



ANSI/NACE MR0175-2021/ISO 15156-1:2020

International Standard
ANSI/NACE MR0175-2021/ISO 15156-1:2020
Fourth Edition
Identical to ISO 15156-1:2020

**Petroleum and natural gas industries —
Materials for use in H₂S-containing environments
in oil and gas production**

Part 1:
**General principles for selection
of cracking-resistant materials**

An American National Standard

Approved 21 Sep 2022

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AMPP values your input. To provide feedback on this standard, please contact: standards@ampp.org

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Part 1:
General principles for selection of cracking-resistant materials

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Foreword

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

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

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

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

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

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 12, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This fourth edition cancels and replaces the third edition (ANSI/NACE MR0175-2015/ISO 15156-1:2015), which has been technically revised. The main changes compared to the previous edition are as follows:

- new definition on “galvanically induced hydrogen stress cracking” (see [3.14](#)), “chemical activity” (see [3.27](#)) and “fugacity” (see [3.28](#));
- inclusion of an expanded description of factors affecting the susceptibility of materials to cracking caused by H₂S. The expanded description includes specific guidance provided in ANSI/NACE MR0175-2021/ISO 15156-2:2020, Annex C for gas phase containing systems using H₂S fugacity (as an alternative to H₂S partial pressure) and application of non-ideal thermodynamic rules for gas-free liquid systems.

ANSI/NACE MR0175-2021/ISO 15156:2020 consists of the following parts, under the general title *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production*:

- *Part 1: General principles for selection of cracking-resistant materials*
- *Part 2: Cracking resistant carbon and low-alloy steels, and the use of cast irons*
- *Part 3: Cracking resistant CRAs (corrosion resistant alloys) and other alloys*

Introduction

The consequences of sudden failures of metallic oil and gas field components, associated with their exposure to H₂S-containing production fluids, led to the preparation of the first edition of NACE MR0175, which was published in 1975 by the National Association of Corrosion Engineers, now known as the Association for Materials Protection and Performance (AMPP).

The original and subsequent editions of NACE MR0175 established limits of H₂S partial pressure above which precautions against sulfide stress cracking (SSC) were always considered necessary. They also provided guidance for the selection and specification of SSC-resistant materials when the H₂S thresholds were exceeded. In more recent editions, NACE MR0175 has also provided application limits for some corrosion-resistant alloys, in terms of environmental composition and pH, temperature, and H₂S partial pressures.

In separate developments, the European Federation of Corrosion issued EFC Publication 16 in 1995 and EFC Publication 17 in 1996. These documents are generally complementary to those of NACE though they differed in scope and detail.

In 2003, the publication of the ISO 15156 series and NACE MR0175/ISO 15156-1 was completed for the first time. These technically identical documents utilized the above sources to provide requirements and recommendations for materials qualification and selection for application in environments containing wet H₂S in oil and gas production systems. They are complemented by NACE TM0177 and NACE TM0284 test methods.

The revision of this document, i.e., ANSI/NACE MR0175/ISO 15156-1, involves a consolidation of all changes agreed and published in the Technical Circular 1, ISO 15156-1:2015/Cir.1:2017, published by the ISO 15156 series Maintenance Agency secretariat at DIN.

The changes were developed by, and approved by the ballot of, representative groups from within the oil and gas production industry. The great majority of these changes stem from issues raised by document users. A description of the process by which these changes were approved can be found at the ISO 15156 series maintenance website: www.iso.org/iso15156maintenance.

When found necessary by oil and gas production industry experts, future interim changes to this document will be processed in the same way and will lead to interim updates to this document in the form of Technical Corrigenda or Technical Circulars. Document users should be aware that such documents can exist and can impact the validity of the dated references in this document.

The ISO 15156 series Maintenance Agency at DIN was set up after approval by the ISO Technical Management Board given in document 34/2007. This document describes the makeup of the agency, which includes experts from AMPP, EFC, and ISO/TC 67, and the process for approval of amendments. It is available from the ISO 15156 series maintenance website and from the ISO/TC 67 Secretariat. The website also provides access to related documents that provide more detail of the ISO 15156 series maintenance activities.

Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 1: General principles for selection of cracking-resistant materials

WARNING — Metallic materials selected using this document are resistant to cracking in defined H₂S-containing environments in oil and gas production but not necessarily immune to cracking under all service conditions. It is the equipment user's responsibility to select materials suitable for the intended service.

1: Scope

This document describes general principles and gives requirements and recommendations for the selection and qualification of metallic materials for service in equipment used in oil and gas production and in natural-gas sweetening plants in H₂S-containing environments, where the failure of such equipment can pose a risk to the health and safety of the public and personnel or to the environment. It can be applied to help to avoid costly corrosion damage to the equipment itself. It supplements, but does not replace, the materials requirements given in the appropriate design codes, standards, or regulations.

This document addresses all mechanisms of cracking that can be caused by H₂S, including sulfide stress cracking, stress corrosion cracking, hydrogen-induced cracking and stepwise cracking, stress-oriented hydrogen-induced cracking, soft zone cracking, and galvanically induced hydrogen stress cracking.

Table 1 provides a non-exhaustive list of equipment to which this document is applicable, including exclusions.

This document applies to the qualification and selection of materials for equipment designed and constructed using load controlled design methods. For design utilizing strain-based design methods, see Clause 5.

This document is not necessarily applicable to equipment used in refining or downstream processes and equipment.

Table 1 — List of equipment

This document is applicable to materials used for the following equipment	Exclusions
Drilling, well construction, and well-servicing equipment	Equipment exposed only to drilling fluids of controlled composition ^a Drill bits Blowout preventer (BOP) shear blades ^b Drilling riser systems Work strings Wireline and wireline equipment ^c Surface and intermediate casing
Wells, including subsurface equipment, gas-lift equipment, wellheads, and christmas trees	Sucker rod pumps and sucker rods ^d Electric submersible pumps Other artificial lift equipment Slips
Flowlines, gathering lines, field facilities, and field processing plants	Crude-oil storage and handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi)
Water-handling equipment	Water-handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi) Water injection and water disposal equipment
Natural-gas treatment plants	—
Transportation pipelines for liquids, gases, and multiphase fluids	Lines handling gas prepared for general commercial and domestic use
For all equipment above	Components loaded only in compression
^a See ANSI/NACE MR0175/ISO 15156-2:2020, A.2.3.2.3 for more information. ^b See ANSI/NACE MR0175/ISO 15156-2:2020, A.2.3.2.1 for more information. ^c Wireline lubricators and lubricator connecting devices are not excluded. ^d For sucker rod pumps and sucker rods, reference can be made to NACE MR0176.	

2: Normative references

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

ANSI/NACE MR0175/ISO 15156-2, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 2: Cracking-resistant carbon and low alloy steels, and the use of cast irons*

ANSI/NACE MR0175/ISO 15156-3, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 3: Cracking-resistant CRAs (corrosion-resistant alloys) and other alloys*

3: Terms and definitions

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

- 3.1 blowout preventer (BOP)**
mechanical device capable of containing pressure, used for control of well fluids and drilling fluids during drilling operations
- 3.2 brazing**
joining metals by flowing a thin layer (of capillary thickness) of a lower-melting-point non-ferrous filler metal in the space between them
- 3.3 carbon steel**
alloy of carbon and iron containing up to 2 % mass fraction carbon and up to 1.65 % mass fraction manganese and residual quantities of other elements, except those intentionally added in specific quantities for deoxidation (usually silicon and/or aluminum)

Note 1 to entry: Carbon steels used in the petroleum industry usually contain less than 0.8 % mass fraction carbon.
- 3.4 christmas tree**
equipment at a wellhead for the control of fluid production or injection
- 3.5 cold work**
plastic deformation of metal under conditions of temperature and strain rate that induce strain hardening, usually, but not necessarily, conducted at room temperature
- 3.6 corrosion-resistant alloy (CRA)**
alloy intended to be resistant to general and localized corrosion of oilfield environments that are corrosive to *carbon steels* (3.3)
- 3.7 ferrite**
body-centered cubic crystalline phase of iron-based alloys
- 3.8 ferritic steel**
steel whose *microstructure* (3.16) at room temperature consists predominantly of *ferrite* (3.7)
- 3.9 hardness**
resistance of metal to plastic deformation, usually measured by indentation
- 3.10 heat-affected zone (HAZ)**
portion of the base metal that is not melted during brazing, cutting, or welding, but whose *microstructure* (3.16) and properties are altered by the heat of these processes

3.11 heat treatment

heating and cooling a solid metal or alloy in such a way as to obtain desired properties

Note 1 to entry: Heating for the sole purpose of hot working is not considered heat treatment.

3.12 hydrogen-induced cracking (HIC)

planar cracking that occurs in carbon and low alloy steels when atomic hydrogen diffuses into the steel and then combines to form molecular hydrogen at trap sites

Note 1 to entry: Cracking results from the pressurization of trap sites by hydrogen. No externally applied stress is required for the formation of hydrogen-induced cracks. Trap sites capable of causing HIC are commonly found in steels with high impurity levels that have a high density of planar inclusions and/or regions of anomalous *microstructure* (3.16) (e.g., banding) produced by segregation of impurity and alloying elements in the steel. This form of hydrogen-induced cracking is not related to welding.

3.13 hydrogen stress cracking (HSC)

cracking that results from the presence of hydrogen in a metal and tensile stress (residual and/or applied)

Note 1 to entry: SSC and GHSC are forms of HSC.

3.14 galvanically induced hydrogen stress cracking (GHSC)

cracking that results due to the presence of hydrogen in a metal induced in the cathode of a galvanic couple and tensile stress (residual and/or applied)

3.15 low-alloy steel

steel with a total alloying element content of less than about 5 % mass fraction, but more than specified for *carbon steel* (3.3)

3.16 microstructure

structure of a metal as revealed by microscopic examination of a suitably prepared specimen

3.17 partial pressure

pressure that would be exerted by a single component of a gas if present alone, at the same temperature, in the total volume occupied by the mixture

Note 1 to entry: For a mixture of ideal gases, the partial pressure of each component is equal to the total pressure multiplied by its mole fraction in the mixture, where its mole fraction is equal to the volume fraction of the component.

3.18 residual stress

stress present in a component free of external forces or thermal gradients

3.19 soft-zone cracking (SZC)

form of SSC that can occur when a steel contains a local “soft zone” of low-yield-strength material

Note 1 to entry: Under service loads, soft zones can yield and accumulate plastic strain locally, increasing the SSC susceptibility to cracking of an otherwise SSC-resistant material. Such soft zones are typically associated with welds in *carbon steels* (3.3).

3.20 sour service

exposure to oilfield environments that contain sufficient H₂S to cause cracking of materials by specific mechanisms

Note 1 to entry: These specific mechanisms are addressed in this document.

3.21 stepwise cracking (SWC)

cracking that connects hydrogen-induced cracks on adjacent planes in a steel

Note 1 to entry: This term describes the crack appearance. The linking of hydrogen-induced cracks to produce stepwise cracking is dependent on the local strain between the cracks and the embrittlement of the surrounding steel by dissolved hydrogen. HIC/SWC is usually associated with low-strength plate steels used in the production of pipes and vessels.

3.22 stress corrosion cracking (SCC)

cracking of metal involving anodic processes of localized corrosion and tensile stress (residual and/or applied) in the presence of water and H₂S

Note 1 to entry: Chlorides and/or oxidants and elevated temperature can increase the susceptibility of metals to this mechanism of attack.

3.23 stress-oriented hydrogen-induced cracking (SOHIC)

staggered small cracks formed approximately perpendicular to the principal stress (residual or applied) resulting in a “ladder-like” crack array linking (sometimes small) pre-existing HIC cracks

Note 1 to entry: The mode of cracking can be categorized as SSC caused by a combination of external stress and the local strain around hydrogen-induced cracks. SOHIC is related to SSC and HIC/SWC. It has been observed in parent material of longitudinally welded pipe and in the *heat-affected zone (HAZ)* (3.10) of welds in pressure vessels. SOHIC is a relatively uncommon phenomenon usually associated with low-strength ferritic pipe and pressure vessel steels.

3.24 sulfide stress cracking (SSC)

cracking of metal involving corrosion and tensile stress (residual and/or applied) in the presence of water and H₂S

Note 1 to entry: SSC is a form of *hydrogen stress cracking (HSC)* (3.13) and involves the embrittlement of the metal by atomic hydrogen that is produced by acid corrosion on the metal surface. Hydrogen uptake is promoted in the presence of sulfides. The atomic hydrogen can diffuse into the metal, reduce ductility, and increase susceptibility to cracking. High-strength metallic materials and hard weld zones are prone to SSC.

3.25 weld

joint between two or more pieces of metal by applying heat and/or pressure with or without filler metal, to produce a union through localized fusion of the substrates and solidification across the interfaces

3.26 yield strength

stress at which a material exhibits a specified deviation from the proportionality of stress to strain

Note 1 to entry: The deviation is expressed in terms of strain by either the offset method (usually at a strain of 0.2 %) or the total-extension-under-load method (usually at a strain of 0.5 %).

3.27 chemical activity

unit-less ratio of actual fugacity (of a gas species) divided by its fugacity at a conveniently defined reference state

Note 1 to entry: In this document, the term chemical activity is primarily used as a property of species in the liquid or aqueous phase, a “pseudo mole fraction”, see also Notes in ANSI/NACE MR0175/ISO 15156-2:2020, C.1.3.

3.28 fugacity

effective pressure of an ideal gas species, which has the same chemical potential (partial Gibbs free energy) as the real gas species

Note 1 to entry: In this document, the term fugacity is primarily used as a property of species in the gas phase, an “effective partial pressure”, see also Notes in ANSI/NACE MR0175/ISO 15156-2:2020, C.1.2.

4: Abbreviated terms

BOP	blowout preventer
CRA	corrosion-resistant alloy
HAZ	heat-affected zone
HIC	hydrogen-induced cracking
HSC	hydrogen stress cracking
SCC	stress corrosion cracking
SOHIC	stress-oriented hydrogen-induced cracking
SWC	step-wise cracking
SSC	sulfide stress cracking
SZC	soft-zone cracking

5: General principles

Users of the ANSI/NACE MR0175/ISO 15156 series shall first assess the conditions to which the materials they wish to select can be exposed. These conditions shall be evaluated, defined, and documented in accordance with this document.

The equipment user shall determine whether or not the service conditions are such that the ANSI/NACE MR0175/ISO 15156 series applies.

Materials selection shall be made following the requirements and recommendations of ANSI/NACE MR0175/ISO 15156-2 or ANSI/NACE MR0175/ISO 15156-3, as appropriate.

The use of ANSI/NACE MR0175/ISO 15156-2 or ANSI/NACE MR0175/ISO 15156-3 can require an exchange of information (for example, concerning required or suitable service conditions) between the equipment user and the equipment or materials supplier. If necessary, the equipment user should advise other parties of the service conditions.

NOTE It can be necessary for the equipment supplier to exchange information with the equipment manufacturer, the materials supplier, and/or the materials manufacturer.

Qualification, with respect to a particular mode of failure, for use in defined service conditions also qualifies a material for use under other service conditions that are equal to or less severe in all respects than the conditions for which qualification was carried out.

It is the equipment user's responsibility to ensure that any material specified for use in their equipment is satisfactory in the service environment.

It is the equipment or materials supplier's responsibility to meet the metallurgical and manufacturing requirements and, when necessary, any additional testing requirements of the ANSI/NACE MR0175/ISO 15156 series for the material selected in the condition in which it enters into service.

It is the equipment or materials supplier's responsibility to conform with the requirements for the marking/documentation of materials in accordance with ANSI/NACE MR0175/ISO 15156-2:2020, Clause 9 or ANSI/NACE MR0175/ISO 15156-3:2020, 7.2, as appropriate.

This document applies to the qualification and selection of materials for equipment designed and constructed using load controlled design methods. For designs utilizing strain-based design methods, use of this document might not be appropriate and other test methods, not addressed in the ANSI/NACE MR0175/ISO 15156 series, might be required. The equipment/material supplier, in conjunction with the equipment user, shall define and agree on other testing requirements and acceptance criteria.

6: Evaluation and definition of service conditions to enable material selection

- 6.1** Before selecting or qualifying materials using ANSI/NACE MR0175/ISO 15156-2 or ANSI/NACE MR0175/ISO 15156-3, the user of the equipment shall define, evaluate, and document the service conditions to which materials can be exposed for each application. The defined conditions shall include both intended exposures and unintended exposures that can result from the failure of primary containment or protection methods. Particular attention shall be paid to the quantification of those factors known to affect the susceptibility of materials to cracking caused by H₂S.

Factors, other than material properties, known to affect the susceptibility of metallic materials to cracking in H₂S service include H₂S partial pressure (or H₂S concentration or chemical activity in the water phase), in situ pH, the concentration of dissolved chloride or other halide, the presence of elemental sulfur or other oxidant, temperature, galvanic effects, mechanical stress, and time of exposure to contact with a liquid water phase.

For systems with a gas phase, evaluations based on H₂S partial pressure imply an environmental severity that equals or exceeds that of the field service considered and are therefore acceptable. For gas-free liquid systems, an alternative approach to partial pressure is needed. ANSI/NACE MR0175/ISO 15156-2:2020, Annex C, provides guidance in C.1 for systems with a gas phase to assess H₂S partial pressure and to reduce excess environmental severity by using H₂S fugacity, and in C.2 for evaluating gas-free liquid systems. This includes a recommendation to apply non-ideal thermodynamic rules for high pressure oil wells.

NOTE 1 The degree to which environmental severity, as characterized by H₂S partial pressure, exceeds that of the service environment considered, is determined by non-ideal thermodynamic effects. Generally, this degree increases with increasing pressure and decreases with increasing temperature.

NOTE 2 The environmental severity regions in ANSI/NACE MR0175/ISO 15156-2, and the prequalified H₂S exposure limits in ANSI/NACE MR0175/ISO 15156-3, are stated in terms of H₂S partial pressure. No guidance is given on equivalent regions or limits in terms of H₂S fugacity in the gas phase or H₂S chemical activity in the water phase.

- 6.2** The documented service conditions shall be used for one or more of the following purposes:
- a) to provide the basis for selection of SSC/SCC-resistant materials from existing lists and tables (see [Clause 7](#));
 - b) to provide the basis for qualification and selection based upon documented field experience (see [8.2](#));
 - c) to define the laboratory test requirements to qualify a material for H₂S service with respect to one or more of SSC, SCC, HIC, SOHIC, SZC, and/or galvanically induced HSC (see [8.3](#));
 - d) to provide the basis for the reassessment of the suitability of existing alloys of construction, using [Clause 7](#), [8.2](#), and/or [8.3](#), in the event of changes to the actual or intended service conditions.

7: Selection of materials resistant to SSC/SCC in the presence of sulfides from existing lists and tables

SSC-resistant carbon and low-alloy steels may be selected from the materials identified in ANSI/NACE MR0175/ISO 15156-2:2020, Annex A.

SSC, SCC-resistant CRAs and other alloys may be selected from the materials identified in ANSI/NACE MR0175/ISO 15156-3:2020, Annex A.

Generally, no additional laboratory testing of materials selected in these ways is required. The materials listed have given acceptable performance under the stated metallurgical, environmental, and mechanical conditions based on field experience and/or laboratory testing. The equipment user should, nevertheless, give consideration to specific testing of materials for applications where they consider the potential consequences of failure make this justifiable (see **WARNING**).

8: Qualification of materials for H₂S service

8.1 Material description and documentation

The material being qualified shall be described and documented, such that those of its properties likely to affect performance in H₂S-containing media are defined. The tolerances or ranges of properties that can occur within the material shall be described and documented.

Metallurgical properties known to affect performance in H₂S-containing environments include chemical composition, method of manufacture, product form, strength, hardness, amount of cold work, heat-treatment condition, and microstructure.

8.2 Qualification based upon field experience

A material may be qualified by documented field experience. The material description shall meet the requirements of 8.1. The description of the service conditions in which the experience has been gained shall meet the relevant requirements of 6.1. The duration of the documented field experience shall be at least two years and should preferably involve a full examination of the equipment following field use. The severity of intended service conditions shall not exceed that of the field experience for which documented records are available.

8.3 Qualification based upon laboratory testing

8.3.1 General

Laboratory testing can only approximate field service.

Laboratory testing in accordance with the ANSI/NACE MR0175/ISO 15156 series may be used for the following:

- to qualify metallic materials for their resistance to SSC and/or SCC under service conditions up to the limits that apply to materials of similar types listed in ANSI/NACE MR0175/ISO 15156-2 and ANSI/NACE MR0175/ISO 15156-3;
- to qualify metallic materials for their resistance to SSC and/or SCC under service conditions with other limits;

EXAMPLE: Qualification up to a higher-than-normally-acceptable level of H₂S, to a lower-than-normally-required test stress or to revised temperature limit(s) or to a lower pH.

- to qualify carbon and low-alloy steels with respect to their resistance to HIC, SOHIC, or SZC;

- to qualify corrosion-resistant or other alloys with respect to their resistance to galvanically induced HSC;
- to provide qualification data for a material not currently listed in ANSI/NACE MR0175/ISO 15156-2:2020, Annex A and ANSI/NACE MR0175/ISO 15156-3:2020, Annex A in such a form that it may be considered for inclusion at a later date.

8.3.2 Sampling of materials for laboratory testing

The method of sampling the material for laboratory testing shall be reviewed and accepted by the equipment user.

The test samples shall be representative of the commercial product.

For multiple batches of a material produced to a single specification, an assessment shall be made of the properties that influence cracking behavior in H₂S-containing environments (see [8.1](#)). The distributions of these properties shall be considered when selecting samples for testing according to the requirements of ANSI/NACE MR0175/ISO 15156-2 and ANSI/NACE MR0175/ISO 15156-3. The materials in the metallurgical condition that has the greatest susceptibility to cracking in H₂S service shall be used for the selection of the test samples.

Materials source, method of preparation, and surface condition of samples for testing shall be documented.

8.3.3 Selection of laboratory test methods

For carbon and low-alloy steels, test methods for SSC, HIC, SOHIC and/or SZC shall be selected from ANSI/NACE MR0175/ISO 15156-2 as required.

For CRAs and other alloys, test methods for SSC, SCC, and galvanically induced HSC shall be selected from ANSI/NACE MR0175/ISO 15156-3 as required.

8.3.4 Conditions to be applied during testing

For qualification of carbon and low-alloy steels for general sour service applications or for more restricted application ranges, standardized test environments and mechanical test conditions shall be chosen from those described in ANSI/NACE MR0175/ISO 15156-2.

For qualification of CRAs or other alloys for the restricted application ranges appropriate to each alloy type, the standardized test environments and mechanical test conditions shall be chosen from those described in ANSI/NACE MR0175/ISO 15156-3.

For qualification of a material for use in application-specific service conditions, the equipment user shall take care to ensure that the test conditions and the test results obtained from them are appropriate for those specific service conditions. All the test conditions applied shall be at least as severe, with respect to the potential mode of failure, as those defined to occur in the field service (see [6.1](#)). The pH applied shall represent the service in situ pH.

The justification of the selection of the test environment and mechanical test conditions with respect to a specific application shall be documented by the equipment user.

8.3.5 Acceptance criteria

Test acceptance criteria shall be as defined for each test method in ANSI/NACE MR0175/ISO 15156-2 and ANSI/NACE MR0175/ISO 15156-3.

9: Report of the method of selection or qualification

Materials selected or qualified in accordance with this document shall have the method of selection documented by reporting item a) from the following list, together with one other item [b), c), or d]):

- a) for all materials, evaluation of the service conditions (see [6.1](#))
- b) for a material selected with respect to SSC and/or SCC resistance, from lists and tables (see [Clause 7](#)), documentation making reference to the relevant subclauses of ANSI/NACE MR0175/ISO 15156-2 or ANSI/NACE MR0175/ISO 15156-3.
- c) for a material selected on the basis of field experience, documentation describing the following:
 - 1) mechanism(s) of cracking for which qualification and selection has been made;
 - 2) material used (see [8.1](#));
 - 3) field experience (see [8.2](#)).
- d) for a material selected on the basis of qualification by laboratory testing, a test report describing the following:
 - 1) mechanism(s) of cracking for which qualification and selection has been made;
 - 2) material selected for laboratory testing (see [8.1](#));
 - 3) selection, sampling, and preparation of test specimens (see [8.3.2](#));
 - 4) justification of the test environment and physical test conditions for qualification (see [8.3.3](#));
 - 5) test results that demonstrate conformance with ANSI/NACE MR0175/ISO 15156-2 or ANSI/NACE MR0175/ISO 15156-3 (see [8.3](#)).

The equipment user shall be responsible for ensuring that the required documentation is prepared.

Bibliography

- [1] ANSI/NACE MR0175-2003, *Metals for Sulfide Stress Cracking and Stress Corrosion Cracking Resistance in Sour Oilfield Environments*
- [2] ANSI/NACE TM0177, *Laboratory testing of metals for resistance to sulfide stress cracking and stress corrosion cracking in H₂S environments*
- [3] ANSI/NACE TM0284, *Evaluation of pipeline and pressure vessel steels for resistance to hydrogen induced cracking*
- [4] NACE MR0176, *Metallic materials for sucker-rod pumps for corrosive oilfield environments*
- [5] EFC Publication 16¹, *Guidelines on materials requirements for carbon and low alloy steels for H₂S-containing environments in oil and gas production*
- [6] EFC Publication 17, *Corrosion resistant alloys for oil and gas production: guidelines on general requirements and test methods for H₂S service*
- [7] the ISO 15156 series maintenance website, <http://www.iso.org/iso15156maintenance>

¹ European Federation of Corrosion (EFC), c/o The Institute of Materials, 1 Carlton House Terrace, London SW1Y 5DB, UK, www.efcweb.org.



ANSI/NACE MR0175-2021/ISO 15156-1:2020

International Standard
ANSI/NACE MR0175-2021/ISO 15156-2:2020
Fourth Edition
Identical to ISO 15156-2:2020

**Petroleum and natural gas industries —
Materials for use in H₂S-containing environments
in oil and gas production**

Part 2:
**Cracking-resistant carbon and low-alloy steels,
and the use of cast irons**

An American National Standard

Approved 21 Sep 2022

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**Petroleum and natural gas industries — Materials for use in
H₂S-containing environments in oil and gas production**

Part 2:
Cracking-resistant carbon and low-alloy steels, and the use of cast irons

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Foreword

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

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

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

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

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

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 12, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This fourth edition cancels and replaces the third edition (ANSI/NACE MR0175-2015/ISO 15156-2:2015), which has been technically revised. The main changes compared to the previous edition are as follows:

- corrections of temperature conversion for welding (see [A.2.1.4](#)), cold deformation and stress relief (see [A.2.1.6](#)), identification stamping (see [A.2.1.9](#)), tubulars and tubular components (see [A.2.2.3.4](#)), compressor impellers (see [A.2.3.3.2](#));
- title change from Shear rams to Rams in [A.2.3.2.2](#);
- addition of C110 and changes the designation of C95 to R95 in [Table A.3](#);
- reference change to NACE TM0316 in [Table B.1](#);
- addition of reference to BS 8701 in [B.4.3](#);
- changes and additions to [Table B.3](#);
- modification of Annex C to include alternative parameters and expanded explanation for the use of chemical activity and fugacity, and to provide some general guidance for the use of thermodynamic modeling for the determination of environmental severity.

ANSI/NACE MR0175/ISO 15156 consists of the following parts, under the general title *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production*

- *Part 1: General principles for selection of cracking-resistant materials*
- *Part 2: Cracking-resistant carbon and low-alloy steels, and the use of cast irons*
- *Part 3: Cracking-resistant CRAs (corrosion-resistant alloys) and other alloys*

ANSI/NACE MR0175-2021/ISO 15156-2:2020

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Introduction

The consequences of sudden failures of metallic oil and gas field components, associated with their exposure to H₂S-containing production fluids, led to the preparation of the first edition of NACE MR0175, which was published in 1975 by the National Association of Corrosion Engineers, now known as the Association for Materials Protection and Performance (AMPP).

The original and subsequent editions of NACE MR0175 established limits of H₂S partial pressure above which precautions against sulfide stress cracking (SSC) were always considered necessary. They also provided guidance for the selection and specification of SSC-resistant materials when the H₂S thresholds were exceeded. In more recent editions, NACE MR0175 has also provided application limits for some corrosion-resistant alloys, in terms of environmental composition and pH, temperature and H₂S partial pressures.

In separate developments, the European Federation of Corrosion issued EFC Publication 16 in 1995 and EFC Publication 17 in 1996. These documents are generally complementary to those of NACE though they differed in scope and detail.

In 2003, the publication of the ISO 15156-series and NACE MR0175/ISO 15156 was completed for the first time. These technically identical documents utilized the above sources to provide requirements and recommendations for materials qualification and selection for application in environments containing wet H₂S in oil and gas production systems. They are complemented by NACE TM0177 and NACE TM0284 test methods.

The revision of this document, i.e., ANSI/NACE MR0175/ISO 15156-2, involves a consolidation of all changes agreed and published in the Technical Circular 1, ISO 15156-2:2015/Cir.1:2017, the Technical Circular 2, ISO 15156-2:2015/Cir.2:2018 and the Technical Circular 3, ISO 15156-2:2015/Cir.3:2019, published by the ISO 15156 series Maintenance Agency secretariat at DIN.

The changes were developed by and approved by the ballot of, representative groups from within the oil and gas production industry. The great majority of these changes stem from issues raised by document users. A description of the process by which these changes were approved can be found at the ISO 15156 series maintenance website: www.iso.org/iso15156maintenance.

When found necessary by oil and gas production industry experts, future interim changes to this document will be processed in the same way and will lead to interim updates to this document in the form of Technical Corrigenda or Technical Circulars. Document users should be aware that such documents can exist and can impact the validity of the dated references in this document.

The ISO 15156 series Maintenance Agency at DIN was set up after approval by the ISO Technical Management Board given in document 34/2007. This document describes the makeup of the agency, which includes experts from AMPP, EFC and ISO/TC 67, and the process for approval of amendments. It is available from the ISO 15156 series maintenance website and from the ISO/TC 67 Secretariat. The website also provides access to related documents that provide more detail of the ISO 15156 series maintenance activities.

Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 2: Cracking-resistant carbon and low-alloy steels, and the use of cast irons

WARNING — Carbon and low-alloy steels and cast irons selected using this document are resistant to cracking in defined H₂S-containing environments in oil and gas production but not necessarily immune to cracking under all service conditions. It is the equipment user's responsibility to select the carbon and low alloy steels and cast irons suitable for the intended service.

1: Scope

This document gives requirements and recommendations for the selection and qualification of carbon and low-alloy steels for service in equipment used in oil and natural gas production and natural gas treatment plants in H₂S-containing environments, whose failure can pose a risk to the health and safety of the public and personnel or to the environment. It can be applied to help to avoid costly corrosion damage to the equipment itself. It supplements, but does not replace, the materials requirements of the appropriate design codes, standards or regulations.

This document addresses the resistance of these steels to damage that can be caused by sulfide stress cracking (SSC) and the related phenomena of stress-oriented hydrogen-induced cracking (SOHIC) and soft-zone cracking (SZC).

This document also addresses the resistance of these steels to hydrogen-induced cracking (HIC) and its possible development into stepwise cracking (SWC).

This document is concerned only with cracking. Loss of material by general (mass loss) or localized corrosion is not addressed.

Table 1 provides a non-exhaustive list of equipment to which this document is applicable, including exclusions. This document applies to the qualification and selection of materials for equipment designed and constructed using load controlled design methods. For design utilizing strain-based design methods, see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5.

[Annex A](#) lists SSC-resistant carbon and low alloy steels, and [A.2.4](#) includes requirements for the use of cast irons.

This document is not necessarily suitable for application to equipment used in refining or downstream processes and equipment.

