Petroleum and natural gas industries — Arctic operations — Material requirements for Arctic operations

Industries du pétrole du gaz naturel — Opérations dans l'Arctique — Prescriptions pour les matériaux pour les opérations dans l'Arctique

DTS stage
Contents

Foreword ................................................................................................................................. 5

Introduction ........................................................................................................................... 6

1 Scope .................................................................................................................................. 7

2 Normative references ......................................................................................................... 7

3 Terms and definitions ......................................................................................................... 7

4 Symbols ............................................................................................................................... 8

5 Abbreviated terms ............................................................................................................. 8

6 Technical basis ................................................................................................................... 9

6.1 Design considerations ....................................................................................................... 9

6.1.1 Present applications and industrial achievements ....................................................... 9

6.1.2 Developments for future applications ....................................................................... 9

6.1.3 Areas of concern in design for Arctic structures ......................................................... 9

6.1.4 Fracture assessment .................................................................................................... 10

6.2 The effects of low temperatures on mechanical properties of steels ............................ 11

6.2.1 Tensile properties ...................................................................................................... 11

6.2.2 Fracture toughness .................................................................................................... 14

6.2.3 Arrest toughness ....................................................................................................... 15

6.2.4 Fatigue ....................................................................................................................... 15

6.2.5 Residual stresses and crack pattern ........................................................................... 16

6.3 Environmental conditions ............................................................................................... 17

6.3.1 General ...................................................................................................................... 17

6.3.2 Temperature and definition of LAST ...................................................................... 17

6.3.3 Seawater conditions ................................................................................................. 17

6.4 Principles for qualification and quality assurance .......................................................... 18

6.4.1 Steel making technology .......................................................................................... 18

6.4.2 Welding technology .................................................................................................. 18

7 Material and fabrication requirements ............................................................................... 18

7.1 Material selection and qualification ............................................................................... 18

7.2 Mechanical properties .................................................................................................... 19
7.2.1   Tensile properties ........................................................................................................... 19
7.2.2   Fracture toughness ......................................................................................................... 19
7.2.3   Pre-qualification testing .............................................................................................. 22
7.3    Crack arrest assessment ................................................................................................. 23
7.4    Fatigue properties, alternative testing ............................................................................ 23
7.5    Welding and fabrication requirements ............................................................................ 24
  7.5.1   Contractor certification .............................................................................................. 24
  7.5.2   Base material ............................................................................................................. 24
  7.5.3   Welding consumables ............................................................................................... 24
  7.5.4   Welding procedure qualification .............................................................................. 24
7.6    Welding procedure qualification test requirements .......................................................... 24
  7.6.1   General requirements .............................................................................................. 24
  7.6.2   Welding procedure qualification testing .................................................................... 25
  7.6.3   Testing requirements ............................................................................................... 25
7.7    Protection against corrosion and wear ........................................................................... 27
  7.7.1   General ...................................................................................................................... 27
  7.7.2   Corrosion protecting coating at low temperature ....................................................... 27
  7.7.3   Cathodic protection ................................................................................................... 27
8   Quality control, quality assurance and documentation ..................................................... 27
  8.1    Structural steel requirements ....................................................................................... 27
  8.2    Welding and fabrication requirements ......................................................................... 28
9   Operational topics .............................................................................................................. 28
  9.1    Requirements for operations in remote areas ............................................................... 28
        9.1.1 General .................................................................................................................... 28
        9.1.2 Low temperature operations ................................................................................... 28
        9.1.3 Ice and snow removal ............................................................................................ 28
  9.2    Corrosion and wear control ......................................................................................... 29
        9.2.1 General .................................................................................................................... 29
        9.2.2 Splash zone surfaces in direct contact with sea ice ................................................ 29
        9.2.3 Submerged surfaces and cathodic protection .......................................................... 29
        9.2.4 Topside surfaces .................................................................................................... 30

Bibliography ............................................................................................................................. 31
Foreword

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

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

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

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

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO’s adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 67, Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries, SC 8, Arctic operations.
Introduction

Operations in Arctic environment is characterised by low ambient temperatures, presence of sea ice, ice bergs and icing of structures and components. In many cases it is also associated with remote locations relative to infrastructure and logistics. Maintenance operations are therefore expensive and accidents leading to emissions can have severe environmental consequences.

Structural failure is in most cases failure of materials, and caused by well-known degradation mechanisms such as fatigue and corrosion. Under Arctic conditions, failure due to possible brittle materials behaviour needs to be given special consideration.

This document is developed to bridge the gap between the functional requirements to offshore structures in Arctic environment given in design standards and the material requirements given in material and fabrication specifications where Arctic operating conditions have not been considered in sufficient detail.
Petroleum and natural gas industries — Arctic operations — Material requirements for Arctic operations

1 Scope

This document provides recommendations for material selection, manufacturing and fabrication requirements, testing and qualification of steel structures and components for offshore and onshore petroleum and natural gas facilities operating in Arctic and cold environment.

This document is intended to be used as a supplement to existing standards for steel structures where the particular operating conditions in Arctic regions are not sufficiently addressed.

This document gives particular requirements to ensure safe operation with respect to the risk of brittle fracture at low temperatures. These requirements will affect the selection of material grade and design class as well as the technical delivery conditions for steel. They will also affect the fabrication requirements as well as testing and qualification requirements.

This document also gives recommendations:

— to mitigate the operational and integrity aspects related to snow and ice accretion on topside structures;

— to take into account the particular Arctic operating conditions in the corrosion assessment and requirements to corrosion protection systems;

— for particular operational requirements to ensure safe operation in Arctic regions.

The requirements in this document are applicable to any operating temperatures, but particular requirements related to de-rating (loss of strength) at high temperatures are not addressed. Limitations to the applicable minimum design temperature caused by the capability of the materials low temperature performance can exist, but is not a limitation for the scope of this document.

As a practical guideline for the use of this document, low temperature is defined as minimum operating temperature lower than –10 °C.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 19902:2007, Petroleum and natural gas industries — Fixed steel offshore structures

EN 10225:2009, Weldable structural steels for fixed offshore structures — Technical delivery conditions

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 19900, ISO 19901-1, ISO 19901-2, ISO 19901-4, ISO 19902 and ISO 19906 apply.
ISO/DTS 35105:2016(E)

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

- ISO Online browsing platform: available at http://www.iso.org/obp

4 Symbols

The following is a summary of the main symbols that are used throughout this document. Other symbols are defined where they are used. This use includes main symbols with one or more subscripts when a more specific use and associated definition of the symbol is intended.

