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Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments

ABSTRACT

This standard establishes guidelines to prevent most forms of environmental cracking of weldments in carbon steel refinery equipment, including pressure vessels, heat exchangers, piping, valve bodies, and pump and compressor cases. Weldments are defined to include the weld deposit, base metal HAZ, and adjacent base metal zones subject to residual stresses from welding. It defines standard practices for producing weldments in P-No. 1 steels resistant to environmental cracking in corrosive petroleum refining environments. This standard is maintained by Task Group 326.

KEYWORDS

Environmental cracking, refinery, pressure vessels, heat excahngers, piping, valve bodies, pump cases, compressor cases

Foreword

This NACE standard defines standard practices for producing weldments in P-No. 1 steels resistant to environmental cracking in corrosive petroleum refining environments. It is intended to be used by refiners, equipment manufacturers, engineering contractors, and construction contractors.

Most petroleum refining equipment are constructed from carbon steel having a minimum specified tensile strength of 485 MPa (70,000 psi) or less, and in almost every case, the equipment is fabricated by welding. The welds for refinery equipment are made to conform to various codes and standards, including the ASME[(1)] Boiler and Pressure Vessel Code, Section VIII[1] for pressure vessels, ASME/ANSI[(2)] B31.3[2] for process piping, or API[(3)] Standards 620[3] and 650[4] for tanks. According to these codes and standards, these carbon steels are classified as P-No. 1, Group 1 or 2, and in this standard, they are referred to as P-No. 1 steels.

Petroleum refineries as well as oil- and gas-processing plants have predominantly used P-No. 1 steels for services containing wet hydrogen sulfide (H_2S), or sour services. They are the basic materials of construction for pressure vessels, heat exchangers, storage tanks, and piping. Decades of successful service have shown them to be generally resistant to a form of hydrogen stress cracking (HSC) called sulfide stress cracking (SSC). HSC occurs in high-strength materials or zones of a hard or high-strength microstructure in an otherwise soft material. With commonly used fabrication methods, P-No. 1 steels should be below the strength threshold for this cracking.

NACE Standard MR0103[5] provides guidance for materials in sour oil and gas environments in refinery services, including limiting the hardness of P-No. 1 steels and reducing the likelihood of SSC. NACE MR0175/ISO 15156[6] provides additional guidance for materials in sour oil and gas environments in production services.

In the late 1960s, a number of SSC failures occurred in hard weld deposits in P-No. 1 steel refinery equipment. To detect hard weld deposits caused by improper welding filler metals or procedures, the petroleum refining industry began requiring hardness testing of production weld deposits under certain conditions and applied a criterion of 200 Brinell hardness (HBW) maximum. These requirements were given in previous editions of this standard and in API RP 942.[7]

In the late 1980s, instances of heat-affected zone (HAZ) cracking were reported in P-No. 1 steel equipment that met the 200 HBW weld deposit hardness limit. Some cases were determined to be SSC that was caused by high hardness in the HAZ. Some were identified as another form of hydrogen damage called stress-oriented hydrogen-induced cracking (SOHIC).[8] These cracks propagated primarily in the HAZs of weldments and were found in both high- and low-hardness HAZs. Other HAZ cracking instances in specific corrosive refinery process environments were attributed to alkaline stress corrosion cracking (ASCC), which can occur as a result of high residual stress levels.

HAZ hardness controls and reduction of residual stresses in weldments were outside the scope of early editions of this standard, which covered only weld deposit hardness limits. The 1995 revision of this standard was expanded to cover the entire weldment and the various in-service cracking mechanisms (HSC in the weld deposit, HSC in the weld HAZ, and ASCC) that can occur in corrosive petroleum refining environments.

[(1)] ASME International (ASME), Two Park Avenue, New York, NY 10016-5990.
[(2)] American National Standards Institute (ANSI), 25 West 43rd St., 4th Floor, New York, NY 10036.
[(3)] American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005-4070.

This standard was originally prepared in 1972 by NACE Task Group (TG) T-8-7, which was composed of corrosion consultants, corrosion engineers, and other specialists associated with the petroleum refining industry. It was reaffirmed in 1974 and revised in 1987 and 1995. It was reaffirmed in 2000 by Specific Technology Group (STG) 34, "Petroleum Refining and Gas Processing," and revised in 2005, 2008, 2010, and 2015, as well as reaffirmed in 2020 by TG 326, "Weldments, Carbon Steel: Prevention of Environmental Cracking in Refining Environments." API previously published a standard, API RP 942, with similar objectives. The API standard has been discontinued with the intention of recognizing this NACE standard as the industry consensus standard. This standard is issued by NACE International under the auspices of STG 34.

> In NACE standards, the terms ***shall, must, should,*** and ***may*** are used in accordance with the definitions of these terms in the NACE Publications Style Manual. The terms ***shall*** and ***must*** are used to state a requirement, and are considered mandatory. The term ***should*** is used to state something good and is recommended, but is not considered mandatory. The term ***may*** is used to state something considered optional.

Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments

FIGURES AND TABLES

Section 1: General

1.1 This standard establishes guidelines to prevent most forms of environmental cracking of weldments in carbon steel refinery equipment, including pressure vessels, heat exchangers, piping, valve bodies, and pump and compressor cases. Weldments are defined to include the weld deposit, base metal HAZ, and adjacent base metal zones subject to residual stresses from welding.

1.1.1 Complete PWHT of field-fabricated storage tanks is impractical and sometimes impossible. Costly techniques of supporting tanks, insulating the outside, and applying gas burners to heat the inside gas have been attempted, but the effectiveness was questionable. Other protection steps such as alternative thermal methods, internal coatings, maintaining lower temperatures, etc. should be used.

1.2 This standard covers only carbon steels classified as P-No. 1, Group 1 or 2. These classifications can be found in the ASME Boiler and Pressure Vessel Code, Section IX[9] for pressure vessels, ASME/ANSI B31.3 for process piping, or API Standards 620 and 650 for tanks. It excludes steels with greater than 485 MPa (70,000 psi) minimum specified tensile strength. Other materials may be vulnerable to cracking, but these materials are outside the scope of this standard.

1.3 The types of equipment covered by this standard include pressure vessels, heat exchangers, piping, valve bodies, and pump and compressor cases. All pressure-containing weldments or internal attachment weldments to the pressure boundary are included. External attachment weldments are sometimes included as discussed in Paragraph 3.5.1. In addition, this standard may be applied to weldments in some non-pressure-containing equipment, such as atmospheric storage tanks.

1.4 Both new fabrication and repair welds are within the scope of this standard. The practices included herein are intended to prevent in-service cracking and are not intended to address cracking that can occur during fabrication, such as delayed hydrogen cracking. In most cases, however, these practices are also helpful in minimizing these fabrication problems. Useful information for preventing delayed hydrogen cracking is provided by F.R. Coe, et al.[10]

1.5 Welding processes covered by this standard include shielded metal arc welding (SMAW); gas metal arc welding (GMAW); flux-cored arc welding (FCAW); gas tungsten arc welding (GTAW); and submerged arc welding (SAW). Almost all types of weld configurations are included. For specific exceptions, such as hot taps, hardness limits and post weld heat treatment (PWHT) requirements should be reviewed on a case-by-case basis.

1.6 Corrosive refinery process environments covered by this standard can be divided into two general categories: services that could cause cracking as a result of hydrogen charging, and services that could cause ASCC. However, identification of the specific environments to which the guidelines set forth in this standard are to be applied to prevent various forms of in-service environmental cracking is the responsibility of the user. Figure 1 is a simplified schematic showing the interrelationships of the various cracking mechanisms discussed in this standard.

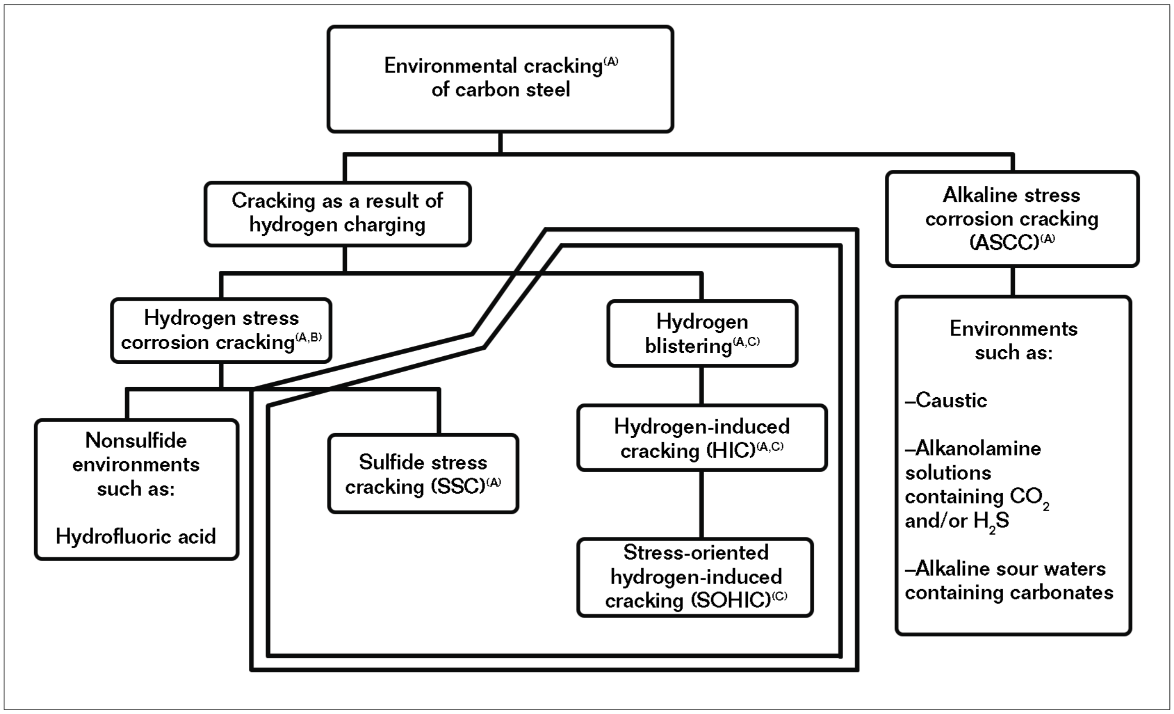
1.6.1 Services that could cause cracking as a result of hydrogen charging:

1.6.1.1 In these services, the environment or corrosion reactions result in diffusion of atomic hydrogen into the base metal and weldment. In high-strength or high-hardness areas, this hydrogen can result in HSC. In petroleum refining processes, the primary manifestation of HSC is SSC of hard weldments in process environments containing wet H_2S. Environmental conditions known to cause SSC in carbon steels are discussed in NACE Standard MR0103. However, other processes that promote aqueous corrosion of steel and promote hydrogen charging (such as hydrofluoric acid) can also cause HSC. Controlling both the weld deposit and HAZ hardness using the guidelines in Section 2 prevents HSC in most cases.