Table 1 — List of equipment

This document is applicable to materials used for the following equipment	Exclusions
Drilling, well construction and well-servicing equipment	Equipment exposed only to drilling fluids of controlled composition ^a Drill bits Blowout preventer (BOP) shear blades ^b Drilling riser systems Work strings Wireline and wireline equipment ^c Surface and intermediate casing
Wells, including subsurface equipment, gas lift equipment, wellheads and christmas trees	Sucker rod pumps and sucker rods ^d Electric submersible pumps Other artificial lift equipment Slips
Flow-lines, gathering lines, field facilities and field processing plants	Crude oil storage and handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi)
Water-handling equipment	Water-handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi) Water injection and water disposal equipment
Natural gas treatment plants	—
Transportation pipelines for liquids, gases and multiphase fluids	Lines handling gas prepared for general commercial and domestic use
For all equipment above	Components loaded only in compression
^a See A.2.3.2.3 for more information. ^b See A.2.3.2.1 for more information. ^c Wireline lubricators and lubricator connecting devices are not excluded. ^d For sucker rod pumps and sucker rods, reference can be made to NACE MR0176.	

2: Normative references

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

ISO 6506 (all parts), *Metallic materials — Brinell hardness test*

ISO 6507 (all parts), *Metallic materials — Vickers hardness test*

ISO 6508 (all parts), *Metallic materials — Rockwell hardness test*

ISO 68921, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

ISO 10423, *Petroleum and natural gas industries — Drilling and production equipment — Wellhead and christmas tree equipment*

ANSI/NACE MR0175-2021/ISO 15156-1:2020, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 1: General principles for selection of cracking-resistant materials*

ANSI/NACE MR0175/ISO 15156-3, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 3: Cracking-resistant CRAs (corrosion-resistant alloys) and other alloys*

ANSI/NACE TM0177¹, *Laboratory testing of metals for resistance to sulfide stress cracking and stress corrosion cracking in H₂S environments*

¹ Association for Materials Protection and Performance (AMPP), 15835 Park Ten Place, Houston, TX 77084-5145, USA, www.ampp.org.

ANSI/NACE TM0284, *Evaluation of pipeline and pressure vessel steels for resistance to hydrogen-induced cracking*

ANSI/NACE TM0316, *Four-point bend testing of materials for oil and gas applications*

SAE AMS-2430², *Shot Peening*

3: Terms and definitions

For the purposes of this document, the terms and definitions given in ANSI/NACE MR0175/ISO 15156-1 and the following apply.

3.1 Brinell hardness (HBW)

hardness value of a material measured normally using a 10 mm diameter tungsten carbide ball indenter with a force of 29.42 kN

Note 1 to entry: The measurement shall be in accordance with the ISO 6506 series. Here, ASTM E10 is equivalent to ISO 6506-1.

3.2 bubble-point pressure (p_B)

pressure under which gas bubbles form in a liquid at a particular operating temperature

Note 1 to entry: See [C.2](#).

3.3 burnishing

process of smoothing surfaces using frictional contact between the material and some other hard pieces of material, such as hardened steel balls

3.4 casting

metal that is obtained at or near its finished shape by the solidification of molten metal in a mold

3.5 cast iron

iron-carbon alloy containing approximately 2 % to 4 % mass fraction carbon

3.5.1 grey cast iron

cast iron that displays a grey fracture surface due to the presence of flake graphite

3.5.2 white cast iron

cast iron that displays a white fracture surface due to the presence of cementite

3.5.3 malleable iron

white cast iron that is thermally treated to convert most or all of the cementite to graphite (temper carbon)

3.5.4 ductile iron

nodular cast iron

cast iron that has been treated while molten with an element (usually magnesium or cerium) that spheroidizes the graphite

3.6 cementite

microstructural constituent of steels composed principally of iron carbide (Fe_3C)

² Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001, USA, www.sae.org.

- 3.7 cold deforming
cold forging
cold forming
cold working**
deforming metal plastically under conditions of temperature and strain rate that induce strain-hardening, usually, but not necessarily, conducted at room temperature
- 3.8 fitness-for-purpose**
suitability for use under the expected service conditions
- 3.9 free-machining steel**
steel to which elements such as sulfur, selenium and lead have been added intentionally to improve machineability
- 3.10 lower critical temperature**
temperature of a ferrous metal at which austenite begins to form during heating or at which the transformation of austenite is completed during cooling
- 3.11 nitriding**
case-hardening process in which nitrogen is introduced into the surface of metallic materials (most commonly ferrous alloys)
- EXAMPLE* Liquid nitriding, gas nitriding, ion nitriding and plasma nitriding.
- 3.12 normalize, verb**
heating a ferrous metal to a suitable temperature above the transformation range (austenitizing), holding at temperature for a suitable time and then cooling in still air (or protective atmosphere) to a temperature substantially below the transformation range
- 3.13 plastically deformed**
permanently deformed by stressing beyond the limit of elasticity, i.e., the limit of proportionality of stress to strain
- 3.14 pressure-containing part**
part whose failure to function as intended results in a release of retained fluid to the atmosphere
- EXAMPLE* Valve bodies, bonnets and stems.
- 3.15 quenched and tempered**
quench hardened and then tempered
- 3.16 Rockwell C hardness (HRC)**
hardness value of a material measured using a Rockwell C diamond cone indenter with a force of 1 471 N
- Note 1 to entry: The measurement shall be in accordance with the ISO 6508 series. Here, ASTM E18 is equivalent to ISO 6508-1.
- 3.17 shot-peening**
inducing compressive stresses in the surface layer of a material by bombarding it with a selected medium (usually round steel shot) under controlled conditions
- 3.18 stress relief**
heating a metal to a suitable temperature, holding at that temperature long enough to reduce residual stresses, and then cooling slowly enough to minimize the development of new residual stresses
- 3.19 tempering**
heat treatment by heating to a temperature below the lower critical temperature, for the purpose of decreasing the hardness and increasing the toughness of hardened steel, hardened cast iron and, sometimes, normalized steel

- 3.20 tensile strength, ultimate strength**
ratio of maximum load to original cross-sectional area
- Note 1 to entry: See ISO 6892-1.
- 3.21 test batch**
group of items representing a production batch whose conformity with a specified requirement can be determined by testing representative samples in accordance with a defined procedure
- 3.22 tubular component**
cylindrical component (pipe) having a longitudinal hole, used in drilling/production operations for conveying fluids
- 3.23 Vickers hardness (HV)**
hardness value of a material using a diamond pyramid indenter and one of a variety of possible applied loads
- Note 1 to entry: The measurement shall be in accordance with the ISO 6507 series. Here, ASTM E384 is equivalent to ISO 6507-1.
- 3.24 weldment**
portion of a component on which welding has been performed, including the weld metal, the heat-affected zone, and the adjacent parent metal
- 3.25 weld metal**
portion of a weldment that has been molten during welding
- 3.26 wrought, adjective**
formed to a desired shape by working (rolling, extruding, forging, etc.), usually at an elevated temperature

4: Symbols and abbreviated terms

AYS	actual yield strength
CLR	crack length ratio
CSR	crack surface ratio
CTR	crack thickness ratio
DCB	double cantilever beam (test)
FPB	four-point bend (test)
HBW	Brinell hardness
HIC	hydrogen-induced cracking
HRC	Rockwell hardness (scale C)
HSC	hydrogen stress cracking
OCTG	oil country tubular goods, i.e., casing, tubing and drill pipe
p_{H_2S}	partial pressure of H_2S
p_{CO_2}	partial pressure of CO_2
$R_{p0.2}$	0.2 % proof stress in accordance with ISO 6892-1
SMYS	specified minimum yield strength
SOHIC	stress-oriented hydrogen-induced cracking
SSC	sulfide stress cracking
SWC	stepwise cracking
SZC	soft-zone cracking
T	temperature
UNS	Unified Numbering System (from SAE-ASTM, <i>Metals and alloys in the Unified Numbering System</i>)
UT	uniaxial tensile (test)

5: Purchasing information

- 5.1** The preparation of material purchasing specifications can require co-operation and exchange of data between the equipment user, the equipment supplier and the material manufacturer to ensure that the material purchased conforms with ANSI/NACE MR0175/ISO 15156-1 and this document.
- 5.2** The following information shall be provided:
- preferred material types and/or grades (if known);
 - equipment type (if known);
 - reference to this document;
 - acceptable bases for selection of materials for SSC resistance (see [Clause 7](#));
 - requirements for HIC resistance (see [Clause 8](#)).
- 5.3** The equipment user and the equipment supplier/material manufacturer may agree that carbon or low-alloy steels other than those described and/or listed in [Annex A](#) may be selected subject to suitable qualification testing in accordance with [Annex B](#) and ANSI/NACE MR0175/ISO 15156-1. The qualification requirements may be extended to include resistance to SOHIC and SZC.

If the purchaser intends to make use of such agreements, extensions and qualifications, the appropriate additional information shall be clearly indicated in the materials purchasing specification. This information may include:

- requirements for SSC testing (see [7.1](#) and [7.2](#)),
- service conditions for specific sour-service application, and
- other special requirements.

- 5.4 [Annex C](#) describes how to calculate the H₂S partial pressure and [Annex D](#) gives guidance on how to determine the pH-value of a fluid.
- 5.5 The information required for material purchasing shall be entered on suitable data sheets. Suggested formats are given in [Annex E](#).

6: Factors affecting the behavior of carbon and low alloy steels in H₂S-containing environments

The behavior of carbon and low-alloy steels in H₂S-containing environments is affected by complex interactions of parameters, including the following:

- a) chemical composition, method of manufacture, product form, strength, hardness of the material and its local variations, amount of cold work, heat-treatment condition, microstructure, microstructural uniformity, grain size and cleanliness of the material;
- b) H₂S partial pressure or equivalent concentration in the water phase;
- c) chloride ion concentration in the water phase;
- d) acidity (pH) of the water phase;
- e) presence of sulfur or other oxidants;
- f) exposure to non-production fluids;
- g) exposure temperature;
- h) total tensile stress (applied plus residual);
- i) exposure time.

These factors shall be considered when using this document for the selection of materials suitable for environments containing H₂S in oil and gas production systems.

7: Qualification and selection of carbon and low-alloy steels with resistance to SSC, SOHIC and SZC

7.1 Option 1 — Selection of SSC-resistant steels (and cast irons) using [A.2](#)

7.1.1 For $p_{\text{H}_2\text{S}} < 0.3 \text{ kPa}$ (0.05 psi)

The selection of materials for SSC resistance for pH₂S below 0.3 kPa (0.05 psi) is not considered in detail in this document. Normally, no special precautions are required for the selection of steels for use under these conditions, nevertheless, highly susceptible steels can crack. Additional information on factors affecting susceptibility of steels and attack by cracking mechanisms other than SSC is given in [7.2.1](#).

7.1.2 For $p_{\text{H}_2\text{S}} \geq 0.3 \text{ kPa}$ (0.05 psi)

If the partial pressure of H₂S in the gas is equal to or greater than 0.3 kPa (0.05 psi), SSC-resistant steels shall be selected using [A.2](#).

NOTE 1 The steels described or listed in [A.2](#) are considered resistant to SSC in oil and natural-gas production and natural-gas treatment plants.

NOTE 2 Users concerned with the occurrence of SOHIC and/or SZC can refer to Option 2 (see [7.2.2](#)).

NOTE 3 For HIC and SWC, see [Clause 8](#).

7.2 Option 2 — Selection of steels for specific sour-service applications or for ranges of sour service

7.2.1 Sulfide stress cracking

7.2.1.1 General

Option 2 allows the user to qualify and select materials for sulfide stress cracking (SSC) resistance for specific sour-service applications or for ranges of sour service.

For a given material, the limits of environmental and metallurgical variables defined for specific sour service or for a range of sour service by qualification in accordance with Option 2 may replace any limits of environmental and metallurgical variables listed for that material in [A.2](#) (Option 1).

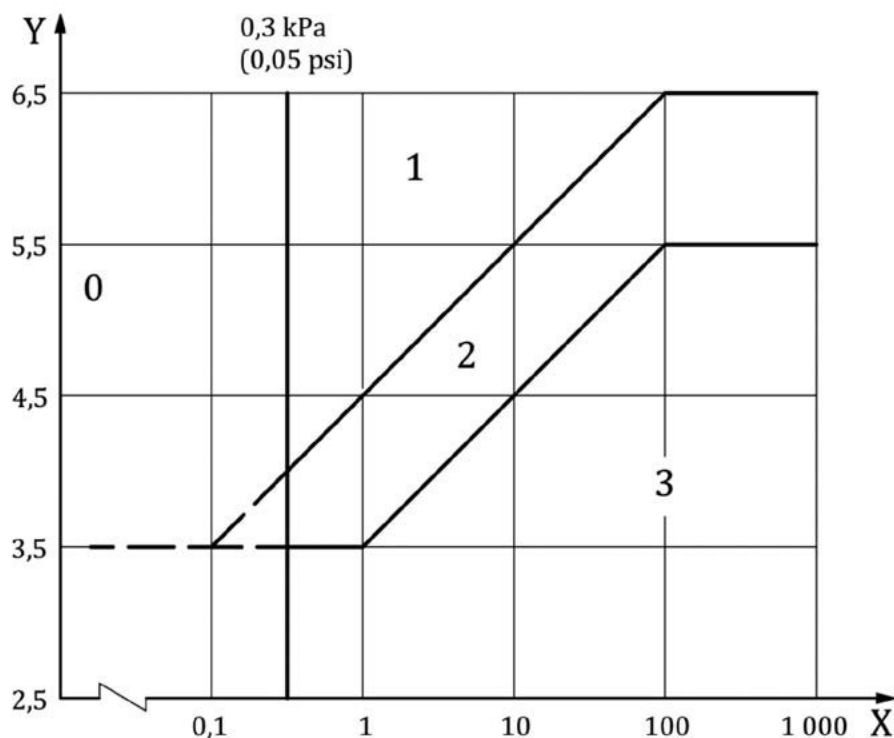
The use of option 2 can require knowledge of both the in situ pH and the H₂S partial pressure and their variations with time; see ANSI/NACE MR0175/ISO 15156-1.

Option 2 facilitates the purchase of bulk materials, such as OCTG or line pipe, where the economic incentive to use materials not described nor listed in [Annex A](#) outweighs the additional qualification and other costs that can be incurred. Steels for other equipment may also be qualified. In some cases, this requires an agreement between the supplier and the equipment user with respect to test and acceptance requirements. Such agreements shall be documented.

Option 2 can also facilitate fitness-for-purpose evaluations of existing carbon or low-alloy steel equipment exposed to sour-service conditions more severe than assumed in the current design.

7.2.1.2 SSC regions of environmental severity

The severity of the sour environment, determined in accordance with ANSI/NACE MR0175/ISO 15156-1, with respect to the SSC of a carbon or low-alloy steel shall be assessed using [Figure 1](#). In defining the severity of the H₂S-containing environment, the possibility of exposure to unbuffered, condensed aqueous phases of low pH during upset operating conditions or downtime, or to acids used for well stimulation and/or the backflow of stimulation acid after reaction should be considered.



Key

X	H ₂ S partial pressure, expressed in kilopascals
Y	in situ pH
0	region 0
1	SSC region 1
2	SSC region 2
3	SSC region 3

NOTE 1 The discontinuities in the figure below 0.3 kPa (0.05 psi) and above 1 MPa (150 psi) partial pressure H₂S effect uncertainty with respect to the measurement of H₂S partial pressure (low ρ_{H_2S}) and the steel's performance outside these limits (for both low and high ρ_{H_2S}).

NOTE 2 Guidance on the calculation of H₂S partial pressure is given in [Annex C](#).

NOTE 3 Guidance on the calculation of pH is given in [Annex D](#).

Figure 1 — Regions of environmental severity with respect to the SSC of carbon and low-alloy steels

7.2.1.3 Region 0 — For $p_{H_2S} < 0.3$ kPa (0.05 psi)

Normally, no precautions are required for the selection of steels for use under these conditions. Nevertheless, a number of factors, as follows, that can affect a steel's performance in this region should be considered.

- Steels that are highly susceptible to SSC and HSC can crack.
- Steel's physical and metallurgical properties affect its inherent resistance to SSC and HSC; see [Clause 6](#).
- Very high-strength steels can suffer HSC in aqueous environments without H_2S . Above about 965 MPa (140 ksi) yield strength, attention should be given to steel composition and processing to ensure that these steels do not exhibit SSC or HSC in region 0 environments.
- Stress concentrations increase the risk of cracking.

7.2.1.4 SSC regions 1, 2 and 3

Referring to the regions of severity of the exposure as defined in [Figure 1](#), steels for region 1 may be selected using [A.2](#), [A.3](#) or [A.4](#); steels for region 2 may be selected using [A.2](#) or [A.3](#); and steels for region 3 may be selected using [A.2](#).

In the absence of suitable choices from [Annex A](#), carbon and low-alloy steels may be tested and qualified for use under specific sour-service conditions or for use throughout a given SSC region. Testing and qualification shall be in accordance with ANSI/NACE MR0175/ISO 15156-1 and [Annex B](#).

Documented field experience may also be used as the basis for material selection for a specific sour-service application; see ANSI/NACE MR0175/ISO 15156-1.

7.2.2 SOHIC and SZC

The user should consider SOHIC and SZC, as defined in ANSI/NACE MR0175/ISO 15156-1, when evaluating carbon steels in plate form and their welded products for sour service in H_2S -containing environments.

[B.4](#) provides guidance on test methods and acceptance criteria to evaluate resistance to SOHIC and SZC.

NOTE The occurrence of these phenomena is rare and they are not well understood. They have caused sudden failures in parent steels (SOHIC) and in the HAZ of welds (SOHIC and SZC). Their occurrence is thought to be restricted to carbon steels. The presence of sulfur or oxygen in the service environment is thought to increase the probability of damage by these mechanisms.

7.3 Hardness requirements

7.3.1 General

The hardness of parent materials and of welds and their heat-affected zones play important roles in determining the SSC resistance of carbon and low alloy steels. Hardness control can be an acceptable means of obtaining SSC resistance.

7.3.2 Parent metals

If hardness measurements on parent metal are specified, sufficient hardness tests shall be made to establish the actual hardness of the steel being examined. Individual HRC readings exceeding the value permitted by this document may be considered acceptable if the average of several readings taken within close proximity does not exceed the value permitted by this document and no individual reading is greater than 2 HRC above the specified value. Equivalent requirements shall apply to other methods of hardness measurement when specified in this document or referenced in a manufacturing specification.

NOTE The number and location of hardness tests on parent metal are not specified in the ANSI/NACE MR0175/ISO 15156 series.

For ferritic steels, EFC Publication 16^[38] shows graphs for the conversion of hardness readings, from Vickers (HV) to Rockwell (HRC) and from Vickers (HV) to Brinell (HBW), derived from the tables of ASTM E140 and ISO 18265. Other conversion tables also exist. Users may establish correlations for individual materials.

7.3.3 Welds

7.3.3.1 General

The metallurgical changes that occur on welding carbon and low-alloy steels affect their susceptibility to SSC, SOHIC and SZC.

Processes and consumables should be selected in accordance with good practice and to achieve the required cracking resistance.

Welding shall be carried out in conformance with appropriate codes and standards as agreed between the supplier and the purchaser. Welding procedure specifications (WPSs) and procedure qualification records (PQRs) shall be available for inspection by the equipment user.

The qualification of welding procedures for sour service shall include hardness testing in accordance with 7.3.3.2, [7.3.3.3](#) and [7.3.3.4](#).

7.3.3.2 Hardness testing methods for welding procedure qualification

Hardness testing for welding procedure qualification shall normally be carried out using the Vickers HV 10 or HV 5 method in accordance with ISO 6507-1, or the Rockwell method in accordance with ISO 6508-1 using the 15N scale.

NOTE For the purposes of this provision, ASTM E384 is equivalent to ISO 6507-1 and ASTM E18 is equivalent to ISO 6508-1.

The HRC method may be used for welding procedure qualification if the design stress does not exceed two-thirds of SMYS and the welding procedure specification includes post-weld heat treatment. The use of the HRC method for welding procedure qualification in all other cases shall require the agreement of the equipment user.

NOTE Hardness surveys using the Vickers or Rockwell 15N testing method produce a more detailed picture of weld hardness and its variations. Hardness surveys using the HRC testing method might not detect small zones in welds or HAZs where the hardness exceeds the acceptance criteria for the Vickers or Rockwell 15N testing method. The significance of such small hard zones is not well understood.

The use of other hardness testing methods shall require the agreement of the equipment user.

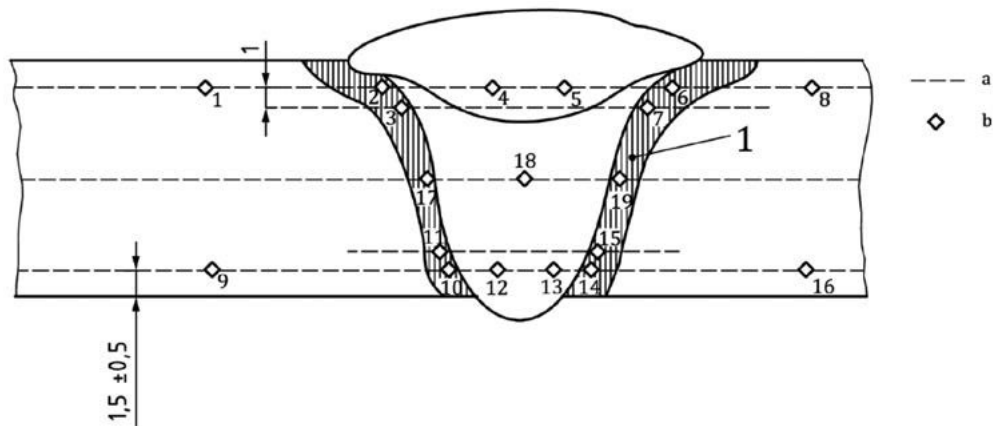
The Vickers or Rockwell 15N hardness testing method shall be used for the qualification of alternative weld-hardness acceptance criteria as permitted in [7.3.3.4](#).

7.3.3.3 Hardness surveys for welding procedure qualification

Vickers hardness surveys shall be in accordance with Figure 2 for butt welds, [Figure 3](#) for fillet welds and [Figure 4](#) for repair and partial penetration welds. HRC surveys of butt welds shall be in accordance with [Figure 5](#). Survey requirements for other joint configurations shall be developed from these figures.

Hardness surveys for qualification of overlay welding procedures shall be in accordance with [Figure 6](#).

Dimensions in millimeters



Key

1 weld heat-affected zone (visible after etching)

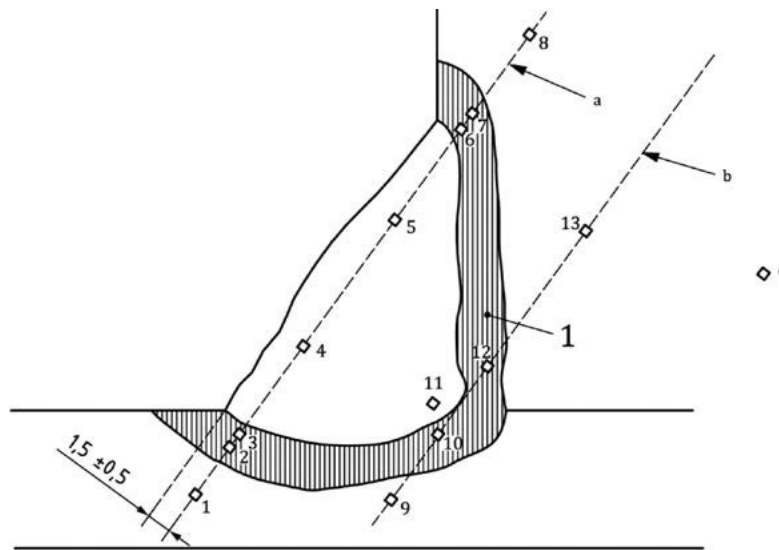
^a Lines of survey.

^b Hardness impressions: Impressions 2, 3, 6, 7, 10, 11, 14, 15, 17 and 19 should be entirely within the heat-affected zone and located as close as possible to the fusion boundary between the weld metal and the heat-affected zone.

The top line of survey should be positioned so that impressions 2 and 6 coincide with the heat-affected zone of the final run or change of profile of the fusion line associated with the final run.

Figure 2 — Butt-weld survey method for Vickers hardness measurement

Dimensions in millimeters



Key

1 weld heat-affected zone (visible after etching)

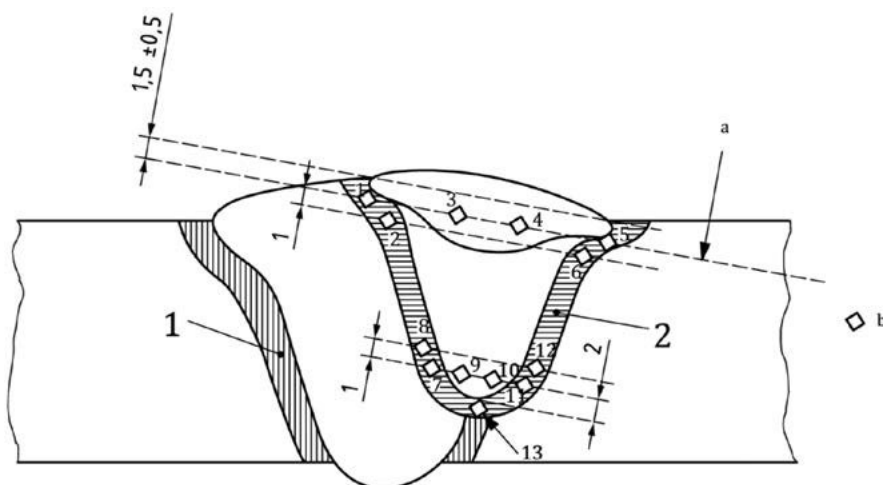
^a Line of survey.

^b Line of survey, parallel to line B and passing through the fusion boundary between the weld metal and the heat-affected zone at the throat.

^c Hardness impressions: Impressions 3, 6, 10 and 12 should be entirely within the heat-affected zone and located as close as possible to the fusion boundary between the weld metal and the heat-affected zone.

Figure 3 — Fillet weld

Dimensions in millimeters



Key

1 original weld heat-affected zone

2 repair-weld heat-affected zone

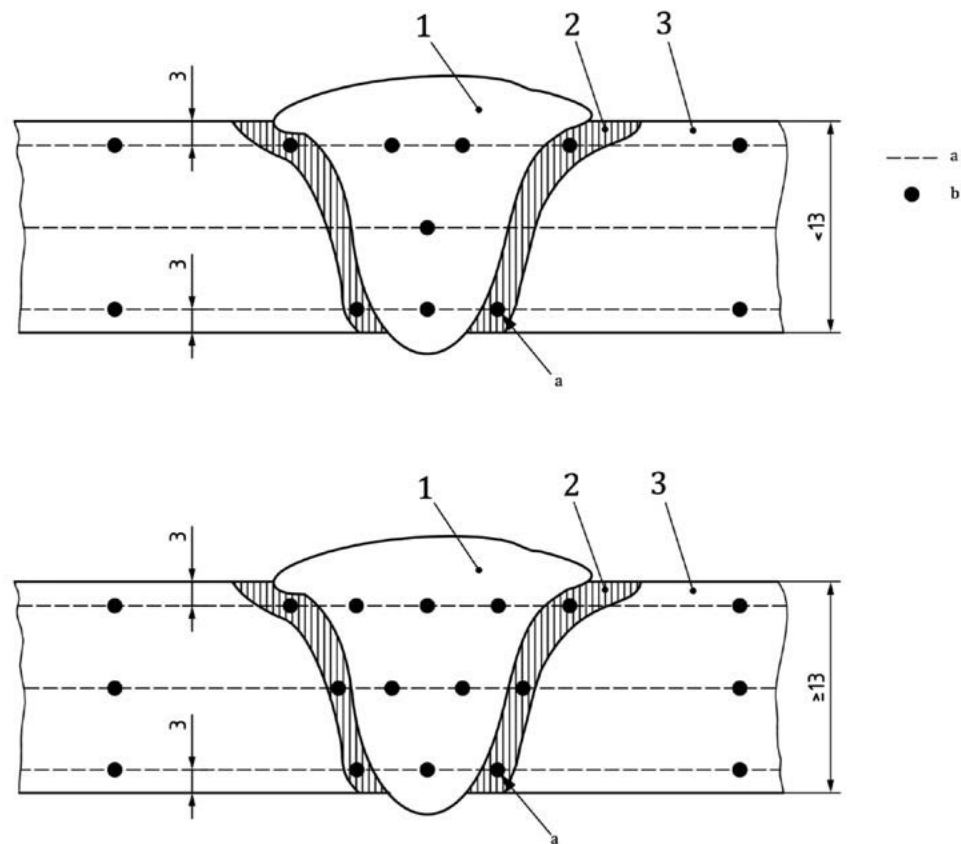
^a Parallel lines of survey.

^b Hardness impressions: Impressions in the heat-affected zone should be located as close as possible to the fusion boundary.

The top line of survey should be positioned so that the heat-affected zone impressions coincide with the heat-affected zone of the final run or change in profile of the cap of fusion line associated with the final run.

Figure 4 — Repair and partial penetration welds

Dimensions in millimeters



Key

1 weld

2 weld heat-affected zone (visible after etching)

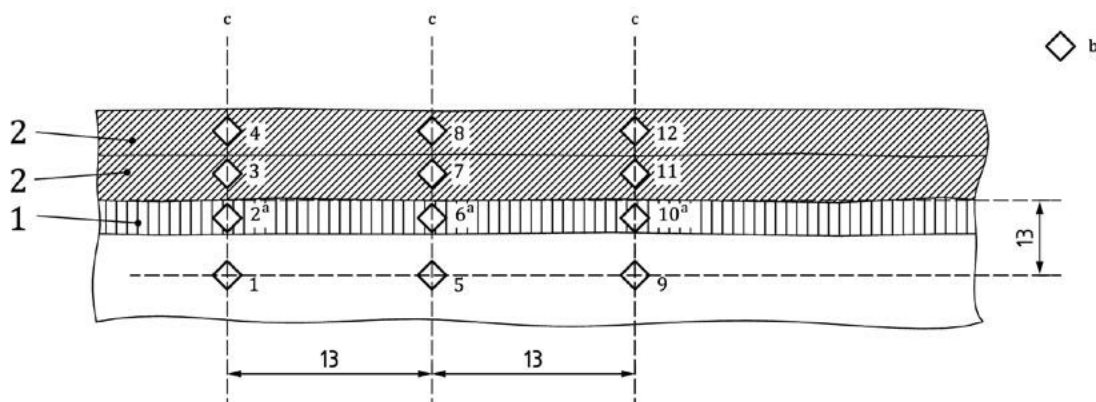
3 parent metal

^a Lines of survey.

^b Hardness impressions: Impressions in the weld heat-affected zone should be located within 2 mm of the fusion boundary.

Figure 5 — Butt weld survey method for Rockwell hardness measurements

Dimensions in millimeters



Key

- 1 weld heat-affected zone (visible after etching)
- 2 layer of weld overlay (visible after etching)

The Rockwell C hardness measurement method may be used subject to the requirements of [7.3.3.2](#). HRC hardness impressions in the HAZ shall be located within 2 mm of the fusion boundary.

- ^a Using the Vickers or Rockwell 15N measurement methods, hardness impressions 2, 6 and 10 should be entirely within the heat-affected zone and located as close as possible to, but no more than 1 mm from, the fusion boundary between the weld overlay and HAZ.
- ^b Hardness impressions.
- ^c Lines of hardness survey indentations 1 to 12.

Figure 6 — Weld overlay

7.3.3.4 Hardness acceptance criteria for welds

Weld hardness acceptance criteria for steels selected using option 1 (see [7.1](#)) shall be as specified in [A.2.1.4](#). Alternative weld hardness acceptance criteria may be established from successful SSC testing of welded samples. SSC testing shall be in accordance with [Annex B](#).

Weld-hardness acceptance criteria for steels qualified and/or selected using option 2 (see [7.2](#)) may be established from successful SSC testing of welded samples. SSC testing shall be in accordance with [Annex B](#).

7.4 Other fabrication methods

For steels that are subject to hardness change caused by fabrication methods other than welding, hardness testing shall be specified as part of the qualification of the fabrication process. Hardness testing shall be specified as part of the qualification of burning/cutting processes if any HAZ remains in the final product. The requirements, interpreted for the fabrication method, and hardness acceptance criteria of [7.3](#) shall apply.

