anodes, has been considered. The lower driving voltage and electrochemical capacity of these anodes compared to the values for conventional aluminium based anodes imply that more anodes will have to be installed to ensure efficient initial polarisation and sufficient anode net mass to last the entire design life. It may therefore be necessary to combine these Al-Ga anodes with conventional Al-Zn-In anodes located elsewhere to fulfil these requirements. The long-term experience with such 'hybrid' CP systems is limited. If not carefully balanced, the conventional CP system(s) may well render the anodes with the lower driving voltage inactive.

The same concern applies for the use of diode-controlled anodes. Here, the minimum amount of current required for satisfactory operation of the diodes must be determined and it must be ensured (e.g. by leaving parts of the structure uncoated) that such current is supplied by the anodes during operation. Again, more realistic CP design input values will have to be used. The installation of the additional components (diodes) that may fail (get damaged) during operation will add to the complexity (and cost) of a CP system based on diode-controlled anodes.

As part of the design of diode-controlled anodes for a 13Cr flowline outlined in Section 7.1.2, the verification scheme of Table 8-1 was identified. In addition to this, the need for sensitivity calculations (what-if analyses) in terms for design parameters were identified, i.e. for potential/current (polarisation curves), temperature, anode distribution, etc.

Table 8-1. Design data verification.

Parameter	Laboratory testing	Full-scale testing (site)
Protection potential	X	X
Current requirement	X	X
Performance of anodes		X

The use of CP systems with diode control has been discussed in several projects with high-strength steel jack-up rigs where FORCE has been involved. However, the conclusion based on thorough evaluations and testing during the design period was that these jack-up rigs were compatible with the use of conventional CP provided by Al-Zn-In anodes. CP models of the jack-ups demonstrated that the potential distribution on all surfaces was within the range expected for a proper CP design.

With regards to coating, this is a factor that will require careful consideration when performing CP design of materials that may be sensitive to hydrogen embrittlement. The possibility of performing inspection for cracks in critical areas is also to be considered.

With conventional Al-Zn-In anodes, a primary concern will be narrow cracks exposed to seawater in an otherwise fully coated structure. Potentials here may become relatively negative. With diode-controlled anodes, on the other hand, the safe operation of the diodes requires a certain amount of current transferred, hence some steel must be left uncoated to ensure this.

In the fatigue design for the jack-up, the risk of corrosion fatigue must be addressed, but also the impact of CP on the fatigue properties. DNV-RP-C203 does not specify potential range for SN-data under CP, but -0.80 to -1.05 V (Ag/AgCl/seawater) appears reasonable [5]. A large part of the fatigue life should be associated with initiation of a fatigue crack and growth of small cracks. For structures with a good coating the cracks must grow to some size before the coating is broken, and until this happens the condition corresponds to that of air. The probability of having a fatigue crack of this size will then have to be considered in the analyses [14].

If a CP design philosophy based on tighter control of potential than specified in conventional CP design based e.g. on DNV-RP-B401 [5] the issue of electrical continuity with adjacent structures (e.g. bridge-linked platforms) or pipelines with conventional CP systems must be addressed, i.e. the need for electrical isolation. If not properly accounted for, the conventional CP system(s) may well render the carefully modified CP system on the jack-up inactive and result in potentials outside of the tight design potential range. Regular CP inspections and/or monitoring will be required to ensure that potentials remain within the design range. It should, however, be noted that once CP systems based on anodes with low driving voltage or diode-controlled anodes have been installed, remedial actions are limited.

Consequently, although steps may be taken to reduce the risk of hydrogen embrittlement/HISC through careful selection of CP design input parameters to reduce conservatism, it is regarded as somewhat complicated to control potentials in a range close to the protection potential limit. With reference to the recommendations from the previous study ([1], ref. Section 3.1), additional steps to be taken are:

- Select materials that ensure a low intrinsic susceptibility to hydrogen embrittlement, demonstrated by testing under relevant conditions.
- Select of weld procedures, QA/QC programs and NDT methods appropriate to preventing weld flaws and other imperfections to remain undetected. For recommendations regarding areas to be inspected and relevant methods for detection of defects from fabrication, reference is made to Ref. [2].

Irrespective of these considerations, the use of CP modelling as a versatile and indispensable tool in the CP design for jack-up rigs is demonstrated.

Further work:

- The main limitation of the present study is that industry stakeholders are not represented. A more detailed survey on how the issue of hydrogen embrittlement/HISC is handled practically in the design and follow-up of jack-up CP systems should be performed, especially since there is some variation in requirements/recommendations given in relevant design documents.
- The amount of literature consulted as part of the present study is relatively limited, e.g. in terms of testing with respect to determine/verify protection potential and negative potential limit vs hydrogen embrittlement. With respect to the latter, a more detailed search for literature regarding fracture mechanics testing under CP is recommended, specifically with the aim of identifying tests performed under conditions that may be relevant for offshore operation and the relevance of results from short-term (laboratory) results.

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