1.6.1.2 SOHIC can also occur in the services described above, but it does not require high strengths or high hardnesses. Hence, limiting weldment hardness does not prevent this form of cracking. Reducing weldment hardness and residual stress is believed to reduce the likelihood of this cracking, so the guidelines in Sections 2 and 3 may still be helpful. However, additional steps, such as the use of special clean steels, water washing, corrosion inhibitors, or corrosion-resistant liners, may be needed for some services. An overview of the materials selection, fabrication, PWHT, and testing practices that have been applied to new pressure vessels for preventing SOHIC is in NACE Publication 8X194.[12]

1.6.1.3 Cases of cracking of hard welds have occurred as a result of short-term upset, start-up, or transient conditions in non-stress-relieved P-No. 1 steel refinery equipment in which hydrogen sulfide is not normally present.

1.6.1.4 Although this standard covers only P-No. 1 steels, welds have also cracked in tanks and pressure vessels constructed of non-stress-relieved P-No. 10A and 10C carbon-manganese steels.



(A) Refer to the NACE/ASTM G193[11] for definitions (including *stress corrosion cracking*).
(B) The forms of environmental cracking included within the double lines are commonly referred to as wet H_2S cracking when they occur in wet H_2S environments.
(C) This form of environmental cracking can also occur in non-sulfide environments such as hydrofluoric acid.

Figure 1: Interrelationships of the various cracking mechanisms

1.6.2 Services that could cause ASCC:

1.6.2.1 Figure 1 provides examples of environments that could cause ASCC, including caustic stress corrosion cracking, amine stress corrosion cracking, and alkaline carbonate cracking (commonly referred to as carbonate cracking). Section 3 provides common practices used to prevent these types of ASCC. Severity of cracking is often dependent on temperature, concentration, level of residual tensile stresses, and other factors. Controlling weldment hardness does not prevent ASCC because high tensile stresses still may be present.

1.6.2.2 Further information about caustic cracking and its prevention is in NACE SP0403.[13]

1.6.2.3 Further information about amine cracking and its prevention is in API RP 945.[14]

1.6.2.4 Further information about carbonate cracking and its prevention is in NACE Publication 34108.[15]

1.6.2.5 It is outside the scope of this standard to detail all the specific environments causing ASCC of P- No. 1 steels. Various reference books and publications contain information on ASCC environments and preventive measures.[13-16]

1.7 One possible environmentally induced cracking mechanism in carbon steel weldments that is not addressed in this standard is high-temperature hydrogen attack. API RP 941[17] gives recommendations on materials selection to avoid this problem. Other types of in-service cracking not addressed by this standard are primarily mechanical in nature (e.g., fatigue, creep, and brittle fracture).

1.8 This standard was reorganized in 2008 to present the standard practices in a specification format in the main body. All other supporting information and guidance are now in appendixes.

1.8.1 Appendix A (nonmandatory) provides the rationale for the guidelines in Section 2 for prevention of HSC. The paragraphs in Appendix A are numbered to correspond with the related paragraph in the main body of the standard for which it is providing the rationale (e.g., Paragraph A.2.3.2 in Appendix A corresponds to Paragraph 2.3.2 in Section 2).

Table 1
"Road Map" of SP0472 Guidelines Applicable to Cracking Mechanisms

General Service: Possible Cracking Mechanism[A]	Weldment Component	Cracking Prevention and/or Hardness Control Method	Hardness Limit	Referenced Guidelines[B]
HSC or SSC	Weld deposit	Use of exempt welding process/filler metal combinations	Hardness testing not required	Paragraph 2.2.3
		Hardness testing of production welds	200 HBW	Paragraph 2.2.6
	HAZ	Base metal chemistry control PLUS PWHT OR		Paragraph 2.3.4 Paragraph 2.3.5.1
		Base metal chemistry control PLUS One of the two thermal methods listed PLUS HAZ hardness survey during welding procedure qualification[D]	248 HV10[C]	Paragraph 2.3.4 Paragraph 2.3.5.2 Paragraph 2.3.5.3
		1. Cooling time ($t_{8/5}$) control		Paragraph 2.3.5.2.1
		2. Temper bead welding		Paragraph 2.3.5.2.2
ASCC service: Caustic cracking	Entire weldment	PWHT	Not applicable[EC]	Paragraph 3.1 Paragraph 3.3
Amine cracking	Entire weldment	PWHT	Not applicable[EC]	Paragraph 3.1 Paragraph 3.3
Carbonate cracking	Entire weldment	PWHT	Not applicable[EC]	Paragraph 3.1 Paragraph 3.4

[A] Specific services requiring controls, and the optimum control method, shall be defined by the user.
[B] Many qualifiers and additional details are given in the referenced paragraphs and nonmandatory appendixes.
[C] Weld deposit hardness shall also be controlled to 200 HBW maximum (per Paragraph 2.2.1).
[D] Preproduction testing specified to validate control options is capable of reducing HAZ hardness.
[E] Weld deposit hardness for ASCC should still be controlled (per Paragraph A2.2 discussion).

1.8.2 Appendix B (nonmandatory) provides the rationale for the guidelines in Section 3 for prevention of ASCC. The paragraphs in Appendix B are numbered to correspond with the related paragraph in the main body of the standard for which it is providing the rationale.

1.8.3 Appendix C (nonmandatory) provides a summary of the cooling time (t8/5) concept discussed in Paragraph 2.3.5.2.

1.8.4 Appendix D (nonmandatory) provides definitions for local PWHT terminology used in Paragraph 3.7.

1.9 Table 1 provides an overview ("road map") of the guidelines applicable to the various types of cracking.

Section 2: Prevention of Hydrogen Stress Cracking

2.1 This section contains guidelines for prevention of HSC in weldments. Paragraph 2.2 addresses control of weld deposit hardness and Paragraph 2.3 addresses control of HAZ hardness.

2.2 Weld Deposit Hardness Control

Table 2
Welding Process/Filler Metal Combinations Exempt from Weld Deposit Hardness Testing

Welding Process	Filler Metal Specification	Filler Metal Classification	Compositional Restrictions (See Paragraph 2.2.3.1)	
SMAW	ASME SFA-5.1 or AWS A5.1	E60XX or E70XX	None	
GTAW	ASME SFA-5.18 or AWS A5.18	ER70S-2, ER70S-3, or ER70S-4	None	
		ER70S-6	Carbon (C)	0.10 wt% max
			Manganese (Mn)	1.60 wt% max
			Silicon (Si)	1.00 wt% max
GMAW (spray, pulsed, and globular transfer modes only)	ASME SFA-5.18 or AWS A5.18	ER70S-2, ER70S-3, or ER70S-4	None	
		ER70S-6	Carbon (C)	0.10 wt% max
			Manganese (Mn)	1.60 wt% max
			Silicon (Si)	1.00 wt% max

2.2.1 The hardness of the completed weld deposit shall not exceed 200 HBW.

2.2.2 Filler metals for the following welding processes shall be certified in accordance with the listed specifications from the ASME Boiler and Pressure Vessel Code, Section II, Part C18 or from the American Welding Society (AWS)[(5)]:

(a) SMAW: ASME SFA-5.1[19] or AWS A5.1.[20]
(b) GTAW and GMAW: ASME SFA-5.18[21] or AWS A5.18.[22]
(c) FCAW: ASME SFA-5.20[23] or AWS A5.20.[24]
(d) SAW: ASME SFA-5.17[25] or AWS A5.17.[26]

2.2.3 Weld Deposit Hardness Testing Exemptions

2.2.3.1 Weld deposits produced using welding process and filler metal combinations listed in Table 2 do not require production hardness testing, unless otherwise specified by the user.

2.2.3.2 Unless otherwise agreed, production GTAW, GMAW, FCAW, and SAW weld deposits shall meet the A-No. 1 chemical composition shown in Table QW-442 of the ASME Boiler and Pressure Vessel Code, Section IX.

2.2.3.3 If an alternative filler metal is required to meet other property needs such as low temperature impact requirements for specified P-No. 1 materials, agreement shall be obtained from the user, including testing of the alternative filler metal weld deposit to the requirements of Paragraph 2.2.7 for weld metal hardness testing and Section 2.3.5.3, Preproduction Weld Procedure HAZ Hardness Controls and Testing, which shall be used to confirm weld deposit hardness.

2.2.3.4 Filler metal classifications listed in Table 2 with compositional restrictions should not be used unless actual chemical analysis is performed on the filler metal, indicating that the corresponding compositional restrictions have been met. The chemical analysis may be obtained by any of the following methods:

(a) Purchasing the filler metal with a certification of the actual chemical analysis.
(b) Performing a chemical analysis on a sample of a specific heat of candidate filler metal in accordance with the requirements listed in Section 10 of ASME SFA-5.18.
(c) Performing a chemical analysis on a weld deposit produced using the specific heat of candidate filler metal. If this method is used, the weld pad in accordance with Figure 3 in ASME SFA-5.18 shall be produced using the welding process and welding procedure specification used in production. The heat input, filler metal size, preheat, and interpass temperature shall be controlled as specified in the production welding procedure specification. The chemical analysis shall be performed in accordance with the requirements listed in Section 10 of ASME SFA-5.18. A hardness test shall also be performed when this method is used. The weld deposit hardness shall not exceed 200 HBW.

2.2.4 When welding process/filler metal combinations in accordance with Table 2 are used in lieu of production weld deposit hardness testing, a process shall be implemented to control and document the identification and use of these filler metals in production welding.

(5) American Welding Society (AWS), 550 N.W. LeJeune Road, Miami, FL 33126.

2.2.5 This production hardness testing waiver may be applied, even if a different filler metal is used for the root pass, provided that the root pass is produced with filler metal that meets the A-No. 1 chemical composition requirements.

2.2.6 Weld deposit hardness testing may be waived for repair welds in cast, forged, or plate components produced using welding process/filler metal combinations other than those listed in Table 2 if they have been prequalified using the following process:

2.2.6.1 A weld test patch shall be created on a test plate with a specific heat of filler metal (and flux, in the case of SAW) using parameters in accordance with the welding procedure specification to be used in production. The test patch shall then be tested to verify that the weld deposit hardness meets the 200 HBW maximum requirement, which then qualifies that heat of the filler metal (and flux, in the case of SAW) to be used for production weld repairs, in accordance with that welding procedure specification, without actual production weld deposit hardness tests.

2.2.6.2 When welding filler metal (and flux, in the case of SAW) is qualified using this method, a process shall be implemented to control and document the identification and use of this filler metal (and flux) in production welding.

2.2.7 Weld Deposit Hardness Testing

2.2.7.1 Hardness testing on completed production welds, when required, shall be done after any PWHT. Only weld deposits require hardness testing unless otherwise specified by the user.

2.2.7.2 Weld deposits shall be hardness tested, where required, on the side contacted by the process, whenever possible. If access to the process side is impractical, such as on piping or small-diameter vessels, hardness testing shall be done on the opposite side.

2.2.7.3 Hardness readings, where required, shall be taken with a Brinell hardness tester in accordance with ASTM[(6)] E102[7] or with a comparison hardness tester in accordance with ASTM A833.[28] Other hardness testing techniques may be used if approved by the user.

2.2.7.4 For vessel or tank butt welds where hardness testing is required, a minimum of one location per weld seam shall be hardness tested. Unless otherwise specified by the user, one hardness test should be made for each 3 m (10 ft) of weld seam. In addition, one hardness test shall be made on each nozzle flange-to-neck and nozzle neck-to-shell/head weld. Each unique welding procedure used shall be hardness tested.

2.2.7.5 When hardness testing of welds is required, fillet weld deposit hardness testing should be done when access is feasible. The number of hardness tests and locations required shall be approved by the user with Paragraph 2.2.7.4 as a guide.