The form and location of the samples for evaluation and testing shall be acceptable to the equipment user.

8: Evaluation of carbon and low alloy steels for their resistance to HIC/SWC

The equipment user shall consider HIC/SWC as defined in ANSI/NACE MR0175/ISO 15156-1 when evaluating flat-rolled carbon steel products for sour service environments containing even trace amounts of H₂S and shall consider HIC/SWC testing of these products. [Annex B](#) provides guidance on test methods and acceptance criteria to evaluate resistance to HIC/SWC.

The probability of HIC/SWC is influenced by steel chemistry and manufacturing route. The level of sulfur in the steel is of particular importance, typical maximum acceptable levels for flat-rolled and seamless products are 0.003 % mass fraction and 0.01 % mass fraction, respectively. Conventional forgings with sulfur levels less than 0.025 % mass fraction, and castings, are not normally considered sensitive to HIC or SOHIC.

NOTE 1 HIC/SWC leading to loss of containment has occurred only rarely in seamless pipe and other products that are not flat-rolled. Furthermore, seamless pipe manufactured using modern technology is much less sensitive to HIC/SWC than older products. Hence, there can be benefits in evaluating seamless pipe for HIC/SWC resistance for applications where the potential consequences of failure make this justifiable.

NOTE 2 The presence of rust, sulfur or oxygen, particularly together with chloride, in the service environment is thought to increase the probability of damage.

9: Marking, labelling, and documentation

Materials conforming with this document shall be made traceable, preferably by marking, before delivery. Suitable labelling or documentation is also acceptable.

For materials qualified and selected for a special application in accordance with [Annex B](#), traceability shall include reference to the environmental conditions of the special application.

The equipment user may request the equipment or materials supplier to provide documentation of the materials used in equipment or components and their environmental service limits as defined in this document.

[Table E.1](#) and [Table E.2](#) provide designations that may be used to identify materials.

Annex A (normative)

SSC-resistant carbon and low alloy steels (and requirements and recommendations for the use of cast irons)

A.1 General

This annex describes and lists SSC-resistant carbon and low alloy steels. Requirements for the use of cast irons are given in [A.2.4](#).

Steels conforming with this annex might not resist SOHIC, SZC, HIC or SWC without the specification of additional requirements (see [7.2.2](#) and/or [Clause 8](#)).

NOTE A.2 is consistent with the previously established requirements of NACE MR0175.

At the time of publication of this document, there are no listings of steels approved for SSC region 2 ([A.3](#)) or SSC region 1 ([A.4](#)). Therefore, [A.3](#) and [A.4](#) indicate only properties typical of steels that are expected to be suitable for use under the defined conditions.

A.2 SSC-resistant carbon and low-alloy steels and the use of cast irons

A.2.1 General requirements for carbon and low alloy steels

A.2.1.1 General

Carbon and low-alloy steels shall conform with A.2.1.2 to [A.2.1.9](#).

Carbon and low-alloy steels, products and components that conform with A.2 are, with stated exceptions, qualified in accordance with this document without further SSC testing. Nevertheless, any SSC testing that forms part of a materials manufacturing specification shall be carried out successfully and the results reported.

The majority of steels that conform with the general requirements of A.2 are not individually listed; however, for convenience, some examples of such steels are listed in [Table A.2](#), [Table A.3](#) and [Table A.4](#).

NOTE 1 The carbon and low-alloy steels described/listed previously in NACE MR0175 (all revisions) were identified by extensive correlations of field failures/successes and laboratory data. The hardness limit of HRC 22 applied to most carbon and low-alloy steels is based on correlations of heat treatment, chemical composition, hardness and failure experience. The higher hardness limits for the chromium-molybdenum steels are based on similar considerations.

NOTE 2 It can be possible to qualify a carbon or low alloy steel not described or listed in the text or tables of A.2 for use in specific sour service applications or for a range of sour service in accordance with Option 2 ([7.2](#)).

A.2.1.2 Parent metal composition, heat treatment and hardness

Carbon and low-alloy steels are acceptable at 22 HRC maximum hardness provided they contain less than 1 % mass fraction nickel, are not free-machining steels and are used in one of the following heat-treatment conditions:

- a) hot-rolled (carbon steels only);
- b) annealed;
- c) normalized;
- d) normalized and tempered;
- e) normalized, austenitized, quenched, and tempered;
- f) austenitized, quenched, and tempered.

A.2.1.3 Carbon steels acceptable with revised or additional restrictions

In addition to the restrictions of [A.2.1.2](#), some carbon steels are acceptable subject to the following revised or additional restrictions.

- a) Forgings produced in accordance with ASTM A105 are acceptable if the hardness does not exceed 187 HBW.
- b) Wrought pipe fittings to ASTM A234, grades WPB and WPC are acceptable if the hardness does not exceed 197 HBW.

A.2.1.4 Welding

Welding and weld-hardness determinations shall be performed in accordance with [7.3.3](#).

Acceptable maximum hardness values for carbon steel, carbon manganese steel and low alloy steel welds are given in [Table A.1](#).

As-welded carbon steels, carbon-manganese steels and low-alloy steels that conform with the hardness requirements of [Table A.1](#) do not require post-weld heat treatment.

Tubular products with an SMYS not exceeding 360 MPa (52 ksi) and listed in [Table A.2](#) are acceptable in the as-welded condition. For these products, hardness testing of welding procedures may be waived if agreed by the equipment user.

Some tubular products with an SMYS exceeding 360 MPa (52 ksi) (see [A.2.2.2](#)) may be acceptable in the as-welded condition if suitable qualified welding procedures are used. The conditions in [Table A.1](#) shall be met.

Carbon steel, carbon manganese and low-alloy steel weldments that do not conform with the other requirements of this subclause shall be post weld heat treated after welding. The heat treatment temperature and its duration shall be chosen to ensure that the maximum weld zone hardness, determined in accordance with [7.3](#), shall be 250 HV or, subject to the restrictions described in [7.3.3](#), 22 HRC.

A minimum post weld heat treatment temperature of 621 °C (1 150 °F) shall be used for low alloy steels.

The acceptability of any effects on mechanical properties, other than hardness, caused by the chosen heat treatment and its duration shall be subject to the approval of the equipment user.

Welding consumables and procedures that produce a deposit containing more than 1 % mass fraction nickel are acceptable after successful weld SSC qualification by testing in accordance with [Annex B](#).

Table A.1 — Maximum acceptable hardness values for carbon steel, carbon-manganese steel and low-alloy steel welds

Hardness test methods	Hardness test locations for welding procedure qualification	Maximum acceptable hardness
Vickers HV 10 or HV 5 or Rockwell HR 15N	Weld root: Base metal, HAZ and weld root metal as shown in Figure 2 , Figure 3 or Figure 4	250 HV 70.6 HR 15N
	Base metal and HAZ for weld overlays as shown in Figure 6 ; see also A.2.1.5 b)	250 HV 70.6 HR 15N
	Weld cap: Base metal, HAZ and weld metal of unexposed weld cap as shown in Figure 2 or Figure 4	275 HVa 73.0 HR 15N
Rockwell HRC; see 7.3.3.2	As shown in Figure 5	22 HRC
	Base metal and HAZ for weld overlays as shown in Figure 6 ; see also A.2.1.5 b)	22 HRC
^a The maximum shall be 250 HV or 70.6 HR 15N unless all three of the following conditions are met: — equipment user agrees the alternative weld cap hardness limit; — parent material(s) are over 9 mm thick; — weld cap is not exposed directly to the sour environment.		

A.2.1.5 Surface treatments, overlays, plating, coatings, linings, etc.

NOTE The composition and cracking resistance of overlays are addressed in ANSI/NACE MR0175/ISO 15156-3.

Metallic coatings (electroplated and electroless plated), conversion coatings, plastic coatings and linings are not acceptable for preventing SSC.

Overlays applied by thermal processes such as welding, silver brazing, or spray metallizing systems are acceptable if they conform with one of the following requirements.

- The heat-treated condition of the substrate is unchanged, i.e., it does not exceed the lower critical temperature during application of the overlay.
- The maximum hardness and final heat-treated condition of the base metal substrate conform with [A.2.1.2](#) and, in the case of welded overlays, [A.2.1.4](#). This requirement may be waived in accordance with ANSI/NACE MR0175-2021/ISO 15156-3:2020, A.13.1. The maximum hardness and/or other properties of the weld deposit shall conform with the requirements of ANSI/NACE MR0175/ISO 15156-3 or this document, as applicable.

Joining of dissimilar materials, such as cemented carbides to steels by silver brazing, is acceptable. The base metal after brazing shall conform with [A.2.1.2](#).

Nitriding, with a maximum case depth of 0.15 mm (0.006 in), is an acceptable surface treatment if conducted at a temperature below the lower critical temperature of the alloy being treated.

A.2.1.6 Cold deformation and thermal stress relief

Carbon and low-alloy steels shall be thermally stress-relieved following any cold deforming by rolling, cold forging or other manufacturing process that results in a permanent outer fiber deformation greater than 5 %. Thermal stress relief shall be performed in accordance with an appropriate code or standard. The minimum stress-relief temperature shall be 593 °C (1 100 °F). The final maximum hardness shall be 22 HRC except for pipe fittings made from ASTM A234 grade WPB or WPC, for which the final hardness shall not exceed 197 HBW.

The above requirement does not apply to cold work imparted by pressure testing according to an applicable code or standard agreed by the equipment user.

Cold-rotary straightened pipe is acceptable only where permitted in the applicable ISO or API product standards; see also [A.2.2.3.4](#).

Cold-worked line pipe fittings of ASTM A53 Grade B, ASTM A106 Grade B, API 5L Grade X-42, ISO 3183 Grade L290, or lower-yield-strength grades with similar chemical compositions, are acceptable with cold strain equivalent to 15 % or less, provided the hardness in the strained area does not exceed 190 HBW.

SSC testing and qualification in accordance with [Annex B](#) may be used to justify other cold deformation limits.

A.2.1.7 Threading

Threads produced using a machine-cutting process are acceptable.

Threads produced by cold forming (rolling) are acceptable in steels that otherwise conform with the heat treatment and hardness requirements of [A.2.1.2](#).

A.2.1.8 Cold deformation of surfaces

Cold deformation of surfaces is acceptable if caused by processes, such as burnishing, that do not impart more cold work than that incidental to normal machining operations (such as turning, boring, rolling, threading, drilling, etc.).

Cold deformation by controlled shot-peening is acceptable if applied to base materials that conform with this document and if restricted to a maximum shot size of 2.0 mm (0.080 in) and an Almen intensity not exceeding 10C. The process shall be controlled in accordance with SAE AMS-2430.

A.2.1.9 Identification stamping

The use of identification stamping using low-stress (dot-, vibratory-, and round V-) stamps is acceptable.

The use of conventional sharp V-stamping is acceptable in low-stress areas, such as the outside diameter of flanges.

Conventional sharp V-stamping shall not be performed in high-stress areas unless subsequently stress-relieved at a minimum temperature of 593 °C (1 100 °F).

A.2.2 Application to product forms

A.2.2.1 General

Except as modified below, the general requirements of [A.2.1](#) shall apply to all product forms.

A.2.2.2 Pipe, plate, and fittings

Examples of tubular products that can conform with [A.2.1](#) are shown in [Table A.2](#).

Pressure vessel steels classified as P-No 1, Group 1 or 2, in Section IX of the ASME Boiler and Pressure Vessel Code are acceptable.

Products made from flat-rolled steels in contact with trace amounts of H₂S [i.e., even if $\rho_{\text{H}_2\text{S}}$ is below 0.3 kPa (0.05 psi)] can be susceptible to HIC/SWC damage.

Table A.2 — Examples of tubular products that can conform with A.2.1

ISO specifications and grades	Other designations
ISO 3183 grades: L245 through L450	API Specification 5L grades: A and B and X-42 through X-65 ASTM A53 ASTM A106 grades A, B and C ASTM A333 grades 1 and 6 ASTM A524 grades 1 and 2 ASTM A381 class 1, Y35 to Y65

Pipe seam welds shall conform with [A.2.1](#).

A.2.2.3 Downhole casing, tubing, and tubular components

A.2.2.3.1 ISO and API grades of casing and tubing are acceptable for the temperature ranges given in [Table A.3](#).

A.2.2.3.2 Tubulars and tubular components made of Cr-Mo low-alloy steels (UNS G41XX0, formerly AISI 41XX, and modifications), if quenched and tempered in the tubular form, are acceptable if their hardness does not exceed 30 HRC and they have SMYS grades of 690 MPa (100 ksi), 720 MPa (105 ksi), and 760 MPa (110 ksi). The maximum yield strength for each grade shall be no more than 103 MPa (15 ksi) higher than the SMYS. SSC resistance shall be demonstrated by testing each test batch and shall conform with [B.1](#) using the UT test.

A.2.2.3.3 Tubulars and tubular components made of Cr-Mo low-alloy steels (UNS G41XX0, formerly AISI 41XX and modifications), if quenched and tempered in the tubular form, are acceptable if the hardness does not exceed 26 HRC. These products should be qualified by SSC testing in accordance with [B.1](#) using the UT test.

A.2.2.3.4 If tubulars and tubular components are cold-straightened at or below 510 °C (950 °F), they shall be stress-relieved at a minimum temperature of 482 °C (900 °F). If tubulars and tubular components are cold-formed (pin-nosed and/or box-expanded) and the resultant permanent outer fiber deformation is greater than 5 %, the cold-formed regions shall be thermally stress-relieved at a minimum temperature of 593 °C (1 100 °F).

If the connections of high-strength tubulars with hardnesses above 22 HRC are cold-formed, they shall be thermally stress-relieved at a minimum temperature of 593 °C (1 100 °F).

Table A.3 — Environmental conditions for which grades of casing and tubing are acceptable

For all temperatures	For ≥ 65 °C (150 °F)	For ≥ 80 °C (175 °F)	For ≥ 107 °C (225 °F)
ISO 11960 ^a grades: H40 J55 K55 M65 L80 type 1 C90 type 1 T95 type 1	ISO 11960 ^a grades: N80 type Q R95 ^c C110	ISO 11960 ^a grades: N80 P110	ISO 11960 ^a grade: Q125 ^b
Proprietary grades as described in A.2.2.3.3	Proprietary Q&T grades with 760 MPa (110 ksi) or less maximum yield strength. Casings and tubulars made of Cr-Mo low-alloy steels as described in A.2.2.3.2 .	Proprietary Q&T grades with 965 MPa (140 ksi) or less maximum yield strength.	

Temperatures given are minimum allowable service temperatures with respect to SSC.

Low temperature toughness (impact resistance) is not considered, equipment users shall determine requirements separately.

^a For the purposes of this provision, API 5CT is equivalent to ISO 11960:2020.

^b Types 1 and 2 based on Q&T, Cr-Mo chemistry to 1 036 MPa (150 ksi) maximum yield strength. C-Mn steels are not acceptable.

^c In earlier editions of ISO 11960/API 5CT this grade was named C95. For the purposes of this provision, R95 and the former C95 are deemed equivalent.

A.2.2.4 Bolting and fasteners

Bolting that can be exposed directly to a sour environment, or that is buried, insulated, equipped with flange protectors or otherwise denied direct atmospheric exposure or direct open seawater exposure, shall conform to the general requirements of [A.2.1](#).

Designers and users should be aware that it can be necessary to lower equipment pressure ratings when using SSC-resistant bolting and fasteners. The use of SSC-resistant bolting and fasteners with API flanges shall be in accordance with ISO 10423.

Table A.4 — Acceptable bolting materials

Bolts	Nuts
ASTM A193 grade B7M ASTM A320 grade L7M	ASTM A194 grades 2HM, 7M

A.2.3 Application to equipment

A.2.3.1 General

The general requirements of [A.2.1](#) apply, with the following modifications.

A.2.3.2 Drilling blowout preventers

A.2.3.2.1 Shear blades

The high-strength steels used for blowout-preventer (BOP) shear blades can be susceptible to SSC. The suitability of shear blades that do not conform with this annex is the responsibility of the equipment user.

A.2.3.2.2 Rams

Rams manufactured in quenched and tempered Cr-Mo low-alloy steels (UNS G41XX0, formerly AISI 41XX, and modifications) are acceptable if the hardness does not exceed 26 HRC. If the hardness of these alloys exceeds 22 HRC, careful attention shall be paid to chemical composition and heat treatment to ensure their SSC resistance. SSC testing, as agreed with the equipment user, shall demonstrate that the performance of the alloy meets or exceeds that of field proven material.

A.2.3.2.3 Drilling, well construction and well-servicing equipment exposed only to drilling fluids of controlled composition

Given the high strength often needed, drilling equipment might not conform with ANSI/NACE MR0175/ISO 15156 (all parts). In such cases, the primary means for avoiding SSC is control of the drilling or well-servicing environment. As service stresses and material hardness increase, drilling-fluid control becomes increasingly important. Care shall be taken to control the drilling environment by maintenance of drilling-fluid hydrostatic head and fluid density to minimize formation-fluid in-flow and by the use of one or more of the following:

- a) maintenance of pH 10 or higher to neutralize H₂S in the drilled formation;
- b) use of chemical sulfide scavengers;
- c) use of a drilling fluid in which oil is the continuous phase.

A.2.3.3 Compressors and pumps

A.2.3.3.1 Compressor impellers

UNS G43200 (formerly AISI 4320) and a modified version of UNS G43200 that contains 0.28 % mass fraction carbon are acceptable for compressor impellers at a maximum yield strength of 620 MPa (90 ksi) provided they have been heat-treated in accordance with the following three-step procedure.

- a) Austenitize and quench.
- b) Temper at 621 °C (1 150 °F) minimum temperature, but below the lower critical temperature. Cool to ambient temperature before the second temper.
- c) Temper at 621 °C (1 150 °F) minimum, but lower than the first tempering temperature. Cool to ambient temperature.

A.2.3.3.2 Special provisions for compressors and pumps

Soft carbon steel and soft, low-carbon iron are acceptable as gaskets.

Cast irons in accordance with [A.2.4](#) are acceptable.

A.2.4 Requirements for the use of cast irons

A.2.4.1 General

Grey, austenitic and white cast irons shall not be used for pressure-containing parts. These materials may be used for internal components if their use is permitted by the equipment standard and has been approved by the equipment user.

Ferritic ductile iron in accordance with ASTM A395 is acceptable for equipment unless otherwise specified by the equipment standard.

A.2.4.2 Packers and subsurface equipment

The listed cast irons are acceptable for the following applications.

Table A.5 — Cast irons acceptable for packers and other subsurface equipment

Component	Cast iron
Drillable packer components	Ductile iron (ASTM A536, ASTM A571/A571M) Malleable iron (ASTM A220, ASTM A602)
Compression members	Grey iron (ASTM A48, ASTM A278)

A.2.4.3 Compressors and pumps

Grey cast iron (ASTM A278, Class 35 or 40) and ductile (nodular) cast iron (ASTM A395) are acceptable as compressor cylinders, liners, pistons and valves.

A.3 SSC-resistant steels for use throughout SSC region 2

A.3.1 General

The steels listed in [A.2](#) are acceptable.

The properties of steels typical of those that have been shown to meet the requirements for sour service throughout SSC region 2 are described below. Qualification according to [Annex B](#) shall be performed for steels that do not conform with [A.2](#).

A.3.2 Downhole casing, tubing, and tubular components

Casing, tubing and tubular components made of Cr-Mo low-alloy steels (UNS G41XX0, formerly AISI 41XX, and modifications) have proven acceptable in the quenched and tempered condition. Typically, the actual yield strength of acceptable steels has been no more than 760 MPa (110 ksi) [an SMYS of approximately 550 MPa (80 ksi)] and their hardness has been no more than 27 HRC. Other requirements shall be in accordance with the applicable manufacturing specification.

A.3.3 Pipeline steels

Pipeline steels require appropriate restricted chemistries to ensure good weldability. Typically, SMYSs of up to 450 MPa (65 ksi) have proven acceptable. Typically, fabrication and field weld hardness should not exceed 280 HV. Other requirements shall be in accordance with the applicable manufacturing specification.

A.4 SSC-resistant steels for use throughout SSC region 1

A.4.1 General

Steels listed in [A.2](#) and A.3 are acceptable.

The properties of steels typical of those that have been shown to meet the requirements for sour service throughout SSC region 1 are described below. Qualification according to [Annex B](#) shall be performed for steels which do not conform with [A.2](#) or [A.3](#).

A.4.2 Downhole casing, tubing, and tubular components

Casing, tubing and tubular components made of Cr-Mo low-alloy steels (UNS G41XX0, formerly AISI 41XX and modifications) have proven acceptable in the quenched and tempered condition. Typically, the actual yield strength of acceptable steels has been no more than 896 MPa (130 ksi) [an SMYS of approximately 760 MPa (110 ksi)] and their hardness has been no more than 30 HRC. Other requirements shall be in accordance with the applicable manufacturing specification.

A.4.3 Pipeline steels

Pipeline steels require appropriate restricted chemistries to ensure good weldability. Typically, SMYSs of up to 550 MPa (80 ksi) have proven acceptable. Typically, fabrication and field weld hardness should not exceed 300 HV. Other requirements shall be in accordance with the applicable manufacturing specification.

Annex B (normative)

Qualification of carbon and low-alloy steels for H₂S service by laboratory testing

B.1 Requirements

This annex specifies requirements for qualifying carbon and low-alloy steels for H₂S service by laboratory testing. Requirements are given for qualifying resistance to the following cracking mechanisms.

- a) SSC qualification by laboratory testing shall require one or more of the following:
- SSC testing in accordance with the materials manufacturing specification; see also [A.2.1.1](#);
 - testing for specific sour service applications in accordance with [B.3](#);
 - testing for SSC regions 1 or 2 of [Figure 1](#) in accordance with [B.3](#) and footnote g of Table B.1;
 - testing for sour service in all SSC regions of [Figure 1](#) in accordance with [B.3](#).

The qualification tests summarized demonstrate varying levels of resistance to SSC in sour environments. Some carbon and low-alloy steels described or listed in [A.2](#) might not pass some of the laboratory test requirements listed above (see [A.2.1](#)).

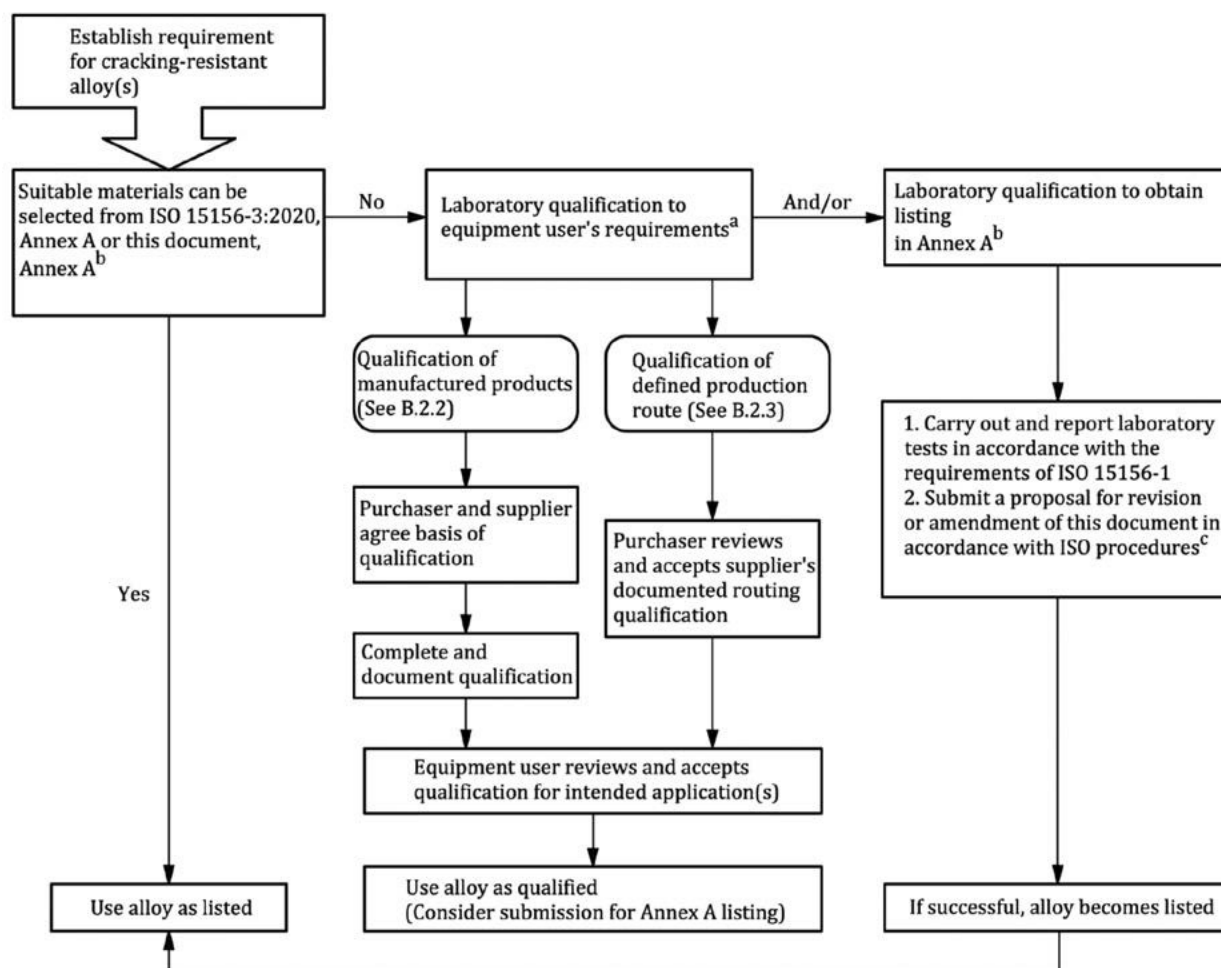
- b) SZC and SOHIC qualification shall require testing in accordance with [B.4](#) using appropriate environmental conditions from those specified for SSC qualification.
- c) HIC and SWC shall be qualified as follows:
- in any service environment (see [B.5](#) and [Table B.3](#));
 - in specific sour service applications (see [B.5](#) and [Table B.3](#)).

In all cases, the equipment user shall ensure that the testing chosen is appropriate to the conditions of the intended service(s). The acceptance of the testing chosen shall be documented.

B.2 Uses of laboratory qualifications

B.2.1 General

An overview of the alternative uses of laboratory qualifications is given in [Figure B.1](#).



^a This document addresses SSC, HIC, SOHIC and SZC of carbon and low-alloy steels. ANSI/NACE MR0175/ISO 15156-3 addresses SSC, SCC and galvanically induced hydrogen stress cracking (GHSC) of corrosion-resistant alloys (CRAs) and other alloys.

^b [Annex A](#) addresses SSC of carbon and low-alloy steels. ANSI/NACE MR0175-2021/ISO 15156-3:2020, Annex A addresses SSC, SCC and GHSC of CRAs and other alloys.

^c See final paragraphs of "Introduction" for further information regarding document maintenance.

NOTE Flowchart omits qualification by field experience as described in ANSI/NACE MR0175/ISO 15156-1.

Figure B.1 — Alternatives for alloy selection and laboratory qualification

B.2.2 Qualification of manufactured products

The user of this document shall define the qualification requirements for the material in accordance with ANSI/NACE MR0175/ISO 15156-1 and this annex.

This definition shall include the application of the following:

- a) general requirements (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5);
- b) evaluation and definition of service conditions (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 6);

- c) material description and documentation (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.1);
- d) requirements for qualification based on laboratory testing (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.3);
- e) report of the method of qualification (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 9).

Appropriate test batches and sampling requirements shall be defined with regard for the nature of the product, the method of manufacture, testing required by the manufacturing specification and the required qualification(s) (SSC, SOHIC, SZC, HIC/SWC).

Samples shall be tested in accordance with [Annex B](#) for each cracking mechanism being qualified. A minimum of three specimens shall be tested per test batch. The test batch shall be qualified if all specimens satisfy the test acceptance criteria.

Re-testing is permitted as follows. If a single specimen fails to satisfy the acceptance criteria, the cause shall be investigated. If the source material conforms to the manufacturing specification, two further specimens may be tested. These shall be taken from the same source as the failed specimen. If both satisfy the acceptance criteria, the test batch shall be considered qualified. Further retests shall require the purchaser's agreement.

Testing of manufactured products may be carried out at any time after manufacture and before exposure to H₂S service.

Before the products are placed in H₂S service, the equipment user shall review the qualification and verify that it satisfies the defined qualification requirements. Products with a qualification that has been verified by the equipment user may be placed into H₂S service.

B.2.3 Qualification of a manufacturing source and route

A defined production route may be qualified for the production of qualified material.

A qualified production route may be followed to avoid order-release testing for H₂S-cracking resistance.

A materials supplier may propose to a materials purchaser that a qualified production route be used to produce qualified materials. The qualified production route may be used if the materials supplier and materials purchaser agree to its use.

A qualified production route may be used to produce qualified material for more than one materials user.

To qualify a production route, the material supplier shall demonstrate that a defined production route is capable of consistently manufacturing material that satisfies the applicable qualification test requirements of [Annex B](#).

The qualification of a production route requires all of the following:

- a) definition of the production route in a written quality plan that identifies the manufacturing location(s), all manufacturing operations and the manufacturing controls required to maintain the qualification;
- b) initial testing of products produced on the defined production route in accordance with [B.2.2](#), with verification that they satisfy the acceptance criteria;

- c) Periodic testing to confirm that the product continues to have the required resistance to cracking in H₂S service; the frequency of “periodic” testing shall be defined in the quality plan and shall be acceptable to the purchaser; a record of such tests shall be available to the purchaser;
- d) retaining and collating the reports of these tests and making them available to material purchasers and/or equipment users.

A material purchaser may agree additional quality control requirements with the manufacturer.

The accuracy of the quality plan may be verified by site inspection by an interested party.

B.2.4 Use of laboratory testing as a basis for proposing additions and changes to [Annex A](#)

Proposals for additions and changes shall be documented in accordance with ANSI/NACE MR0175/ ISO 15156-1.

1. They shall also be subject to the following additional conditions and requirements.
 - Laboratory testing for the evaluation of carbon and low-alloy steels for addition to [Annex A](#) is for use with steels that do not conform with the general requirements described in [A.2.1](#).
 - Addition of a carbon or low-alloy steel to [A.2](#) requires the testing described in [Table B.1](#) for all SSC regions of [Figure 1](#) (see [7.2](#)).
 - Addition of a carbon or low-alloy steel to [A.3](#) or [A.4](#) requires the testing described in [Table B.1](#) for the appropriate SSC region of [Figure 1](#) (see [7.2](#)).
 - The steel being qualified by laboratory testing shall be selected in accordance with ANSI/NACE MR0175/ISO 15156-1.
 - Material representing a minimum of three separately processed heats shall be tested for SSC resistance in accordance with B.3.
 - Sufficient data shall be provided to allow the members of ISO/TC 67 to assess the material and decide on the suitability of the material for inclusion into this document, by amendment or revision, in accordance with the ANSI/NACE MR0175/ISO 15156 series maintenance process as described in the introduction.

B.3 Test procedures to evaluate the resistance of carbon and low-alloy steels to SSC

Qualification shall be in accordance with [B.1](#) and, as appropriate, [Table B.1](#).

Unless otherwise indicated, test requirements shall be in accordance with NACE TM0177.

Generally, testing is performed at ambient temperature [$24\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ ($75\text{ }^{\circ}\text{F} \pm 5\text{ }^{\circ}\text{F}$)]. For testing at elevated temperatures, reference may be made to the guidance on test environments given in ANSI/NACE MR0175-2021/ISO 15156-3:2020, Annex B.

For materials testing to a materials manufacturing specification, reference should be made to the appropriate specification, and to [A.1](#) and [B.1](#).