- $a$: defect height
- $c$: defect half length
- $h_{\text{char}}$: characteristic height
- $T$: temperature
- $t$: thickness
- $X_\delta$: constraint correction factor for CTOD
- $\gamma_{\text{CTOD}}$: safety factor on characteristic CTOD
- $\gamma_m$: materials safety factor
- $\sigma_b$: average bending stress acting over the characteristic height
- $\sigma_{\text{eff}}$: effective stress utilization
- $\sigma_{\text{TS}}$: tensile strength
- $\sigma_t$: average tensile stress acting over the characteristic height
- $\sigma_y$: yield stress
- $\sigma_{y0.2}$: 0.2 % yield stress
- $\tau_t$: average shear stress acting over the characteristic height

5 Abbreviated terms

- BM: base material
- C-Mn: carbon manganese
- CTOD: crack-tip opening displacement
- HAZ: heat affected zone
LAST  lowest anticipated service temperature
PWHT  post weld heat treatment
SMYS  specified minimum yield stress
UEL   uniform elongation
WM    weld metal

6 Technical basis

6.1 Design considerations

6.1.1 Present applications and industrial achievements

Offshore field developments have been carried out in the northern part of the Atlantic Sea offshore New
Foundland, United Kingdom and Norway with successful application of structural steels designed for
LAST equal to \(-10^\circ\text{C}\) with technical delivery conditions specified by EN 10225 and corresponding API
standards with weldability qualification in accordance with API RP 2Z. NORSOK N-004 has also
extended the application range of the design requirements to \(-14^\circ\text{C}\).

Developments have also taken place in colder areas, such as Barents Sea, offshore Sakhalin and the
Caspian Sea. In these cases project specific requirements to structural steel qualification has been
provided to compensate the lack of industry standards. After delivery to these projects, the steel
industry has promoted “Arctic steel grades” as available for more industrial applications. However,
unified requirements and documentation of performance is still missing.

6.1.2 Developments for future applications

As the offshore industry moves to Arctic and other cold areas, cost efficient solutions for low
temperature applications are needed. Therefore, the low temperature performance, testing
requirements and acceptance criteria as well as alternative steel grades has been investigated to reach
this goal. In addition to the field experience, results from such investigations form the basis for this
document. Investigations have been carried out at temperatures down to \(-60^\circ\text{C}\). A short term realistic
temperature limit is \(-40^\circ\text{C}\) unless very specialized alloying systems are implemented.

As a design consideration, it shall be taken into account that it is not sufficient to demonstrate
acceptable properties at low temperatures. It is also mandatory to demonstrate that these properties
can be combined with cost efficient fabrication procedures including e.g. heat input, pre-heating and
post weld heat treatment.

6.1.3 Areas of concern in design for Arctic structures

At low temperatures the risk of brittle fracture in structural steels will be more significant and it is
required to establish a specific fracture limit state to verify a safe design. A particular feature of a brittle
fracture mechanism is that it can affect the redundancy of the structure after a local overloading, as it is
difficult to predict the extent and path of brittle crack extension.

The introduction of a fracture limit state include an á priori assumption that a crack is present at the
location considered. As the combination of high stress level and crack is associated with certain
likelihood, this is inevitably a probabilistic issue, and it is highly dependent on the fabrication quality and inspection level of the structure.

The most critical failure locations associated with low temperature behaviour of welded steel structures are WM and HAZ. The BM is usually less critical, because the properties are normally better and the likelihood of defects is smaller. However, in forged and cast steel, also BM should be considered.

The brittle fracture resistance is controlled by the steel temperature, while the LAST has to be defined on the basis of environmental temperature data in combination with operational factors. The minimum steel temperature should be estimated as part of the design process, but can be conservatively estimated from the ambient temperature.

The main effects of low temperatures on mechanical properties of steels shall be clarified in order to document the feasibility of the steel and welding procedure in terms of weld metal and HAZ toughness, see ISO 19902:2007, Annex F, or if other requirements should be given. With regard to “low temperatures” the main focus will be temperatures in the range $–60 \, ^\circC$ to $–10 \, ^\circC$. For testing, this may require temperatures down to $–90 \, ^\circC$. The temperature will have an effect on both elastic, plastic, and fracture properties of steels. The former is apparently less significant than the two others in the temperature range considered, and is not discussed in detail. Regarding plastic and fracture properties the following main categories are considered:

— tensile properties;

— fracture toughness;

— arrest toughness;

— fatigue.

6.1.4 Fracture assessment

Resistance to deformation and separation in atomic lattices is intimately linked to energies representing barriers to these features. In general the thermal energy in the material will affect the available energy to overcome barriers for these mechanisms. For plastic deformation, it is observed that the resistance will increase with decreasing temperature due to less thermal energy available in the system to help overcome e.g. barriers to dislocation movements. This leads to an observed increase in yield stress with decreasing temperature. The resistance to initiation of cleavage fracture is closely linked to the stress level possible to achieve in the material. This stress level is again correlated with the tensile properties of the material. As the yield stress increase with decreasing temperature, the local stress level in the material increases, and the likelihood of initiation of fracture increases accordingly.

Fracture assessments in general address both considerations regarding initiation of crack growth and possibly arrest of propagating cracks. Further, a distinction between initiation of crack growth and arrest will depend on the magnification used to study the phenomenon. Fracture is a strongly multiscale phenomenon, ranging from the details around separation of atoms up to observations at the continuum level. In this document classification is related to the continuum level. Thus, the term “fracture toughness” is taken to represent the resistance to initiation of crack growth leading to crack extension typically of the order of 1 mm or more (i.e. significantly longer than the typical microstructural length scales). In the same fashion, the “arrest toughness” is taken as the resistance needed to arrest cracks having propagated 1 mm or more.
6.2 The effects of low temperatures on mechanical properties of steels

6.2.1 Tensile properties

With regard to the effects of tensile properties on low temperature behaviour of steels, they can be divided into explicit and implicit effects. The explicit effects consider the resistance to plastic deformation in the material and the level mismatch in inhomogeneous material systems (e.g. welds). Implicit effects are addressing fracture and fatigue through influence of the magnitude of stress levels and size of local plastic zones.

The key engineering tensile properties are:

— the yield stress;
— the tensile strength;
— the uniform elongation (UEL);
— the fracture strain.