2.2.7.6 For piping welds on which hardness testing is required, a minimum of 5% of butt welds shall be hardness tested, unless otherwise specified by the user.

2.2.7.7 Repair welds in cast, forged, or plate components shall be hardness tested, when required, in accordance with the following requirements:

2.2.7.7.1 Hardness testing shall be performed on each component that has been weld repaired.

2.2.7.7.2 At least one hardness test shall be performed for each unique welding process/filler metal heat number combination used on the component.

2.2.7.7.3 Hardness testing shall be performed on actual weld repairs when the weld repair area is accessible, large enough to accommodate an indentation, and in a location where an indentation can be tolerated.

2.2.7.7.4 When actual weld repairs cannot be hardness tested, weld test patches shall be created on an accessible area of the component to allow hardness testing.

2.2.7.8 Weld deposits found to exceed the maximum hardness criterion in Paragraph 2.2.1 are unacceptable and shall be reported to the user. Unless accepted by the user, hard welds shall be both removed and rewelded, or heat treated to reduce the hardness to an acceptable value. The specific approach to be used to correct the high-hardness condition shall be subject to the user's approval before any corrective action is taken. Regardless of the method of corrective action taken, the weld deposits

[(6)] ASTM International, 100 Barr Harbor Dr., PO Box C700, West Conshohocken, PA 19428-2959.

shall be retested to ensure that the corrective action has resulted in acceptable hardness values. Also, additional welds should be hardness tested for each high-hardness weld that is found, at a rate determined by the user.

2.3 HAZ Hardness Control

2.3.1 HAZ hardness shall be controlled by the use of base metal chemistry control in conjunction with one or more thermal methods. The thermal methods promote a soft HAZ microstructure by either (a) using slow cooling rates to prevent the initial formation of a hard HAZ microstructure, or (b) tempering the HAZ microstructure to reduce the hardness. The thermal method(s) and associated base metal chemistry control selected from the list below shall be specified and documented by the producer of the subject components or the fabricator of the equipment.

2.3.2 Alternate controls based on scientific knowledge, experience, and/or risk-based analysis may be used in specific instances when approved by the user.

2.3.2.1 The requirements for HAZ hardness control may be waived by the user for seamless piping fabrication that is single-sided welded.

2.3.3 The user may review and approve and may dictate methods, limits, and/or controls for any given application.

2.3.4 Base Metal Chemistry Control.

2.3.4.1 Base metal chemistry control shall be accomplished by specifying and monitoring the base metal carbon equivalent (CE), as determined by the formula in Equation (1).

$$E = wt\%C + \frac{wt\%Mn}{6} + \frac{(wt\%Ni + wt\%Cu)}{15} + \frac{(wt\%Cr + wt\%Mo + wt\%V)}{5} \quad (1)$$

2.3.4.2 The following are base metal chemistry control levels that should be specified for HAZ hardness controls:

2.3.4.2.1 Steels with maximum specified C content > 0.18 wt% C, maximum CE of 0.43.

2.3.4.2.2 When thickness of component is > 1 inch, the CE maximum may be increased to 0.45.

2.3.4.2.3 Steels with maximum specified C content ≤ 0.18 wt% C shall have maximum CE specified by user.

2.3.4.2.4 Maximum vanadium (V) content of 0.02 wt%.

2.3.4.2.5 Maximum niobium (Nb) content of 0.02 wt%.

2.3.4.2.6 Maximum V plus Nb content of 0.03 wt%.

2.3.5 Thermal Methods

2.3.5.1 PWHT: PWHT as a means to control HAZ hardness without the need for weld procedure qualification hardness surveys can be used in conjunction with chemistry controls of 2.3.4 and the following requirements:

2.3.5.1.1 PWHT involves heat treatment after welding at a temperature high enough to ensure softening of the HAZ microstructure by tempering.

2.3.5.1.2 The PWHT temperature shall be 620 °C (1,150 °F) minimum and the hold time shall be specified to ensure complete heat treatment. Hold times shall be per code except that regardless of the thickness of the base metal, a one hour minimum hold time shall be specified to ensure complete heat treatment. If lower PWHT temperatures or shorter times are considered necessary by the manufacturer or fabricator, because of concerns with strength or impact toughness, this shall be reviewed and agreed with the user.

2.3.5.1.3 A PWHT procedure shall be developed prior to heat treating. It should include the type of heating process, the number and locations of thermocouples, supporting details, heat up and cooldown rates, maximum allowable temperature differentials, gradient control, hold time, and PWHT temperature range.

2.3.5.1.4 The user shall specify whether submittal of the PWHT procedure is required for approval prior to the use of PWHT.

2.3.5.1.5 A minimum 93 °C (200 °F) preheat is used for all welding.

2.3.5.1.6 If local PWHT is to be undertaken, the requirements of Paragraph 3.7 should be included in the PWHT procedure.

2.3.5.2 Alternative Thermal Methods: The following alternatives to PWHT for thermal control of HAZ hardness can be used in conjunction with chemistry controls of 2.3.4 and require the Preproduction Weld Procedure HAZ Hardness Controls and Testing of 2.3.5.3.

2.3.5.2.1 Cooling Time Control: Cooling time control involves controlling the time for the weldment to cool from 800 °C to 500 °C (1,470 °F to 930 °F), denoted as $t_{8/5}$, to avoid formation of a hard microstructure in the HAZ. The minimum $t_{8/5}$ for production welding shall be specified. Appendix C is a summary of the cooling time ($t_{8/5}$) concept and provides information on parameters and methods that are used to determine $t_{8/5}$.

2.3.5.2.2 Temper Bead Welding

(a) Temper bead welding techniques involve sequencing of weld passes such that the heat input from weld beads tempers the HAZ microstructure formed by previous weld passes.
(b) The temper bead technique shall involve proper sequencing of the weld beads to produce a tempering effect in the HAZ. Nomenclature and diagrams for temper bead welding are provided in QW-462.12 of the ASME Boiler and Pressure Vessel Code, Section IX. Proper sequencing of the weld beads against the base metal and the first layer temper beads shall be controlled, with particular attention to the cap layer passes, to ensure that effective tempering occurs. The surface temper beads shall not contact the base metal. The distance from the edge of the surface temper beads to the toe of the weld, as defined in QW-462.12, shall be 3.0 mm (0.12 in) maximum and 1.5 mm (0.060 in) minimum. The successful execution of this technique requires consistent heat input and deposition rate from bead to bead. Therefore, care must be taken when welding is performed using manual welding processes to ensure consistent heat input and deposition rates. Such care is especially important for manual GTAW, which inherently has higher heat input than other manual welding processes as a result of the restricted travel speed of GTAW relative to the other welding processes.
(c) When the temper bead technique is used to repair minor defects in cast, forged, and plate components, the defect shall be excavated to a minimum diameter of four times the filler metal diameter prior to welding. The weld shall be built up using at least two layers until the cavity is filled above the prevailing base metal surface. The final cap layer shall be applied such that it does not contact the base metal, and such that the distance from the edge of the surface temper beads to the toe of the weld, as defined in QW-462.12, shall be 3.0 mm (0.12 in) maximum and 1.5 mm (0.060 in) minimum.
(d) If the final cap pass results in an unacceptable profile, as determined by construction code requirements or the user, the excess weld shall be removed by grinding.

2.3.5.3 Preproduction Weld Procedure HAZ Hardness Controls and Testing

2.3.5.3.1 To verify that the methods used effectively control the HAZ hardness, preproduction hardness testing may be included in the weld procedure qualification process to ensure that the hardness in the HAZ and the weld deposit is acceptable.

2.3.5.3.2 When base metal chemistry controls per paragraph 2.3.4 and PWHT in accordance with Paragraph 2.3.5.1 are specified, along with using a minimum preheat of 93 °C (200 °F) during welding, preproduction hardness testing is not required.

2.3.5.3.3 Production welding procedures shall be qualified using the ASME Boiler and Pressure Vessel Code, Section IX procedure qualification rules, with the addition of the selected HAZ hardness control method(s).

2.3.5.3.4 When preproduction hardness surveys are required, they shall be performed in accordance with NACE Standard MR0103.

2.3.5.3.5 The maximum allowable HAZ hardness shall be 248 HV 10.

2.3.5.3.6 Weld deposit hardness shall also be evaluated. No readings shall exceed 248 HV (70.5 HR 15N), and the average weld deposit hardness shall not exceed 210 HV 10.

2.3.5.3.7 Individual HAZ hardness readings exceeding the value permitted by this standard are considered acceptable if the average of three hardness readings taken in the equivalent HAZ profile location adjacent to the hard HAZ reading (by repolishing the existing procedure qualification specimens or extracting additional procedure qualification specimens) does not exceed the values permitted by this standard and no individual hardness reading is greater than 10 HV 10 units above the acceptable value.

2.3.5.3.8 The hardness test results shall be appended to the ASME procedure qualification record (PQR). The results shall include a sketch of the hardness test locations and corresponding results. The weld procedure specification (WPS) shall reflect the limits imposed by the specified limits for hardness control. The user may require that both forms be submitted for approval prior to production welding.

2.3.5.4 Preproduction Weld Procedure Base Metal Chemistry Controls and Reporting

2.3.5.4.1 The WPS shall state that the maximum CE of the production base metal shall not exceed the CE of the procedure qualification specimen by more than 0.03%. The base metal chemistry of the procedure qualification specimen shall be reported in the PQR. All base metal chemistry requirements shall be applied to ladle analyses, unless otherwise specified by the user.

2.3.5.4.2 For product forms in which deliberately added microalloying elements (such as niobium [Nb] [aka columbium {Cb}], vanadium [V], titanium [Ti], and boron [B]) are used, the maximum content shall not exceed the corresponding value on the procedure qualification specimen. Deliberate additions are generally considered to be:

(a) Nb(Cb) > 0.01 wt%
(b) V > 0.01 wt%
(c) Ti > 0.01 wt%
(d) B > 0.0005 wt%

All base metal chemistry requirements shall be applied to ladle analyses, unless otherwise specified by the user.

2.3.5.5 Preproduction Weld Procedure Thermal-Related Controls and Reporting

2.3.5.5.1 If cooling time control is used, the WPS shall control production welding such that the calculated t8/5 is equal to or greater than the t8/5 calculated for the procedure qualification specimen. The user may specify a minimum t8/5 required for future repair or alteration scenarios.

2.3.5.5.2 Preheating may also be applied to thermal cutting and tack welding (if subsequent grinding is not done). Guidelines for when to preheat and minimum preheat temperatures are given in applicable design codes (e.g., the nonmandatory Appendix R in the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1).

2.3.5.5.3 Small fillet welds on large sections are often prone to high HAZ hardnesses. The user shall determine whether this configuration is necessary in production, which may define the limiting t8/5 required for procedure qualification.

2.3.5.5.4 For SMAW, an alternative simplified thermal control method may be based on the maximum weld bead size and the maximum length of weld bead per unit length of weld rod used in the welding of the procedure qualification specimen, which shall be the basis for limits applied to production welding.

2.3.5.5.5 For GMAW and FCAW, the filler metal size used for production welding should be the same as that used during procedure qualification tests. For other welding processes, only one size variation between the filler metal size used for the procedure qualification tests and for subsequent production welding should be permitted.