Table B.1 — SSC laboratory testing for sour service

Qualification validity ^f	Test type ^{a,b,i}	Applied stress ^{c,d}	Environment	H ₂ S partial pressure	Acceptance criteria	Remarks
Specific application, or SSC region 1 or region 2 of Figure 1	FPB _j	≥90 % AYS	5 % mass fraction NaCl + 0.4 % mass fraction CH ₃ COONa, pH adjusted to required value using HCl or NaOH ^e	Appropriate to intended application or SSC region	No SSC cracks in accordance with NACE TM0316 assessment method	Specific application or less severe environments. Region qualification subject to adequate “coverage” ^g
	UT or CR	≥90 % AYS			No SSC cracks in accordance with NACE TM0177 assessment method	
	DCB ^h	Not applicable			Assessment shall be in accordance with NACE TM0177. Acceptance criteria shall be by documented agreement ^k	Use as qualification at equipment user's discretion and with documented justification
All SSC regions of Figure 1	FPB _j	≥80 % AYS	NACE TM0177 Environment A (5 % mass fraction NaCl + 0.5 % mass fraction CH ₃ COOH)	100 kPa (15 psi) in accordance with NACE TM0177	No SSC cracks in accordance with NACE TM0316 assessment method	—
	UT or CR	≥80 % AYS			No SSC cracks in accordance with NACE TM0177 assessment method	
	DCB ^h	Not applicable			Assessment shall be in accordance with NACE TM0177. Acceptance criteria shall be by documented agreement ^k	Use as qualification at equipment user's discretion and with documented justification

^a The test types are as follows:

- UT test in accordance with NACE TM0177, Method A;
- FPB test in accordance with NACE TM0316;
- CR test in accordance with NACE TM0177, Method C;
- DCB test in accordance with NACE TM0177, Method D;
- Other test specimens, including full-size components, may be used when appropriate. Their use shall be by agreement between the purchaser and the supplier.

^b FPB, CR or UT tests are preferred for the qualification of welding and joining procedures; see [7.3](#) and [7.4](#). For welded samples, specimens shall normally be taken transverse to welds; testing shall be based on the actual yield strength of the lowest yield strength parent metal; side 4-point bend testing may be used, subject to the agreement of the equipment user. For details of side bend tests, see Reference [27].

^c For applications where a low service stress level, as a proportion of yield strength, is guaranteed, the test stress may be reduced to the maximum service stress. In such cases, the tests and acceptance criteria shall be agreed with the equipment user. Such agreements shall be documented.

^d AYS indicates the actual yield strength of material in finished form at the test temperature. The AYS shall be as defined in the product specification or the 0.2 % proof stress ($R_{p0.2}$) determined as the “non-proportional elongation” in accordance with ISO 6892-1.

^e For SSC tests with pH control, the pH value during tests should be less than or equal to the required value. Control to within a range of 0.1 pH units is achievable in practice.

^f See ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5, for more information regarding designs utilizing plastic design criteria.

^g Testing under the conditions listed in [Table B.2](#) provides qualification for use throughout a region.

^h For special cases, including components of heavy section or of complex shape, DCB tests may be used to support designs based on fracture mechanics.

ⁱ Test types are not necessarily equivalent and results might not be directly comparable.

^j When SOHC and/or SZC evaluation of a test specimen are carried out, see [7.2.2](#), the requirements of this table and of [B.4](#) shall be met.

^k See ISO 11960 for information on tubing and casing grades C90 and T95.

Table B.2 — Test conditions

pH	Required H ₂ S partial pressures for tests kPa	
	Set of conditions for SSC region 1	Set of conditions for SSC region 2
3.5	—	1
4.0	0.3	—
4.5	1	10
5.5	10	100
6.5	100	—

B.4 Test procedures to evaluate the resistance of carbon and low-alloy steels to SOHIC and SZC

B.4.1 General

The test methods described in this annex have been used successfully to demonstrate sensitivity to SOHIC or SZC.

Materials shall have been qualified with respect to SSC resistance for the design conditions prior to SOHIC/SZC evaluation.

When evaluating welds, [7.3.3](#) shall also apply.

The validity of the test results for conditions other than those evaluated is defined in ANSI/NACE MR0175/ISO 15156-1.

Test methods described for SOHIC and SZC are not standardized. Alternative tests are under development. The equipment user may choose other tests at his discretion. The justification of the use of such tests shall be documented.

B.4.2 Small-scale tests

B.4.2.1 Specimen selection

The test samples used to determine susceptibility to SOHIC/SZC shall be the apparently unfailed UT or FPB test specimens taken from successful SSC qualification testing. Steels selected using [A.2](#) shall also undergo SSC testing according to [B.1](#) prior to the SOHIC/SZC evaluation.

For small-scale testing of welds, specimens shall be taken transverse to the weld.

B.4.2.2 Evaluation and acceptance criteria for UT test specimens

One of the following evaluations and acceptance criteria for UT test specimens shall apply.

- Heat the specimens to 150 °C and hold at that temperature for 2 h to remove absorbed hydrogen. Measure the tensile strength of the specimen. The tensile strength shall be not less than 80 % of the actual tensile strength of the material as determined on identical, previously unused, specimens.
- Make at least two metallographic sections parallel to the sample axis. Examine the sections for possible ladder-like HIC features and other cracks related to SOHIC or to the soft zones of a weld (SZC). No ladder-like HIC

indications nor cracks exceeding a length of 0.5 mm in the through thickness direction are allowed.

B.4.2.3 Evaluation and acceptance criteria for FPB test specimens

A wet-magnetic-particle examination shall be carried out on the side of the sample that was under tensile stress during H₂S exposure.

Below any magnetic particle indications running perpendicular to the stress axis, metallographic sectioning shall be made perpendicular to the indications or, in the absence of magnetic particle indications, at least two metallographic sections shall be made parallel to the stress axis of the specimen.

Sections produced in these ways shall be examined for possible ladder-like HIC features and other cracks related to SOHIC or to the soft zones of a weld (SZC). No ladder-like HIC features nor cracks exceeding a length of 0.5 mm in the through thickness direction are allowed.

To assist the detection of damage, specimens may be plastically deformed by 5 % in the previous bending direction prior to metallographic sectioning. Prior to deformation, the specimens shall be heated to 150 °C and maintained at that temperature for 2 h to remove absorbed hydrogen.

Damage developed on the tensile side of a specimen in the form of blisters less than 1 mm below the surface, or on the compression side regardless of the depth of the blister, may be disregarded for the assessment of SOHIC/SZC but shall be reported.

B.4.3 Full pipe ring tests

Full pipe ring tests may be used. BS 8701 describes a test and acceptance criteria.

NOTE Residual stress has been shown to play an important role in the initiation of SOHIC and SZC. It is sometimes considered that such stresses in field situations are better represented in large-scale specimens.

B.5 Test procedures and acceptance criteria to evaluate the resistance of carbon and low-alloy steels to HIC/SWC

Test procedures and acceptance criteria shall be in accordance with [Table B.3](#).

Unless otherwise indicated, test requirements shall be in accordance with NACE TM0284.

Table B.3 — HIC/SWC test procedure and acceptance criteria

Product type	Applied stress	Environment	H ₂ S partial pressure	Acceptance criteria ^{e,g}	Qualification validity ^f
Flat-rolled steels or their products ^{a,b}	No applied stress	NACE TM0284 Test Solution A ^c	In accordance with NACE TM0284 for Test Solution A testing, i.e., 100 kPa (15 psi) ^c	Average values of the 3 sections of each individual specimen CLR ≤ 15 % CTR ≤ 5 % CSR ≤ 2 %	Any sour service
		NACE TM0284 Test Solution C, pH adjusted to required value using HCl or NaOH ^d	Appropriate to intended application ^d	Average values of the 3 sections of each individual specimen CLR ≤ 15 % CTR ≤ 5 % CSR ≤ 2 %	Specific, or less severe duty

^a Qualification of seamless tubular products may also be appropriate; see [Clause 8](#).

^b The samples being taken to represent the general performance of an order should be agreed between the producer and the equipment user. The sampling of materials for testing shall conform with ANSI/NACE MR0175/ISO 15156-1.

^c The user is responsible for deciding whether this test environment is adequate to represent the severity of the intended application.

^d Application-specific tests of steel for new or existing installations may be carried out. In such cases, the test duration shall be in accordance with NACE TM0284, dependent on the partial pressure of H₂S in the test gas.

^e At the request of the equipment user, ultrasonic evaluation of coupons may be used to find and evaluate areas of cracking prior to the selection of locations for metallurgical sectioning. See also EFC Publication 16 and NACE TM0284.

^f See ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5, for further information regarding designs utilizing plastic design criteria.

^g Other acceptance criteria may be used subject to the documented approval of the equipment user.

Annex C (informative)

Determination of H₂S partial pressure and use of alternative parameters

C.1 Calculation of partial pressure of H₂S for systems with a gas phase

C.1.1 General

The partial pressure of H₂S, p_{H_2S} , expressed in megapascals (pounds per square inch), may be calculated by multiplying the system total pressure by the mole fraction of H₂S in the gas phase as given in Formula (C.1):

$$p_{H_2S} = p \times \frac{X_{H_2S}}{100} \quad (C.1)$$

where

p is the system total absolute pressure, expressed in megapascals (pounds per square inch);

X_{H_2S} is the mole fraction of H₂S in the gas, expressed as a percentage.

For example, in a 70 MPa (10 153 psi) gas system, where the mole fraction of H₂S in the gas is 10 %, the H₂S partial pressure is 7 MPa (1 015 psi).

If the system total pressure and concentration of H₂S are known, H₂S partial pressures can also be estimated using [Figure C.1](#).

C.1.2 Gas phase considerations, H₂S partial pressure and fugacity

The partial pressure concept, based on the ideal gas law, provides an accurate representation of thermodynamic activity of gas species like CO₂ and H₂S at near atmospheric total pressures. At higher pressures, the true thermodynamic activity (chemical potential), expressed as gas phase fugacity, drops below the partial pressure. Therefore, the partial pressure concept introduces an excess in severity that increases with total pressure. (Generally, this excess decreases with increasing temperature.) Hence, assessments of systems with a gas phase, based on partial pressure, imply an environmental severity that equals or exceeds that of the corresponding field service considered and are therefore an acceptable approach for any total pressure, in line with historical practice for evaluation of the severity of a sour environment.

Equipment users may employ H₂S fugacity rather than partial pressure to characterize the environmental severity of the production environment and to define the test environment representing field service, thereby reducing excess severity introduced by the partial pressure concept. The degree to which this excess would be reduced by considering gas phase fugacity depends on total pressure, temperature and composition of the hydrocarbon-water system.

NOTE Systems with an extreme total pressure, typically above 1 500 bar (21 756 psi), would be characterized as a dense fluid rather than gas or liquid and are preferably evaluated based on fugacity.

Fugacity models used in these calculations need to be validated to ensure they adequately reflect the severity of the production environment and that all the test conditions applied are at least as severe, with respect to the potential mode of failure, as those defined to occur in the field service (see ANSI/NACE MR0175-2021/ISO 15156-1:2020 8.3.4). This generally includes thermodynamic analysis of both production and test environments and verification of the thermodynamic model under these conditions, along with confirmation by physically testing.

C.1.3 Aqueous phase considerations, H₂S concentration and chemical activity

Since corrosion cracking occurs in the aqueous phase, it is acceptable to assess the likelihood of cracking on the basis of H_2S dissolved in the aqueous phase instead of H_2S partial pressure in the gas phase. At near atmospheric pressure, assessments based on gas phase partial pressure, gas phase fugacity, aqueous concentration or aqueous phase chemical activity are all equivalent. However, at higher pressure, thermodynamic activity, be it fugacity in the gas phase as discussed above or chemical activity in the aqueous phase, deviates from strictly ideal partial pressure and aqueous concentration, respectively.

NOTE For the purpose of this discussion, fugacity and chemical activity can be considered equivalent as they are based on the same thermodynamic equilibrium considerations, using the chemical potential concept. Note that the effect of salinity of the aqueous phase should be considered as well. This is commonly accounted for by including an activity coefficient in the activity calculation.

Generally, as for gas phase fugacity, assessments based on chemical activity or aqueous concentration imply a more modest environmental severity than those based on partial pressure. Hence the principle given in ANSI/NACE MR0175-2021/ISO 15156-1:2020 8.3.4 as quoted above, applies: when using these parameters, the equipment user needs to demonstrate that the severity of the environment is properly taken into account, which generally includes detailed thermodynamic analysis.

NOTE 1 Fugacity can be considered an “effective partial pressure”, incorporating the non-ideal thermodynamic effects in the real gas that are ignored in the partial pressure derived from the ideal gas law. It is dependent on and generally calculated from the total pressure, the mole fraction of the species in the mixture and its fugacity coefficient, which in turn depends on temperature. The concept of fugacity is applicable to all phases, gas or liquid, and can be thought of as “escaping tendency” — the driver for a component to leave a phase. At equilibrium, the fugacity for each component is the same in all phases of a mixture, gas or liquid. In this standard, the term fugacity is primarily used as a property of species in the gas phase.

NOTE 2 Activity or chemical activity can be considered a “pseudo mole fraction”, and incorporates the non-ideal thermodynamic effects in the real liquid phase that are ignored if just concentration is accounted for. Activity is meaningless if the reference state is not specified. Activity also incorporates the effect of brine salinity on a species. Activity is often expressed as the mole fraction of the species multiplied by an activity coefficient. Since activity and fugacity are unambiguously related and are derived from the thermodynamic concept of chemical potential (partial Gibbs free energy), it is sufficient to specify either activity or fugacity. In this document, the term chemical activity is primarily used as a property of species in the liquid or aqueous phase.

NOTE 3 Examples of non-ideal thermodynamic effects and their analysis in the context of sour corrosion cracking are given in the following publications NACE C2014, papers 3870, 4243, 4285 and NACE C2015, paper 6050.

As indicated in the definitions given in ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 3, fugacity is a function of pressure, temperature, and mixture composition; the impact of activity is further complicated by the salinity of the aqueous phase. Care shall be taken to ensure thermodynamic analyses apply valid parameters.

NOTE 4 The *in-situ* pH, referred to as a factor affecting corrosion cracking, is defined based on the chemical activity of protons in the water phase. This activity in turn depends on the CO_2 and H_2S chemical activities in the water phase which are equivalent to the respective CO_2 and H_2S fugacities. This implies high pressures have an effect on pH, which can be accounted for by thermodynamic analysis.

C.2 Calculations of effective H₂S partial pressure for gas-free liquid systems

C.2.1 General

For liquid systems (for which no equilibrium gas composition is available), the effective thermodynamic activity of H₂S is defined by a virtual partial pressure of H₂S that may be determined in the following way.

- a) Determine the bubble-point pressure, p_B , of the fluid at operating temperature by any suitable method.

NOTE For a liquid-full pipeline downstream of gas separation units, a good approximation for bubble-point pressure is the total pressure of the last gas separator.

- b) Determine the mole fraction of H₂S in the gas phase at bubble-point conditions by any suitable method.
- c) Calculate the partial pressure of H₂S, p_{H_2S} , expressed in megapascals (pounds per square inch), in the gas at the bubble point as given in Formula (C.2):

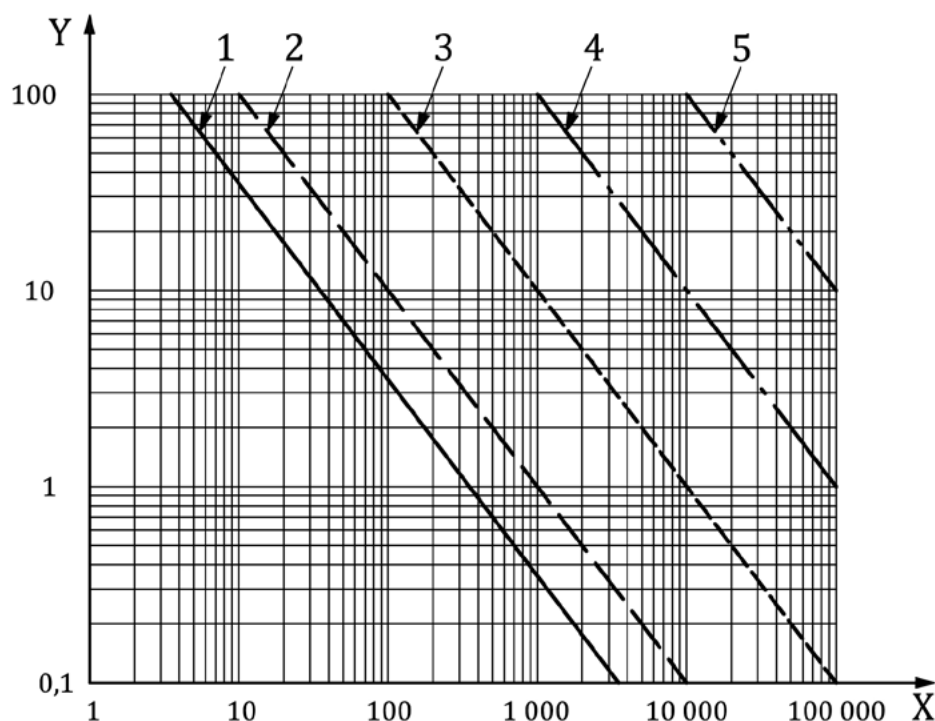
$$p_{H_2S} = p_B \times \frac{x_{H_2S}}{100} \quad (C.2)$$

where

p_B is the bubble-point pressure, expressed in megapascals (pounds per square inch);

x_{H_2S} is the mole fraction of H₂S in the gas, expressed as a percentage.

- d) Use this as the H₂S partial pressure for the liquid system. This value can be used to determine whether a system is sour in accordance with option 1 (see [7.1](#)) or to determine its degree of sourness in accordance with option 2 (see [7.2](#)).



Key

X mole fraction H_2S in gas, expressed in percent volume fraction times 10^4

NOTE Percent volume fraction times 10^4 is the equivalent of the deprecated unit “parts per million by volume.”

Y total absolute pressure, expressed in megapascals

- 1 $\rho_{H_2S} = 0.3 \text{ kPa}$
- 2 $\rho_{H_2S} = 1 \text{ kPa}$
- 3 $\rho_{H_2S} = 10 \text{ kPa}$
- 4 $\rho_{H_2S} = 100 \text{ kPa}$
- 5 $\rho_{H_2S} = 1\,000 \text{ kPa}$

Figure C.1 — H_2S partial pressure isobars in sour-gas systems

- e) Thermodynamic models indicate that the bubble-point approach above in a) to d) may not adequately represent environmental severity for high total pressure gas-free liquid applications [oil wells with a total pressure typically above 350 bar (5 076 psi)] with bubble-point pressures significantly lower than the total pressure. In these instances, fugacity or activity calculations are recommended.

C.2.2

Considerations for high pressure gas-free oil wells, H_2S activity

The above approach assumes the H_2S severity of the environment is adequately represented by ρ_{H_2S} at bubble-point at any pressure higher than the bubble-point. This assumption is generally correct at low to moderate pressures, but is not necessarily true at high pressures.

For gas-free liquid systems operating well above the bubble-point, increasing the pressure does not result in increased concentration of H_2S in the aqueous phase, but does increase the chemical activity of H_2S in water (resulting from the Poynting correction factor for the effect of compressibility of the liquid on H_2S). Hence, the environment behaves as if there is more H_2S .

NOTE The Poynting correction factor describes the effect of pressure on the fugacity (or chemical activity) of a gas species, e.g., CO₂ or H₂S, in the liquid phase. This effect derives from the liquid's compressibility under pressure. Commonly the concentration of a gas species dissolved in a liquid phase is described by Henry's law, stating proportionality between the gas species partial pressure and its dissolved concentration. To incorporate non-ideal thermodynamic effects in gas and liquid, the extended or "ensemble" Henry's law uses fugacity instead of partial pressure and activity coefficient and Poynting correction factor as multipliers for the species' concentration in the liquid.

An example oil well case assessment showed that at total pressures typically exceeding 350 bar to 500 bar (5 076 psi to 7 252 psi), H₂S fugacity could surpass the bubble-point p_{H₂S}, rendering the latter an inadequate indicator of environmental severity (see NACE C2014, paper 3870).

In line with ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.3.4 as also quoted in [C.1](#) above, the severity of the environment for such cases is more appropriately represented by H₂S chemical activity (or equivalent fugacity) at pressure than by p_{H₂S} at bubble-point. It is therefore recommended that, at least for high pressure gas-free oil wells, a thermodynamic analysis considering aqueous chemical activity is performed to ensure environmental severity is properly characterized in the H₂S cracking assessment. This is reflected in item e) above.

Annex D (informative)

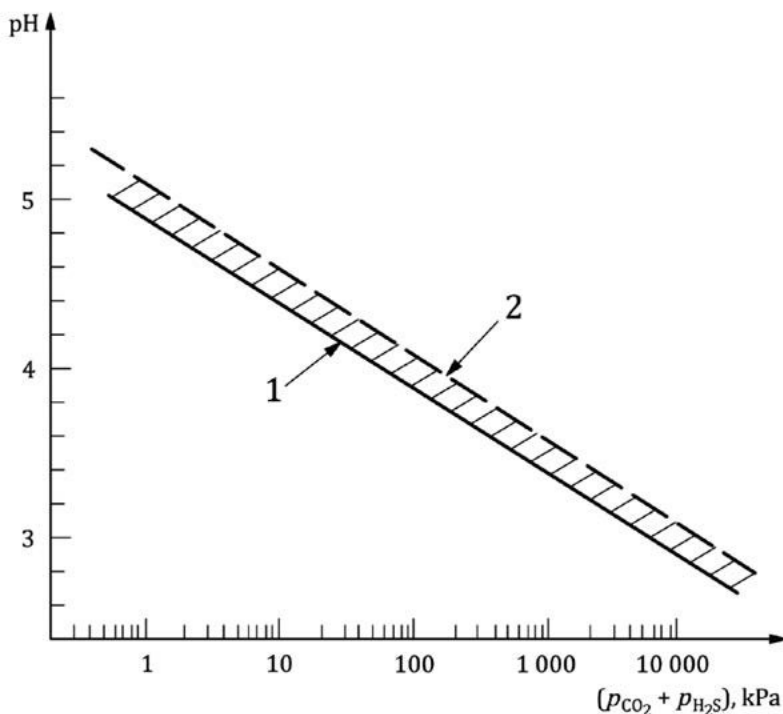
Recommendations for determining pH

The use of [Figure 1](#) requires the determination of in situ pH for the production conditions. Figures D.1 to D.5 (adapted from Reference [25]) give general guidance for the determination of an approximate pH value of the water phase for various conditions. pH determined in this way may be used if no proven calculation or reliable in situ measuring techniques are available.

The likely error band may be taken as $^{+0,5}_0$ pH units.

In Figures D.1 to D.5, the ordinate axis is in situ pH. pH values routinely reported for depressurized water samples should not be mistaken as valid in situ pH values.

The in situ pH can also be influenced by the presence of organic acids, such as acetic acid, propionic acid, etc. (and their salts), that are not considered in Figures D.1 to D.5. The importance of the influences of these acids on in situ pH and on the results of conventional water analyses are described in EFC Publication 17. Analysis for these components should be made in order to make the necessary adjustments to the calculated in situ pH.

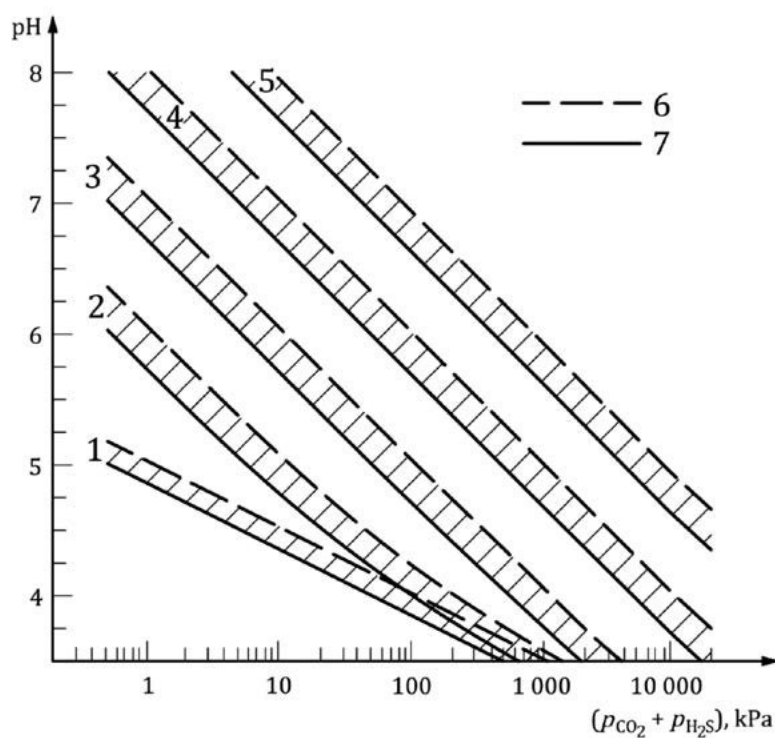


Key

1 $T = 20\text{ °C}$

2 $T = 100\text{ °C}$

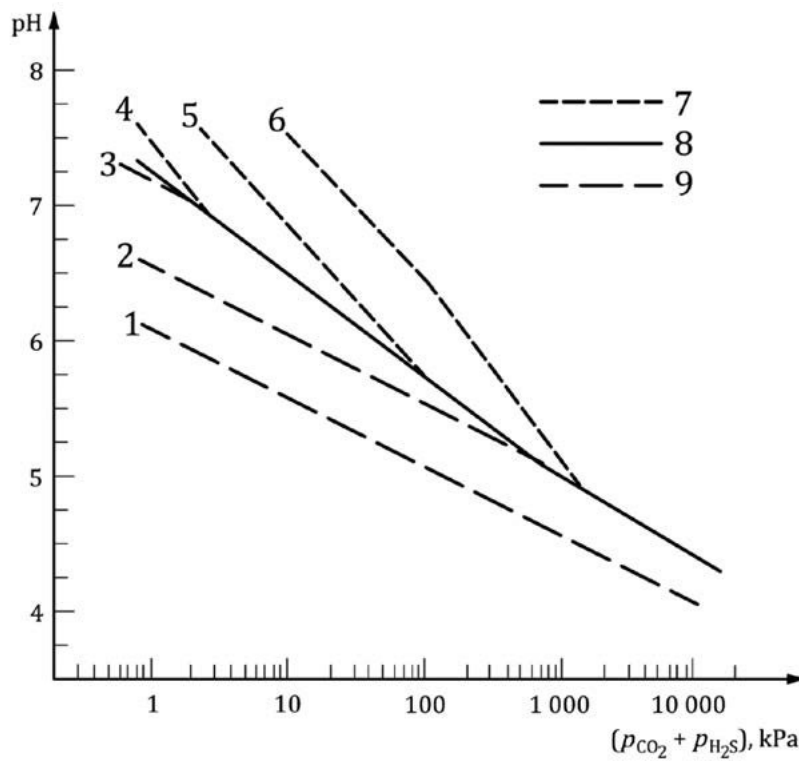
Figure D.1 — pH of condensed water under CO₂ and H₂S pressure



Key

- 1 $\text{HCO}_3^- = 0 \text{ meq/l}$
- 2 $\text{HCO}_3^- = 0.1 \text{ meq/l}$
- 3 $\text{HCO}_3^- = 1 \text{ meq/l}$
- 4 $\text{HCO}_3^- = 10 \text{ meq/l}$
- 5 $\text{HCO}_3^- = 100 \text{ meq/l}$
- 6 $T = 100^\circ\text{C}$
- 7 $T = 20^\circ\text{C}$

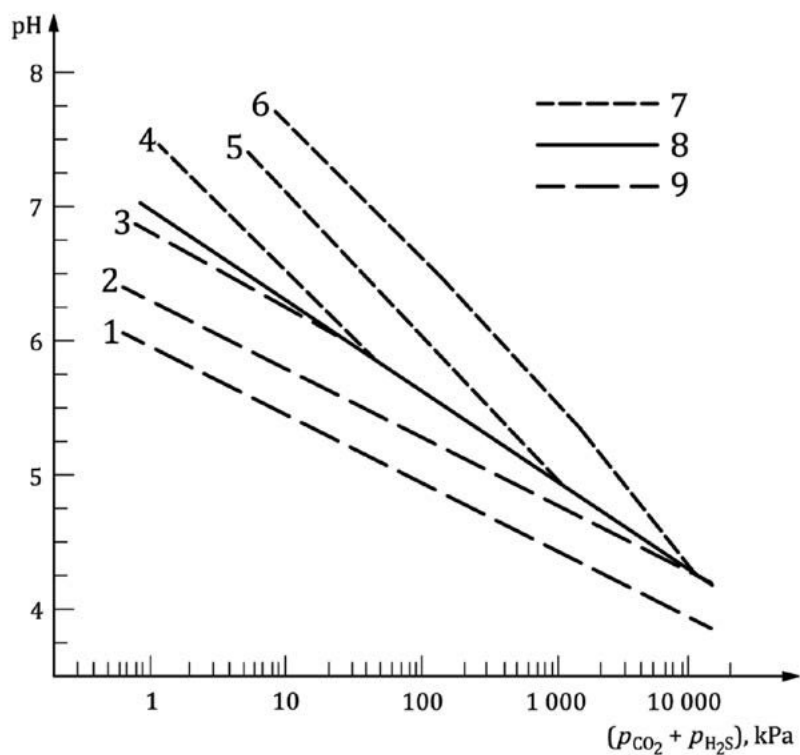
Figure D.2 — pH of condensate water (wet gas) or formation waters containing bicarbonate (undersaturated in CaCO_3) under CO_2 and H_2S pressure



Key

- 1 $\text{Ca}^{2+} = 1\,000 \text{ meq/l}$
- 2 $\text{Ca}^{2+} = 100 \text{ meq/l}$
- 3 $\text{Ca}^{2+} = 10 \text{ meq/l}$
- 4 $\text{HCO}_3^- = 10 \text{ meq/l}$
- 5 $\text{HCO}_3^- = 30 \text{ meq/l}$
- 6 $\text{HCO}_3^- = 100 \text{ meq/l}$
- 7 $\text{Ca}^{2+} < \text{HCO}_3^-$
- 8 $\text{Ca}^{2+} = \text{HCO}_3^-$
- 9 $\text{Ca}^{2+} > \text{HCO}_3^-$

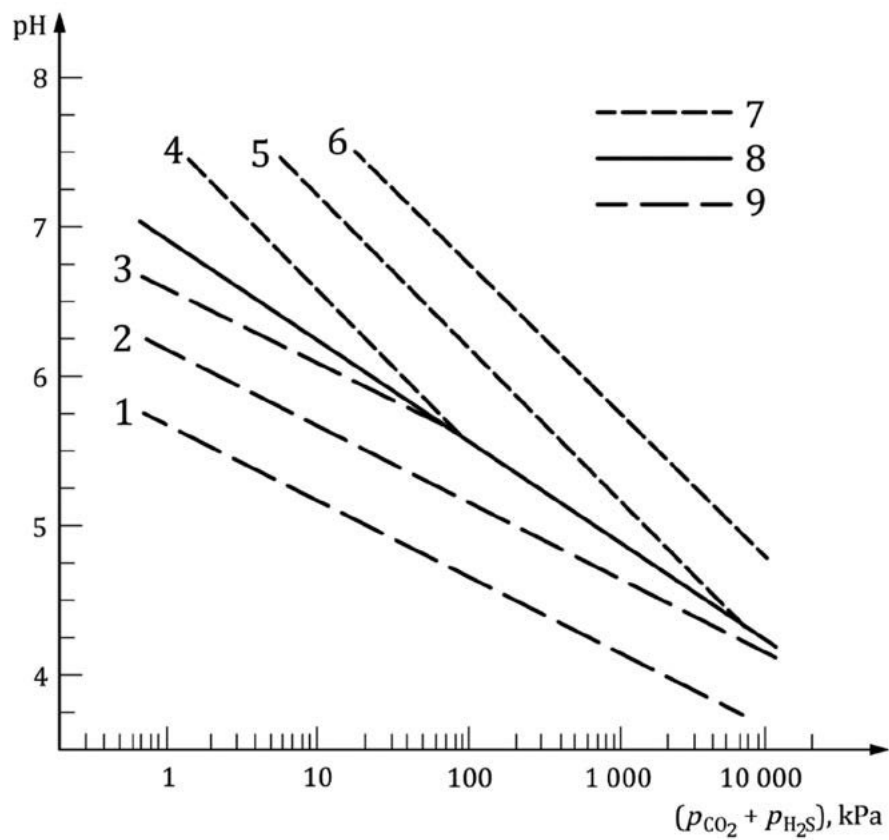
Figure D.3 — pH of formation waters (super)saturated in CaCO_3 (stoichiometric or non-stoichiometric) under CO_2 and H_2S pressure at 20 °C



Key

- 1 $\text{Ca}^{2+} = 1\,000 \text{ meq/l}$
- 2 $\text{Ca}^{2+} = 100 \text{ meq/l}$
- 3 $\text{Ca}^{2+} = 10 \text{ meq/l}$
- 4 $\text{HCO}_3^- = 10 \text{ meq/l}$
- 5 $\text{HCO}_3^- = 30 \text{ meq/l}$
- 6 $\text{HCO}_3^- = 100 \text{ meq/l}$
- 7 $\text{Ca}^{2+} < \text{HCO}_3^-$
- 8 $\text{Ca}^{2+} = \text{HCO}_3^-$
- 9 $\text{Ca}^{2+} > \text{HCO}_3^-$

Figure D.4 — pH of formation waters (super)saturated in CaCO_3 (stoichiometric or non-stoichiometric) under CO_2 and H_2S pressure at 60°C



Key

- 1 $\text{Ca}^{2+} = 1\,000 \text{ meq/l}$
- 2 $\text{Ca}^{2+} = 100 \text{ meq/l}$
- 3 $\text{Ca}^{2+} = 10 \text{ meq/l}$
- 4 $\text{HCO}_3^- = 10 \text{ meq/l}$
- 5 $\text{HCO}_3^- = 30 \text{ meq/l}$
- 6 $\text{HCO}_3^- = 100 \text{ meq/l}$
- 7 $\text{Ca}^{2+} < \text{HCO}_3^-$
- 8 $\text{Ca}^{2+} = \text{HCO}_3^-$
- 9 $\text{Ca}^{2+} > \text{HCO}_3^-$

Figure D.5 — pH of formation waters (super)saturated in CaCO_3 (stoichiometric or non-stoichiometric) under CO_2 and H_2S pressure at 100 °C

Annex E (informative)

Information that should be supplied for material purchasing

Column 2 of Table E.1 and [Table E.2](#) should be completed by the materials purchaser. Acceptable/required options should be indicated.