The parameters are illustrated in Figure 1. Regarding the yield stress different definition are applied, however, the most frequently used is the stress level corresponding to 0.2 % permanent deformation of the material. In addition, some steels will display discontinuous yielding, or so-called Lüders band formation.

![Figure 1 — Tensile property parameters](image)

Leaving out very high strain rate scenarios, where inertia effects start to play significant roles, the effects of temperature and strain rate on plastic properties are claimed to be of similar nature. The basis for this is that they are affecting the activation energy for dislocation movement in the same way. Zener and Holomon proposed the following general relation to describe the phenomenon:
\[ \sigma_y = f \left( T \log \left( \frac{A}{\dot{\varepsilon}} \right) \right) \]  

(1)

where

\( \sigma_y \) is the yield stress;

\( T \) is the temperature;

\( A \) is some constant related to the activation energy;

\( \dot{\varepsilon} \) is the strain rate.

The detailed nature of the function should be determined through experimental testing as there are no theoretical models available to deduce this directly. Figure 2 shows examples of evolution of yield stress and tensile strength with temperature for two different materials not normally used for structural applications.

**Figure 2 — Temperature dependence of yield and tensile strength**

There are empirical relations proposed in the literature to describe the effect of temperature on tensile properties. BS 7910 provides expressions for both the yield stress and tensile strength as function of temperature. The formula for the yield stress is as follows:

\[ \sigma_{0.2,T} = \sigma_{0.2,T,\text{room}} + \frac{10^5}{491+1.8T} - 189 \text{ [MPa]} \]  

(2)

where

\( \sigma_{0.2,T} \) is the yield stress at the actual temperature;

\( \sigma_{0.2,T,\text{room}} \) is the yield stress at room temperature;

\( T \) is the temperature.
The formula for the tensile strength is:

\[
\sigma_{TS,T} = \sigma_{TS,\text{room}} \left( 0.7857 + 0.2423 \exp \left( -\frac{T}{170.646} \right) \right)
\]  

(3)

where

\(\sigma_{TS,T}\) is the tensile strength at temperature \(T\);

\(\sigma_{TS,\text{room}}\) is tensile strength at room temperature.

No relation to describe the effect of temperature on the UEL has been found in the literature. The actual fracture strain will also be linked to damage evolution and local fracture in the material, and believed to be a complex function of the microstructure. In case of localized yielding heating of the material due to frictional heating from the plastic deformation can affect the local tensile properties. Thus, in case of higher strain rates, adiabatic effects may also be needed to consider. However, this is outside normal structural applications.

Systematic experimental investigations of the effect of temperature on tensile properties in structural C-Mn steels in the strength range 350 MPa - 500 MPa have provided the following observations (see reference [22]):

— The yield stress increases with decreasing temperature, however, the magnitude depends on the microstructure. The relation proposed in Formula (1) tends to overestimate the increase in yield stress for some steels and will usually be neglected.

— The increase in tensile strength is more linear with decreasing temperature compared to the yield stress.

— The UEL does not seem to be significantly affected by a reduction in temperature (an exception is materials displaying Lüders strain, where it actually increases with decreasing temperature; see comment regarding Lüders strain at next bullet).

— For materials exhibiting Lüders strain, it has been observed that the length of the Lüders plateau increases with decreasing temperature.

— The actual fracture strain may be somewhat affected by a reduction in the temperature. However, this effect is related to evolution of damage in the materials and is thus not only described by engineering tensile properties of the material.

In case of structural design (not covering fracture and fatigue assessments) the implications are as follows:

— for design in the elastic region the observed results may be neglected;

— for design at low temperatures, possibly involving gross plasticity, the following aspects should be considered:
  
  — the \(Y/T\) ratio will increase with decreasing temperature;

  — the detailed shape of the stress-strain curve will change;
— for inhomogeneous materials, systems mismatch levels between different materials may change compared to the ones observed at room temperature.

6.2.2 Fracture toughness

As defined in 6.1.4 the fracture toughness is taken as the resistance to initiation of fracture. To distinguish between minor microcracking events and fracture, propagation should be in the order of 1 mm or more. The type of fracture considered is primarily cleavage crack growth. Steel with ferritic or martensitic microstructure (body centered cubic (BCC)) lattice is associated with ductile to brittle transition, as illustrated in Figure 3. At high temperatures the materials ultimately fail by a ductile mechanism, usually requiring a significant supply of energy to be sustained. This temperature region is usually termed the “upper shelf”. At very low temperatures the materials are intrinsically brittle and fail by the cleavage mechanism. Crack propagation takes place with very little requirements for additional energy being supplied to the system. This temperature region is usually termed the “lower shelf”. In between the two regions mentioned above the so-called “transition region” is found. In this region ultimate failure is still governed by cleavage fracture, however, the resistance to initiation of fracture is progressively increasing as the temperature increases and plasticity starts to play a greater role. The transition region is sometimes divided into the “lower transition” and “upper transition”. The reason for this is that there is apparently a shift in the role played by different microstructural features in the material, which again affects the shape of the transition curve.

![Figure 3 — Schematic toughness transition curve](image)

The temperature range in which the transition takes places is strongly connected to the microstructures and chemistry of the steel. Further, from a continuum point of view the fracture toughness tends to be a statistical parameter with a significant associated scatter. In addition, the actual fracture toughness of the material will be affected by parameters like the load level, defect size, and possible mismatch conditions through so-called constraint effects.

For many C-Mn steels, and especially associated HAZ microstructure and weld metals, the materials response can be in the transition region for temperatures of relevance for Arctic applications. Thus, a
failure by the cleavage mechanism cannot be ruled out. Safe design of steels structures should take this into account. There are currently no predictive models for fracture toughness estimation based on chemical composition and microstructural features. Hence, the fracture toughness should be established through experimental testing. There are however semi-empirical models available, e.g. the master curve and the Beremin models, that can be used to describe scatter and quantify effects of temperature and constraint on fracture toughness.

6.2.3 Arrest toughness

A cleavage fracture that has been initiated may eventually be stopped, or arrested, if:

— the applied load levels are no longer capable of sustaining the crack growth;

— the propagation takes place towards an increasing temperature gradient resulting in increasing resistance to crack propagation;

— the propagation takes place towards a materials gradient with increasing resistance to crack propagation.

Thus, crack arrest may be regarded as a potential second barrier to failure due to fracture, if the propagating crack can be stopped prior to reaching a critical size with regard to global structural stability. The first category is associated with the applied loads, whereas the two last ones are associated with the properties of the materials.