2.3.5.5.6 For fillet weld procedure qualification tests, position should be an essential variable; however, tests on welds made in the overhead position shall qualify all other fillet weld positions.

2.3.5.5.7 If PWHT is used, the welding procedure shall require PWHT at a minimum temperature and minimum hold time, stated as a function of metal thickness, equal to or greater than the temperature and hold time used to PWHT the procedure qualification specimen.

2.3.5.5.8 If a temper bead welding technique is used during procedure qualification, the production procedure shall require that the cap pass be applied so that the edges of the weld beads come within 3.0 mm (0.12 in) of the base metal, but do not touch the base metal. If this results in an unacceptable profile, the excess weld deposit should be removed by grinding, machining, or other low-heat input processes.

2.4 During original fabrication, weldments shall be inspected for defects such as lack of fusion, delayed hydrogen cracking, or severe undercut, and any relevant defects found should be removed. The definition of relevant defects shall be established and approved by the user.

Section 3: Prevention of Alkaline Stress Corrosion Cracking

3.1 PWHT shall be used to reduce residual stresses when prevention of ASCC is specified by the user. In services where both ASCC and HSC/SSC are concerns, weldment hardness controls shall be applied in addition to PWHT.

3.2 PWHT procedures as described in 3.4 and 3.5 can negatively affect the tensile strength and impact toughness of the base metal. Each situation should be evaluated with the steel supplier to determine whether this specified thermal stress relief is adequate for all other considerations in addition to ASCC prevention.

3.3 ASME Boiler and Pressure Vessel Code, Section VIII, allows PWHT to be performed at lower than the normally specified temperature if it is held for a longer time. However, when PWHT is being performed for prevention of ASCC, these lower temperatures shall not be used.

3.4 For amine and caustic cracking services, an effective PWHT procedure shall consist of heating weldments to 635 ± 15 °C (1,175 ± 25 °F) for a hold time of one hour for each 25 mm (1.0 in), or a fraction thereof, of metal thickness, with a minimum hold time of one hour.

3.4.1 When PWHT is used for ASCC, the requirements for HAZ hardness control for SSC as defined in Paragraph 2.3 also must be considered for services exposed to both SSC and ASCC. The allowable variation in the chemical composition of steels could be considerable, even within the same grade. In conjunction with welding variables, this can produce high hardness in HAZs that might not be adequately softened by this specified thermal stress relief. Each situation should be evaluated to determine whether this thermal stress relief is adequate.

3.5 For carbonate cracking services, an enhanced stress-relieving heat treatment should be used. The heat treatment temperature should be a minimum 649° C (1200 °F) for a hold time of one hour for each 25 mm (1.0 in) of thickness, with a minimum hold time of one hour.

3.6 When heat treatment is used to prevent ASCC, all welds and weld heat-affected areas shall receive PWHT, including all pressure-containing welds, seal welds, internal attachment welds, nozzle-reinforcing pad welds, temporary fabrication attachment welds, and arc strikes.

3.6.1 External attachment welds often generate residual stresses extending through the entire wall thickness. If they do, they shall also receive PWHT. Only if an evaluation shows that the residual stresses do not extend through wall may PWHT be considered optional.

3.7 Investigations have shown that an inadequate heated band width during local PWHT can induce or inadequately relieve residual stresses in the weld region. The following local PWHT procedures, derived from AWS[(7)] D10.10 and WRC[(8)] Bulletin 452[41] should be used for piping and vessels to minimize residual stresses and thereby increase resistance to alkaline SCC.

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(7) American Welding Society (AWS), 550 N.W. LeJeune Rd., Miami, FL 33126.
(8) Welding Research Council (WRC), PO Box 201547, Shaker Heights, OH 44120.

3.7.1 Terminology used in this section includes soak band (SB), heated band (HB), and gradient control band (GCB). Definitions and further information on local PWHT are provided in Appendix D (nonmandatory).

3.7.2 The minimum HB and GCB widths for pipe should be as shown in Table 3:

Table 3
Minimum Recommendations for Local 360° Band PWHT on ASME B31.3 Piping(A)

DN (NPS)	Minimum HB Centered Width Over the Weld(B)	Minimum GCB Width Centered Over the Weld
≤ 50 (≤ 2)	280 mm (11.0 in)	330 mm (13.0 in)
100 (4)	370 mm (14.5 in)	465 mm (18.5 in)
150 (6)	435 mm (17 in)	575 mm (23.0 in)
≥ 200 (≥ 8)(C)	$HB = SB + 4\sqrt{Rt}$ 230 mm (9.05 in) minimum	$GCB = SB + 8\sqrt{Rt}$ 355 mm (14.0 in) minimum

(A) Widths are for thickest piping schedules per AWS D10.10. Thinner pipe can reduce widths using AWS D10.10 Table 4.
(B) The HB width uses the HB2 formula per AWS D10.10 for smaller diameter pipe, but for ease of implementation and use consistent with WRC 452, the HB1 formula is used for the larger diameter piping.
(C) ≥ 200 mm (8.00 in) diameter pipe may have HB and GCB less than smaller diameter piping, in accordance with AWS D10.10.

Where:
SB = 50 mm (2.0 in) + width of weld, mm (in)
R = pipe outside radius, mm (in)
t = pipe wall thickness, mm (in)

3.7.2.1 The GCB should be insulated using a 50 mm (2.0 in) minimum thickness insulation blanket.

3.7.2.2 In the case of flange welds, the entire flange (inside and outside) and a minimum of 230 mm (9.0 in) runout on the pipe from the weld should be insulated for pipes 200 DN (8 NPS) and smaller. For flange welds in pipes 250 DN (10 NPS) and greater, 230 mm (9.00 in) + $4\sqrt{Rt}$ should be insulated.

3.7.2.3 If possible, the ends of the pipe should be closed to minimize convection currents.

3.7.3 The minimum heated band width for vessels should be as shown in Table 4:

Table 4
Minimum Recommendations for Local 360° Band PWHT on ASME Section VIII, Division 1 Vessels[18]

Minimum Soak Band Width Centered Over Weld	Minimum HB Width Center Over Weld	Minimum GCB Width Centered Over Weld
SB = W + [2t or 100 mm (4 in), whichever is less]	— $HB = SB + 4\sqrt{Rt}$	— $GCB = SB + 8\sqrt{Rt}$

Where:
W = weld width, mm (in)
R = pipe outside radius, mm (in)
t = pipe wall thickness, mm (in)

3.8 After PWHT, actions that reintroduce high residual stresses, such as straightening, should be avoided. If these actions have been done, a second PWHT should be performed when deemed necessary by the user.

3.9 The shot peening process should not be used for applications in ASCC environments as a substitute for PWHT.

3.10 Alternative welding methods such as temper bead welding and controlled-deposition welding shall not be used for prevention of ASCC.

3.11 During original fabrication, weldments should be inspected for defects such as lack of fusion, delayed hydrogen cracking, or severe undercut. Any defects found should be removed.

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Appendix A
Rationale for Guidelines for Prevention of Hydrogen Stress Cracking (Nonmandatory)

> This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

The rationale statements in this nonmandatory appendix are included to explain the background behind the requirements in Section 2. The numbering of these statements matches the paragraph numbers of this standard plus the use of the prefix "A" for clarity.

A2.2 For most refinery services, weld deposit hardness is often controlled, even if not exposed to an internal operating environment that can cause HSC. This practice primarily helps avoid the use of improper welding filler metals (and fluxes), welding procedures, or heat treatment. It also minimizes the risk of HSC from external wet atmospheric corrodents, process upsets, or future changes in service.

[8] Materials Technology Institute (MTI), 1215 Fern Ridge Parkway, Suite 206, St. Louis, MO 63141-4405.
[9] International Institute of Welding (IIW), BP 51362 Villepinte, 95942 Roissy CDG, Cedex, France.
[10] British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, United Kingdom.

A2.2.1 A number of SSC failures occurred in the late 1960s in hard weld deposits in P-No. 1 steel refinery equipment. The petroleum refining industry established a maximum hardness limit of 200 to 225 HBW for P-No. 1, Group 1 and 2 steels to ensure that weld deposits would be resistant to HSC. The 200 HBW maximum hardness requirement specified in this standard is lower than the 22 HRC (237 HBW) maximum hardness requirement listed in NACE MR0175/ISO 15156 and previous editions of NACE Standard MR0175. The lower limit was applied to compensate for both the nonhomogeneity of some weld deposits and the normal variations in production hardness test results that are obtained using a comparison hardness tester. 200 HBW is readily and consistently achievable with common A-1 filler metals and represents a lower bound.

A2.2.2 AWS or ASME-certified filler metals are required to ensure that the composition and quality of the filler metals are consistent, which forms the basis of the exemptions from weld deposit hardness testing within this standard.

A2.2.3 The compositional restrictions listed in Table 2 are in addition to the requirements specified by the filler metal specification. These compositional restrictions are based on hardenability calculations performed in accordance with methods described in IIW Document IX-2058-03.[32]

A2.2.3.1 This standard originally specified production hardness testing of all weld deposits. However, experience eventually indicated that hardness values above 200 HBW rarely occurred in weld deposits produced using SMAW, GTAW, and GMAW (spray, pulsed, or globular transfer) welding processes in combination with certain filler metal classifications. Hence, it is generally not considered necessary to perform production hardness testing on weld deposits produced with these welding process/filler metal combinations.

A2.2.3.2 High weld deposit hardnesses can occur with SAW when using a low- or medium-Mn wire in combination with an active flux.[33-35] Also, some SAW welds with high Mn and Si contents can have highly localized hard zones that are not softened significantly by PWHT.[36] Most welding consumable manufacturers recommend against the use of active fluxes for multipass welds. Some GTAW, GMAW, and FCAW filler metal classifications allow high Mn concentrations. Hence, the chemistry of weld deposits must be restricted to the A-No. 1 composition in accordance with ASME Boiler and Pressure Vessel Code, Section IX to ensure achieving weld deposit hardness limits.

A2.2.3.3 Use of alternative fillers other than fully compliant A-1 may be required on occasion to address a combination of very unique service such as low temperature impact requirements. The user needs to agree with the supplier/fabricator on the filler metal suitability to resist SSC/HSC. The requirement should include the specified weld metal hardness testing and preproduction procedure qualification and testing to validate weld metal compliance to these requirements for SSC/HSC resistance.

A2.2.3.4 Use of additional compositional restrictions for the common GMAW filler metal classification ER70S-6 for exemption requires a confirmation of the actual filler metal chemistry because the standard specification is much broader than the A-No. 1 compositional limit. The same welding process and welding variables are specified to be used for this method because the relationship between filler metal chemistry and weld deposit chemistry is a function of the welding process and variables. For example, in GMAW welding using CO_2 mixtures, oxygen generated by breakdown of the CO_2 causes oxidation of Mn and Si in the weld metal, thus reducing the concentration of these elements in the weld deposit matrix. Reductions of 0.3 wt% in Mn and 0.2 wt% in Si are common in GMAW deposits produced using 100% CO_2. ER70S-2 has been reported on occasion to cause hard weld deposits in conjunction with very high cooling rates and with high levels of residual Ti.

A2.2.4 Exemption from weld deposit hardness testing based on the Table 2 filler metal exemptions require that quality control procedures be in place to ensure that only these exempted filler metals are being used in production.