NOTE The designation ISO 15156-2A, in column 5, is generally equivalent to previously specifying carbon steels, low-alloy steels or cast irons in accordance with NACE MR0175.

Table E.1 — Minimum information for material purchasing

Purchaser's reference				
Equipment type				
Preferred steel (or cast iron) type and/or grade				
Governing sour service specification: ANSI/NACE MR0175/ISO 15156 (all parts) Materials requirements for this purchase order		Reference (sub)clause in ANSI/NACE MR0175/ISO 15156-2	Remarks	Sour-service designation ANSI/NACE MR0175/ISO 15156-x, (multiple codes can be required)
SSC resistance option 1: Carbon steel, low-alloy steel or cast iron for sour service selected from A.2	Yes/No	7.1	—	2A
SSC resistance option 2: Carbon or low-alloy steel for specific sour-service applications or for ranges of sour service	Yes/No	7.2	If selected, see also 5.3 and Table E.2	—
HIC resistance:				
(a) Material for any sour service?	Yes/No		—	2H
(b) Material for specific sour-service applications or for ranges of sour service?	Yes/No	Clause 8 and B.5	If selected, see also 5.3 and Table E.2	—

Table E.2 — Additional information for SSC testing and other special cases

Purchaser's reference				
Materials requirements for this purchase order		Reference (sub)clause in ANSI/NACE MR0175/ ISO 15156-2	Remarks	Sour service designation ANSI/NACE MR0175/ ISO 15156-x, (multiple codes can be required)
Resistance to SSC following option 2	Indicate preferred options	7.2	—	—
a) Sour service for any SSC region? Test specimen type	Yes/No	7.2.1.4, Figure 1, Table B.1 and its Notes	UT test specimens by default	2R3
b) Sour service for SSC regions 2 and 1? Test specimen type	Yes/No	7.2.1.4, Figure 1, Table B.1 and its Notes	UT test specimens by default	2R2
c) Sour service for SSC region 1? Test specimen type	Yes/No	7.2.1.4, Figure 1, Table B.1 and its Notes	UT test specimens by default	2R1
d) Specific sour service application required? Test specimen type	Yes/No	7.2.1.4, Table B.1 and its Notes	Test condition data below required. UT test specimens by default	2S
Resistance to HIC for specific sour service application?	Yes/No	Clause 8 and Table B.1	Test condition data below required	2HS
Description of test conditions	—	Table B.1 and/or Table B.3	Default values per Table B.1 , other values require documented justification according to ANSI/NACE MR0175/ ISO 15156-1	—
Test stress for SSC testing	—	—	% AYS (or as appropriate)	—
CO ₂	—	—	MPa (psi)	—
H ₂ S	—	—	MPa (psi)	—
Temperature	—	—	°C	—
In situ pH	—	—	For calculation of pH, see Annex D .	—
Cl ⁻ or other halide	—	—	mg/l	—
Elemental sulfur (S ⁰)	—	—	Present or absent	—
Special requirements	—	—	—	—
SOHIC and SZC resistance requirements	Yes/No	7.2.2 and B.4	SSC testing always required before SOHIC/SZC testing	2Z with SSC designation from above

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- [4] API Spec 5CT³, *Specification for Casing and Tubing*
- [5] ANSI/API Spec 5L/ISO 3183⁶, *Specification for Line Pipe*
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³ American Petroleum Institute (API), 1220 L Street NW, Washington, DC 20005-4070, USA, www.api.org.

⁴ American Society of Mechanical Engineers (ASME), Two Park Avenue, New York, NY 10016-5990, USA, www.asme.org.

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⁶ British Standards Institution (BSI), 389 Chiswick High Road, London W4 4AL, UK, www.bsigroup.com.

⁷ European Federation of Corrosion (EFC), c/o The Institute of Materials, 1 Carlton House Terrace, London SW1Y 5DB, UK, www.efcweb.org.



ANSI/NACE MR0175-2021/ISO 15156-3:2020

International Standard
ANSI/NACE MR0175-2021/ISO 15156-3:2020
Fourth Edition
Identical to ISO 15156-3:2020

**Petroleum and natural gas industries —
Materials for use in H₂S-containing environments
in oil and gas production**

Part 3:
**Cracking-resistant CRAs
(corrosion-resistant alloys) and other alloys**

An American National Standard

Approved 21 Sep 2022

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Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production

Part 3: **Cracking-resistant CRAs (corrosion-resistant alloys) and other alloys**

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Foreword

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

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

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

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

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

This document was prepared by Technical Committee ISO/TC 67, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 12, *Materials, equipment and offshore structures for petroleum, petrochemical and natural gas industries*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This fourth edition cancels and replaces the third edition (ANSI/NACE MR0175-2015/ISO 15156-3:2015), which has been technically revised. The main changes compared to the previous edition are as follows:

- [Table A.27](#) UNS S17400 (17-4PH SS) has new limits. The use of the alloy at the annotated environmental conditions is now limited to applications where sustained stress is no more than 50 % of SMYS;
- [Table A.32](#) new limits and annotations for UNS N09946 separate from UNS N09945;
- [Table A.41](#) inclusion of UNS R55400 (new a-b Ti alloy);
- [Table A.3](#) UNS S20910 (Nitronic 50) note modifications;
- [Tables A.22, A.23, A.26](#) through [A.30](#), and [A.33](#) temperature conversion corrections;
- [Table A.23](#) new note for maximum design tensile stress for UNS J91540;
- [Table A.32](#) newly added UNS N07718 (high strength Alloy 718, with two-step aging cycle, meeting API 6A CRA composition and a maximum hardness of 45 HRC) and UNS N09955 requirements and note letters designation changes on UNS N09925, N09935, N09945 and N09946;

- [Table A.40](#) title modification and note clarification;
- [Clause A.13](#) Cladding, overlays, and wear-resistant alloys modifications;
- [Table A.18](#) and [Table A.19](#) (Martensitic SS) remarks modifications;
- [Table A.24](#) Duplex SS Hot Isostatically Pressed (HIP) inclusion and remarks modification;
- the informative Annex D, “Materials chemical compositions and other information”, has been removed due to copyright reasons;
- additions to the bibliography.

ANSI/NACE MR0175-2021/ISO 15156:2020 consists of the following parts, under the general title *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production*:

- *Part 1: General principles for selection of cracking-resistant materials*
- *Part 2: Cracking resistant carbon and low-alloy steels, and the use of cast irons*
- *Part 3: Cracking resistant CRAs (corrosion resistant alloys) and other alloys*

Introduction

The consequences of sudden failures of metallic oil and gas field components associated with their exposure to H₂S-containing production fluids led to the preparation of the first edition of NACE MR0175 which was published in 1975 by the National Association of Corrosion Engineers, now known as the Association for Materials Protection and Performance (AMPP).

The original and subsequent editions of NACE MR0175 established limits of H₂S partial pressure above which precautions against sulfide stress cracking (SSC) were always considered necessary. They also provided guidance for the selection and specification of SSC-resistant materials when the H₂S thresholds were exceeded. In more recent editions, NACE MR0175 has also provided application limits for some corrosion-resistant alloys in terms of environmental composition and pH, temperature, and H₂S partial pressures.

In separate developments, the European Federation of Corrosion issued EFC Publication 16 in 1995 and EFC Publication 17 in 1996. These documents are generally complementary to those of NACE, though they differed in scope and detail.

In 2003, the publication of the ISO 15156 series and NACE MR0175/ISO 15156 was completed for the first time. These technically identical documents utilized the above sources to provide requirements and recommendations for materials qualification and selection for application in environments containing wet H₂S in oil and gas production systems. They are complemented by NACE TM0177 and NACE TM0284 test methods.

The revision of this document, i.e., ANSI/NACE MR0175/ISO 15156, involves a consolidation of all changes agreed and published in the Technical Circular 1, ISO 15156-3:2015/Cir.1:2016, the Technical Circular 2, ISO 15156-3:2015/Cir.2:2018 and the Technical Circular 3, ISO 15156-3:2015/Cir.3:2019, published by the ISO 15156 series Maintenance Agency secretariat at DIN.

The changes were developed by, and approved by the ballot of, representative groups from within the oil and gas production industry. The great majority of these changes stem from issues raised by document users. A description of the process by which these changes were approved can be found at the ISO 15156 series maintenance website: www.iso.org/iso15156maintenance.

When found necessary by oil and gas production industry experts, future interim changes to this document will be processed in the same way and will lead to interim updates to this document in the form of Technical Corrigenda or Technical Circulars. Document users should be aware that such documents can exist and can impact the validity of the dated references in this document.

The ISO 15156 series Maintenance Agency at DIN was set up after approval by the ISO Technical Management Board given in document 34/2007. This document describes the makeup of the agency, which includes experts from AMPP, EFC, and ISO/TC 67, and the process for approval of amendments. It is available from the ISO 15156 series maintenance website and from the ISO/TC 67 Secretariat. The website also provides access to related documents that provide more detail of the ISO 15156 series maintenance activities.

Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 3: Cracking-resistant CRAs (corrosion-resistant alloys) and other alloys

WARNING — CRAs (corrosion-resistant alloys) and other alloys selected using this document are resistant to cracking in defined H₂S-containing environments in oil and gas production, but not necessarily immune to cracking under all service conditions. It is the equipment user's responsibility to select the CRAs and other alloys suitable for the intended service.

1: Scope

This document gives requirements and recommendations for the selection and qualification of CRAs (corrosion-resistant alloys) and other alloys for service in equipment used in oil and natural gas production and natural gas treatment plants in H₂S-containing environments whose failure can pose a risk to the health and safety of the public and personnel or to the environment. It can be applied to help avoid costly corrosion damage to the equipment itself. It supplements, but does not replace, the materials requirements of the appropriate design codes, standards, or regulations.

This document addresses the resistance of these materials to damage that can be caused by sulfide stress cracking (SSC), stress corrosion cracking (SCC), and galvanically induced hydrogen stress cracking (GHSC).

This document is concerned only with cracking. Loss of material by general (mass loss) or localized corrosion is not addressed.

Table 1 provides a non-exhaustive list of equipment to which this document is applicable, including exclusions.

This document applies to the qualification and selection of materials for equipment designed and constructed using load controlled design methods. For design utilizing strain-based design methods, see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5.

This document is not necessarily suitable for application to equipment used in refining or downstream processes and equipment.

Table 1 — List of equipment

This document is applicable to materials used for the following equipment	Exclusions
Drilling, well construction, and well-servicing equipment	Equipment exposed only to drilling fluids of controlled composition ^a Drill bits Blowout-preventer (BOP) shear blades ^b Drilling riser systems Work strings Wireline and wireline equipment ^c Surface and intermediate casing
Wells including subsurface equipment, gas lift equipment, wellheads, and christmas trees	Sucker rod pumps and sucker rods ^d Electric submersible pumps Other artificial lift equipment Slips
Flow-lines, gathering lines, field facilities, and field processing plants	Crude oil storage and handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi)
Water-handling equipment	Water-handling facilities operating at a total absolute pressure below 0.45 MPa (65 psi) Water injection and water disposal equipment
Natural gas treatment plants	—
Transportation pipelines for liquids, gases, and multi-phase fluids	Lines handling gas prepared for general commercial and domestic use
For all equipment above	Components loaded only in compression
^a See ANSI/NACE MR0175-2021/ISO 15156-2:2020, A.2.3.2.3 for more information. ^b See ANSI/NACE MR0175-2021/ISO 15156-2:2020, A.2.3.2.1 for more information. ^c Wireline lubricators and lubricator connecting devices are not excluded. ^d For sucker rod pumps and sucker rods, reference can be made to NACE MR0176.	

2: Normative references

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

ISO 6507-1, *Metallic materials — Vickers hardness test — Part 1: Test method*

ISO 6508-1, *Metallic materials — Rockwell hardness test — Part 1: Test method*

ISO 6892-1, *Metallic materials — Tensile testing — Part 1: Method of test at room temperature*

ISO 10423, *Petroleum and natural gas industries — Drilling and production equipment — Wellhead and christmas tree equipment*

ISO 11960, *Petroleum and natural gas industries — Steel pipes for use as casing or tubing for wells*

ANSI/NACE MR0175-2021/ISO 15156-1:2020, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 1: General principles for selection of cracking-resistant materials*

ANSI/NACE MR0175-2021/ISO 15156-2:2020, *Petroleum and natural gas industries — Materials for use in H₂S-containing environments in oil and gas production — Part 2: Cracking-resistant carbon and low alloy steels, and the use of cast irons*

ASTM A747/A747M¹, *Standard Specification for Steel Castings, Stainless, Precipitation Hardening*

¹ ASTM International (ASTM), 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, USA, www.astm.org.

ASTM E29, *Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications*

ASTM E562, *Standard Test Method for Determining Volume Fraction by Systematic Manual Point Count*

EFC Publication 17², *Corrosion resistant alloys for oil and gas production: guidelines on general requirements and test methods for H₂S service*

NACE CORROSION/95 Paper 47, *Test methodology for elemental sulfur-resistant advanced materials for oil and gas field equipment*

NACE TM0177:2016, *Laboratory testing of metals for resistance to sulfide stress cracking and stress corrosion cracking in H₂S environments*

SAE AMS-2430³, *Shot Peening*

SAE — ASTM, Metals and alloys in the Unified Numbering System

3: Terms and definitions

For the purposes of this document, the terms and definitions given in ANSI/NACE MR0175/ISO 15156-1, ANSI/NACE MR0175/ISO 15156-2 and the following apply.

- 3.1 aging**
change in metallurgical properties that generally occurs slowly at room temperature (natural aging) and more rapidly at higher temperature (artificial ageing)
- 3.2 anneal**
heat to and hold at a temperature appropriate for the specific material and then cool at a suitable rate for such purposes as reducing hardness, improving machineability, or obtaining desired properties
- 3.3 austenite**
face-centered cubic crystalline phase of iron-based alloys
- 3.4 duplex stainless steel**
austenitic/ferritic stainless steel
stainless steel (3.13) whose microstructure at room temperature consists primarily of a mixture of *austenite* (3.3) and *ferrite* (3.5)
- 3.5 ferrite**
body-centered cubic crystalline phase of iron-based alloys
- 3.6 ferritic stainless steel**
stainless steel (3.13) whose microstructure at room temperature consists predominantly of *ferrite* (3.5)
- 3.7 galvanically induced hydrogen stress cracking (GHSC)**
cracking that results due to the presence of hydrogen in a metal induced in the cathode of a galvanic couple and tensile stress (residual and/or applied)
- 3.8 martensite**
hard, supersaturated solid solution of carbon in iron characterized by an acicular (needle-like) microstructure
- 3.9 martensitic steel**
steel in which a microstructure of *martensite* (3.8) can be attained by quenching at a cooling rate fast enough to avoid the formation of other microstructures

² European Federation of Corrosion (EFC), c/o The Institute of Materials, 1 Carlton House Terrace, London SW1Y 5DB, UK, www.efcweb.org.

³ Society of Automotive Engineers (SAE), 400 Commonwealth Drive, Warrendale, PA 15096-0001, USA, www.sae.org.

3.10 pitting-resistance equivalent number (PREN)

F_{PREN}

number developed to reflect and predict the pitting resistance of a CRA based upon the proportions of the elements Cr, Mo, W, and N in the chemical composition of the alloy

Note 1 to entry: See [6.3](#) for further information.

3.11 production environment

natural occurring produced fluids without contamination from chemicals that will temporarily or continuously reduce the in situ pH

Note 1 to entry: Flow back of chemicals for stimulation and scale removal may temporarily reduce the pH significantly and some continuously injected chemicals, such as scale inhibitors, can continuously reduce pH.

3.12 solid solution

single crystalline phase containing two or more elements

3.13 stainless steel

steel containing 10.5 % mass fraction or more chromium, possibly with other elements added to secure special properties

4: Symbols and abbreviated terms

AYS	actual yield strength
bal	balance of composition up to 100 %
BOP	blowout preventer
CR	c-ring
CRA	corrosion-resistant alloy
DCB	double cantilever beam (test)
FPB	four-point bend (test)
GHSC	galvanically induced hydrogen stress cracking
HAZ	heat-affected zone
HBW	Brinell hardness
HIC	hydrogen-induced cracking
HIP	hot isostatically pressed
HRB	Rockwell hardness (scale B)
HRC	Rockwell hardness (scale C)
HSC	hydrogen stress cracking
HV	Vickers hardness
NDS	no data submitted
pCO_2	partial pressure of CO_2
pH_2S	partial pressure of H_2S
PREN	pitting-resistance equivalent number
PWHT	post-weld heat treatment
RSRT	rippled strain rate test
S^0	elemental sulfur
SCC	stress-corrosion cracking
SMYS	specified minimum yield strength
SOHIC	stress-oriented hydrogen-induced cracking
SSC	sulfide stress cracking
SSRT	slow strain rate test
SZC	soft-zone cracking
UNS	unified (alloy) numbering system
UT	uniaxial tensile (test)

5: Factors affecting the cracking-resistance of CRAs and other alloys in H₂S-containing environments

The cracking behavior of CRAs and other alloys in H₂S-containing environments can be affected by complex interactions of parameters including the following:

- chemical composition, strength, heat treatment, microstructure, method of manufacture, and finished condition of the material;
- H₂S partial pressure or equivalent dissolved concentration in the water phase;
- acidity (in situ pH) of the water phase;
- chloride or other halide ion concentration;
- presence of oxygen, sulfur, or other oxidants;
- exposure temperature;
- pitting resistance of the material in the service environment;
- galvanic effects;
- total tensile stress (applied plus residual);
- exposure time.

These factors shall be considered when using this document for the selection of materials suitable for environments containing H₂S in oil and gas production systems.

6: Qualification and selection of CRAs and other alloys with respect to SSC, SCC, and GHSC in H₂S-containing environments

6.1 General

CRAs and other alloys shall be selected for their resistance to SSC, SCC, and/or GHSC as required by the intended service.

Conformance of a CRA or other alloy with this document implies cracking-resistance within defined environmental service limits. These limits are dependent on the material type or the individual alloy.

To enable qualification and/or selection of CRAs and other alloys, the equipment purchaser can be required to provide information on the proposed conditions of exposure to the equipment supplier.

In defining the severity of H₂S-containing environments, exposures that can occur during system upsets or shutdowns, etc. shall also be considered. Such exposures can include unbuffered, low pH condensed water. The limits given in the tables in [Annex A](#) are for production environments and do not cover conditions occurring during injection or flowback of chemicals that can reduce the in situ pH.

CRAs and other alloys shall be selected using [Annex A](#) or following qualification by successful laboratory testing in accordance with [Annex B](#). Qualification based on satisfactory field experience is also acceptable. Such qualification shall conform with ANSI/NACE MR0175/ISO 15156-1.

In [Annex A](#), materials are identified by materials groups. Within each group, alloys are identified by materials type (within compositional limits) or as individual alloys. Acceptable metallurgical conditions and environmen-

tal limits are given for which alloys are expected to resist cracking. Environmental limits are given for H₂S partial pressure, temperature, chloride concentration, and elemental sulfur.

A CRA or other alloy can be qualified by testing for use under operating conditions that are more severe than the environmental limits given in [Annex A](#). Similarly, a CRA or other alloy can be qualified for use in different metallurgical conditions (higher strength, alternative heat treatment, etc.) to those given in [Annex A](#).

The documentation of qualifications performed in accordance with [Annex B](#) shall meet the requirements in ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 9.

The equipment user shall verify qualifications (see [B.2.2](#)) and retain documentation supporting the materials selections made.

6.2 Evaluation of materials properties

6.2.1 Hardness of parent metals

If hardness measurements on parent metal are specified, sufficient hardness tests shall be made to establish the actual hardness of the CRA or other alloy being examined. Individual HRC readings exceeding the value permitted by this document may be considered acceptable if the average of several readings taken within close proximity does not exceed the value permitted by this document and no individual reading is greater than 2 HRC above the specified value. Equivalent requirements shall apply to other methods of hardness measurement when specified in this document or referenced in a manufacturing specification.

The conversion of hardness readings to or from other scales is material-dependent. The user may establish the required conversion tables.

NOTE The number and location of hardness tests on parent metal are not specified in ANSI/NACE MR0175/ISO 15156 (all parts).

6.2.2 Cracking-resistance properties of welds

6.2.2.1 General

The metallurgical changes that occur when welding CRAs and other alloys can affect their susceptibility to SSC, SCC, and/or GHSC. Welded joints can have a greater susceptibility to cracking than the parent material(s) joined.

The equipment user may allow the cracking susceptibility of weldments to govern the limits of safe service conditions for a fabricated system.

Processes and consumables used in welding should be selected in accordance with good practice and to achieve the required corrosion and cracking resistances.

Welding shall be carried out in conformance with appropriate codes and standards as agreed between the supplier and the purchaser. Welding procedure specifications (WPSs) and procedure qualification records (PQRs) shall be available for inspection by the equipment user.

Welding PQRs shall include documented evidence demonstrating satisfactory cracking resistance under conditions at least as severe as those of the proposed application. Such evidence shall be based upon one or more of the following:

- conformance with the requirements and recommendations for the specific materials group of Annex A (see also [6.2.2.2](#) and [6.2.2.3](#));

- weld cracking-resistance qualification testing in accordance with [Annex B](#);
- documented field experience modelled upon that specified for parent materials in ANSI/NACE MR0175/ISO 15156-1.

The requirements and recommendations given in Annex A might not be appropriate for all combinations of parent and weld metals used in the fabrication of equipment and components. The equipment user may require evidence of successful cracking-resistance testing as part of the welding procedure qualification to ensure the weldment produced provides adequate resistance to SSC, SCC, and GHSC for the application.

6.2.2.2 Qualification of welding procedures in accordance with [Annex A](#) based upon hardness

6.2.2.2.1 General

The qualification of welding procedures for sour service shall, if specified in Annex A, include hardness testing in accordance with 6.2.2.2.2, 6.2.2.2.3 and 6.2.2.2.4.

6.2.2.2.2 Hardness testing methods for welding procedure qualification

Unless otherwise approved by the user, hardness testing for welding procedure qualification shall be carried out using Vickers HV 10 or HV 5 methods in accordance with ISO 65071 or the Rockwell 15N method in accordance with ISO 65081.

NOTE For the purposes of this document, ASTM E384 is equivalent to ISO 65071 and ASTM E18 is equivalent to ISO 65081.

6.2.2.2.3 Hardness surveys for welding procedure qualification

Hardness surveys for butt welds, fillet welds, repair, and partial penetration welds and overlay welds shall be carried out as described in ANSI/NACE MR0175-2021/ISO 15156-2:2020, 7.3.3.3.

6.2.2.2.4 Hardness acceptance criteria for welds

Weld hardness acceptance criteria for CRAs or other alloys given in Annex A shall apply to alloys selected using [Annex A](#).

Hardness acceptance criteria can also be established from successful cracking-resistance testing of welded samples. Testing shall be in accordance with [Annex B](#).

6.2.2.3 Qualification of welding procedures in accordance with Annex A by other means of testing

Where appropriate, requirements and recommendations to ensure adequate cracking-resistance of welds using other means of testing are provided in the materials groups of [Annex A](#).

6.2.3 Cracking-resistance properties associated with other fabrication methods

For CRAs and other alloys that are subject to metallurgical changes caused by fabrication methods other than welding, cracking-resistance qualification testing of the material affected by fabrication shall be specified as part of the qualification of the fabrication process.

Qualification testing shall be specified as part of the qualification of burning and cutting processes if any HAZ remains in the final product.

The requirements and acceptance criteria of 6.2.2 shall apply to the qualification testing of both fabrication methods and burning/cutting processes subject to the suitable interpretation of the hardness survey requirements of 6.2.2.2.3 for the fabrication method or burning/cutting process.

The form and location of the samples used for evaluation and testing shall be acceptable to the equipment user.

6.3 PREN

For the purpose of determining conformance with the requirements of this document, all F_{PREN} limits specified in this document shall be considered absolute limits as defined in ASTM E29. With the absolute method, an observed value or a calculated value is not to be rounded, but is to be compared directly with the specified limiting value. Conformance or non-conformance with the specification is based on this comparison.

The F_{PREN} calculation is based on actual composition, not nominal composition. Nominal composition is used for general classification only.

The PREN (F_{PREN}) shall be calculated as given in Formula (1):

$$F_{\text{PREN}} = w_{\text{Cr}} + 3,3 (w_{\text{Mo}} + 0,5w_{\text{W}}) + 16w_{\text{N}} \quad (1)$$

where

w_{Cr} is the mass fraction of chromium in the alloy, expressed as a percentage mass fraction of the total composition;

w_{Mo} is the mass fraction of molybdenum in the alloy, expressed as a percentage mass fraction of the total composition;

w_{W} is the mass fraction of tungsten in the alloy, expressed as a percentage mass fraction of the total composition;

w_{N} is the mass fraction of nitrogen in the alloy, expressed as a percentage mass fraction of the total composition.

NOTE There are several variations of the PREN. All were developed to reflect and predict the pitting resistance of Fe/Ni/Cr/Mo CRAs in the presence of dissolved chlorides and oxygen, e.g., in sea water. Though useful, these indices are not directly indicative of corrosion resistance in H₂S-containing oil field environments.

7: Purchasing information and marking

7.1 Information that should be supplied for material purchasing

7.1.1 The preparation of material purchasing specifications can require cooperation and exchange of data between the equipment user, the equipment supplier, and the material manufacturer to ensure that the material purchased conforms with ANSI/NACE MR0175/ISO 15156-1 and this document.

7.1.2 The following information shall be provided:

- preferred materials types and/or grades (if known);
- equipment type (if known);

- reference to this document, i.e., ANSI/NACE MR0175-2021/ISO 15156-3:2020;
- acceptable bases for selection of materials for cracking-resistance (see [Clause 6](#)).

7.1.3 The equipment user and the equipment supplier/material manufacturer may agree that CRAs and other alloys other than those described and or listed in [Annex A](#) may be selected subject to suitable qualification testing.

If the purchaser intends to make use of such agreements, extensions, and qualifications, the appropriate additional information shall be clearly indicated in the materials purchasing specification. This information includes the following:

- requirements for SSC, SCC, and/or GHSC testing (see [Clause 6](#) and [Annex B](#));
- service conditions for the specific sour service application.

7.1.4 The information required for material purchasing shall be entered on suitable data sheets. Suggested formats are given in [Annex C](#).

7.2 Marking, labelling, and documentation

Materials conforming with this document shall be made traceable, preferably by marking, before delivery. Suitable labelling or documentation is also acceptable.

For materials qualified and selected for a special application in accordance with Annex B, traceability shall include reference to the environmental conditions of the special application.

The equipment user may request the equipment or materials supplier to provide documentation of the materials used in equipment or components and their environmental service limits as defined in this document.

The tables in [Annex C](#) provide designations that can be used.

Annex A (normative)

Environmental cracking-resistant CRAs and other alloys (including Table A.1 — Guidance on the use of the materials selection tables)

A.1 General

A.1.1 Materials groups

The materials groups used to list CRAs or other alloys (see [6.1](#)) are as follows:

- austenitic stainless steels (identified as material type and as individual alloys) (see [A.2](#));
- highly alloyed austenitic stainless steels (identified as material types and as individual alloys) (see [A.3](#));
- solid-solution nickel-based alloys (identified as material types and as individual alloys) (see [A.4](#));
- ferritic stainless steels (identified as material type) (see [A.5](#));
- martensitic stainless steels (identified as individual alloys) (see [A.6](#));
- duplex stainless steels (identified as material types) (see [A.7](#));
- precipitation-hardened stainless steels (identified as individual alloys) (see [A.8](#));
- precipitation-hardened nickel-based alloys (identified as individual alloys) (see [A.9](#));
- cobalt-based alloys (identified as individual alloys) (see [A.10](#));
- titanium and tantalum (identified as individual alloys) (see [A.11](#));
- copper, aluminum (identified as materials types) (see [A.12](#)).

Subject to A.1.2, [A.1.3](#), [A.1.4](#), and [A.1.5](#) below, the CRAs and other alloys listed in [Table A.1](#) to [Table A.42](#) may be used without further testing for SSC, SCC, and GHSC cracking-resistance within the environmental limits shown.

Information on the use of copper and aluminum alloys is contained in [A.12](#).

[A.13](#) contains recommendations on the use of cladding, overlays, and wear-resistant alloys.

NOTE The materials listed and the restrictions shown are those originally listed in NACE MR0175:2003⁴ except for balloted changes introduced since 2003.

A.1.2 Limits of chemical composition

The user of a CRA or other alloy shall ensure that the chemical analysis of the material used meets the material analysis requirements shown for the material in SAE — ASTM, *Metals and alloys in the Unified Numbering System*.

The material shall also meet any provision shown in the text and/or tables of its materials group.

⁴ Withdrawn.

A.1.3 Environmental and metallurgical limits for cracking-resistance

[A.2.2](#) to [A.11.2](#) contain materials selection tables showing the environmental limits of the materials when used for any equipment or component. These subclauses also often contain materials selection tables showing the less restrictive environmental limits of the materials when used for named equipment or components.

The tables show the application limits with respect to temperature, $\rho\text{H}_2\text{S}$, Cl^- , pH, S^0 . These limits apply collectively. The pH used in the tables corresponds to the minimum in situ pH.

NOTE 1 In the tables of this annex, the SI unit “milligrams per liter” is used for mass concentration. In US Customary units, these are commonly expressed in parts per million (ppm).

NOTE 2 Guidance on the calculation of $\rho\text{H}_2\text{S}$ is given in ANSI/NACE MR0175-2021/ISO 15156-2:2020, Annex C.

NOTE 3 Guidance on the calculation of pH is given in ANSI/NACE MR0175-2021/ISO 15156-2:2020, Annex D.

NOTE 4 In preparing the materials selection tables, it is assumed that no oxygen is present in the service environment.