As for the fracture toughness associated with initiation of cleavage fracture, the arrest toughness is also depending on the temperature. Experimental observations show that the arrest toughness goes down as the temperature is decreasing. It has been proposed that the dependency of temperature is similar to the one found in the master curve for fracture toughness. However, as the arrest of propagation crack is rather a “strongest link” mechanism as opposed of initiation of fracture which follows a “weakest link” mechanism, the dependency of temperature is probably differing between the two. Results in the literature indicate this to be the case, and there are evidence that the resistance to crack propagation drops faster with temperature compared to the resistance to crack initiation. Whereas the main concern regarding fracture toughness is associated with HAZs and weld metals, the arrest toughness of the base materials can be of significant importance as the running cracks is highly likely to propagating in the latter material.

The topic of quantitative crack arrest assessments is challenging both due to the issue of establishing relevant arrest toughness data and performing detailed analysis of the crack tip conditions in complex structures. There are several different test methods to assess crack arrest properties ranging from simpler go/no-go criteria to quantitative estimates of the arrest toughness, but none have materialized as the primary choice. Despite the challenges of assessing crack arrest, the ability to arrest running cracks can be of significant importance for design under Arctic conditions. This is related to uncertainties whether experience at higher temperatures are mainly associated with characteristic fracture toughness values at the actual temperature, or whether arrest properties also having played an important role.

6.2.4 Fatigue

Fatigue damage is both related to the initiation of fatigue crack growth in the absence of macro defects and threshold values/growth rates for existing macro defects. The former issue is usually designed
against using the SN-approach. The effect of temperature on the SN-approach has not been investigated in detail. Some studies have been presented regarding the effect of low temperatures on fatigue crack growth in presence of macro defects, based on the use of fracture mechanics. The results from these studies have pointed towards the following main features:

— There apparently exists a transition temperature also in case of fatigue growth.

— For temperatures above the transition temperature, lower temperatures in general results in somewhat lower fatigue crack growth rates and somewhat higher threshold values, when evaluated against $\Delta K$, compared to values established at room temperature.

— Below the transition temperature the fatigue crack growth rate tends to increase significantly compared to room temperature.

The mechanisms of reduced fatigue crack growth rate and increased threshold values for lower temperatures, above the transition temperature are explained due to the increasing yield stress with decreasing temperature. The size of the plastic zone in front of the crack scales inversely with the square of the yield stress. Thus for a fixed $\Delta K$, the plastic zone believed to be associated with both fatigue crack growth rate and threshold values, is reduced, thus resulting in lower crack growth rate/higher fatigue threshold value. The mechanism behind the fatigue transition is currently not established.

From a design point of view, the first key question will be whether any significant fatigue loading can take place below the fatigue transition temperature. If this is not the case, the results in the literature suggest that conservative assessments may be made using room temperature data. The transition temperature can be established through actual fatigue crack growth rate testing. However, such testing is extremely time consuming and it is considered to be acceptable to perform fatigue testing at room temperature as long as the fracture toughness is acceptable at low temperature. Until further data is available today's standard for fatigue assessment should be applied, assuming that materials with proper fracture toughness are used such that brittle failure for small fatigue cracks (less than the plate thickness in depth) is avoided. Reference is made to ISO 19902 Section 16. If material with less fracture toughness is used, such that the probability of an unstable fracture is increased with small fatigue cracks present, this may be accounted for by a larger design fatigue factor (DFF) or alternatively by shorter in-service inspection intervals.

### 6.2.5 Residual stresses and crack pattern

Although not directly a materials property, residual stresses will affect the fracture behaviour of materials/structures, especially in case of low fracture toughness/small applied loads (as in the case of high cycle fatigue crack growth). Residual stress can have several sources and action ranges including local stresses from welding and more long ranging stresses that builds up during assembly of complex structures.

The topic of the effect of low temperature on residual stresses has not been studied in detail. The following general considerations can be made. Long range residual stress due to assembly of components could possibly increase, as the thermal contraction can lead to further increase of the misfit induced stresses. For local welding induced stresses the topic is probably related to whether the temperature would have any effect on possible plastic deformation. In case of residual stresses having been introduced at higher temperatures, and which not lead to any new plastic deformation at
reduction of temperature, the effect of temperature on the residual stresses is most likely not very high. Actually performing welding at lower temperatures could potentially affect the cooling times, which again can affect the build-up of residual stresses.

The effect of reducing the temperature on ductile fracture resistance has not been studied in detail. It is believed to be of secondary importance compared to the effect of temperature on the possible transition to cleavage fracture controlled failure. Further, the general use for predicting longer ductile crack extensions is mainly associated with design scenarios looking into larger gross plastic deformation. This latter scenario is not seen to be the most relevant design scenario for low temperatures in the Arctic.

Creep of materials is mainly a high temperature phenomenon and is not believed to be of concern for low temperature design scenarios in the Arctic.

6.3 Environmental conditions

6.3.1 General

Guidance on environmental conditions for Arctic regions in included in ISO 19906.

6.3.2 Temperature and definition of LAST

The risk of brittle fracture in structural steel is associated with the steel temperature. The steel temperature is in turn controlled by the ambient temperature, but there is a time dependence caused by the limitations of the heat flux to cool down and heat up the structure. Hence, the definition of the lowest anticipated service temperature (LAST) should be based on a reliable estimate of the minimum steel temperature.

ISO 19906 defines LAST as “minimum hourly average extreme temperature”. This definition has several functions including material performance, machinery lubrication, sealants and other winterisation aspects. For structural steel, this definition might be conservative, as it is associated with the ambient temperature and not the steel surface temperature. It is therefore recommended to allow for an assessment of the appropriate averaging period (e.g. 3 hours or 6 hours). In this assessment, the effect of coating, wind chill, wall thickness, etc. should be included.

LAST shall also be associated with a statistical significance in terms of a return period. ISO 19902 does not provide explicit guidance on this. In NORSOK N-003, where also a lower extreme value is used to define a minimum design temperature, it is proposed to use a return period of 100 years (annual probability of 10^{-2}). This value is considered as a reasonable number to ensure that the annual probability of failure is acceptable (e.g. 10^{-4}). However, as the low temperature integrity assessment normally is a combined assessment of load resistance at low temperature, it is actually the joint distribution of temperature and loading that shall be associated with the selected return period. It is therefore recommended to address this in a reliability analysis to determine a combined set of loading conditions and temperatures that reflects the ULS conditions at low temperature.