A2.2.5 Because it is not possible to perform production hardness testing on the root pass, the hardness test is usually waived even if a different filler metal is used for the root pass. However, to ensure that the root pass weld deposit is not hard, the same restriction to use only A-No. 1 chemical composition is specified in accordance with ASME Boiler and Pressure Vessel Code, Section IX.

A2.2.6 Base metals can undergo weld repairs as part of their specification. This paragraph addresses the need to ensure that these weld deposits are also produced to the requirements of this section. Because base metals are manufactured around the world and other filler metals than those specified herein may be used, this paragraph provides a qualification practice for these filler metals because production testing may not be practically possible (e.g., inner surfaces of components).

A2.2.6.1 This paragraph specifies how each heat of filler metal is hardness tested in a sample weld production that includes welding within the parameters of the production welding procedure to ensure similar cooling times.

A2.2.6.2 Once the qualification is complete, the component manufacturer must/should ensure that only the tested filler metal is used in production.

A2.2.7 The hardness testing practices in this and subsequent paragraphs are used in services covered by the scope of this standard, except for the waiver given to some SMAW, GTAW, and GMAW welds in Paragraph 2.2.3, unless otherwise specified by the user. The practices may also be applied to other services for the reasons given in Paragraph 1.6.1.1.

A2.2.7.1 PWHT can provide temper softening of weld deposits. Typically, the macrohardness testing techniques in this section cannot detect the narrow HAZ hardenability zone of P-No. 1 steels, so weld deposits are what are specified to be tested.

A2.2.7.2 Exposure to the hydrogen charging environment of the process service can cause HSC.

A2.2.7.3 Both laboratory-type Brinell testers that can be used for procedure qualification or the more typical field comparison hardness tests are the standard technique for evaluating weld deposit hardness. There may be other acceptable portable techniques (e.g., dynamic/rebound or ultrasonic) based on evaluation of their capability and approval by the user.

A2.2.7.4 Guidelines are provided so that production welding is adequately sampled to ensure weld deposits meet the hardness requirement of this standard.

A2.2.7.5 Fillet welds may represent a difficult profile or may be difficult to access, though there are smaller size Brinell devices that can facilitate weld deposit hardness testing. Requirements for frequency of testing for fillet welds may use frequency guidelines suggested for butt welds in Paragraph 2.2.7.4.

A2.2.7.6 Guidelines are provided so that piping production welding is adequately sampled to ensure weld deposits meet the hardness requirement of this standard.

A2.2.7.7 Guidelines are provided to ensure that weld repairs often used in base metals are sampled and that weld deposits meet the hardness requirements of this standard. In some cases, internal access may not allow weld deposit testing; therefore, alternative testing guidelines are provided.

A2.2.7.8 High hardness weld deposits are addressed by the user and are required to be included in the corrective action decision. Guidelines are provided for retesting to verify the hardness of the repaired or heat-treated weld deposit. Further testing of other welds to validate the extent of the problem is discussed.

A2.3 HAZ Hardness Control

A2.3.1 High-hardness microstructures in HAZs may be susceptible to cracking, even with soft weld deposits in severely corrosive petroleum refinery services. For these services, several options are available to the fabricator or user to control the maximum HAZ hardness. Most users and fabricators have found that it requires base metal chemistry control plus PWHT to provide HAZ hardness control. Non-PWHT options are included for other thermal methods to ensure HAZ hardness is effectively controlled. This is supported by Gysbers,[37] who demonstrated the interrelationship between base metal chemistry and its impact on both as-welded hardenability and temper-softening response during PWHT. The concept of the cooling time ($t_{8/5}$) during welding is used to summarize the impact of preheat, heat input, joint configuration, and component thickness. The degree and type of base metal chemistry control needed depends on the type of thermal method(s) selected. The thermal methods are:

1. PWHT control.
2. Cooling time control.
3. Temper bead welding.

Table A1 summarizes the influences that various combinations of welding parameters and thermal methods have on the level of necessary base metal chemistry controls for butt welds.

A2.3.2 In some instances, users successfully perform certain types of welding without base metal chemistry controls (e.g., piping). The combination of the base metal chemistry control and thermal methods to control HAZ hardness may vary depending on user needs and other demands (toughness, strength) of the weldment. Examples of instances in which certain controls may not be acceptable include the following:

Table A1
Level of Base Metal Chemistry Control as a Function of Butt Weld Joint Configurations and HAZ Hardness Control Method Used

Thermal Method	Weld Type	Layers per Side	Comments	Level of Base Metal Chemistry
PWHT control	One-sided	Multilayer	Because this is multilayer, bead tempering occurs naturally in the HAZ adjacent to the root pass, which is in contact with the sour process, making it even more likely that it is soft after PWHT.	Least Stringent ↓
PWHT control	Two-sided	Multilayer	Because this is multilayer, bead tempering occurs naturally in the HAZ adjacent to all layers except possibly the cap layers, one of which is in contact with the sour process. Therefore, the HAZ adjacent to all layers other than the cap layers experiences both bead tempering and PWHT.	↓
PWHT control	Two-sided	Single layer	The heat from the pass on the second side welded may produce some bead tempering of the HAZ produced adjacent to the pass on the first side welded, reducing the likelihood of a hard through-wall HAZ. The PWHT alone must temper any hard HAZ locations that remain.	↓
PWHT control	One-sided	Single layer	Because this is a one-pass weld, there is no opportunity for bead tempering, and as such, it is possible that there is a hard through-wall HAZ. The PWHT alone must temper any hard HAZ locations.	↓
Temper bead welding	One-sided	Multilayer	Bead tempering occurs naturally in the HAZ adjacent to the root pass, which is in contact with the sour process. The remainder of the HAZ should be soft if temper bead welding techniques are used for the remainder of the layers.	↓
Temper bead welding	Two-sided	Multilayer	The entire HAZ should be soft if temper bead welding techniques are used for all layers.	↓
Cooling time control	One-sided	Multilayer	Bead tempering occurs naturally in the HAZ adjacent to the root pass, which is in contact with the sour process. The remainder of the HAZ should be soft if the cooling time and base metal chemistry controls are well matched.	↓
Cooling time control	Two-sided	Multilayer	Because this is multilayer, bead tempering occurs naturally in the HAZ adjacent to all layers except possibly the cap layers, one of which is in contact with the sour process. The HAZ adjacent to the cap layer on the process side should be soft if the cooling time and base metal chemistry controls are well matched.	↓
Cooling time control	Two-sided	Single layer	Because bead tempering occurs to some degree on the first side welded when the second side is welded, this is less risky than a one- sided, single-layer weld, but the entire HAZ adjacent to the weld on the second side could be hard if base metal chemistry and cooling time are not controlled.	↓
Cooling time control	One-sided	Single layer	Because a single layer weld could produce a through-wall HAZ that is excessively hard, base metal chemistry and cooling time both need to be well controlled.	Most Stringent

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Table A1 *(continued)*
Level of Base Metal Chemistry Control as a Function of Butt Weld Joint Configurations and HAZ Hardness Control Method Used

Thermal Method	Weld Type	Layers per Side	Comments	Level of Base Metal Chemistry
Temper bead welding	Two-sided	Single layer	The heat from the pass on the second side welded may produce some bead tempering of the HAZ produced adjacent to the pass on the first side welded, reducing the likelihood of a hard through-wall HAZ. The second side welded does not experience bead tempering. If this technique were to be used, the first pass would have to be located on the side exposed to the sour process.	Not Recommended
Temper bead welding	One-sided	Single layer	Not possible.	Not Acceptable

(a) Restrictive base metal chemistry controls may not allow weldment strength and toughness requirements to be achieved.
(b) Welding controls may not be practical for some field configurations and conditions.
(c) PWHT may not be practical for some welds on valves, pumps, compressor casings, or compressor heads, especially after final machining.

A2.3.2.1 Industry experience with single sided welding of seamless P-1 piping without HAZ hardness controls has generally been successful, with few reports of through-wall SSC or HSC. Users may waive the HAZ hardness control requirements for this type of application.

A2.3.3 Although the manufacturer or fabricator has primary responsibility for selecting the controls that are used for complying with HAZ hardness requirements of this standard, there may be user-based decision issues (service exposures, risks, etc.) that may warrant input into the decisions for control options.

A2.3.4 Control of the base metal chemistry of all production base metals for a given application can contribute to controlling the HAZ microstructure and hardness.

A2.3.4.1 The equation for calculating the CE provided in this paragraph is commonly used as a nominal hardenability index for carbon steel base metals within the cooling times typically found during most welding. This equation uses the specified elements (C and Mn) and the residual elements (Ni, Cu, Cr, Mo, and V) that are controlled in carbon steels assigned to the P-No. 1 grouping in Section IX of the ASME Boiler and Pressure Vessel Code. A steel should be selected for welding procedure qualification with a base metal chemistry at the maximum level that would be experienced in production welding. This ensures that the production base metals are no more hardenable than the steel used in qualification testing.

A2.3.4.2 The chemistry controls specified here are specified based on an industry survey of company specified levels and current steel supplemental practices.

A2.3.4.2.1 Steels with > 0.18 wt% specified maximum C, maximum CE of 0.43. This is the majority of users' specified CE content. C content is included, as lower C content steels with special heat treatments to obtain strength are infrequently used.

A2.3.4.2.2 When the thickness of a component is > 1 in, strength levels may not be sustainable at a lower CE, so allowance is given to expand CE levels to accommodate.

A2.3.4.2.3 Steels with < 0.18 wt% specified maximum C shall have maximum CE specified by user. Some applications of special heat treated steels with lower C content require users to work with the steel manufacturer to identify a CE level.

A2.3.4.2.4 Maximum V content of 0.02 wt%.

A2.3.4.2.5 Maximum Nb content of 0.02 wt%.

A2.3.4.2.6 Maximum V plus Nb content of 0.03 wt%.

P-No. 1 steels described in Paragraph 1.2 that have deliberate additions of microalloying elements may require additional preheat and higher PWHT temperatures to obtain acceptable HAZ hardnesses. These heat treatments needed to obtain acceptable HAZ hardnesses may adversely affect toughness values. Deliberate additions are generally considered to be greater than 0.01 wt% for each of Nb (Cb), V, and Ti, and greater than 0.0005 wt% of B. Ti and B levels are not included, as these are often not measured in typical plate specifications and would be difficult to enforce.

A2.3.5 Thermal methods seek to control weld HAZ hardness by either preventing a hard microstructure from ever forming or by tempering the microstructure.

A2.3.5.1 PWHT temper softens hard HAZ constituents and is the most used thermal control method for HAZ hardness control. Preproduction weld procedure hardness testing is not typically necessary for the combination of chemistry controls and PWHT-based thermal control. The ASME Boiler and Pressure Vessel Code, Section VIII, Division 1, allows PWHT to be performed at temperatures below the minimum specified temperature provided the temperature is held for a longer time (see Paragraph UCS-56 of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 1). The general trend in the industry has been to specify higher PWHT temperatures (see NACE Publication 8X194) to both facilitate tempering of the hard HAZ (particularly with residual alloying elements) and improve residual stress reduction.

A2.3.5.1.1 PWHT involves heat treatment after welding at a temperature high enough to ensure softening of the HAZ microstructure by tempering.

A2.3.5.1.2 Both temperature and time are needed to adequately soften hard HAZ microstructures. Shorter hold times may not consistently provide proper tempering.