Where no specified limit for a variable can be defined in a table, explanatory remarks that reflect current knowledge have been included in the table.

The environmental limits for an alloy are valid only within any additional metallurgical limits given for the alloy in the text of the same table. Where tempering of a material is required, the tempering time shall be sufficient to ensure the achievement of the required through-thickness hardness. When purchasing materials, metallurgical properties known to affect the materials' performance in H_2S -containing oil and gas environments in addition to those specifically listed in this annex should also be considered. ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.1 lists such properties.

A.1.4 Requirements and recommendations on welding

The clauses for the materials groups contain requirements and recommendations for welding the materials of the group to achieve satisfactory cracking-resistance in the weldment produced.

A.1.5 Other requirements and recommendations on CRAs and other alloys

A.1.5.1 Requirements for overlays, surface treatments, plating, coatings, linings, etc.

For the composition, cracking-resistance and use of overlays, see [A.13](#).

Metallic coatings (electroplated and electroless plated), conversion coatings, plastic coatings, or linings may be used, but are not acceptable for preventing cracking.

The effect of their application on the cracking-resistance of the substrate shall be considered.

Nitriding with a maximum case depth of 0.15 mm (0.006 in) is an acceptable surface treatment if conducted at a temperature below the lower critical temperature of the alloy being treated. The use of nitriding as a means of preventing cracking in sour service is not acceptable.

A.1.5.1.2 Threading

Threads produced using a machine-cutting process are acceptable.

Threads produced by cold forming (rolling) are acceptable on CRAs and other alloys if the material and the limits of its application otherwise conform with this document.

A.1.5.3 Cold deformation of surfaces

Cold deformation of surfaces is acceptable if caused by processes such as bur-nishing that do not impart more cold work than that incidental to normal machining operations (such as turning or boring, rolling, threading, drilling, etc.).

Cold deformation by controlled shot-peening is acceptable if applied to base materials that conform with this document and if restricted to a maximum shot size of 2.0 mm (0.080 in) and an Almen intensity not exceeding 10C. The process shall be controlled in accordance with SAE AMS-2430.

A.1.5.4 Identification stamping

The use of identification stamping using low-stress (dot, vibratory, and round-V) stamps is acceptable.

The use of conventional sharp V-stamping is acceptable in low-stress areas such as the outside diameter of flanges. Conventional sharp V-stamping shall not be performed in high-stress areas unless agreed with the equipment user.

A.1.6 Use of materials selection tables

[Table A.1](#) provides a guide to the materials selection tables for any equipment or component. It also provides a guide to additional materials selection tables for specific named equipment or components when other, less restrictive, environmental, or metallurgical limits may be applied.

Table A.1 — Guidance on the use of the materials selection tables of Annex A based on equipment or component type

Equipment or components	Material selection table numbers for various materials groups									
	Austenitic stainless steel (see A.2)	Highly-alloyed austenitic stainless steels (see A.3)	Solid-solution nickel-based alloys (see A.4)	Ferritic stainless steels (see A.5)	Martensitic stainless steels (see A.6)	Duplex stainless steels (see A.7)	Precipitation-hardened stainless steels (see A.8)	Precipitation-hardened nickel-based alloys (see A.9)	Cobalt-based alloys (see A.10)	Titanium and tantalum (see A.11)
Any equipment or component	A.2	A.8	A.13 A.14	A.17	A.18	A.24	A.26	A.31 A.32 A.33	A.38	A.41 A.42
Additional materials selection tables for casing, tubing and downhole equipment										
Downhole tubular components	—	A.9	—	—	A.19	A.25	—	—	—	—
Packers and other subsurface equipment	—	A.9	—	—	A.20, A.21	A.25	A.27	—	—	—
Gas lift equipment	A.7	A.10	A.16	—	—	—	—	A.37	—	—
Injection tubing and equipment	A.7	—	—	—	—	—	—	—	—	—
Downhole control line tubing and downhole screens	A.7	A.11	—	—	—	—	—	—	—	—
Additional materials selection tables for wellheads, Christmas trees, valves, chokes and level controllers										
Wellhead and tree components (with various specified exclusions)	—	—	A.13	—	A.23	—	A.27	A.34	—	—
Valve and choke components (with various specified exclusions)	—	—	—	—	A.23	—	A.27	A.34	—	—
Shafts, stems and pins	A.3	—	—	—	—	—	—	—	—	—
Non-pressure-containing internal- valve, pressure-regulator, and level- controller components	—	—	—	—	—	—	A.28	A.35	—	—
Additional materials selection tables for process plant										
Compressor components	A.6	—	—	—	A.22	—	A.30	—	—	—
Additional materials selection tables for other equipment										
Instrumentation and control devices	A.6	—	—	—	—	—	—	—	—	—
Instrument tubing and associated compression fittings, surface control line tubing and surface screens	A.4	A.11	—	—	—	—	—	—	—	—
Springs	—	—	—	—	—	—	—	A.36	A.39	—
Diaphragms, pressure measuring devices and pressure seals	—	—	—	—	—	—	—	—	A.40	—
Seal rings and gaskets	A.5	—	—	—	—	—	—	—	—	—
Snap rings	—	—	—	—	—	—	A.29	—	—	—
Bearing pins	—	—	A.15	—	—	—	—	—	—	—
Miscellaneous equipment as named in the tables (including hardware (e.g. set screws, etc.), downhole and surface temporary-service tool applications)	A.7	—	A.16	—	—	—	A.28	A.35	—	—

A.2 Austenitic stainless steels (identified as material type and as individual alloys)

A.2.1 Materials analyses

Austenitic stainless steels of this material type shall contain the following elements in the following proportions, expressed as mass fractions: C, 0.08 % max; Cr, 16 % min; Ni, 8 % min; P, 0.045 % max; S, 0.04 % max; Mn, 2.0 % max; and Si, 2.0 % max. Other alloying elements are permitted.

Higher carbon contents for UNS S30900 and S31000 are acceptable up to the limits of their respective specifications.

It is common industry practice to dual certify 300 series stainless steels as standard grade and low carbon grade such as S31600 (316) and S31603 (316L). The environmental limits given for low carbon 300 series stainless steels are acceptable for the dual certified grades.

Free-machining austenitic stainless steel products shall not be used.

A.2.2 Environmental and materials limits for the uses of austenitic stainless steels

Table A.2 — Environmental and materials limits for austenitic stainless steels used for any equipment or components

Materials type/ individual alloy UNS number	Temperature	Partial pressure H_2S pH_2S	Chloride conc.	pH	Sulfur-resistant?	Remarks
	max °C (°F)	max kPa (psi)	max mg/l			
Austenitic stainless steel from materials type described in A.2 ^a	60 (140)	100 (15)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
	See “Remarks” column	See “Remarks” column	50	See “Remarks” column	No	These materials have been used without restrictions on temperature, pH_2S , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
S31603 ^b	60 (140)	1 000 (145)	50 000	≥4.5	NDS ^d	
	90 (194)	1 000 (145)	1 000	≥3.5	NDS ^d	
	90 (194)	1 (0.145)	50 000	≥4.5	NDS ^d	
93 (200)		10.2 (1.5)	5 000	≥5.0	NDS ^d	
	120 (248)	100 (14.5)	1 000	≥3.5	NDS ^d	
	149 (300)	10.2 (1.5)	1 000	≥4.0	NDS ^d	
S20910 ^c	66 (150)	100 (15)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.

A limit on the martensite content of these austenitic stainless steels should be considered.

The stress corrosion cracking resistance of all austenitic stainless steels of the material type described in A.2 can be adversely affected by cold working.

^a These materials shall

- be in the solution-annealed and quenched or annealed and thermally-stabilized heat-treatment condition,
- be free of cold work intended to enhance their mechanical properties, and
- have a maximum hardness of 22 HRC.

^b UNS S31603 shall be in the solution-annealed and quenched condition when used in environments outside the limits imposed for the material type (i.e., in the top two rows), but within those given specifically for S31603. The following conditions shall apply:

- the material shall be free from cold work caused by shaping, forming, cold reducing, tension, expansion, etc. after the final solution annealing and quenching treatment;
- after the final solution annealing and quenching treatment, hardness and cold work incidental to machining or straightening shall not exceed the limits imposed by the appropriate product specification.

^c UNS S20910 is acceptable for environments inside the limits imposed for the material type and for this alloy, specifically, in the annealed or hot-rolled (hot/cold-worked) condition at a maximum hardness of 35 HRC.

^d No data submitted (NDS) to ascertain whether these materials are acceptable in service with presence of elemental sulfur in the environment.

Table A.3 — Environmental and materials limits for austenitic stainless steels used as valve stems, pins, and shafts

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
S20910	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	Any combination of temperature, ρH ₂ S, chloride concentration, and in situ pH occurring in production environments is acceptable.
For these applications, the following material restrictions shall also apply: — UNS S20910 at a maximum hardness level of 35 HRC may be used in (1) the as-hot worked condition, (2) the solution annealed condition or (3) the solution annealed condition followed by cold-working. Note that the cold worked condition shall be preceded by solution annealing. ^a No data submitted (NDS) to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.4 — Environmental and materials limits for austenitic stainless steels used in surface applications for control-line tubing, instrument tubing, associated fittings, and screen devices

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur resistant?	Remarks
S31600	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This material has been used for these components without restriction on temperature, ρH ₂ S, Cl ⁻ , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
UNS S31600 stainless steel may be used for compression fittings and instrument tubing even though it might not satisfy the requirements stated for any equipment or component in Table A.2. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.5 — Environmental and materials limits for austenitic stainless steels used as seal rings and gaskets

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S ma kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
J92600, J92900 S30400, S30403 S31600, S31603	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature, pH ₂ S, chloride concentration, and in situ pH occurring in production environments is acceptable.
For these applications, the following materials restrictions shall apply; — J92600, J92900 API compression seal rings and gaskets made of centrifugally cast material in the as-cast or solution-annealed condition shall have a hardness of 160 HBW (83 HRB) maximum; — S30400, S30403, S31600 or S31603 API compression seal rings and gaskets made of wrought material in the solution-annealed condition shall have a hardness of 160 HBW (83 HRB) maximum. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.6 — Environmental and materials limits for austenitic stainless steels used in compressors and instrumentation and control devices

Materials type	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Compressors						
Austenitic stainless steel from materials type described in A.2	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	These materials have been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
Instrumentation and control devices ^b						
Austenitic stainless steel from materials type described in A.2	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	These materials have been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
For these applications, these materials shall also — be in the solution-annealed and quenched or annealed and stabilized heat-treatment condition, — be free of cold work intended to enhance their mechanical properties, and — have a maximum hardness of 22 HRC. A limit on the martensite content of these austenitic stainless steels should be considered. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment. ^b Instrumentation and control devices include, but are not limited to diaphragms, pressure measuring devices, and pressure seals.						

Table A.7 — Environmental and materials limits for austenitic stainless steels used in gas lift service and for special components for subsurface applications such as downhole screens, control-line tubing, hardware (e.g., set screws, etc.), injection tubing, and injection equipment

Materials type	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Austenitic stainless steel from materials group described in A.2	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	These materials have been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.2.3 Welding of austenitic stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the HAZ after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective alloy used for the welding consumable.

Austenitic stainless steel, “L”, filler metal shall have a maximum carbon content of 0.03 % mass fraction.

Weldments may be repair-welded if they meet the welding procedure requirements.

A.3 Highly alloyed austenitic stainless steels (identified as material types and as individual alloys)

A.3.1 Materials chemical compositions

Highly alloyed austenitic stainless shall be as required in [Table A.8](#) and [Table A.9](#). Free-machining highly alloyed austenitic stainless steels shall not be used.

Free-machining highly alloyed austenitic stainless steels shall not be used.

A.3.2 Environmental and materials limits for the uses of highly alloyed austenitic stainless steels

Table A.8 — Environmental and materials limits for highly-alloyed austenitic stainless steels used for any equipment or components

Materials type/ individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Materials type 3a, 3b, and J93254	60 (140)	100 (15)	See "Remarks" column	See "Remarks" column	No	Any combinations of chloride concentration, and in situ pH occurring in production environments are acceptable.
	See "Remarks" column	See "Remarks" column	50	See "Remarks" column	No	These materials have been used without restrictions on temperature, ρH ₂ S, or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
Materials type 3b	121 (250)	700 (100)	5 000	See "Remarks" column	No	The in situ pH values occurring in production environments are acceptable.
	149 (300)	310 (45)	5 000	See "Remarks" column	No	
	171 (340)	100 (15)	5 000	See "Remarks" column	No	
N08926	121 (250)	700 (100)	65 000	≥3.5; See also "Remarks" column	No	pH estimated from laboratory test conditions. UNS N08926 is material type 3b tested to higher limits of chloride concentration than apply for the materials type as a whole.
J95370	150 (302)	700	101 000	See "Remarks" column	No	The in situ pH values occurring in production environments are acceptable.
These materials shall also conform with the following: — materials type 3a shall be highly alloyed austenitic stainless steel with $(w_{Ni} + 2w_{Mo}) > 30$ (where w_{Mo} has a minimum value of 2 %). The symbol w represents the percentage mass fraction of the element indicated by the subscript; — materials type 3b shall be highly alloyed austenitic stainless steel with $F_{PREN} > 40.0$; — materials types 3a and 3b (including N08926) shall be in the solution-annealed condition; — UNS J93254 (CK3McuN, cast 254SMO) in accordance with ASTM A351, ASTM A743, or ASTM A744 shall be in the cast, solution heat-treated and water-quenched condition, and shall have a maximum hardness of 100 HRB; — UNS J95370 shall be in the solution heat-treated and water-quenched condition and shall have a maximum hardness of 94 HRB.						

Table A.9 — Environmental and materials limits for highly-alloyed austenitic stainless steels used for downhole tubular components and packers and other subsurface equipment

Materials type/ individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
Materials type 3a and 3b	60 (140)	100 (15)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
Materials type 3a	60 (140)	350 (50)	50	See “Remarks” column	No	The in situ pH values occurring in production environments are acceptable.
Materials type 3b	121 (250)	700 (100)	5 000	See “Remarks” column	No	
	149 (300)	310 (45)	5 000	See “Remarks” column	No	
	171 (340)	100 (15)	5 000	See “Remarks” column	No	
N08926	121 (250)	700 (100)	65 000	≥3,5; See also “Remarks” column	No	pH is estimated from laboratory test conditions. UNS N08926 is material type 3b tested to higher limits of chloride concentration than apply for the materials type as a whole.
For these applications, these materials shall also conform with the following: — highly alloyed austenitic stainless steels used for downhole tubular components shall contain at least these elements, expressed as percentage mass fractions: C, 0.08 % max; Cr, 16 % min; Ni, 8 % min; P, 0.03 % max; S, 0.030 % max; Mn, 2 % max; and Si, 0.5 % max. Other alloying elements may be added; — materials type 3a shall be highly alloyed austenitic stainless steel with $(w_{Ni} + 2w_{Mo}) > 30$ (where w_{Mo} has a minimum value of 2 %); — materials type 3b shall be highly alloyed austenitic stainless steel with a $F_{PREN} > 40.0$. All the above alloys shall be in the solution-annealed and cold-worked condition with a maximum hardness of 35 HRC.						

Table A.10 — Environmental and materials limits for highly-alloyed austenitic stainless steels used in gas lift service

Materials type	Temperature max °C (°F)	Partial pressure H_2S ρH_2S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Highly alloyed austenitic stainless steel from materials group described in A.3	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	These materials have been used for these components without restriction on temperature, ρH_2S , Cl^- , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.11 — Environmental and materials limits for highly alloyed austenitic stainless steels used as instrument tubing, control-line tubing, compression fittings, and surface and downhole screen devices

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H_2S ρH_2S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Materials types 3a and 3b	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	These materials have been used for these components without restriction on temperature, ρH_2S , Cl^- , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
N08904	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature, ρH_2S , chloride concentration, and in situ pH occurring in production environments is acceptable.
Materials type 3a shall be highly alloyed austenitic stainless steel with $(w_{Ni} + 2w_{Mo}) > 30$ (where w_{Mo} has a minimum value of 2 % mass fraction). The symbol w represents the percentage mass fraction of the element indicated by the subscript. Materials type 3b shall be highly alloyed austenitic stainless steel with a $F_{PREN} > 40.0$. Wrought N08904 for use as instrument tubing shall be in the annealed condition with a maximum hardness of 180 HV10. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.3.3 Welding highly alloyed austenitic stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the HAZ after welding shall not exceed the maximum hardness allowed for the base metal, and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective alloy used for the welding consumable.

Weldments may be repair-welded if they meet the weld procedure requirements.

A.4 Solid-solution nickel-based alloys (identified as material types and as individual alloys)

A.4.1 Materials chemical compositions

Table A.12 provides a breakdown of this materials group into types 4a, 4b, 4c, 4d, and 4e used in [Table A.13](#) and [Table A.14](#).

Table A.12 — Materials types of solid-solution nickel-based alloys

Materials type	Cr mass fraction min %	Ni + Co mass fraction min %	Mo mass fraction min %	Mo + W mass fraction min %	Metallurgical condition
Type 4a	19.0	29.5	2.5	—	Solution-annealed or annealed
Type 4b	14.5	52	12	—	Solution-annealed or annealed
Type 4c	19.5	29.5	2.5	—	Solution-annealed or annealed and cold-worked
Type 4d	19.0	45	—	6	Solution-annealed or annealed and cold-worked
Type 4e	14.5	52	12	—	Solution-annealed or annealed and cold-worked
Type 4f ^a	20.0	58	15.5	—	a) Solution-annealed or annealed and cold-worked condition b) Solution-annealed or annealed and cold-worked and aged condition

^a The type 4f family is currently limited to only UNS N07022.

A.4.2 Environmental and materials limits for the uses of solid-solution nickel-based alloys

**Table A.13 — Environmental and materials limits for solid-solution nickel-based alloys
used in any equipment or component**

Materials type/ individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
Annealed alloys of types 4a and 4b	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	Yes	These materials have been used without restriction on temperature, ρH ₂ S, chloride concentration, or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
N04400 N04405	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	

Wrought or cast solid-solution nickel-based products made from alloys of types 4a and 4b shall be in the solution-annealed or annealed condition.

UNS N04400 and UNS N04405 shall have a maximum hardness of 35 HRC.

Wellhead and christmas tree components shall also be in accordance with ISO 10423.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.14 — Environmental and materials limits for annealed and cold-worked, solid-solution nickel-based alloys used as any equipment or component^a

Materials type	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Cold-worked alloys of types 4c, 4d and 4e	232 (450)	200 (30)	See "Remarks" column	See "Remarks" column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
	218 (425)	700 (100)	See "Remarks" column	See "Remarks" column	No	
	204 (400)	1 000 (150)	See "Remarks" column	See "Remarks" column	No	
	177 (350)	1 400 (200)	See "Remarks" column	See "Remarks" column	No	
	132 (270)	See "Remarks" column	See "Remarks" column	See "Remarks" column	Yes	Any combination of hydrogen sulfide, chloride concentration, and in situ pH in production environments is acceptable.
Cold-worked alloys of types 4d and 4e	218 (425)	2 000 (300)	See "Remarks" column	See "Remarks" column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
	149 (300)	See "Remarks" column	See "Remarks" column	See "Remarks" column	Yes	Any combinations of hydrogen sulfide, chloride concentration, and in situ pH in production environments are acceptable.
Cold-worked alloys of type 4e	232 (450)	7 000 (1 000)	See "Remarks" column	See "Remarks" column	Yes	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
	204 (400)	See "Remarks" column	See "Remarks" column	See "Remarks" column	Yes	Any combination of hydrogen sulfide, chloride concentration, and in situ pH in production environments is acceptable.
Cold-worked alloys of type 4f	204 (400)	3 500 (500)	180 000	See "Remarks" column	Yes	Any in situ production environment pH is acceptable for ρCO ₂ + ρH ₂ S ≤ 7 000 kPa (1 000 psi)
	288 (550)	7 000 (1 000)	180 000	See "Remarks" column	NDS ^b	Any in situ production environment pH is acceptable for ρCO ₂ such that: For ρH ₂ S < 3 000 kPa (450 psi): ρCO ₂ + ρH ₂ S ≤ 10 000 kPa (1 450 psi). For ρH ₂ S from 3 000 kPa to 7 000 kPa: ρCO ₂ ≤ 7 000 kPa (1 000 psi).

Wrought or cast solid-solution nickel-based products in these applications shall be in the annealed and cold-worked condition or annealed, cold-worked, and aged for type 4f and shall meet all of the following as applicable:

- 1) the maximum hardness value for types 4c, 4d, and 4e in these applications shall be 40 HRC;
- 2) the maximum yield strength of the alloys achieved by cold work shall be
 - type 4c: 1 034 MPa (150 ksi);
 - type 4d: 1 034 MPa (150 ksi);
 - type 4e: 1 240 MPa (180 ksi).
- 3) UNS N10276 (Type 4e) when used at a minimum temperature of 121 °C (250 °F) shall have a maximum hardness of 45 HRC;
- 4) UNS N07022 (Type 4f) in the annealed and cold-worked condition shall have a maximum hardness of 43 HRC and a maximum yield strength of 1 413 MPa (205 ksi);
- 5) UNS N07022 (Type 4f) in the annealed and cold-worked and aged condition shall have a maximum hardness of 47 HRC and a maximum yield strength of 1 420 MPa (206 ksi).

^a The limits of application of the materials types 4c, 4d, and 4e in this table overlap.

^b No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.15 — Environmental and materials limits for nickel-based alloys used for bearing pins

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
N10276	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	Any combination of temperature, ρH ₂ S, chloride concentration, and in situ pH occurring in production environments is acceptable.
N10276 bearing pins, e.g., core roll pins, shall be in the cold-worked condition with a maximum hardness of 45 HRC.						
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.16 —Environmental and materials limits for nickel-based alloys used in gas lift service and for downhole running, setting, and service tool applications for temporary service

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
ρH ₂ S	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	These materials have been used for these components without restriction on temperature, ρH ₂ S, Cl ⁻ , or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.4.3 Welding solid-solution nickel-based alloys of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the HAZ after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective alloy used for the welding consumable.

There are no hardness requirements for welding solid-solution nickel-based alloys with solid-solution nickel-based weld metal.

A.5 Ferritic stainless steels (identified as material type)

A.5.1 Environmental and materials limits for the uses of ferritic stainless steels

Table A.17 — Environmental and materials limits for ferritic stainless steels used for any equipment or components

Materials type	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Ferritic stainless steels from materials type described in A.5	See “Remarks” column	10 (1.5)	See “Remarks” column	≥3.5	NDS ^a	Subject to limitations on pH ₂ S and pH. These materials have been used without restrictions on temperature or chloride concentration in production environments. No limits on these two parameters are set, but some combinations of their values might not be acceptable.
These materials shall be in the annealed condition and shall have a maximum hardness of 22 HRC.						
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.5.2 Welding of ferritic stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

Hardness testing of qualification welds shall be carried out and the maximum hardness shall be 250 HV or, if a different hardness test method is permitted, its equivalent.

A.6 Martensitic (stainless) steels (identified as individual alloys)

A.6.1 Materials chemical compositions

Free-machining martensitic stainless steels shall not be used.

A.6.2 Environmental and materials limits for the uses of martensitic stainless steels

Table A.18 — Environmental and materials limits for martensitic stainless steels used for any equipment or components

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
S41000 S41500 S42000 J91150 J91151 J91540 S42400	See "Remarks" column	10 (1.5)	See "Remarks" column	≥3.5	NDS ^a	Subject to limitations on the in situ pH and pH ₂ S, these materials have been used for these components without restriction on temperature and chloride concentration in production environments. No limits on these parameters are set, but some combinations of their values might not be acceptable.
S41425	See "Remarks" column	10 (1.5)	See "Remarks" column	≥3.5	No	

These materials shall also conform with the following:

- a) cast or wrought alloys UNS S41000, J91150 (CA15), and J91151 (CA15M) shall have a maximum hardness of 22 HRC and shall be
 - 1) austenitized and quenched or air-cooled;
 - 2) tempered at 621 °C (1 150 °F) minimum, then cooled to ambient temperature;
 - 3) tempered at 621 °C (1 150 °F) minimum, but lower than the first tempering temperature, then cooled to ambient temperature.
- b) low-carbon, martensitic stainless steels, either cast J91540 (CA6NM), or wrought S42400 or S41500 (F6NM) shall have a maximum hardness of 23 HRC and shall be
 - 1) austenitized at 1 010 °C (1 850 °F) minimum, then air- or oil-quenched to ambient temperature;
 - 2) tempered at 649 °C to 691 °C (1 200 °F to 1 275 °F), then air-cooled to ambient temperature;
 - 3) tempered at 593 °C to 621 °C (1 100 °F to 1 150 °F), then air-cooled to ambient temperature.
- c) cast or wrought alloy UNS S42000 shall have a maximum hardness of 22 HRC and shall be in the quenched and tempered heat-treatment condition;
- d) wrought low-carbon UNS S41425 martensitic stainless steel in the austenitized, quenched, and tempered condition shall have a maximum hardness of 28 HRC.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.19 — Environmental and materials limits for martensitic stainless steels used as downhole tubular components and for packers and other subsurface equipment

Specification/ Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
ISO 11960 L-80 Type 13 Cr, S41426, S42500	See “Remarks” column	10 (1.5)	See “Remarks” column	≥3.5	NDS ^a	Subject to limitations on the in situ pH and ρH ₂ S, these materials have been used for these components without restriction on temperature and chloride concentration in production environments. No limits on these parameters are set, but some combinations of their values might not be acceptable.
S41429	See “Remarks” column	10 (1.5)	See “Remarks” column	≥4.5	NDS ^a	

For these applications, these materials shall also conform with the following:

- a) UNS S41426 tubular components shall be quenched and tempered to maximum 27 HRC and maximum yield strength 724 MPa (105 ksi);
- b) UNS S42500 (15 Cr) tubing and casing is acceptable as Grade 80 [SMYS 556 MPa (80 ksi)] only and shall be in the quenched and double-tempered condition with a maximum hardness of 22 HRC. The quench and double-temper process shall be as follows:
 - 1) austenitize at minimum 900 °C (1 652 °F), then air- or oil-quench;
 - 2) temper at minimum 730 °C (1 346 °F), then cool to ambient temperature;
 - 3) temper at minimum 620 °C (1 148 °F), then cool to ambient temperature.
- c) UNS S41429 tubular components shall be quenched and tempered or normalized and tempered to a maximum hardness of 27 HRC and a maximum yield strength of 827 MPa (120 ksi).

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.20 — Environmental and materials limits for martensitic alloy steel used as subsurface equipment

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
K90941	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	These materials have been used without restrictions on temperature, ρH ₂ S, chloride concentration, or in situ pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.

For these applications, UNS K90941 (martensitic 9Cr 1Mo to ASTM A276 type 9, ASTM A182/A182M grade F9 or ASTM A213/A213M grade T9) shall have a maximum hardness of 22 HRC.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.21 — Environmental and materials limits for martensitic stainless steels used as packers and subsurface equipment

Alloy specification	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
AISI 420 (modified)	See "Remarks" column	10 (1.5)	See "Remarks" column	≥3.5	NDS ^a	Any combination of temperature and chloride concentration occurring in production environments is acceptable
S41427	See "Remarks" column	10 (1.5)	6 100	≥3.5	NDS ^a	Temperatures occurring in production environments are acceptable.
For these applications, AISI 420 (modified) shall have chemical composition in accordance with ISO 11960 L-80 Type 13 Cr and shall be quenched and tempered to 22 HRC maximum. UNS S41427 shall have a maximum hardness of 29 HRC and shall have been heat-treated in accordance with the following three-step process: - austenitize at 900 °C to 980 °C (1 652 °F to 1 796 °F), then air-cool or oil-quench to ambient temperature; - tempered at 600 °C to 700 °C (1 112 °F to 1 292 °F), then air-cool to ambient temperature; - tempered at 540 °C to 620 °C (1 004 °F to 1 148 °F), then air-cool to ambient temperature. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.22 — Environmental and materials limits for martensitic stainless steels used as compressor components

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
S41000 S41500 S42400 J91150 J91151 J91540	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	Any combination of temperature, pH ₂ S, chloride concentration, and in situ pH occurring in production environments is acceptable.
For these applications, these materials shall also conform with the following: a) cast or wrought alloys UNS S41000, J91150 (CA15), and J91151 (CA15M) shall have 22 HRC maximum hardness if used for compressor components and shall be 1) austenitized and quenched or air-cooled; 2) tempered at 621 °C (1 150 °F) minimum, then cooled to ambient temperature; 3) tempered at 621 °C (1 150 °F) minimum, but lower than the first tempering temperature, then cooled to ambient temperature. b) low-carbon, martensitic stainless steels, either cast J91540 (CA6NM) or wrought S42400 or S41500 (F6NM), shall have a maximum hardness of 23 HRC and shall be 1) austenitized at 1 010 °C (1 850 °F) minimum, then air- or oil-quenched to ambient temperature; 2) tempered at 649 °C to 691 °C (1 200 °F to 1 275 °F), then air-cooled to ambient temperature; 3) tempered at 593 °C to 621 °C (1 100 °F to 1 150 °F), then air-cooled to ambient temperature. c) if used for impellers, cast or wrought alloys UNS S41000, J91150 (CA15) and J91151 (CA15M), cast J91540 (CA6NM) and wrought S42400, or S41500 (F6NM) shall exhibit a threshold stress ≥95 % of actual yield strength in the anticipated service environment. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.23 — Environmental and materials limits for martensitic stainless steels used as wellhead and tree components and valve and choke components (excluding casing and tubing hangers and valve stems)

Individual alloy UNS number	Temperature max. °C (°F)	Partial pressure H ₂ S ρH ₂ S max. kPa (psi)	Chloride conc. max. mg/l	pH	Sulfur-resistant?	Remarks
S41000 S41500 S42000 J91150 J91151 J91540 S42400	See "Remarks" column	See "Remarks" column	See "Remarks" column	≥3.5	NDS ^a	Subject to limitations on in situ pH, these materials have been used for these components without restriction on temperature, ρH ₂ S, or Cl ⁻ in production environments. No limits on these parameters are set, but some combinations of their values might not be acceptable.
For these applications, these materials shall also conform with the following: a) cast or wrought alloys UNS S41000, J91150 (CA15), and J91151 (CA15M), shall have 22 HRC maximum hardness and shall be 1) austenitized and quenched or air-cooled; 2) tempered at 621 °C (1 150 °F) minimum, then cooled to ambient temperature; 3) tempered at 621 °C (1 150 °F) minimum, but lower than the first tempering temperature, then cooled to ambient temperature. b) low-carbon, martensitic stainless steels either cast J91540 (CA6NM) or wrought S42400 or S41500 (F6NM) shall have 23 HRC maximum hardness and shall be 1) austenitized at 1 010 °C (1 850 °F) minimum, then air- or oil-quenched to ambient temperature; 2) tempered at 649 °C to 691 °C (1 200 °F to 1 275 °F), then air-cooled to ambient temperature; 3) tempered at 593 °C to 621 °C (1 100 °F to 1 150 °F), then air-cooled to ambient temperature. c) cast or wrought alloy UNS S42000 shall have a maximum hardness of 22 HRC and shall be in the quenched and tempered heat-treatment condition. d) low-carbon, martensitic stainless steel J91540; the maximum design tensile stress shall not exceed 2/3 specified minimum yield strength or 345 MPa (50 ksi) whichever is less. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.6.3 Welding of martensitic stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the HAZ after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective alloy used for the welding consumable.

Martensitic stainless steels welded with nominally matching consumables shall meet the following requirements.

Weldments in martensitic stainless steels shall undergo a PWHT at 621 °C (1 150 °F) minimum and shall conform with [6.2.2.2](#).

Weldments in the low-carbon martensitic stainless steels [cast J91540 (CA6NM) or wrought S42400 or S41500 (F6NM)] shall undergo a single- or double-cycle PWHT after first being cooled to 25 °C (77 °F), as follows:

- single-cycle PWHT shall be at 580 °C to 621 °C (1 075 °F to 1 150 °F);
- double-cycle PWHT shall be at 671 °C to 691 °C (1 240 °F to 1 275 °F), then cooled to 25 °C (77 °F) or less, then heated to 580 °C to 621 °C (1 075 °F to 1 150 °F).