6.3.3 Seawater conditions

Correct determination of seawater conditions is essential for the design of cathodic protection systems. The main parameters to be considered are seawater temperature, salinity, calcium and carbonate
content, oxygen concentration and distribution in the water column, electrical conductivity and presence of microbiological species.

Some international standards provide guidance on some of these parameters, but it is recommended to investigate these parameters for the particular field where the structure will be located. Guidance on corrosion protection design is given in 9.3.

6.4 Principles for qualification and quality assurance

6.4.1 Steel making technology

The low temperature properties of base material and heat affected zone are essentially controlled by the steel chemistry and steel manufacturing process in combination with the subsequent fabrication processes. The qualification fracture toughness of the weld heat affected zone should therefore be part of the steel qualification process (e.g. EN 10225 or API RP 2Z). It is also recommended to define temperature intervals for the qualification in order to avoid arbitrary qualification temperatures defined by customers.

6.4.2 Welding technology

Qualification of welding procedures should be valid for the minimum service temperature, and should in general match the minimum service temperature specified for the steel.

7 Material and fabrication requirements

7.1 Material selection and qualification

Material selection shall be performed in compliance with the design class (DC) approach as defined in ISO 19902:2007, Clause 19.

NOTE The requirements in ISO 19902:2007, Clause 19 are in line with the corresponding requirements in ISO 19906:2010, 11.9.

Steel grades for the DC approach are listed in ISO 19902:2007, Annex D. Equivalent material grades of from national or international standards are acceptable, provided that the qualification complies with the selected set of requirements. For components in DC1 or DC2, where weldability qualification is needed (CV2, CV2Z, CV2X, CV2ZX), weldability shall be qualified in accordance with API RP 2Z or EN 10225:2009, Annex E. Additional guidance is given in ISO 19902:2007, Annex B.

Consideration shall be given to the steel performance characteristics affected by the LAST. The LAST shall be in accordance to applicable regulatory requirements in the applicable region as included in ISO 19902:2007, Annex H). Suggested LAST values for certain offshore regions are given in ISO 19902:2007, Annex A.

Qualification and documentation of base metal shall cover the delivered and the PWHT condition, if applicable.
7.2 Mechanical properties

7.2.1 Tensile properties

It is recommended that the design is based on room temperature tensile data. This will represent a conservative approach for low temperature operations in the case of stress based design. However, there is a potential for taking advantage of increased tensile properties for assessment of fracture limit state at a specified temperature. Such assessment shall take into consideration the eventual effect of local strength mismatch and residual stresses.

In the case of strain based design, where stress level is estimated from the predicted strain and the actual stress-strain curve, it is less conservative to assume lower tensile properties. Such cases require particular consideration, also addressing features like UEL and Lüders strain.

If tensile data at a specified temperature is used, the data should be provided on the basis of testing according to ISO 6892-3.

7.2.2 Fracture toughness

7.2.2.1 General

Acceptable fracture toughness shall be documented as part of the weldability documentation from steel supplier, if required. The basis for qualification shall be fracture mechanics testing (i.e. CTOD or J-integral testing).

Charpy V-notch impact testing shall be carried out as part of the product certification and weldability documentation.

The acceptance criteria can be differentiated in accordance with requirements to the design and the associated loading condition and defect tolerance applicable for the structure. Two alternative categories are defined (see 7.2.2.2 and 7.2.2.3). The reference defect dimensions are defined in Figure 4 and are applicable for both categories.

![Crack dimensions](image)

**Figure 4 — Crack dimensions**
The effective utilization is to be calculated based on the average tensile, bending, and shear stresses acting over the characteristic height, $h_{\text{char}}$. For structures welded together by plates, the characteristic height is the plate thickness. For more complex structures, e.g. cast nodes, the characteristic height is to be taken as the height over which the forces are transferred.

The effective stress $\sigma_{\text{eff}}$ to be used to characterise the utilization of the material yield strength is defined as:

$$\sigma_{\text{eff}} = \sqrt{(\sigma_t + \sigma_b)^2 + \tau^2}$$

where

$\sigma_t$ is the average tensile stress acting over the characteristic height

$\sigma_b$ is the average bending stress acting over the characteristic height

$\tau$ is the average shear stress acting over the characteristic height

With reference to Figure 5, the average stress components are calculated from:

$$\sigma_t = \frac{F}{h_{\text{char}}} \quad \sigma_b = \frac{6M}{h_{\text{char}}^2} \quad \tau = \frac{S}{h_{\text{char}}}$$

The material yield strength $\sigma_Y$ is defined as SMYS at LAST (see 7.1). It is allowed to use room temperature SMYS, if data for LAST is not available.

The material safety factor $\gamma_M$ is 1,15 unless otherwise specified. This is representative for ULS.

### 7.2.2.2 Category 1

Category 1 is applicable if the following conditions are fulfilled:

1) defect depth $a \leq 5$ mm;
2) defect length $2c \leq 1.5a$;

3) the effective utilization $\frac{\sigma_{\text{eff}} Y_M}{\sigma_Y} \leq 0.8$

The acceptance criterion for characteristic CTOD fracture toughness is:

$$\delta_{\text{char}} > \frac{0.1 \gamma_\delta}{X_\delta} \ [mm]$$

where

$\gamma_\delta \geq 4/3$ is the safety factor on characteristic CTOD value;

$X_\delta$ is the constraint correction factor determined from Table 1.

**Table 1 — Constraint factor, category 1**

<table>
<thead>
<tr>
<th>Range of application</th>
<th>$X_\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{char}} \leq 0.05 \ mm$</td>
<td>1.0</td>
</tr>
<tr>
<td>$\delta_{\text{char}} &gt; 0.05 \ mm$</td>
<td>$1.5 + 0.1 \frac{\sigma_t}{\sigma_b}$</td>
</tr>
<tr>
<td>$\delta_{\text{char}} &gt; 0.05 \ mm$</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### 7.2.2.3 Category 2

If conditions for Category 1 are not fulfilled, acceptance criteria shall be based on a representative engineering critical assessment (ECA) in accordance with BS 7910 or API 579-1/ASME FFS-1.

Constraint correction can be applied if:

1) defect depth to be considered in the structure is less than 25 % of wall thickness ($a < 0.25t$);

2) testing is carried out with full thickness SENB test specimens with initial crack depth between 45 % and 55 % of specimen width.