A2.3.5.1.3 A documented procedure is typically necessary to ensure consistent application of the PWHT process as well to avoid improper heat treatments that may generate insufficient tempering or create inadvertent residual stresses.

A2.3.5.1.4 PWHT can have significant variation in procedures that can impact the effectiveness of this thermal method. This paragraph allows users to review the procedures in detail so they are satisfied with the viability.

A2.3.5.1.5 This paragraph explains that PWHT has provided good industry experience in reducing HSC damage without having to verify the weld HAZ hardness via weld procedure hardness profiles. The residual risk with the PWHT control thermal method is that PWHT may not be able to reduce HAZ hardness sufficiently for short cooling time ($t_{8/5}$) type of welds, such as fillet welds for attachments that create high-hardness HAZ not sufficiently recoverable with PWHT. To support waiving the prequalification testing for the PWHT control thermal method, preheat is suggested for these types of welds, which increases the cooling time ($t_{8/5}$) to reduce the initial HAZ hardness these type welds would create.

A2.3.5.1.6 Local PWHT controls are included (as outlined in the ASCC section) for other forms of stress-assisted HSC damage such as SOHIC in the services associated with HF/H_2S exposure.

A2.3.5.2 Options for HAZ hardness reduction other than PWHT are available that require not only chemistry control but also the use of the Preproduction Weld Procedure HAZ Hardness Controls and Testing of 2.3.5.3 to confirm these two thermal control methods succeed in reducing the HAZ hardness.

A2.3.5.2.1 Cooling Time Control: The temperature/time cycles during welding have a significant effect on the mechanical properties (hardness, impact toughness) of the HAZ of a welded joint. These are particularly influenced by the metal thickness, the form of weld, the heat input during welding, and the preheating temperature. Generally, the cooling time ($t_{8/5}$) is chosen to characterize the temperature/time cycle of an individual weld run during welding and is the time taken, during cooling, for a weld run and its HAZs to pass through the temperature range from 800 °C to 500 °C (1,470 °F to 930 °F). For a given base metal chemistry, a preproduction test done at the shortest (minimum) cooling time (highest HAZ hardness potential) that passes the required HAZ hardness maximum can qualify for any production welding done at cooling times longer than this preproduction test.

The minimum cooling time determines the maximum hardness a certain base metal chemistry is able to achieve, as discussed in Appendix C. This is a function of thickness, joint configuration, preheat and welding heat input. Hence, a single minimum specified cooling time can be applied to a wide variety of production welding, provided the cooling time used in production is longer than the cooling time the preproduction testing has demonstrated.

A2.3.5.2.2 Temper bead welding uses heat from subsequent weld passes to temper the HAZ caused by previous weld passes.

(a) Proper sequencing of beads is imperative, especially in the cap layer, because this is where hard HAZ readings usually occur. Extra caution is advised and steps have been identified to ensure last pass tempering. It is important to avoid recreating a hard HAZ caused by a new weld bead too close to the base metal.

(b) ASME Boiler and Pressure Vessel Code, Section IX has specific procedures for qualifying temper bead weld procedures. In addition, this paragraph cautions that care should be taken in using some techniques (such as manual GTAW), for which it can be very difficult to reproduce tempering sequences, particularly in field situations without standard configuration. Manual GTAW has been used in shop temper bead repairs of castings, where control is more achievable.

(c) Minor weld repairs in base metal components are commonly performed in one layer containing one pass. This affords no opportunity for the bead tempering concept to work. Therefore, application of at least two layers (most likely consisting of one pass each) is required, and the top layer is not allowed to contact the base metal; otherwise it may form another hard HAZ.

(d) The final cap pass of temper bead welding may cause a high profile that can be removed by grinding, machining, or other low heat-input methods.

A2.3.5.3 Preproduction Weld Procedure HAZ Hardness Controls and Testing

A2.3.5.3.1 The effectiveness of the combination of base metal chemistry control and thermal method(s) (cooling time control and/or temper bead welding) used are validated by performing HAZ hardness testing during welding procedure qualification. Additional practices are needed to ensure that the hardness tests are representative of production weldments. Base metal, filler metals, and welding conditions used for the procedure qualification tests are discussed in subparagraphs, as compared to what is used for the production welding.

A2.3.5.3.2 The requirements for preproduction weld procedure hardness testing is waived if chemistry controls, PWHT and adequate preheat to ensure sufficiently slow $t_{8/5}$ conditions are all specified, as these have demonstrated the capability to consistently generate a HAZ of acceptable hardness.

A2.3.5.3.3 ASME Boiler and Pressure Vessel Code, Section IX methods provide a commonly accepted basis for welding procedure development, and this discusses supplementing the procedure qualification with the hardness verification of this standard.

A2.3.5.3.4 Preproduction hardness survey details are now provided in the new combined NACE MR0103 for any materials including the P1 materials of this standard.

A2.3.5.3.5 248 HV 10 is equivalent to 22 HRC, the commonly referenced maximum hardness level for carbon steel to resist SSC.

A2.3.5.3.6 Individual readings may indicate very small regions that are excessively hard. This paragraph provides a means for acceptance if the region is demonstrated to be very small by providing guidelines on how to retest the hard area.

A2.3.5.3.7 This paragraph discusses requirements for documentation with the weld procedure qualification and the resulting WPS, providing particulars of the hardness surveys performed, as these are performance proof to the user of the capability of the weld procedure to achieve soft HAZs.

A.2.3.5.4 Preproduction Weld Procedure Base Metal Chemistry Controls and Reporting

A2.3.5.4.1 The base metal chemistry of the procedure qualification specimen and the hardness test results are discussed here, and they are to be added to the PQR for future review and validation purposes. CE is not an absolute index of hardenability. A steel with a lower CE value can exhibit higher weld HAZ hardness than a steel with a higher CE value, and vice versa, depending on the cooling time. It may be very difficult to purchase and control to a tight single value. Therefore, it is reasonable to allow some flexibility in the CE value of a production base metal with respect to the CE value of the procedure qualification specimen. BS EN 288-9[39] provides the basis for the + 0.03 allowance used here.

A2.3.5.4.2 The base metal chemistry of the procedure qualification specimen is discussed with respect to the microalloying levels expected for the production welding.

A.2.3.5.5 Preproduction Weld Procedure Thermal-Related Controls and Reporting

A2.3.5.5.1 This paragraph discusses the requirements to calculate the cooling time in the weld procedure qualification if cooling time control is used. Production welding can be performed at cooling times no shorter than in the weld procedure qualification.

A2.3.5.5.2 Other processes, such as thermal cutting and tack welding, can also create hard HAZs. Appropriate preheating should be considered to mitigate this.

A2.3.5.5.3 Small fillet welds onto components may have short cooling times (low $t_{8/5}$ values), making them especially susceptible to creation of hard HAZs. Cooling time control as a thermal method for procedures that may entail this type of production welding are flagged to ensure that qualification of procedures consider these joint configurations.

A2.3.5.5.4 This paragraph describes a simple approach for cooling time control by estimating the heat input for the SMAW process. This technique is not precise, so user approval is recommended.

A2.3.5.5.5 This paragraph describes a simple approach for cooling time control by estimating the heat input for other welding processes. These techniques are not precise, so user approval is recommended.

A2.3.5.5.6 Fillet weld heat input and cooling time can be sensitive to the weld position, so these are critical variables to include in qualification tests. Because overhead welding creates the shortest cooling times, it has the ability to qualify for other higher heat-input positions.

A2.3.5.5.7 The extent of tempering by PWHT is a function of the time at temperature, so to ensure that adequate tempering in production welding occurs, PWHT used for production should have times and temperatures equal to or greater than those used in the procedure qualification, which includes metal thickness.

A2.3.5.5.8 Qualification with temper bead welding should be consistent with the requirements in this standard.

A2.4 In some cases, environmental cracking (both HSC and ASCC) has initiated from pre-existing weldment fabrication defects. Keeping defects to a minimum can be accomplished by doing thorough inspections upon fabrication to help reduce the onset of in-service damage. In addition, future defect inspections may be carried out to help users understand whether findings were generated by in-service exposure.

Appendix B
Rationale for Guidelines for Prevention of Alkaline Stress Corrosion Cracking (Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

The rationale statements in this nonmandatory appendix are numbered to correspond with the associated paragraphs in Section 3 of this standard plus use of the prefix B for clarity.

B3.1 The occurrence of ASCC requires three factors: a crack-inducing environment, a susceptible material, and a tensile stress exceeding a threshold value. Residual stresses from welding and/or forming are the most common sources of the tensile stress necessary for cracking. Residual tensile stresses in weldments are usually highest in the HAZ, but can sometimes extend up to 50 mm (2.0 in) away from the weld deposit. Hence, these are the most common locations for ASCC, with the cracks typically oriented parallel to the weld. PWHT is an effective method of preventing ASCC because it reduces residual stresses from welding.

B3.2 The higher temperature PWHT specified for ASCC reduction can impact properties of steel, particularly at the longer times for thicker plates. This paragraph flags the need for review to ensure the impact is not going to compromise strength or toughness properties.

B3.3 PWHT procedures, including temperatures, times, heating rates, and cooling rates, are given in the ASME Boiler and Pressure Vessel Code. PWHT requirements for preventing ASCC differ somewhat from those listed in the ASME Boiler and Pressure Vessel Code.

B3.4 It has been demonstrated that a higher PWHT temperature and a minimum hold time of one hour at temperature has been required to significantly reduce residual stresses.

B3.4.1 Paragraph warns that services that can cause SSC need to address HAZ hardness control requirements.

B3.5 Carbonate cracking has occurred in equipment that was stress relieved using the standard heat treatment procedures for other types of ASCC. This is believed to be attributable to a lower threshold stress for carbonate cracking. Field welds (especially in piping) have been found to be particularly vulnerable to carbonate cracking because of the difficulties often associated with field heat treatment (e.g., hold times and temperature control) and the presence of other local high stresses (e.g., bending stresses associated with elbows).

B3.6 This paragraph states that any welding can generate sufficient residual stresses to cause ASCC and warns that all welds, including temporary welds and arc strikes, require PWHT.

B3.6.1 External welds, even if not exposed to the alkaline environment, can generate sufficient through- wall residual stresses to trigger ASCC and hence are flagged to be included in PWHT requirements.

B3.7 Local PWHT may be used at times to meet the requirement to reduce residual stresses. There is considerable industry experience in performing these correctly to avoid inducing additional residual stresses, and these paragraphs (along with Appendix D) provide guidelines to successfully perform local PWHT.

B3.8 Mechanical stress-relief methods are not universally accepted as effective methods to prevent ASCC in these environments. A concern is that, although shot peening produces a surface layer with compressive stresses, this layer may eventually corrode away, exposing subsurface metal that still has residual tensile stresses.

B3.9 Alternative welding methods, such as temper bead welding and controlled-deposition welding, are not effective in preventing ASCC. These methods do not sufficiently reduce residual stress and therefore should not be considered in lieu of thermal stress relief.

B3.10 In some cases, environmental cracking (both HSC/SSC and ASCC) has initiated from pre-existing weldment fabrication defects, so these should be minimized.