A.7 Duplex stainless steels (identified as material types)

A.7.1 Environmental and materials limits for the uses of duplex stainless steels

Table A.24 — Environmental and materials limits for duplex stainless steels used for any equipment or component

Materials type/ individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
$30 \leq F_{\text{PREN}} \leq 40.0$ Mo ≥ 1.5 %	232 (450)	10 (1.5)	180 000	See “Remarks” column	NDS ^a	These materials have been used without restrictions on <i>in situ</i> pH in production environments. No limits on pH are set, but some values might not be acceptable.
$30 \leq F_{\text{PREN}} \leq 40.0$ Mo ≥ 1.5 % (HIP)	232 (450)	10 (1.5)		See “Remarks” column	NDS ^a	
$40.0 < F_{\text{PREN}} \leq 45$	232 (450)	20 (3)		See “Remarks” column	NDS ^a	
$40.0 < F_{\text{PREN}} \leq 45$ (HIP)	232 (450)	20 (3)		See “Remarks” column	NDS ^a	
$30 \leq F_{\text{PREN}} \leq 40.0$ Mo ≥ 1.5 %	See “Remarks” column	See “Remarks” column	50	See “Remarks” column	NDS ^a	These materials have been used without restrictions on temperature, pH ₂ S or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
$40.0 < F_{\text{PREN}} \leq 45$	See “Remarks” column	See “Remarks” column		See “Remarks” column	NDS ^a	
Wrought, cast and hot isostatically pressed (HIP) ^[15] duplex stainless steels shall						
— be solution-annealed and liquid-quenched or rapidly cooled by other methods ^b ,						
— have a ferrite content (volume fraction) of between 35 % and 65 %, and						
— not have undergone aging heat-treatments.						
NOTE Higher values of F_{PREN} provide higher corrosion resistance; however, they also lead to increased risk of sigma- and alpha-prime phase formation in the materials' ferrite phase during manufacture depending on product thickness and achievable quench rate. The ranges of F_{PREN} quoted are typical of those found to minimize the problem of sigma- and alpha-prime phase formation.						
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						
^b A rapid cooling rate is one sufficiently fast to avoid the formation of deleterious phases such as sigma-phase and precipitates. The presence of deleterious phases can reduce the cracking-resistance of duplex stainless steels.						

Table A.25 — Environmental and materials limits for duplex stainless steels used as downhole tubular components and as packers and other subsurface equipment

Materials type	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
$30 \leq F_{\text{PREN}} \leq 40.0$ Mo ≥ 1.5 %	See "Remarks" column	2 (0.3)	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature, chloride concentration and <i>in situ</i> pH occurring in production environments is acceptable.
$40.0 < F_{\text{PREN}} \leq 45$	See "Remarks" column	20 (3)	120 000	See "Remarks" column	NDS ^a	Any combination of temperature and <i>in situ</i> pH occurring in production environments is acceptable. Chloride limits have been found to be strongly dependent upon yield strength and the level of cold work.

For these applications, these materials shall

- be in the solution-annealed, liquid-quenched, and cold-worked condition,
- have a ferrite content (volume fraction) of between 35 % and 65 %, and
- have a maximum hardness of 36 HRC.

NOTE Higher values of F_{PREN} provide higher corrosion resistance; however, they also lead to increased risk of sigma- and alpha-prime phase formation in the materials' ferrite phase during manufacture depending on product thickness and achievable quench rate. The ranges of F_{PREN} quoted are typical of those found to minimize the problem of sigma- and alpha-prime phase formation.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

A.7.2 Welding of duplex stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the HAZ after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective alloy used for the welding consumable.

A cross-section of the weld metal, HAZ, and base metal shall be examined as part of the welding procedure qualification. The microstructure shall be suitably etched and examined at $\times 400$ magnification and shall have grain boundaries with no continuous precipitates. Intermetallic phases, nitrides, and carbides shall not exceed 1.0 % in total. The sigma phase shall not exceed 0.5 %. The ferrite content in the weld metal root and unreheated weld cap shall be determined in accordance with ASTM E562 and shall be in the range of 30 % to 70 % volume fraction.

A.8 Precipitation-hardened stainless steels (identified as individual alloys)

A.8.1 Materials chemical compositions

Austenitic precipitation-hardened stainless steels are addressed in [Table A.26](#). Martensitic precipitation-hardened stainless steels are addressed in [Table A.27](#) to [Table A.30](#).

A.8.2 Environmental and materials limits for the uses of precipitation-hardened stainless steels

Table A.26 — Environmental and materials limits for austenitic precipitation-hardened stainless steels used for any equipment or component

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
S66286	66 (150)	100 (15)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and in situ pH occurring in production environments is acceptable.
UNS S66286 shall have a maximum hardness of 35 HRC and shall be in either the solution-annealed and aged or solution-annealed and double-aged condition.						

Table A.27 — Environmental and materials limits for martensitic precipitation-hardened stainless steels used for wellhead and christmas tree components (excluding bodies and bonnets), valves and chokes (excluding bodies and bonnets), and packers and other subsurface equipment

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
UNS S17400	See “Remarks” column	3.4 (0.5)	See “Remarks” column	≥4.5	NDS ^a	See ^b ; the safe use limits on chloride and temperature have not been defined.
UNS S45000	See “Remarks” column	10 (1.5)	See “Remarks” column	≥3.5	NDS ^a	Any combination of temperature and chloride concentration occurring in production environments is acceptable.

For these applications, these materials shall also conform with the following:

- a) wrought UNS S17400 precipitation-hardening martensitic stainless steels shall have a maximum hardness of 33 HRC and shall have been heat-treated in accordance with either 1) or 2), as follows:
 - 1) double age-hardening process at 621 °C (1 150 °F):
 - solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F] and air-cool or liquid-quench to below 32 °C (90 °F);
 - first precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature, then air-cool or liquid-quench to below 32 °C (90 °F);
 - second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature, then air-cool or liquid-quench to below 32 °C (90 °F).
 - 2) modified double age-hardening process:
 - solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F], then air-cool or liquid-quench to below 32 °C (90 °F);
 - first precipitation-hardening cycle at (760 ± 14) °C [(1 400 ± 25) °F] for 2 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F);
 - second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature, then air-cool or liquid-quench to below 32 °C (90 °F).
 - b) wrought UNS S45000 molybdenum-modified martensitic precipitation-hardened stainless steel shall have a maximum hardness of 31 HRC (equivalent to 306 HBW for this alloy) and shall have undergone the following two-step heat-treatment procedure:
 - 1) solution-anneal;
 - 2) precipitation-harden at (621 ± 8) °C [(1 150 ± 15) °F] for 4 h minimum at temperature.
- ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.
- ^b The use of UNS S17400 is restricted to those applications where the sustained stress is no more than 50 % of the specified minimum yield strength (SMYS) or 380 MPa (55 ksi), whichever is less. The use of UNS S17400 is acceptable for wellhead valve trim where the stem is subjected to higher stress levels for very short periods of time during actuation; other or longer stress duration applications are prohibited above 50 % of the specified minimum yield strength (SMYS) or 380 MPa (55 ksi), whichever is less.

Table A.28 — Environmental and materials limits for martensitic precipitation-hardened stainless steels used as non-pressure-containing internal-valve, pressure-regulator, and level-controller components and miscellaneous equipment

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
Non-pressure-containing internal-valve, pressure-regulator, and level-controller components						
CB7Cu-1 CB7Cu-2	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	These materials have been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
S17400 S15500	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	
S45000	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	
Miscellaneous equipment						
S17400	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This alloy has been used in service tool applications at the surface and for temporary drilling and subsurface well- servicing equipment when stressed at less than 60 % of its specified minimum yield strength under working conditions. Environmental limits for this alloy for these applications have not been established.
For these applications, these materials shall also conform with the following:						
a) cast CB7Cu-1 and CB7Cu-2 shall be in the H1150 DBL condition in accordance with ASTM A747/A747M and shall have a maximum hardness of 30 HRC;						
b) wrought UNS S17400 and S15500 precipitation-hardening martensitic stainless steels shall have a maximum hardness of 33 HRC and shall have been heat-treated in accordance with either 1) or 2), as follows:						
1) double age-hardening process at 621°C (1 150°F):						
— solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F], then air-cool or liquid-quench to below 32 °C (90 °F);						
— first precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F);						
— second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F).						
2) modified double age-hardening process:						
— solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F] and air-cool or liquid-quench to below 32 °C (90 °F);						
— first precipitation-hardening cycle at (760 ± 14) °C [(1 400 ± 25) °F] for 2 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F);						
— second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F).						
c) for UNS 17400, limits on its ferrite content should be considered;						
d) wrought UNS S45000 precipitation-hardening martensitic stainless steel shall have a maximum hardness of 31 HRC (equivalent to 306 HBW for this alloy) and shall be heat-treated using the following two-step process:						
1) solution-anneal;						
2) precipitation-harden at (621 ± 8) °C [(1 150 ± 14) °F] for 4 h minimum at temperature.						
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.29 — Environmental and materials limits for martensitic precipitation-hardened stainless steels used as snap rings

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
S15700	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature. pH ₂ S, Cl ⁻ , and <i>in situ</i> pH occurring in production environments is acceptable.

For this application, UNS S15700 snap rings originally in the RH950 solution-annealed and aged condition shall also be further heat-treated to a hardness of between 30 HRC and 32 HRC using the following three-step process:

- temper at 621 °C (1 150 °F) for 4 h, 15 min, then cool to room temperature in still air;
- re-temper at 621 °C (1 150 °F) for 4 h, 15 min, then cool to room temperature in still air;
- temper at 566 °C (1 050 °F) for 4 h, 15 min, then cool to room temperature in still air.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.30 — Environmental and materials limits for martensitic precipitation-hardened stainless steels used in compressor components

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
S17400 S15500	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature. pH ₂ S, Cl ⁻ , and <i>in situ</i> pH occurring in production environments is acceptable.
S45000	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature. pH ₂ S, Cl ⁻ , and <i>in situ</i> pH occurring in production environments is acceptable.

For these applications, these materials shall also conform with the following:

- wrought UNS S17400 and S15500 precipitation-hardening martensitic stainless steels shall have a maximum hardness of 33 HRC and shall have been heat-treated in accordance with either 1) or 2), as follows:
 - double age-hardening process at 621 °C (1 150 °F):
 - solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F] and air-cool or liquid-quench to below 32 °C (90 °F);
 - first precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F);
 - second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F).
 - modified double age-hardening process:
 - solution-anneal at (1 038 ± 14) °C [(1 900 ± 25) °F] and air-cool or liquid-quench to below 32 °C (90 °F);
 - first precipitation-hardening cycle at (760 ± 14) °C [(1 400 ± 25) °F] for 2 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F);
 - second precipitation-hardening cycle at (621 ± 14) °C [(1 150 ± 25) °F] for 4 h minimum at temperature and air-cool or liquid-quench to below 32 °C (90 °F).
- for UNS 17400, limits on its ferrite content should be considered;
- for use as impellers at higher hardness (strength) levels, these alloys shall be tested in accordance with Annex B at a test stress level of at least 95 % of AYS;
- wrought UNS S45000 molybdenum-modified martensitic precipitation-hardened stainless steel shall have a maximum hardness of 31 HRC (equivalent to 306 HBW for this alloy) and shall have undergone the following two-step heat-treatment procedure:
 - solution annealing;
 - precipitation hardening at (621 ± 8) °C [1 150 ± 15) °F] for 4 h minimum at temperature.
- UNS S17400 or S15500 used for impellers at a hardness of >33 HRC shall exhibit a threshold stress ≥95 % of AYS in the anticipated service environment (see [B.3.4](#)).

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

A.8.3 Welding of precipitation-hardened stainless steels of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the base metal after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective metal for the weld alloy.

A.9 Precipitation-hardened nickel-based alloys (identified as individual alloys)

A.9.1 Environmental and materials limits for the uses of precipitation-hardened nickel-based alloys

Table A.31 to [Table A.33](#) give the environmental and materials limits for the uses for any equipment or component of precipitation-hardened nickel-based alloys divided into groups I, II, and III, respectively.

**Table A.31 — Environmental and materials limits for precipitation-hardened nickel-based alloys (I)
used for any equipment or component**

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
N07031 N07048 N07773 N09777 (wrought) N07718 (cast) N09925 (cast)	232 (450)	200 (30)	See "Remarks" column	See "Remarks" column	No	Any combination of chloride concentration and <i>in situ</i> pH occurring in production environments is acceptable.
	204 (400)	1 400 (200)	See "Remarks" column	See "Remarks" column	No	
	149 (300)	2 700 (400)	See "Remarks" column	See "Remarks" column	No	
N07031 N07048 N07773 N09777 (wrought)	135 (275)	See "Remarks" column	See "Remarks" column	See "Remarks" column	Yes	Any combination of hydrogen sulfide, chloride concentration, and <i>in situ</i> pH in production environments is acceptable.
N09925 (cast)	135 (275)	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	
N07718 (cast)	135 (275)	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	
N07924 (wrought)	175 (347)	3 500 (500)	139 000	≥3.5, See also "Remarks" column	No	pH estimated from laboratory test conditions.

These materials shall also conform with the following:

- wrought UNS N07031 shall be in either of the following conditions:
 - solution-annealed to a maximum hardness of 35 HRC;
 - solution-annealed and aged at 760 °C to 871 °C (1 400 °F to 1 600 °F) for a maximum of 4 h to a maximum hardness of 40 HRC.
- wrought UNS N07048, wrought UNS N07773, and wrought UNS N09777 shall have a maximum hardness of 40 HRC and shall be in the solution-annealed and aged condition;
- wrought UNS N07924 shall be in the solution-annealed and aged condition at a maximum hardness of 35 HRC;
- cast UNS N09925 shall be in the solution-annealed and aged condition at a maximum hardness of 35 HRC;
- cast UNS N07718 shall be in the solution-annealed and aged condition at a maximum hardness of 40 HRC.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

**Table A.32 — Environmental and materials limits for precipitation-hardened nickel-based alloys (II)
used for any equipment or component**

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
N07718 ^{a)} N09925 ^{b)}	232 (450)	200 (30)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and <i>in situ</i> pH occurring in production environments is acceptable.
	204 (400)	1 400 (200)	See “Remarks” column	See “Remarks” column	No	
	199 (390)	2 300 (330)	See “Remarks” column	See “Remarks” column	No	
	191 (375)	2 500 (360)	See “Remarks” column	See “Remarks” column	No	
	149 (300)	2 800 (400)	See “Remarks” column	See “Remarks” column	No	
	135 (275)	See “Remarks” column	See “Remarks” column	See “Remarks” column	Yes	Any combination of hydrogen sulfide, chloride concentration, and <i>in situ</i> pH in production environments is acceptable.
N07718 ^{c)}	205 (401)	3 500 (500)	180 000	See “Remarks” column	NDS ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 7\,000$ kPa (1 000 psi).
N09925 ^{b) 3)}	205 (401)	3 500 (500)	180 000	See “Remarks” column	NDS ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 7\,000$ kPa (1 000 psi).
N09935 ^{d)}	232 (450)	2 800 (400)	180 000	See “Remarks” column	NDS ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 8\,300$ kPa (1 200 psi)
N09945 ^{e)} N09946 ^{f)}	232 (450)	3 500 (508)	139 000	See “Remarks” column	NDS ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 7\,000$ kPa (1 000 psi)
	205 (401)	3 500 (508)	180 000	See “Remarks” column	NDS ^a	
N09945 ^{e)}	177 (350)	7 700 (1 100)	125 000	See “Remarks” column	Yes ^{b)}	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2$ such that: For $\rho\text{H}_2\text{S} < 5\,800$ kPa (842 psi): $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 10\,000$ kPa (1 450 psi). For $\rho\text{H}_2\text{S}$ from 5 800 kPa to 7 700 kPa: $p\text{CO}_2 \leq 4\,200$ kPa (610 psi).
N09955 ^{g)}	205 (401)	3 500 (500)	180 000	See “Remarks” column	NDS ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + \rho\text{H}_2\text{S} \leq 7\,000$ kPa (1 000 psi).

These materials shall also conform with the following:

- a) except as stated in c), wrought UNS N07718 shall be in any one of the following conditions:
 - 1) solution-annealed to a maximum hardness of 35 HRC;
 - 2) hot-worked to a maximum hardness of 35 HRC;
 - 3) hot-worked and aged to a maximum hardness of 35 HRC;
 - 4) solution-annealed and aged to a maximum hardness of 40 HRC.
- b) wrought UNS N09925 shall be in any one of the following conditions:
 - 1) cold-worked to a maximum hardness of 35 HRC;
 - 2) solution-annealed to a maximum hardness of 35 HRC;
 - 3) solution-annealed and aged to a maximum hardness of 38 HRC;
 - 4) cold-worked and aged to a maximum hardness of 40 HRC;
 - 5) hot-finished and aged to a maximum hardness of 40 HRC.
- c) wrought UNS N07718 meeting the composition of API 6A CRA is acceptable to a maximum hardness of 45 HRC, when solution annealed and aged as follows:
 - 1) solution-annealed 1 021 °C to 1 052 °C (1 870 °F to 1 925 °F) for 1 to 2.5 hours at temperature, air cool or faster.
 - 2) age hardened 700 °C to 750 °C (1 292 °F to 1 382 °F), hold for 8 hours minimum, furnace cool to 600 °C to 650 °C (1 112 °F to 1 202 °F) and hold for an additional 8 hours minimum, air cool.
- d) wrought UNS N09935 shall be in the solution annealed and aged condition to a maximum hardness of 34 HRC;
- e) wrought UNS N09945 shall be in the solution annealed and aged condition to a maximum hardness of 42 HRC;
- f) wrought UNS N09946 shall be in solution annealed and aged condition to a maximum hardness of 46 HRC;
- g) wrought UNS N09955 shall be in solution annealed and aged condition to a maximum hardness of 42 HRC.
- ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.
- ^b Sulfur resistant as tested in accordance with Group 1 as defined in NACE Conference paper 95047 and EFC 17, Appendix S1.

**Table A.33 — Environmental and materials limits for precipitation-hardened nickel-based alloys (III)
used for any equipment or component**

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
N07626 (powder metal)	232 (450)	1 000 (150)	See “Remarks” column	See “Remarks” column	No	Any combination of chloride concentration and <i>in situ</i> pH occurring in production environments is acceptable.
N07716 N07725 (wrought)	218 (425)	2 000 (300)	See “Remarks” column	See “Remarks” column	Yes	
N07626 (powder metal)	204 (400)	4 100 (600)	See “Remarks” column	See “Remarks” column	No	
N07716 N07725 (wrought)	204 (400)	4 100 (600)	See “Remarks” column	See “Remarks” column	Yes	
N07022 (wrought)	204 (400)	3 500 (500)	180 000	See “Remarks” column	Yes	Any <i>in situ</i> production environment pH is acceptable for ρCO ₂ + ρH ₂ S ≤ 7 000 kPa (1 000 psi)
N07626 (powder metal) N07716 N07725 (wrought)	177 (350)	See “Remarks” column	See “Remarks” column	See “Remarks” column	Yes	Any combination of hydrogen sulfide, chloride concentration, and <i>in situ</i> pH in production environments is acceptable.
These materials shall also conform with the following: a) UNS N07626, totally dense hot-compacted by a powder metallurgy process, shall have a maximum hardness of 40 HRC and a maximum tensile strength of 1 380 MPa (200 ksi) and shall be either 1) solution-annealed [927 °C (1 700 °F) minimum] and aged [538 °C to 816 °C (1 000 °F to 1 500 °F)], or 2) direct-aged [538 °C to 816 °C (1 000 °F to 1 500 °F)]. b) wrought UNS N07716 and wrought UNS N07725 shall have a maximum hardness of HRC 43 and shall be in the solution-annealed and aged condition; c) wrought UNS N07716 and wrought UNS N07725 in the solution-annealed and aged condition can also be used at a maximum hardness of HRC 44 in the absence of elemental sulfur and subject to the other environmental limits shown for the maximum temperature of 204 °C (400 °F); d) wrought UNS N07022 shall have a maximum hardness of HRC 39 in the annealed and aged condition.						

**Table A.34 — Environmental and materials limits for precipitation-hardened nickel-based alloys
used for wellhead and christmas tree components (excluding bodies and bonnets) and valve and choke
components (excluding bodies and bonnets)**

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
N05500	See “Remarks” column	3.4 (0.5)	See “Remarks” column	≥4.5	NDS ^a	Any combination of temperature and chloride concentration occurring in production environments is acceptable.
For these applications, this material shall also conform with the following. Wrought UNS N05500 shall have a maximum hardness of 35 HRC and shall be either a) hot-worked and age-hardened, b) solution-annealed, or c) solution-annealed and age-hardened. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.35 — Environmental and materials limits for precipitation-hardened nickel-based alloys used as non-pressure containing internal valve, pressure regulator, and level controller components and miscellaneous equipment

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
Non-pressure-containing internal-valve, pressure-regulator, and level controller components						
N07750 N05500	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	Any combination of temperature, pH ₂ S, chloride concentration, and in situ pH occurring in production environments is acceptable.
Miscellaneous equipment						
N05500	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This alloy has been used in downhole running, setting and service tool applications for temporary service and in temporary surface service tool applications with the exceptions of bodies and bonnets. Environmental limits for this alloy for these applications have not been established.
For these applications, these materials shall also conform with the following: a) wrought UNS N07750 shall have a maximum hardness of 35 HRC and shall be either 1) solution-annealed and aged, 2) solution-annealed, 3) hot-worked, or 4) hot-worked and aged. b) wrought UNS N05500 shall have a maximum hardness of 35 HRC and shall be either 1) hot-worked and age-hardened, 2) solution-annealed, or 3) solution-annealed and age-hardened. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.36 — Environmental and materials limits for precipitation-hardened nickel-based alloys used as springs

Individual alloy UNS Number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
N07750	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This material has been used for these components without restriction on temperature, pH ₂ S, chloride concentration, or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters have led to field failures.
N07090	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This material has been used for these components without restriction on temperature, pH ₂ S, chloride concentration, or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.

For this application these materials shall also conform with the following:

- UNS N07750 springs shall be in the cold-worked and age-hardened condition and shall have a maximum hardness of 50 HRC;
- UNS N07090 can be used for springs for compressor valves in the cold-worked and age-hardened condition with a maximum hardness of 50 HRC.

^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.

Table A.37 — Environmental and materials limits for precipitation-hardened nickel-based alloys used in gas lift service

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
N05500	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	This material has been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.9.2 Welding of precipitation-hardened nickel-based alloys of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the base metal after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective metal for the weld alloy.

A.10 Cobalt-based alloys (identified as individual alloys)

A.10.1 Environmental and materials limits for the uses of cobalt-based alloys

Table A.38 — Environmental and materials limits for cobalt-based alloys used for any equipment or component

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
R30003 R30004 R30035 BS HR.3 R30605 R31233	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	Yes	Any combination of temperature, ρH ₂ S, chloride concentration, and <i>in situ</i> pH occurring in production environments is acceptable.

These materials shall also conform with the following:

a) alloys UNS R30003, UNS R30004, and BS HR.3 shall have a maximum hardness of 35 HRC;

b) UNS R30035 shall have a maximum hardness of 35 HRC except that it can have a maximum hardness of 51 HRC if it is in the cold-reduced and high-temperature aged heat-treated condition in accordance with the minimum time and the temperature of one of the following aging treatments:

Minimum time h	Temperature °C (°F)
4	704 (1,300)
4	732 (1,350)
6	774 (1,425)
4	788 (1,450)
2	802 (1,475)
1	816 (1,500)

c) wrought UNS R31233 shall be in the solution-annealed condition and shall have a maximum hardness of 22 HRC;

d) UNS R30605 shall have a maximum hardness of 35 HRC.

Table A.39 — Environmental and materials limits for cobalt-based alloys used as springs

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur- resistant?	Remarks
R30003 R30035	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	These materials have been used for these components without restriction on temperature, ρH ₂ S, Cl ⁻ , or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
For this application, these materials shall also conform with the following: — UNS R30003 shall be in the cold-worked and age-hardened condition and maximum 60 HRC; — UNS R30035 shall be in the cold-worked and age-hardened condition and maximum 55 HRC when aged for a minimum of 4 h at a temperature no lower than 649 °C (1 200 °F). ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

Table A.40 — Environmental and materials limits for cobalt-based alloys used as diaphragms, pressure measuring devices, pressure seals, and springs in spring-energized seals

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
R30003, R30004, R30260	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	Any combination of temperature, pH ₂ S, chloride concentration, and <i>in situ</i> pH occurring in production environments is acceptable.
R30159	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	NDS ^a	This material has been used for these components without restriction on temperature, pH ₂ S, Cl ⁻ , or <i>in situ</i> pH in production environments. No limits on individual parameters are set, but some combinations of the values of these parameters might not be acceptable.
For these applications, these materials shall also conform with the following: a) UNS R30003 and UNS R30004 shall have a maximum hardness of 60 HRC; Historically the cold worked and cold worked and age hardened conditions have been used. b) UNS R30260 shall have a maximum hardness of 52 HRC; c) wrought UNS R30159 for pressure seals shall have a maximum hardness of 53 HRC and the primary load-bearing or pressure-containing direction shall be parallel to the longitudinal or rolling direction of wrought product. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.10.2 Welding of cobalt-based alloys of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the base metal after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective metal for the weld alloy.

A.11 Titanium and tantalum (individual alloys)

A.11.1 Environmental and materials limits for the uses of titanium and tantalum alloys

Table A.41 — Environmental and materials limits for titanium used for any equipment or component

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S pH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
R50250 R50400 R56260 R53400 R56323 R56403 R56404 R58640	See "Remarks" column	See "Remarks" column	See "Remarks" column	See "Remarks" column	Yes	Any combination of temperature, pH ₂ S, chloride concentration, and <i>in situ</i> pH occurring in production environments is acceptable.
R55400	288 (550)	3 450 (500)	180 500	See "Remarks" column	Yes ^a	Any <i>in situ</i> production environment pH is acceptable for $p\text{CO}_2 + p\text{H}_2\text{S} \leq 7\,000$ kPa (1 000 psi)
These materials shall also conform with the following: a) UNS R50250 and R50400 shall have a maximum hardness of 100 HRB; b) UNS R56260 shall have a maximum hardness of 45 HRC and shall be in one of the three following conditions: 1) annealed; 2) solution-annealed; 3) solution-annealed and aged. c) UNS R53400 shall be in the annealed condition. Heat treatment shall be annealing at $(774 \pm 14)^\circ\text{C}$ [$(1\,425 \pm 25)^\circ\text{F}$] for 2 h followed by air-cooling. Maximum hardness shall be 92 HRB; d) UNS R56323 shall be in the annealed condition and shall have a maximum hardness of 32 HRC; e) wrought UNS R56403 shall be in the annealed condition and shall have a maximum hardness of 36 HRC; f) UNS R56404 shall be in the annealed condition and shall have a maximum hardness of 35 HRC; g) UNS R58640 shall have a maximum hardness of 42 HRC; h) UNS R55400 shall be used in the Solution-Treat plus Age (STA) condition, and have a maximum hardness of 41 HRC. ^a Sulfur resistant as tested in accordance with Group 1 as defined in NACE Conference paper 95047 and EFC 17, Appendix S1. Specific guidelines shall be followed for successful applications of each titanium alloy specified in this document. For example, hydrogen embrittlement of titanium alloys can occur if these alloys are galvanically coupled to certain active metals (e.g., carbon steel) in H₂S-containing aqueous media at temperatures greater than 80 °C (176 °F). Some titanium alloys can be susceptible to crevice corrosion and/or SSC in chloride environments. Hardness has not been shown to correlate with susceptibility to SSC/SCC. However, hardness has been included for alloys with high strength to indicate the maximum testing levels at which failure has not occurred.						

Table A.42 — Environmental and materials limits for tantalum used for any equipment or component

Individual alloy UNS number	Temperature max °C (°F)	Partial pressure H ₂ S ρH ₂ S max kPa (psi)	Chloride conc. max mg/l	pH	Sulfur-resistant?	Remarks
R05200	See “Remarks” column	See “Remarks” column	See “Remarks” column	See “Remarks” column	NDS ^a	Any combination of temperature, ρH ₂ S, chloride concentration, and <i>in situ</i> pH occurring in production environments are acceptable.
UNS R05200 shall have a maximum hardness of 55 HRB and shall be either — annealed, or — gas tungsten arc-welded and annealed. ^a No data submitted to ascertain whether these materials are acceptable for service in the presence of elemental sulfur in the environment.						

A.11.2 Welding of titanium and tantalum alloys of this materials group

The requirements for the cracking-resistance properties of welds shall apply (see [6.2.2](#)).

The hardness of the base metal after welding shall not exceed the maximum hardness allowed for the base metal and the hardness of the weld metal shall not exceed the maximum hardness limit of the respective metal for the weld alloy.

A.12 Copper- and aluminum-based alloys (identified as materials types)

A.12.1 Copper-based alloys

Copper-based alloys have been used without restriction on temperature, ρH₂S, Cl⁻, or *in situ* pH in production environments.

NOTE 1 Copper-based alloys can undergo accelerated mass loss corrosion (weight loss corrosion) in sour oil field environments, particularly if oxygen is present.

NOTE 2 Some copper-based alloys have shown sensitivity to GHSC.

A.11.2 Aluminum-based alloys

These materials have been used without restriction on temperature, ρH₂S, Cl⁻, or *in situ* pH in production environments.

The user should be aware that mass loss corrosion (weight loss corrosion) of aluminum-based alloys is strongly dependent on environmental pH.

A.13 Cladding, overlays, and wear-resistant alloys

A.13.1 Corrosion-resistant claddings and linings

The materials listed and defined in [A.2 to A.11](#) can be used as corrosion-resistant claddings and linings.

Unless the user can demonstrate and document the likely long-term in-service integrity of the cladding or lining as a protective layer, the base material, after application of the cladding or lining, shall conform with ANSI/NACE MR0175/ISO 15156-2 or this document, as applicable.

This may involve the application of heat or stress-relief treatments that can affect the cladding or lining properties.

Factors that can affect the long-term in-service integrity of a cladding or lining include environmental cracking under the intended service conditions, the effects of other corrosion mechanisms, and mechanical damage.

A.13.2 Corrosion-resistant weld overlays

The materials listed and defined in [A.2 to A.11](#) can be used as corrosion-resistant weld overlay consumables.

Unless the user can demonstrate and document the likely long-term in-service integrity of the weld overlay as a protective layer, the base material, after application of the weld overlay, shall conform with ANSI/NACE MR0175/ISO 15156-2 or this document, as applicable. This may involve the application of heat or stress-relief treatments that can affect the weld overlay properties.

Factors that can affect the long-term in-service integrity of a weld overlay include environmental cracking under the intended service conditions, the effects of other corrosion mechanisms and mechanical damage.

Dilution of a weld-overlay that occurs during application can impact on its corrosion resistance or mechanical properties and shall be considered.

The chemical composition limits of a corrosion-resistant overlay at the minimum qualified thickness shall be as specified in the two following paragraphs. For reference, ASME BPVC Section IX^[1] and ISO 15614-7^[2] provide a methodology for establishing the minimum qualified overlay thickness.

For UNS N06625 overlays applied using UNS N06625 type filler metals (i.e., AWS classification ERNiCrMo-3), the composition of the overlays at the minimum qualified thickness shall be controlled by limiting the iron composition to 5 % or 10 % maximum (by weight). The end user may specify either 5 % or 10 % maximum iron, based on their needs for a specific application or field.

For other alloys, the chemical composition limits of a corrosion-resistant overlay, at the minimum overlay thickness, shall meet the requirements agreed to between the equipment manufacturer and the equipment user.

A.13.3 Wear-resistant alloys

A.13.3.1 Wear-resistant alloys used for sintered, cast, or wrought components

Environmental cracking resistance of alloys specifically designed to provide wear-resistant components is not specified in ANSI/NACE MR0175/ISO 15156 (all parts). No production limits for temperature, $\rho\text{H}_2\text{S}$, Cl^- , or *in situ* pH have been established.