The constraint corrected CTOD fracture toughness parameter $\delta_{\text{mat}}$ to be entered into the ECA is defined as:

$$\delta_{\text{mat}} > \frac{\delta_{\text{char}}}{X_\delta} \ [mm]$$

where $X_\delta$ is determined by Table 2
Table 2 — Constraint factor, category 2

<table>
<thead>
<tr>
<th>Range of application</th>
<th>$X_\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta_{\text{char}} \leq 0.05 \text{ mm}$</td>
<td>$X_\delta = 1.0$</td>
</tr>
<tr>
<td>$\delta_{\text{char}} \geq 0.05 \text{ mm}$ and $\frac{\sigma_t}{\sigma_y} &lt; 0.9$</td>
<td>$X_\delta = 1 + 1.11 \frac{\sigma_{\text{eff}}}{\sigma_y} (0.5 + 0.1 \frac{\sigma_t}{\sigma_b})$</td>
</tr>
<tr>
<td>if $\frac{\sigma_t}{\sigma_b} \leq 5$</td>
<td>$X_\delta = 1 + 1.11 \frac{\sigma_{\text{eff}}}{\sigma_y}$</td>
</tr>
<tr>
<td>if $\frac{\sigma_t}{\sigma_b} &gt; 5$</td>
<td></td>
</tr>
<tr>
<td>$\delta_{\text{char}} \geq 0.05 \text{ mm}$ and $\frac{\sigma_t}{\sigma_y} \geq 0.9$</td>
<td>$X_\delta = 1.5 + 0.1 \frac{\sigma_t}{\sigma_b}$</td>
</tr>
<tr>
<td>if $\frac{\sigma_t}{\sigma_b} \leq 5$</td>
<td>$X_\delta = 2.0$</td>
</tr>
<tr>
<td>if $\frac{\sigma_t}{\sigma_b} &gt; 5$</td>
<td></td>
</tr>
</tbody>
</table>

Application of constraint corrected test specimens can be applied, if it is demonstrated that the constraint of the test specimen is equal or larger than the case used in the representative ECA.

7.2.3 Pre-qualification testing

Table 3 provides recommendation for number of test specimens and test temperatures for weldability test programs. EN 10225 provides the specification of test methods.

Table 3 — Number of test specimens and test temperatures for weldability test program

<table>
<thead>
<tr>
<th>Test</th>
<th>Test temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTOD</td>
<td>LAST</td>
</tr>
<tr>
<td>Charpy</td>
<td>LAST – 30°C</td>
</tr>
<tr>
<td>Charpy transition curve</td>
<td>Tests shall be performed from +20 °C down to –80 °C at 20 °C intervals 3 specimens at each temperature</td>
</tr>
</tbody>
</table>

Charpy toughness requirements shall be in accordance with ISO 19902.

Required CTOD testing as a function of temperature and thickness shall be according to Table 4.
Table 4 — Test matrix for structural steel

<table>
<thead>
<tr>
<th>Design temperature range °C (LAST)</th>
<th>Thickness range</th>
<th>Steel quality for DC1 and DC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>T &gt; −15 °C</td>
<td>40mm (^a) - 150 mm</td>
<td>CV1, CV2, CV2Z, CV2X and CV2ZX</td>
</tr>
<tr>
<td>−5 °C &gt; T ≤ −25 °C</td>
<td>30 mm - 150 mm</td>
<td>CV1, CV2, CV2Z, CV2X and CV2ZX</td>
</tr>
<tr>
<td>−25 °C &gt; T ≤ −60 °C</td>
<td>20 mm - 150 mm</td>
<td>CV1, CV2, CV2Z, CV2X and CV2ZX</td>
</tr>
</tbody>
</table>

\(^a\) As of current practice.

7.3 Crack arrest assessment

For normal conditions the preferred test for assurance of a material’s ability to arrest a crack is the ESSO test according to WES 2815. This test should show that the $K_{ca}$ of the material is at least 6 000 N/mm\(^{3/2}\) at LAST. While this is the preferred test, it is acknowledged that it is an unrealistically expensive test for common use.

Alternatively, Pellini testing according to ASTM E208 may be acceptable. In this case, it is required that two samples are tested at a temperature 30 °C below the value found in Figure 6 and result in two repetitions of a “no-break” condition. For material of 75 mm thickness and with a LAST of −40°C, a test temperature of −107°C would be required.

Recent research has indicated that other approaches can be more relevant with less stringent requirements. More documentation is required before a reliable conclusion can be drawn.

Test temperature shall be 30 °C below actual reading.

**Figure 6 — Representative LAST for Pellini tests as a function of material thickness**

7.4 Fatigue properties, alternative testing

Sufficient fatigue resistance shall normally be documented in accordance with the defined structural criticality and the corresponding steel requirements. However, in cases where ordinary requirements cannot be met by the specified minimum Charpy value, the required value should be at least 27 J when tested at a temperature of LAST −18 °C. If this is not achieved, then one of the following two analyses should be performed:
1) Fatigue tests should be performed at RT and LAST. If there is a significant acceleration of fatigue at LAST relative to RT, then analyses should be performed to show that the structure maintains an acceptable fatigue life.

2) Fatigue crack growth rate calculations should be carried out at RT. Fatigue crack growth rates five times the RT rate shall be used for all service conditions in which the temperature is below the lowest test temperature +18 °C. If a Charpy transition curve is established, the temperature corresponding to 27 J impact toughness (T27J) can be determined. In this case the temperature limit for use of higher crack growth rate is T27J +18 °C.

7.5 Welding and fabrication requirements

7.5.1 Contractor certification

All contractors shall be certified to meet requirements of ISO 19902:2007, Annex H. Certification documents issued shall state the scope of certification.

7.5.2 Base material

When thickness T > 40 mm steel grades selected to satisfy toughness classes CV2X and CV2ZX, CTOD testing at a temperature corresponding to LAST for the particular project is required. CTOD testing of the HAZ shall be required to cover low heat input and high heat input procedures/practices. CTOD requirements shall be 0.25 mm in the as-welded condition and 0.20 mm in the PWHT condition, unless other requirements are given by the project.

7.5.3 Welding consumables

All welding consumables shall be delivered in accordance with manufacturer's data sheets and with certification in accordance with ISO 10474/EN 10204 Type 3.1. Alternatively, welding consumables certified in accordance to national specification can be accepted by the owner's engineer, provided that certification testing has been witnessed by an accredited third party agency.