Appendix C
Summary of Cooling Time ($t_{8/5}$) Concept (Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

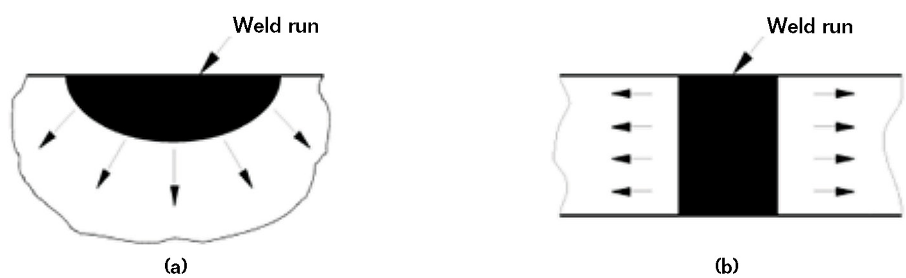
Determination of cooling time ($t_{8/5}$)

This information has been primarily derived from Annex D of BS EN 1011-2.[40]

There are three steps in determining $t_{8/5}$ for a given set of weld joint configuration and welding conditions. The first step is to determine the type of heat flow during welding, that is, whether the heat flow is either two- or three-dimensional. The second step is to calculate the heat input. The third step is to determine $t_{8/5}$ using either the calculation method or the graphical method.

Step 1—Determining two- or three-dimensional heat flow

The determination of the type of heat flow during welding, whether two- or three-dimensional, depends on the thickness of the components that impact the heat flow, as shown conceptually in Figure C1.



Key

(a) Three-dimensional heat flow. Relatively thick plates; plate thickness does not affect cooling time.
(b) Two-dimensional heat flow. Relatively thin plates; plate thickness has a decisive influence on cooling time.

Figure C1: Types of heat flow during welding.

Figure C2 is a diagram that provides information regarding the relationship between the transition thickness (d_t, in mm), heat input (Q, in kJ/mm), and preheat temperature (T_p, in °C), for any type of weld and any welding process. This diagram indicates whether the heat flow is two- or three-dimensional for any particular combination of plate thickness, heat input, and preheat temperature.

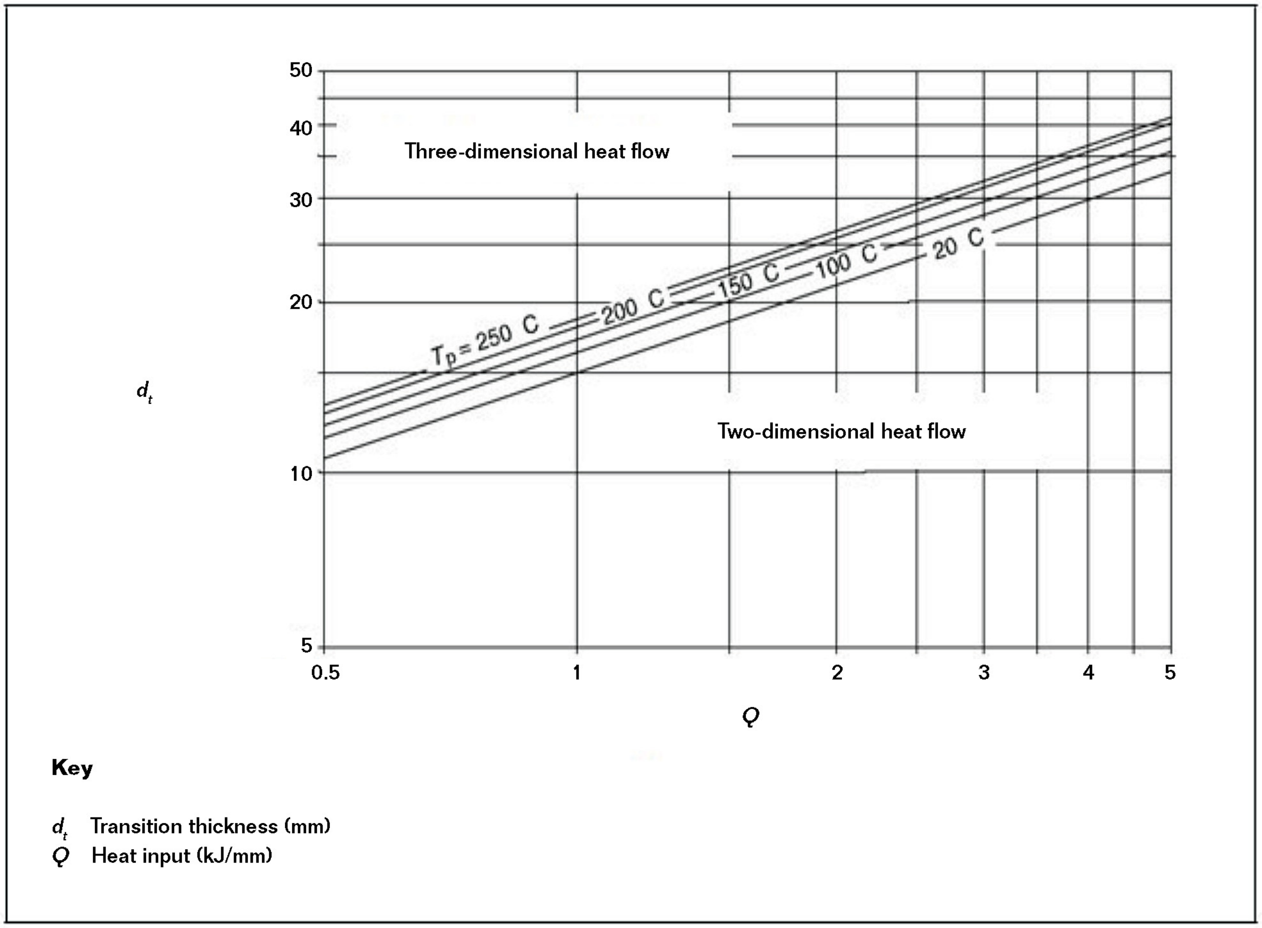


Figure C2: Transition plate thickness (d_t) from three-dimensional to two-dimensional heat flow as a function of heat input (Q) for different preheat temperatures (T_p).

Step 2—Calculating the heat input

The heat input (*Q*, in kJ/mm) can be calculated using Equation (C1):

$$Q = \varepsilon \times U \times (I/v) / 1{,}000 \text{ (kJ/mm)} \quad \text{(C1)}$$

Where:
Q = total welding heat input
U = welding voltage (V)
I = welding current (A)
v = travel speed (mm/s)
ε = thermal efficiency of the welding procedure
GTAW: ε = 0.48
SMAW: ε = 0.85
FCAW: ε = 0.80
GMAW: ε = 0.85
SAW: ε = 1.0

Step 3—Determining $t_{8/5}$ by the calculation method

The relationship between the welding conditions and $t_{8/5}$ can be described by equations that differentiate between two- and three-dimensional heat flow.

For three-dimensional heat flow in unalloyed and low-alloyed steels, $t_{8/5}$ can be determined using Equation (C2):

$$t_{8/5} = (6{,}700 - 5T_p) \times Q \times \left(\frac{1}{500 - T_p} - \frac{1}{800 - T_p}\right) \times F_3 \qquad \text{(C2)}$$

Where:
$t_{8/5}$ = cooling time
T_p = preheat temperature
Q = heat input (kJ/mm) calculated in accordance with Equation (C1)
F_3 = appropriate shape factor for three-dimensional heat flow from Table C1.

For two-dimensional heat flow in unalloyed and low-alloyed steels, $t_{8/5}$ can be determined using Equation (C3):

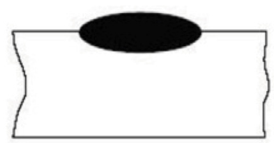
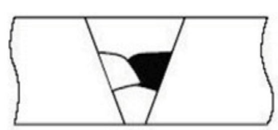
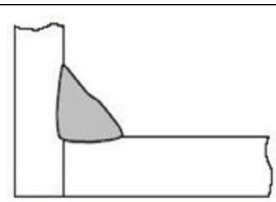
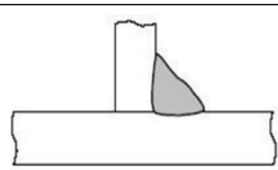
$$t_{8/5} = (4{,}300 - 4.3T_p) \times 10^5 \times \frac{Q^2}{d^2} \times \left[\left(\frac{1}{500 - T_p}\right)^2 - \left(\frac{1}{800 - T_p}\right)^2\right] \times F_2 \qquad \text{(C3)}$$

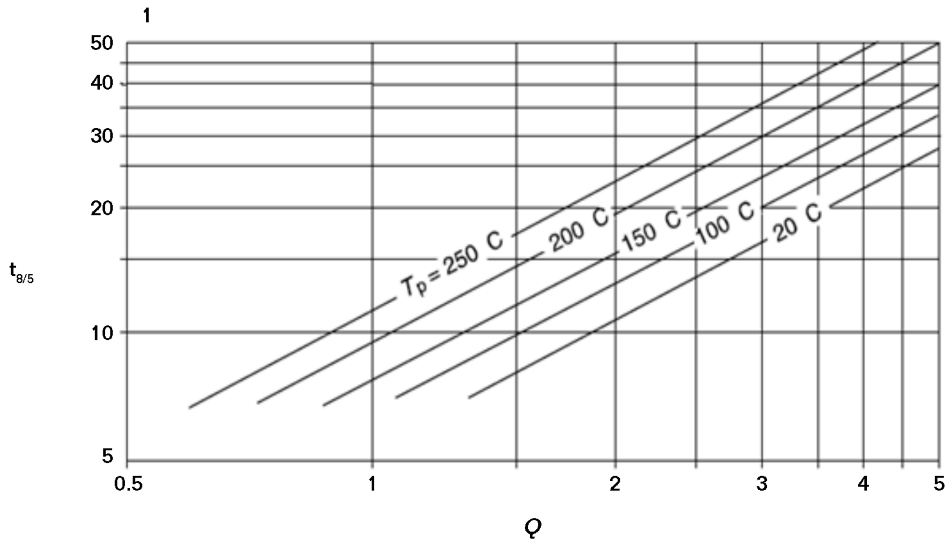
Where:
$t_{8/5}$ = cooling time
T_p = preheat temperature (C)
Q = heat input (kJ/mm) calculated in accordance with Equation (C1)
F_2 = appropriate shape factor for two-dimensional heat flow from Table C1.
d = thickness mm (Thickness selected by user to reflect heat sink of the weld.)

Step 3—Determining $t_{8/5}$ by the graphical method

The cooling time ($t_{8/5}$) can be determined using Figures C3 and C4, having first established the type of heat flow using Figure C1 and calculated the heat input (Q) using Equation (C1). Figures C3 and C4 can also be used to determine the heat input for a given cooling time.

Table C1
Shape Factors for Influence of the Form of Weld on $t_{8/5}$

		Shape Factor	
Form of Weld		F_2 Two-dimensional heat flow	F_3 Three-dimensional heat flow
Run on plate		1	1
Between runs in butt weld		0.9	0.9
Single run fillet weld on a corner joint		0.9 to 0.67	0.67
Single run fillet weld on a T-joint		0.45 to 0.67	0.67



Key

$t_{8/5}$ Cooling time
Q Heat input (kJ/mm)

Figure C3: Cooling time ($t_{8/5}$) for three-dimensional heat flow as a function of heat input (*Q*) for different preheat temperatures (T_p).