Some materials used for wear-resistant applications can be brittle. Environmental cracking can occur if these materials are subject to tension. Components made from these materials are normally loaded only in compression.

A.13.3.2 Hard-facing materials

Hard facing may be used.

Environmental cracking resistance of alloys or surface layers specifically designed to provide hard facing is not specified in ANSI/NACE MR0175/ISO 15156 (all parts). No production limits for temperature, $\rho\text{H}_2\text{S}$, Cl^- , or *in situ* pH have been established.

Some materials used for hard-facing applications can be brittle. Environmental cracking of the hard facing can occur if these materials are subjected to tension.

Unless the user can demonstrate and document the likely long-term in-service integrity of the hard-facing materials, the base material after application of the hard-facing material shall conform with ANSI/NACE MR0175/ISO 15156-2 or this document, as applicable.

Annex B (normative)

Qualification of CRAs for H₂S-service by laboratory testing

B.1 General

This annex specifies minimum requirements for qualifying CRAs for H₂S service by laboratory testing. Requirements are given for qualifying resistance to the following cracking mechanisms:

- SSC at ambient temperature;
- SCC at maximum service temperature in the absence of elemental sulfur, S⁰;
- HSC of CRAs when galvanically coupled to carbon or low alloy steel, i.e., GHSC.

Supplementary requirements concern

- a) testing at intermediate temperatures when the distinction between SSC and SCC is unclear, and
- b) SCC testing in the presence of S⁰.

Guidance on the potential for corrosion to cause cracking of CRAs is given in [Table B.1](#). The alloy groups are the same as those used in [Annex A](#).

The test requirements of this annex do not address the possible consequences of sequential exposure to different environments. For example, the consequence of cooling after hydrogen uptake at a higher temperature is not evaluated.

Table B.1 — Cracking mechanisms that shall be considered for CRA and other alloy groups

Materials groups of Annex A	Potential cracking mechanisms in H ₂ S service ^{a, b}			Remarks
	SSC	SCC	GHSC	
Austenitic stainless steels (see A.2)	S	P	S	Some cold-worked alloys contain martensite and can therefore be sensitive to SSC and/or HSC.
Highly-alloyed austenitic stainless steels (see A.3)	—	P	—	These alloys are generally immune to SSC and HSC. Low-temperature cracking tests are not normally required.
Solid-solution nickel-based alloys (see A.4)	S	P	S	Some Ni-based alloys in the cold-worked condition and/ or aged conditions contain secondary phases and can be susceptible to HSC when galvanically coupled to steel. In the heavily cold-worked and well-aged condition coupled to steel, these alloys can experience HSC.
Ferritic stainless steels (see A.5)	P	—	P	—
Martensitic stainless steels (see A.6)	P	S	P	Alloys containing Ni and Mo can be subject to SCC whether or not they contain residual austenite.
Duplex stainless steels (see A.7)	S	P	S	Cracking sensitivity can be highest at a temperature below the maximum service temperature and testing over a range of temperatures shall be considered.
Precipitation-hardened stainless steels (see A.8)	P	P	P	—
Precipitation-hardened nickel base alloys (see A.9)	S	P	P	Some Ni-based alloys in the cold-worked condition and/ or aged conditions contain secondary phases and can be susceptible to HSC when galvanically coupled to steel.
Cobalt-based alloys (see A.10)	S	P	P	—
Titanium and tantalum (see A.11)	See “Remarks” column			Cracking mechanisms depend upon the specific alloy. The equipment user shall ensure appropriate testing and qualification is carried out.
Copper and aluminum (see A.12)	See “Remarks” column			These alloys are not known to suffer from these cracking mechanisms

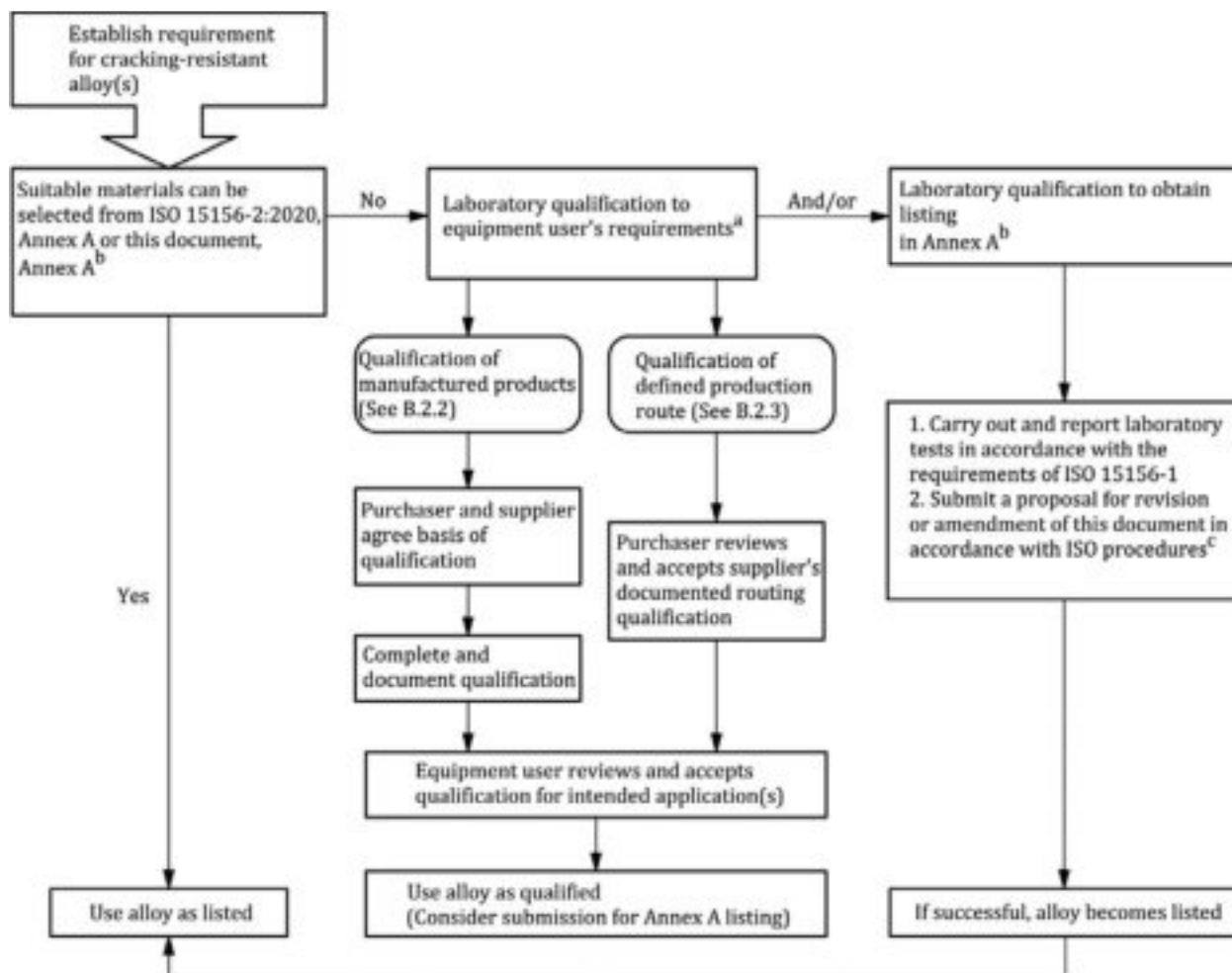
^a P indicates primary cracking mechanism.

^b S indicates secondary, possible, cracking mechanism.

B.2 Uses of laboratory qualifications

B.2.1 General

An overview of the uses of laboratory qualifications is given in [Figure B.1](#).



^a This document addresses SSC, SCC, and GHSC of CRAs and other alloys. ISO 15156-2 addresses SSC, HIC, SOHIC, and SZC of carbon and low alloy steels.

^b [Annex A](#) addresses SSC, SCC, and GHSC of CRAs and other alloys. ISO 15156-2:2020, [Annex A](#) addresses SSC of carbon and low alloy steels.

^c See final paragraphs of “Introduction” for further information regarding document maintenance.

NOTE Flowchart omits qualification by field experience as described in ANSI/NACE MR0175/ISO 15156-1.

Figure B.1 — Alternatives for alloy selection and laboratory qualification

B.2.2 Qualification of manufactured products

The user of this document shall define the qualification requirements for the material in accordance with ANSI/NACE MR0175/ISO 15156-1 and [Annex B](#).

This definition shall include the application of the following:

- a) general requirements (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 5);

- b) evaluation and definition of service conditions (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 6);
- c) material description and documentation (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.1);
- d) requirements for qualification based upon laboratory testing (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.3);
- e) report of the method of qualification (see ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 9).

Appropriate “test batches” and sampling requirements shall be defined having regard to the nature of the product, the method of manufacture, testing required by the manufacturing specification, and the required qualification(s) (see [Table B.1](#)).

Samples shall be tested in accordance with this annex, i.e., [Annex B](#), for each cracking mechanism to be qualified. A minimum of three specimens shall be tested per test batch. The test batch shall be qualified if all specimens satisfy the test acceptance criteria.

Retesting is permitted in accordance with the following. If a single specimen fails to meet the acceptance criteria, the cause shall be investigated. If the source material conforms to the manufacturing specification, two further specimens may be tested. These shall be taken from the same source as the failed specimen. If both satisfy the acceptance criteria, the test batch shall be considered qualified. Further retests shall require the purchaser’s agreement.

Testing of manufactured products may be carried out at any time after manufacture and before exposure to H₂S service.

Before the products are placed in H₂S service, the equipment user shall review the qualification and verify that it satisfies the defined qualification requirements. Products with a qualification that has been verified by the equipment user may be placed into H₂S service.

B.2.3 Qualification of a defined production route

A defined production route may be qualified for the production of qualified material.

A qualified production route may be followed to avoid order release testing for H₂S cracking resistance.

A materials supplier may propose to a materials purchaser that a qualified production route be used to produce qualified materials. The qualified production route may be used if the materials supplier and materials purchaser agree to its use.

A qualified production route may be used to produce qualified material for more than one materials user.

To qualify a production route, the material supplier shall demonstrate that a defined production route is capable of consistently manufacturing material that satisfies the applicable qualification test requirements of this annex.

The qualification of a production route requires all of the following:

- a) definition of the production route in a written quality plan that identifies the manufacturing location(s), all manufacturing operations, and the manufacturing controls required to maintain the qualification;
- b) initial testing of products produced on the defined production route in accordance with [B.2.2](#) and verifying they satisfy the acceptance criteria;

- c) periodic testing to confirm that the product continues to have the required resistance to cracking in H₂S service. The frequency of "periodic" testing shall also be defined in the quality plan and shall be acceptable to the purchaser. A record of such tests shall be available to the purchaser;
- d) retaining and collating the reports of these tests and making them available to material purchasers and/or equipment users.

A material purchaser may agree additional quality control requirements with the manufacturer.

The accuracy of the quality plan may be verified by site inspection by an interested party.

Changes to a production route that fall outside the limits of its written quality plan require qualification of a new route in accordance with a), b), c), and d) above.

B.2.4 Use of laboratory testing as a basis for proposing additions and changes to [Annex A](#)

Changes to [Annex A](#) may be proposed (see Introduction). Proposals for changes shall be documented in accordance with ANSI/NACE MR0175/ISO 15156-1. They shall also be subject to the following additional requirements.

Representative samples of CRAs and other alloys for qualification by laboratory testing shall be selected in accordance with ANSI/NACE MR0175/ISO 15156-1.

Material representing a minimum of three separately processed heats shall be tested for resistance to cracking in accordance with B.3. Test requirements shall be established by reference to the appropriate materials group in [Table B.1](#).

Tests shall be performed for the primary cracking mechanisms listed in [Table B.1](#).

Tests shall also be performed for the secondary cracking mechanisms listed in [Table B.1](#); otherwise, the justification for their omission shall be included in the test report.

For other alloys not covered by [Table B.1](#), the choice of qualification tests used shall be justified and documented.

Sufficient data shall be provided to allow the members of ISO/TC 67 to assess the material and decide on the suitability of the material for inclusion into this document, by amendment or revision, in accordance with the ANSI/NACE MR0175/ISO 15156 series maintenance process as described in the introduction.

B.3 General requirements for tests

B.3.1 Test method descriptions

The test requirements are based on NACE TM0177 and EFC Publication 17. These publications shall be consulted for details of test procedures. When necessary, suppliers, purchasers, and equipment users may agree variations to these procedures. Such variations shall be documented.

B.3.2 Materials

The materials tested shall be selected in accordance with the requirements found in ANSI/NACE MR0175-2021/ISO 15156-1:2020, 8.3.2.

In addition, consideration shall be given to the following:

- a) the cracking mechanism for which testing is required (see [Table B.1](#));

- b) the testing of appropriately aged samples of alloys that can age in service, particularly HSC testing of downhole materials that can be subject to aging in service ("well aging");
- c) the directional properties of alloys because cold-worked alloys may be anisotropic with respect to yield strength and for some alloys and products, the susceptibility to cracking varies with the direction of the applied tensile stress and consequent orientation of the crack plane.

B.3.3 Test methods and specimens

Primary test methods use constant load, sustained load (proof-ring), or constant total strain (constant displacement) loading of smooth test specimens.

Uniaxial tensile (UT) tests, four-point bend (FPB) tests, and C-ring (CR) tests may be performed with the above loading arrangements.

Generally, constant load tests using UT specimens are the preferred method of testing homogeneous materials.

Test specimens shall be selected to suit the product form being tested and the required direction of the applied stress. A minimum of three specimens shall be taken from each component tested.

UT specimens may be taken from welded joints in accordance with EFC Publication Number 17, Figure 8.1. Other specimens taken from welded joints may be tested with weld profiles as intended for service.

When double (back-to-back) FPB specimens are used (in accordance with EFC Publication Number 17, Figure 8.2a, or similar), uncracked specimens shall be disqualified as invalid if the opposing specimen cracks.

Alternative test methods or specimens may be used when appropriate. The basis and use of such tests shall be documented and agreed with the equipment user.

Examples of test methods that may be considered are as follows.

- Fracture mechanics tests, e.g., double cantilever beam (DCB) tests, may be used if cracks are unaffected by branching and remain in the required plane. This normally limits DCB tests to SSC and HSC tests.
- Tests involving the application of a slow strain rate, e.g., SSRT in accordance with NACE TM0198^[23], interrupted SSRT in accordance with ISO 7539-7^[21] or RSRT in accordance with the method published as NACE CORROSION/97 Paper 58^[22].

Tests may utilize testing of full-size or simulated components when appropriate.

B.3.4 Applied test stresses/loads for smooth specimens

The yield strengths of CRAs used to derive test stresses shall be determined at the test temperature in accordance with the applicable manufacturing specification. In the absence of an appropriate definition of yield strength in the manufacturing specification, the yield strength shall be taken to mean the 0.2 % proof stress of non-proportional elongation $R_{p0.2}$ as defined in ISO 6892-1 determined at the test temperature.

Directional properties shall be considered when selecting test specimens and defining test stresses.

For welded specimens, the parent metal yield strength shall normally be used to determine test stresses. For dissimilar joints, the lower parent metal yield strength shall normally be used. When

design stresses are based on the yield strength of a weld zone that is lower than the yield strength of either adjoining parent metals, the yield strength of the weld zone may be used to determine test stresses.

For constant-load tests and sustained-load (proof-ring) tests, specimens shall be loaded to 90 % of the AYS of the test material at the test temperature.

For constant total strain (deflection) tests, specimens shall be loaded to 100 % of the AYS of the test material at the test temperature.

NOTE Constant total strain (deflection) tests might not be suitable for materials that can relax by creep when under load.

Lower applied stresses can be appropriate for qualifying materials for specific applications. The use and basis of such tests shall be agreed with the purchaser and documented.

B.3.5 SSC/SCC test environments

B.3.5.1 General

The following environmental test variables shall be controlled and recorded:

- $\rho\text{H}_2\text{S}$;
- ρCO_2 ;
- temperature;
- test solution pH, the means of acidification, and pH control (all pH measurements shall be recorded);
- test solution formulation or analysis;
- elemental sulfur, S^0 , additions;
- galvanic coupling of dissimilar metals (the area ratio and coupled alloy type shall be recorded).

In all cases, the $\rho\text{H}_2\text{S}$, chloride, and S^0 concentrations shall be at least as severe as those of the intended application. The maximum pH reached during testing shall be no greater than the pH of the intended application.

It can be necessary to use more than one test environment to achieve qualification for a particular service.

The following test environments may be used either to simulate intended service conditions or to simulate a nominated condition when intended applications are insufficiently defined.

Use can be made of nominated test conditions to provide information on the environmental limits within which a CRA or other alloy is resistant to cracking if no specific application is foreseen.

Table D.1 may be used to define the test environments for the standard tests for SSC and GHSC (identified as level II and level III, respectively). For type 1 environments (see [B.3.5.2](#)), [Table D.1](#) also provides a number of nominated sets of conditions (for temperature, ρCO_2 , $\rho\text{H}_2\text{S}$, and chloride concentration) that may be considered. These are identified as levels IV, V, VI, and VII.

When using nominated test conditions, all other requirements of this annex shall be met.

NOTE 1 The nominated sets of conditions are not intended to limit the freedom of the document user to test using other test conditions of their choice.

The equipment user should be aware that oxygen contamination of the service environment can influence the cracking resistance of an alloy and should be considered when choosing the test environment.

NOTE 2 Reference [15] gives information on the charging of autoclaves.

B.3.5.2 Service simulation at actual H₂S and CO₂ partial pressures — Type 1 environments

In these test environments, the service (in situ) pH is replicated by controlling the parameters that determine pH under field conditions. Test environments shall be established in accordance with the following requirements:

- a) test limits: the pressure shall be ambient or greater;
- b) test solution: synthetic produced water that simulates the chloride and bicarbonate concentrations of the intended service. The inclusion of other ions is optional;
- c) test gas: H₂S and CO₂ at the same partial pressures as the intended service;
- d) pH measurement: pH is determined by reproduction of the intended service conditions. The solution pH shall be determined at ambient temperature and pressure under the test gas or pure CO₂ immediately before and after the test. This is to identify changes in the solution that influence the test pH. Any pH change detected at ambient temperature and pressure is indicative of a change at the test temperature and pressure.

B.3.5.3 Service simulation at ambient pressure with natural buffering agent — Type 2 environments

In these test environments, the service (in situ) pH is replicated by adjusting the buffer capacity of the test solution using a natural buffer to compensate for the reduced pressure of acid gases in the test. Test environments shall be established in accordance with the following requirements:

- a) test limits: the pressure shall be ambient, temperature shall be maximum 60 °C and pH shall be 4.5 or greater;
- b) test solution: distilled or de-ionized water with sodium bicarbonate (NaHCO₃) added to achieve the required pH. Chloride shall be added at the concentration of the intended service. If necessary, a liquid reflux shall be provided to prevent loss of water from the solution;
- c) test gas: H₂S at the partial pressure of the intended service and CO₂ as the balance of the test gas. The test gas shall be continuously bubbled through the test solution;
- d) pH control: the solution pH shall be measured at the start of the test, periodically during the test and at the end of the test, adjusting as necessary by adding HCl or NaOH. The variation of the test pH shall not exceed ±0.2 pH units.

B.3.5.3 Service simulation at ambient pressure with acetic buffer —
Type 3a and Type 3b environments

In these test environments, the service (in situ) pH is replicated by adjusting the buffer capacity of the test solution using an artificial buffer and adding HCl to compensate for the reduced pressure of acid gases in the test. Test environments shall be established in accordance with the following requirements:

- a) test limits: the pressure shall be ambient, the temperature shall be $(24 \pm 3) ^\circ\text{C}$;
- b) test solution: one of the following test solutions shall be used:
 - 1) for general use (environment 3a), distilled or de-ionized water containing 4 g/l sodium acetate and chloride at the same concentration as the intended service;
 - 2) for super-martensitic stainless steels prone to corrosion in solution for environment 3a (environment 3b), de-ionized water containing 0.4 g/l sodium acetate and chloride at the same concentration as the intended service.

HCl shall be added to both solutions to achieve the required pH;

- c) test gas: H_2S at the partial pressure of the intended service and CO_2 as the balance of the test gas. The test gas shall be continuously bubbled through the test solution;
- d) pH control: the solution pH shall be measured at the start of the test, periodically during the test and at the end of the test, adjusting as necessary by adding of HCl or NaOH. The variation of the test pH shall not exceed ± 0.2 pH units.

B.3.6 Test duration

Constant-load, sustained-load, and constant-total-strain tests shall have a minimum duration of 720 h. Tests shall not be interrupted.

B.3.7 Acceptance criteria and test report

Specimens exposed in constant-load, sustained-load, and constant-total-strain tests shall be assessed in accordance with NACE TM0177:2016, test methods A, and C. No cracks are permissible.

Specimens exposed in fracture mechanics and slow strain rate tests shall be assessed as required by the test method. Fracture toughness values shall only be valid for substantially unbranched cracks. Acceptance criteria for fracture toughness tests shall be specified by the equipment user.

In all cases, any indication of corrosion causing metal loss including pitting or crevice corrosion shall be reported.

NOTE The occurrence of pitting or crevice corrosion outside the stressed section of a specimen can suppress SCC of the specimen.

A written test report conforming to the requirements in ANSI/NACE MR0175-2021/ISO 15156-1:2020, Clause 9, shall be completed and retained.

B.3.8 Validity of tests

Satisfactory test results qualify materials for environmental conditions that are less severe than the test environment. Users shall determine the validity of tests for individual applications. Environmental severity is decreased by the following at any given temperature:

- a lower $\rho\text{H}_2\text{S}$;
- a lower chloride concentration;
- a higher pH;
- the absence of S^0 .

B.4 SSC testing

Tests shall be performed in accordance with the general requirements for tests given in [B.3](#).

Tests shall normally be performed at $(24 \pm 3)^\circ\text{C}$ [$(75 \pm 5)^\circ\text{F}$] in accordance with NACE TM0177 and/or EFC Publication 17.

The test temperature may be at the lowest service temperature if this is above 24°C (75°F). The use of a test temperature above 24°C shall be justified in the test report.

B.5 SCC testing without S^0

Tests shall be performed in accordance with the general requirements of [B.3](#).

SCC testing procedures shall be based on NACE TM0177 and/or EFC Publication 17 subject to the following additional requirements, options, and clarifications:

- a) the test temperature shall not be less than the maximum intended service temperature. This can require the use of a pressurized test cell;
- b) water vapor pressure shall be allowed for in determining gas-phase partial pressures;
- c) acetic acid and acetates shall not be used for pH control. The solution pH shall be controlled as described in [B.3.5.2](#);
- d) during initial exposure of specimens to the test environment, the applied load and the environmental conditions shall be controlled so that all test conditions are already established when the test temperature is first attained;
- e) for constant-total-strain tests, applied stresses shall be verified by measurement;

NOTE It is good practice to verify the deflection calculations in many CRA material specifications.

- f) loading procedures used for constant-total-strain tests shall be shown to achieve a stable stress before specimens are exposed to the test environment.

B.6 SSC/SCC testing at intermediate temperatures

Testing at intermediate temperatures, i.e., between $(24 \pm 3)^\circ\text{C}$ [$(75 \pm 5)^\circ\text{F}$] and the maximum intended service temperature, shall meet the requirements of the equipment user. Testing shall be performed at the specified temperature in accordance with the above requirements for SCC testing.

For qualification for inclusion by amendment in [A.7](#), duplex stainless steels shall be tested at $(24 \pm 3)^\circ\text{C}$

$[(75 \pm 5) ^\circ\text{F}]$, $(90 \pm 3) ^\circ\text{C}$ $[(194 \pm 5) ^\circ\text{F}]$, and at the maximum intended service temperature of the alloy.

B.7 SCC testing in the presence of S^0

Tests shall be performed in accordance with the previous requirements for SCC tests with the addition that the procedure published in NACE CORROSION/95 Paper 47 shall be implemented for control of S^0 additions. The integration of this procedure into CRA test methods is addressed in EFC Publication 17.

B.8 GHSC testing with carbon steel couple

GHSC tests shall be performed in accordance with the previously stated requirements for SSC testing, subject to the following additional requirements, options, and clarifications:

- a) the CRA specimen shall be electrically coupled to unalloyed (i.e., carbon) steel that is fully immersed in the test solution. The ratio of the area of the unalloyed steel to the wetted area of the CRA specimen shall be between 0.5 and 1 as required by NACE TM0177. Loading fixtures shall be electrically isolated from the specimen and the coupled steel. For application-specific qualifications, the CRA may be coupled to a sample of the lower alloyed material to which it will be coupled in service.
- b) the test environment shall be NACE TM0177, Solution A under H_2S at a pressure of 100 kPa and at a temperature of $(24 \pm 3) ^\circ\text{C}$ $[(75 \pm 5) ^\circ\text{F}]$. For application-specific qualifications, SSC test environments described in B.3.5 may be used.

Annex C (informative)

Information that should be supplied for material purchasing

ANSI/NACE MR0175/ISO 15156-1 indicates that cooperation and exchange of information can be necessary between the various users of this document, e.g., equipment users, purchasers and manufacturers of equipment, purchasers of materials, and manufacturers and suppliers of materials. The following tables can be used to assist this cooperation.

The materials purchaser should indicate the required options in Table C.1 and [Table C.2](#).

Table C.1 and [Table C.2](#) also suggest designations that may be included in markings of materials to show conformance of individual CRAs or other alloys with this document.

The purchase order details should form part of a material's documentation to ensure its traceability. Where selection of materials is based upon laboratory testing in accordance with [Annex B](#), traceability documentation should also include the details of the conditions derived from [Table C.2](#) that were applied during testing.

Table C.1 — Information for material purchase and marking

Materials selection options and other information		Materials purchaser's requirements	Reference in this document	Remarks	Sour service designation for marking
Preferred CRA or other alloy and condition ^a		^b	—	—	—
Equipment type		^c	—	—	—
Method of selection/qualification	CRA or other alloy selected from Annex A ?	Option A ^d	6.1	Service exposure conditions as shown in Table C.2 (optional)	A.nn ^e
	CRA or other alloy qualified in accordance with Annex B ?	Option B ^d	6.1, Annex B	See also Table C.2	B, B1, B2, etc. ^e
	Either of the above methods of selection/qualification	Option C ^d	See option A and option B	See option A and option B	See option A and option B

^a For use when a purchaser requires a known material that is either listed in Annex A or qualified in accordance with Annex B. The purchaser should indicate the method of qualification below.

^b User may insert material type and condition.

^c User may insert equipment type for which material is required.

^d Indicate which option is required.

^e A suggested scheme for designation of listed CRAs to be included in markings of materials is for manufacturers/suppliers to indicate conformance of individual CRAs or other alloys by reference to the materials group clause number, e.g., A.2. For materials qualified to Annex B, the suggested designations are B, B1, B2, B3 (see Table C.2).

Table C.2 — Additional information for SSC, SCC, and GHSC testing and suggested marking

Cracking qualification test		Materials purchaser's requirements for cracking resistance and service exposure	Reference in this document	Remarks	Sour service designation for marking ^b
Resistance to SSC		Option 1 ^{a,c}	B.4	—	B1
Resistance to SCC		Option 2 ^{a,c}	B.5 to B.7	—	B2
Resistance to GHSC		Option 3 ^{a,c}	B.8	—	B3
Resistance to SSC, SCC, and GHSC		Option 4 ^{a,c}	B.4 to B.8	—	B
Description of service conditions documented in accordance with ISO ANSI/NACE MR0175/15156 1	CO ₂ pressure, kPa	—	B.3	—	—
	H ₂ S pressure, kPa	—		—	
	Temperature, °C	—		—	
	In situ pH	—		—	
	Cl ⁻ or other halide, mg/l	—		—	
	S ⁰	Present or absent ^a		—	
Laboratory test requirements		—	B.3	—	—
Non-standard test stress, % AYS		—		—	
Specimen type		—		—	

^a Indicate which option(s) is (are) required.

^b For materials qualified to [Annex B](#), the suggested designations for marking are B, B1, B2, and B3 where B1 is SSC, B2 is SCC, B3 is GHSC, and B indicates that the material has been shown to be resistant to all three cracking mechanisms.

^c Test conditions to be appropriate to the service conditions shown in this table (see also [B.2](#) and [B.3](#)).

Annex D (informative)

Nominated sets of test conditions

The nominated sets of test conditions shown in Table D.1 can be used to help determine acceptable limits for the application of CRAs and other alloys.

The “levels” shown in the table were previously established in NACE MR0175. These are retained to provide continuity of terminology with that of the data set on which many of the environmental limits for materials types and individual alloys shown in the tables of Annex A are based.

Table D.1 — Test conditions

Environmental factor	Specific test conditions						
	Level I	Level II	Level III	Level IV	Level V	Level VI	Level VII
Temperature °C (°F)	25 ± 3 (77 ± 5)	Test in accordance with B.4	Test in accordance with B.4 and B.8	90 ± 5 (194 ± 9)	150 ± 5 (302 ± 9)	175 ± 5 (347 ± 9)	205 ± 5 (401 ± 9)
ρCO_2 MPa (psi)	Test conditions defined and documented by the user			0.7 (100)	1.4 (200)	3.5 (500)	3.5 (500)
$\rho\text{H}_2\text{S}$ MPa (psi)				0.003 (0.4)	0.7 (100)	3.5 (500)	3.5 (500)
NaCl minimum percentage mass fraction				15	15	20	25
Calculated Cl ^a milligrams per liter				101 000	101 000	139 000	180 000
pH				See B.3.5.1 and B.3.5.2			
S ⁰				Optional (see B.7)			
Galvanic coupling to steel				Optional; see Clause B.8			
Other				See B.3.5.1			

^a The equivalent mg/l concentration for ambient temperature used in [Tables A.1 to A.42](#) was calculated from the corresponding percentage mass fraction value^[18].

Bibliography

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- [2] ISO 15614-7, *Specification and qualification of welding procedures for metallic materials — Welding procedure test — Part 7: Overlay welding*
- [3] ISO 13680, *Petroleum and natural gas industries — Corrosion-resistant alloy seamless tubes for use as casing, tubing and coupling stock — Technical delivery conditions*
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- [5] ASTM A182/A182M, *Standard Specification for Forged or Rolled alloy and steel pipe flanges, forged fittings, and valves and parts for high-temperature service*
- [6] ASTM A213/A213M, *Standard specification for seamless ferritic and austenitic alloy-steel boiler, superheater, and heat-exchanger tubes*
- [7] ASTM A276, *Standard Specification for Stainless Steel Bars and Shapes*
- [8] ASTM A351/A351M, *Standard Specification for Castings, Austenitic, for Pressure-Containing Parts*
- [9] ASTM A743/A743M, *Standard Specification for Castings, Iron-Chromium, Iron-Chromium-Nickel, Corrosion Resistant, for General Application*
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- [13] EFC Publication 16, *Guidelines on materials requirements for carbon and low alloy steels for H₂S-containing environments in oil and gas production*
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- [16] NACE TM0284, *Evaluation of Pipeline and Pressure Vessel Steels for Resistance to Hydrogen Induced Cracking*
- [17] *ASM Materials Engineering Dictionary*
- [18] ASTM E18, *Standard Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials*
- [19] ASTM E384, *Standard Test Method for Knoop and Vickers Hardness of Materials*
- [20] CRC Handbook of Chemistry and Physics⁷
- [21] ISO 7539-7, *Corrosion of metals and alloys — Stress corrosion testing — Part 7: Method for slow strain rate testing*
- [22] NACE CORROSION/97 Paper 58, *Rippled strain rate test for CRA sour service materials selection*
- [23] NACE TM0198, *Slow Strain Rate Test Method for Screening Corrosion Resistant Alloys (CRAs) for Stress Corrosion Cracking in Sour Oilfield Service*
- [24] the ISO 15156 series maintenance website, <http://www.iso.org/iso15156maintenance>

⁵ ASME, Two Park Ave., New York, NY 10016-5990, www.asme.org.

⁶ British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, UK, www.bsigroup.com.

⁷ Available from CRC online.