7.5.4 Welding procedure qualification

All welding procedures for welding of steels in toughness classes CV1, CV2, CV2X and CV2ZX (generally used for primary and secondary structures) as listed in ISO 19902:2017, Table 19.4.1 shall be qualified by welding procedure qualification testing, in accordance with 7.6.

Welding procedures for steels designated as tertiary steel, such as access platforms, stairways, handrails, and minor equipment, supports and stands can be tested in accordance to relevant parts of ISO 15614 or national standards, if acceptable to the client.

7.6 Welding procedure qualification test requirements

7.6.1 General requirements

The welding procedure qualification test requirements in ISO 19902:2007, Clause 20 and Annex F shall be met.
7.6.2 Welding procedure qualification testing

7.6.2.1 General

The extent of testing shall be in compliance with general requirements. The test conditions shall be similar to the actual conditions that will be encountered in construction. Procedures tested in shops may also be used outdoors, provided that adequate temporary weatherproofing is installed as protection against weather conditions during outdoor site welding.

Unless otherwise specified by contract specification, PWHT is normally not applicable for weld procedure qualification of jacket and topside structural steelwork. CTOD testing shall be performed in lieu of PWHT for weld procedures where CV2ZX and CV2X class have been used in qualification. For thickness and temperature requirements see 7.2.2.

Butt welds in plate test coupons shall be made parallel to the rolling direction with at least 150 mm of plate width on either side of the weld. Wider plates shall be used where CTOD testing is specified in order to accommodate the dimensions of the CTOD specimens. The length of the plate test coupon is dependent on the number of mechanical tests required (see Table 1), but shall not be shorter than 450 mm.

Plate groove welded butt joints may qualify plate groove welded tee joints and 90° groove welded tubular tee joints welded to a flat surface, but not tubular TKY joints, provided that the weld test coupon joint preparation has one square edge, i.e. a bevel joint configuration.

7.6.2.2 Butt joints in a pipe

For butt joints in a pipe, tubular or box tubing having a “GR” type preparation shall also qualify tubular TKY joints, provided that the supplemental TKY mock up assembly has been appropriately qualified.

NOTE GR pipe/tubular weld test coupons qualify GR box tubing weld test coupons but not vice versa.

7.6.2.3 Heat input

If welding procedure has been qualified for both the highest heat input and the lowest heat input, all intermediate heat input ranges are also qualified. The qualification on a single test assembly representing the only weld position to be used in production, shall limit the heat input qualification range for each zone of the weld (root pass; hot pass/initial fill pass; fill passes; cap passes).

7.6.3 Testing requirements

7.6.3.1 Complete joint penetration in butt welds in plates

Butt welds requiring to be qualified for multiple weld position can be performed on two separate test assemblies in the two positions that represent the highest and lowest heat inputs. For single weld position qualifications, the butt weld shall be qualified in the position representing the production weld position and the qualifying heat input shall be restricted to the tolerances detailed in the essential variables.

3G (PF) vertical upward progression position shall represent the highest heat input and the 2G (PC) horizontal position shall represent the lowest heat input.
Butt welds qualified for plate shall also qualify butt welds in tubulars with the outside diameter OD ≥ 624 mm within the framework of the essential variables.

For butt joints welded from one side between equal thickness base metals without backing or back gouging, qualification shall be performed on an "open root" single vee or single bevel (as appropriate) butt weld joint.

7.6.3.2 Complete joint penetration in butt joints in tubular

Joints with open root welded from one side only.

Butt welds in tubular connections required to be qualified for multiple weld position can be performed on two separate test assemblies (open root) in the two positions that represent the highest and lowest heat inputs. For single weld position qualifications, the butt weld shall be qualified in the position representing the production weld position and the qualifying heat input shall be restricted to the tolerances detailed in the essential variables.

3G (PF) vertical upward progression position shall represent the highest heat input and the 2G (PC) horizontal position shall represent the lowest heat input.

Butt welds qualified for tubulars shall also qualify butt welds in plate within the framework of essential variables.

7.6.3.3 T-, K- and Y-joints welded from one side

Butt welds for tubular TKY joints required to be qualified for multiple weld position shall be qualified on GR type test assemblies (see Figure 1) in two positions to represent the highest and lowest heat inputs.

The 5GR or 6GR (vertical upward progression) position shall represent the highest heat input and the 2GR position shall represent the lowest heat input.

Additionally a TKY test assembly shall be required to be welded. The TKY test assembly shall consist of two tubulars of different diameters that represent the greatest thickness for branch and chord members, and most acute dihedral heel angle. Welding of three quadrants around the circumference that incorporates welding positions corresponding to the 1G (flat), 3G (vertical upward progression), and 4G (overhead) positions shall be performed first. Welding of the fourth quadrant that incorporates the 2G (horizontal) position shall be performed after the TKY test assembly has been moved in the new position as illustrated in Figure 2.

7.6.4 Fillet weld on plates

The largest size single pass and smallest size multipass fillet welds shall be qualified within the weld parameters framework of the qualified butt weld(s) in each of the 2F (horizontal) and 3F (vertical) weld positions for all welding processes and only the 2F (horizontal) weld position for the SAW (12) process.

NOTE Qualification of plate and tubular CJP butt welds also qualifies fillet welds for all applications, provided that the above fillet weld qualifications have been completed on plates.

If fillet weld is required to be qualified over weldable primer, without of removing it prior to welding in production, a separate fillet weld test qualification is required.
7.7 Protection against corrosion and wear

7.7.1 General

Offshore structures in Arctic environment will in general be subjected to the same environmental loads as in other northern areas with offshore activities such as the east coast of Canada, northern Atlantic Sea and Barents Sea. In addition, the effects of low temperature, particular local conditions with respect to seawater salinity, microbiological conditions and particular local conditions with respect to ice formation on topside components, sea ice acting on the structure in the waterline area and eventually ice bergs.

7.7.2 Corrosion protecting coating at low temperature

Qualification testing shall be performed at the actual minimum design temperature where mechanical impact is considered. The particular requirements to coating are associated with the risk of cracking and de-cohesion of the coating at low temperature. The main sources of mechanical impact are removal of ice and snow from the structure and drifting ice in the water line that leads to scouring wear. The combination of waves and ice rubbles in the sea can also lead to some impact on the hull plating and its coating.

For areas in the water line region and submerged parts where ice scouring is expected, sea ice formed by seawater will have pockets with concentrated brine caused by segregation of salt during the freezing process. Severe corrosion attacks have been revealed on ice breakers where coating is damaged by scouring and steel surface is exposed to sea ice.