For three-dimensional heat flow, the relationship between the cooling time ($t_{8/5}$), the heat input (Q), and the preheat temperature (T_p), is given in Figure C3 for a run on plate weld with a shape factor of 1.0. Figure C3 is based on Equation (C2). If Figure C3 is applied to another form of weld, consideration should be given to the corresponding shape factor (F_3) given in Table C1. If the cooling time is to be determined for a particular combination of heat input and preheat temperature, the heat input should first be multiplied by F_3. If, however, the heat input is to be determined for a particular combination of cooling time and preheat temperature, it should be divided by F_3.

For two-dimensional heat flow, the relationship between the cooling time ($t_{8/5}$), the heat input (Q), and the preheat temperature (T_p), is given in Figure C4 for a run on plate weld with a shape factor of 1.0 for different plate thicknesses (d). Figure C4 is based on Equation (C3). If Figure C4 is applied to another form of weld, consideration should be given to the corresponding shape factor (F_2) given in Table C1. If the cooling time is to be determined for a particular combination of heat input and preheat temperature, the heat input should first be multiplied by $(F_2)^{1/2}$. If, however, the heat input is to be determined for a particular combination of cooling time and preheat temperature, it should be divided by $(F_2)^{1/2}$.

If, in the case of two-dimensional heat flow, the actual plate thickness does not correspond exactly to the plate thickness shown on one of the diagrams in Figure C4, the diagram closest to the actual plate thickness should be used. The cooling time should then be corrected in accordance with the plate thickness ratio. To do this, the cooling time taken from the diagram is multiplied by the square of the plate thickness taken from the diagram, and then divided by the square of the actual plate thickness.

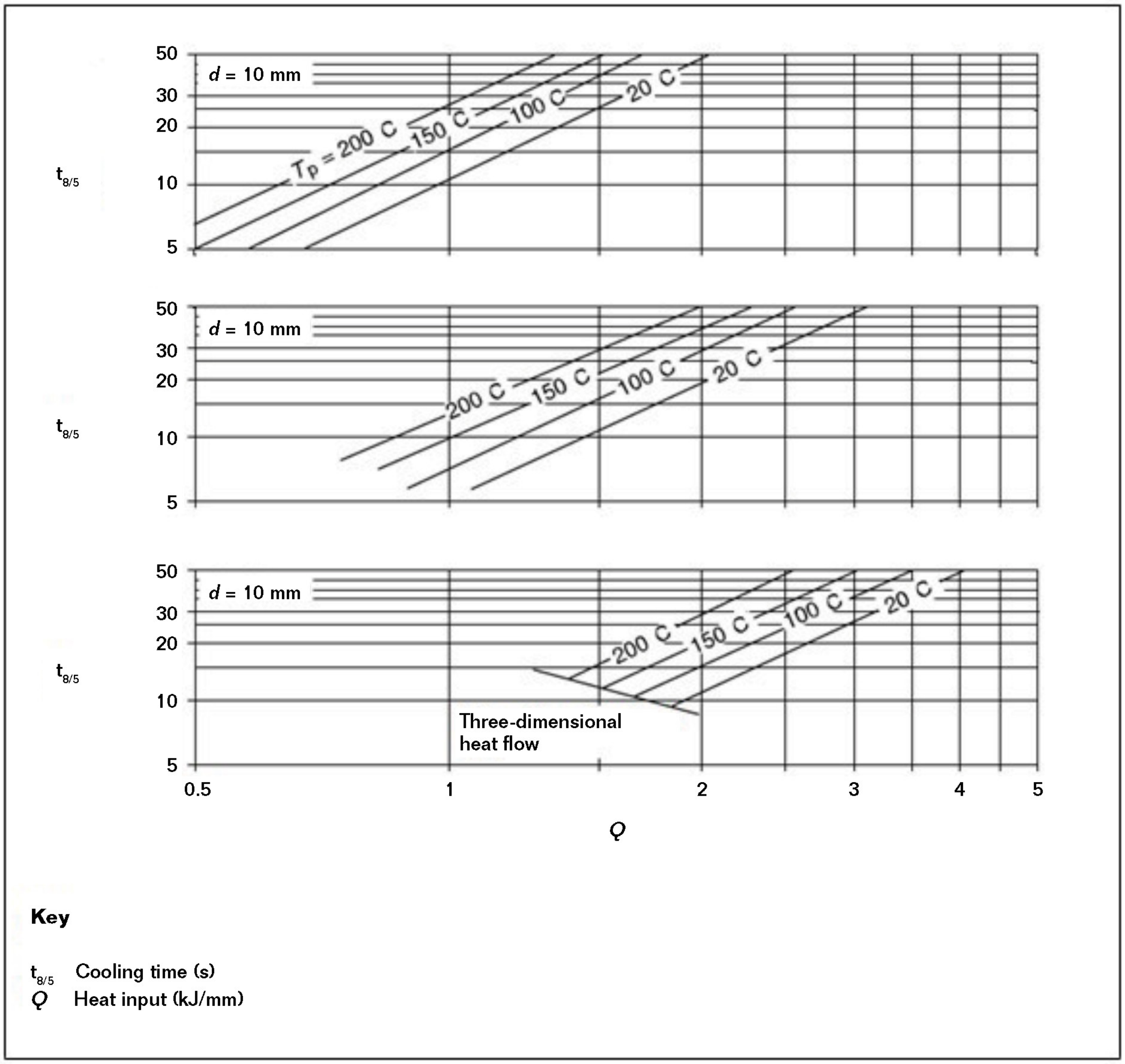


Figure C4: Cooling time ($t_{8/5}$) for two-dimensional heat flow as a function of heat input (*Q*) for different preheat temperatures (T_p) and plate thicknesses (*d*).

Appendix D
Guidance on Local PWHT
(Nonmandatory)

This appendix is considered nonmandatory, although it may contain mandatory language. It is intended only to provide supplementary information or guidance. The user of this standard is not required to follow, but may choose to follow, any or all of the provisions herein.

Terms used in Section 3 to define local PWHT for piping are from AWS D10.10 and are:

D1.1 Soak Band (SB)—The soak band consists of the through-thickness volume of metal, which is heated to the minimum, but does not exceed the maximum temperature. As a minimum, it should consist of the weld metal, HAZ, and a portion of the base metal adjacent to the weld being heated. The minimum SB width should be t or 2 in (50 mm), whichever is less, on either side of the weld, at its greatest width, where t = pipe wall thickness.

D1.2 Heated Band (HB)—The heated band consists of the surface area over which the heat source is applied to achieve the required temperature in the SB and limit induced stresses in the vicinity of the weld. It should consist of the SB plus any adjacent base metal necessary to both control the temperature and limit induced stress within the SB.

D1.2.1 The minimum recommend HB for PWHT is the larger of HB1 or HB2, as defined in Equations D1 and D2:

$$HB1 = SB + 4\sqrt{Rt} \tag{D1}$$

$$HB2 = H_i \frac{\left[\frac{OD^1 + OD^2}{2} + (ID)(SB)\right]}{OD} \tag{D2}$$

Where:
SB = soak band
R = pipe inside radius t = pipe wall thickness
H_i = ratio of heat source area to heat loss area OD = outside pipe diameter
ID = inside pipe diameter

D1.2.2 Use H_i = 5 for piping in the horizontal position up to 150 DN (6 NPS). Use H_i = 3 for piping in the horizontal position with pipe sizes over 150 DN (6 NPS). See Annex A of AWS D10.10 for further discussion of the H_i ratio.

D1.3 Gradient Control Band (GCB)—The gradient control band consists of the surface area over which insulation and/or supplementary heat source(s) are placed. It should encompass the SB, HB, and sufficient adjacent base metal such that the maximum permissible axial temperature gradient within the heated band is not exceeded.

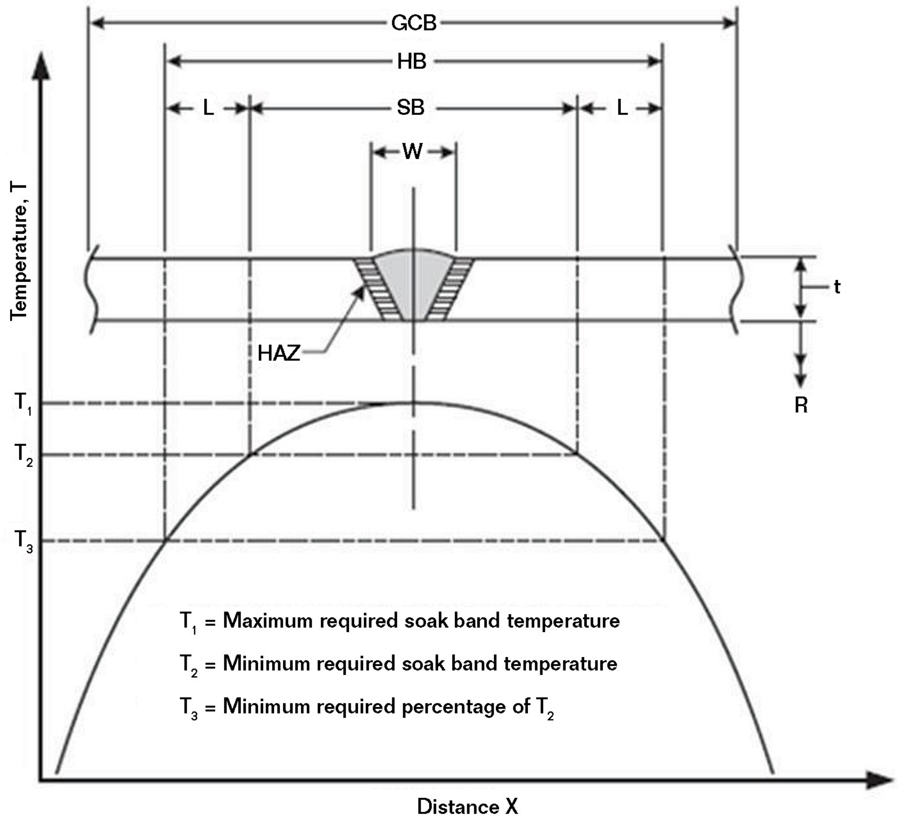
D1.3.1 The minimum gradient control band width and insulation characteristics should be as defined in Equation D3:

$$GCB = HB + 8\sqrt{Rt} \tag{D3}$$

Use Equation D3 to calculate the minimum GCB width, with a minimum R-value for the insulation of 2° to 4° F-ft^2-hr/BTU.

Figure D1 provides a schematic diagram which uses the terms recommended for PWHT from AWS D10.10. The terms are defined as:

WRC uses the same terminology, which is also used in Section 3 of this document. The equations for vessels, based on WRC 452, are shown in Section 3.7.



Nomenclature:

W	=	Widest width of butt or attachment weld.
HAZ	=	Heat-affected zone.
SB	=	Soak band (width of the volume of the material where the holding temperature equals or exceeds the minimum and equals or is below the maximum required. The minimum width is typically specified as W plus a multiple of t on each side of the weld).
L	=	Minimum distance over which the temperature may drop to a percentage of that at the edge of the soak band.
HB	=	Heated band (width of heat source).
GCB	=	Gradient control band (minimum width of insulation and/or gradient heat source).
t	=	Nominal thickness of piping, branch connection, nozzle neck, or attachment.
R	=	Inside radius of piping, branch connection, or nozzle neck.

Figure D1: Schematic diagram for description of local 360° band heating.[14]