7.7.3 Cathodic protection

For submerged parts of the structure, cathodic protection can be designed by the same electrochemical models as for normal offshore structures as long as the appropriate seawater salinity and oxygen content is included in the calculations.

For areas in the water line region where ice impact is expected, the anodes shall be designed such that they are not damaged by the ice. Alternatively the use of impressed current should be evaluated.

The resistivity of ice is 100 times to 1 000 times larger than that of seawater. This can reduce anode output and shall be considered if parts of the structure in periods will be completely embedded in ice.

8 Quality control, quality assurance and documentation

8.1 Structural steel requirements

Qualification of steel grades for primary and secondary structural steel shall comply to

— EN 10225, including option 18 (weldability tests described in Annexes E, F and G)

or

— API Spec 2H, API Spec 2W or API Spec 2Y including supplementary requirement S11 (preproduction qualification in accordance with API RP 2Z) with the clarifications that test temperatures shall be in accordance with ISO 19902:2007, Table 19.4-1, where LAST is defined in accordance with 6.3 of this document.
Other steel structures shall be qualified in accordance with the above or alternative steel specifications where low temperature performance for the actual application and design environmental conditions can be documented.

8.2 Welding and fabrication requirements

All welding work shall be according to ISO 19902. Welding fabricator and erector shall have an implemented and documented quality system according with ISO 3834-2. For fabrication of tertiary structural steel, ISO 3834-3 may be accepted by the third party agency.

9 Operational topics

9.1 Requirements for operations in remote areas

9.1.1 General

Normal operating requirements can be assumed for structures in Arctic environment with respect to inspection and maintenance of corrosion protected surfaces, inspection and maintenance of cathodic protection systems and structural integrity assessment including inspection and repair of fatigue and fracture damage.

Precautions that are specific for Arctic operations are associated with the complications related to low temperatures and formation of ice.

9.1.2 Low temperature operations

As part of the winterisation philosophy for the facility, the minimum temperature for safe operation of different systems should be defined. This will include assessment of the function of mechanical devices (cranes, winches, etc.) and the risk of material failure caused by low temperature if the loading conditions are affected by the operation itself. If the ambient temperature falls below the defined LAST for the actual component, it should not be operated.

9.1.3 Ice and snow removal

The presence of ice shall be included in the design loading conditions and should therefore not affect the operation of the facility as such. However, removal of ice and snow is required to maintain functional and safety requirements. The objective of requirements given here is to ensure that ice and snow removal shall not impose damage to the facility and lead to reduced integrity or service life. The following precautions shall be considered when removing ice and snow:

— If it is not strictly required for functional or safety reasons, ice and snow should not be removed.

— Use of hot water high pressure water and steam should only be used on surfaces where the materials and coatings are not damaged by the removal operation. Mechanical devices should not be in direct contact with material surfaces to avoid damage of material and coating.
9.2 Corrosion and wear control

9.2.1 General

The main aspects for corrosion control in Arctic environment are related to temperature, presence of ice and different seawater characteristics (salinity, calcium and carbonate content, microorganisms, etc.). There are both design considerations and operational considerations to be taken to control corrosion and wear.

9.2.2 Splash zone surfaces in direct contact with sea ice

Due to segregation of salt during the formation of sea ice, it will always contain pockets with unfrozen brine. This brine will come in direct contact with the steel surface when sea ice is crushed onto the structure and severe corrosion attacks are to be expected, unless the coating is in good condition. Hence wear resistance of the coating is essential in these areas. Corrosion resistant plating (ice belt) is recommended to be considered on critical areas where maintenance of coating is difficult.

Wear on steel surface caused by moving ice will also remove calcareous deposits caused by the CP. This can lead to increased current density compared to normal CP protected surfaces. Mechanical wear of the coating system by sea ice leads to accelerated coating breakdown. Adjusted coating breakdown factors should therefore be considered for the ice impact surfaces.

Normal stand-off sacrificial anodes can be damaged by moving ice. It is therefore recommended to use anodes that are flush with the steel surface. This will increase the required amount of anodes. Impressed current systems may also be considered with reference electrodes and platinum anodes flush with the steel surface. The system should be designed to allow for in-situ replacement and/or repair.

9.2.3 Submerged surfaces and cathodic protection

Arctic seawater is characterised by:

— relatively low temperature;
— relatively high oxygen content;
— relatively high resistivity;
— rough conditions leading to vertical mixing of the water and consequently more oxygen further down in the water column.

These characteristics lead to reduced anode performance and slower formation of calcareous deposits. Even if the chemical processes in general is slowed down by the lower temperatures, these aspects leads to increased current density requirements and reduced distance between anodes to maintain a protecting potential on the entire surface.

Factors that should be investigated in connection with the CP design are the actual seawater composition including calcium and carbonate content, vertical variation of the composition and the electrical properties of the water. In addition the variety of microorganisms should be investigated to assess the marine growth and risk of corrosion processes caused be these organisms.
9.2.4 Topside surfaces

The corrosion protection of external surfaces of topside process equipment and structures relies on the coating performance. The Arctic challenges for the coatings caused by low temperature and more rough mechanical impact suggests that stainless steel grades are more competitive, but material selection shall be carried out on a more comprehensive basis. This document does not provide direct advices on material selection other than the required low temperature performance.

The design aspects to be taken for corrosion protection of topside surfaces are:

— mechanical resistance to take the impact of ice and snow accumulated on topside structure and components;

— mechanical resistance to take the impact of ice and snow removal operations;

— use of ice-repellent coating systems that can reduce the ice accretion and accumulation on the surfaces.

The latter is yet to be established as standardised technology and qualified coating systems and will need particular qualification for new projects.
### Bibliography


[5] ISO 15614 (all parts), *Specification and qualification of welding procedures for metallic materials — Welding procedure test*


[9] ISO 19901-4, *Petroleum and natural gas industries — Specific requirements for offshore structures — Part 4: Geotechnical and foundation design considerations*

[10] ISO 19906, *Petroleum and natural gas industries — Arctic offshore structures*


[15] API 579-1 / ASME FFS-1, *Fitness-For-Service*


[18] EN 10204, *Metallic products — Types of inspection documents*

[19] NORSOK N-003, *Actions and action effects*

[20] NORSOK N-004, *Design of steel structures*
[21] WES 2815, Test method for brittle crack arrest toughness, $K_{ca}$