

PART 2, ANNEX C CONTENTS

RISK-BASED INSPECTION METHODOLOGY PART 2—PROBABILITY OF FAILURE METHODOLOGY
ANNEX 2.C—DETERMINATION OF INTERNAL STRESS CORROSION CRACKING SUSCEPTIBILITIES⁵

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Risk-Based Inspection Methodology

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Annex 2.C—Determination of Internal Stress Corrosion Cracking Susceptibilities

2.C.1 Overview

2.C.1.1 Determination of Stress Corrosion Cracking Susceptibilities

Stress corrosion cracking susceptibilities should be based on assignments for each potential cracking mechanism using this document or as estimated by a corrosion specialist.

Screening questions are used to determine which of the cracking mechanism sections may apply. The applicable sections are used to determine conservative estimated cracking susceptibilities for potential cracking mechanisms. The screening questions listed in [Table 2.C.1.1](#) are used to select the applicable thinning mechanism.

2.C.1.2 Tables

Table 2.C.1.1—Screening Questions for Stress Corrosion Cracking Damage

Screening Questions	Action
ACSCC Cracking 1. Carbon or low alloy steel? 2. Is free water present in the process stream (including initial condensing condition)? 3. Is the pH > 7.5?	If Yes to all, proceed to Section 2.C.2
Amine Cracking 1. Carbon or low alloy steel? 2. Is the operating temperature > 100 °F (51 °C)? 3. Is equipment exposed to acid gas treating amines (MEA, DEA, DIPA, or MDEA)?	If Yes to both, proceed to Section 2.C.3
Caustic SCC 1. Carbon or low alloy steel? 2. Process containing caustic? 3. Is the operating temperature > 100 °F (51 °C)?	If Yes to both, proceed to Section 2.C.4
CISCC 1. Austenitic stainless steel or nickel-based alloy? 2. Is free water present containing chlorides in the process stream (including initial condensing condition)? 3. Temperature between 75°F (23.90 °C) and 345°F (173.90 °C) and a pH > 2.5 and ≤ 10.5	If Yes, proceed to Section 2.C.5
Hydrofluoric Acid – HIC/SOHIC-HF 1. Carbon or low alloy steel? 2. Process containing HF?	If Yes, proceed to Section 2.C.6
Hydrofluoric Acid – HSC 1. Carbon or low alloy steel? 2. Process containing HF?	If Yes, proceed to Section 2.C.7

Table 2.C.1.3—SCC DFs—All SCC Mechanisms

S_{VI}	Inspection Effectiveness												
	E	1 Inspection				2 Inspections				3 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	10	8	3	1	1	6	2	1	1	4	1	1	1
50	50	40	17	5	3	30	10	2	1	20	5	1	1
100	100	80	33	10	5	60	20	4	1	40	10	2	1
500	500	400	170	50	25	300	100	20	5	200	50	8	1
1,000	1,000	800	330	100	50	600	200	40	10	400	100	16	2
5,000	5,000	4,000	1,670	500	250	3,000	1,000	250	50	2,000	500	80	10
S_{VI}	Inspection Effectiveness												
	E	4 Inspections				5 Inspections				6 Inspections			
		D	C	B	A	D	C	B	A	D	C	B	A
0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	1	1	1	1	1	1	1	1	1	1	1	1	1
10	10	2	1	1	1	1	1	1	1	1	1	1	1
50	50	10	2	1	1	5	1	1	1	1	1	1	1
100	100	20	5	1	1	10	2	1	1	5	1	1	1
500	500	100	25	2	1	50	10	1	1	25	5	1	1
1,000	1,000	200	50	5	1	100	25	2	1	50	10	1	1
5,000	5,000	1,000	250	25	2	500	125	5	1	250	50	2	1

2.C.2 SCC DF—Alkaline Carbonate Stress Corrosion Cracking (ACSCC)

2.C.2.1 Scope

The DF calculation for components subject to ACSCC is covered in this section.

2.C.2.2 Description of Damage

ACSCC is the common term applied to surface breaking cracks that occur at or near carbon and low alloy steel welds under the combined action of tensile stress and in the presence of alkaline water containing moderate to high concentrations of carbonate ions (CO_3^{2-}).

On a macroscopic level, ACSCC typically propagates parallel to the weld in the adjacent base material, but can also occur in the weld deposit or HAZs.

At times surface inspection results of ACSCC may be mistaken for SSC or SOHIC, but further review will show that ACSCC is usually located further from the toe of the weld into the residual stress field of the base material and can contain multiple parallel cracks. When cracking is in the weld metal, the pattern of cracking observed on the steel surface is sometimes described as a “spider web” of small cracks, which often initiate at or interconnect with weld-related flaws that serve as local stress risers. Finally, from the microscopic perspective the cracking is characterized by predominantly intergranular, oxide-filled cracks similar in appearance to ACSCC found in caustic and amine services.

Historically, ACSCC has been most prevalent in fluid catalytic cracking unit (FCCU) main fractionator overhead condensing and reflux systems, the downstream wet gas compression system, and the sour water systems emanating from these areas. Based upon recent survey results, sour water strippers with side-pump around designs, CO₂ removal facilities for hydrogen manufacturing units and delayed coker light ends units have been added to the list of affected units. There have also been cases of ACSCC in nonrefining industries. In all instances, both piping and vessels are affected.

Assuming the presence of an alkaline water phase containing H₂S, three key parameters are used to assess the susceptibility of steel fabrications to ACSCC: pH of the water, carbonate ion concentration of the water, and the residual stress level of the exposed carbon or low alloy steel.

- a) pH—Typically, pHs are greater than 7.5 and process streams that are lower in H₂S or higher in NH₃ causing higher pHs will be more susceptible to this form of ACSCC. Although H₂S is often present, no threshold level has been established; no evidence exists to indicate cyanides or polysulfides have an impact.
- b) Carbonates—Plants that generate more carbonate ions in the water will be more susceptible to ACSCC.
- c) Residual Stresses—ACSCC appears to be very susceptible to residual stress levels so that welded structures and cold worked structures will be susceptible.

Studies have concluded that the electrochemical potential of the water can be used to assess the likelihood of ACSCC. However, accurate measurement in a field environment is difficult. Therefore, further discussion of the electrochemical potential is outside the scope of this document.

With regard to mitigation techniques, the application of a post-fabrication stress-relieving heat treatment (e.g. PWHT) is the most commonly used method of preventing ACSCC in carbon and low alloy steels. A heat treatment of about 1200 °F to 1225 °F (649 °C to 663 °C) in accordance with WRC 452 or AWS D1010 is considered effective to minimize residual stresses. The heat treatment requirements apply to all exposed welds as well as any external welds with HAZs in contact with the service environment. Other mitigation techniques include: process barriers (either organic or metallic), alloy upgrades (solid or clad 300 series, Alloy 400 or other corrosion-resistant alloys), effective water washing, and inhibitor injection.

2.C.2.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the process environment contains water at pH > 7.5 in any concentration, then the component should be considered for evaluation for susceptibility to ACSCC. Another trigger would be changes in FCCU feed sulfur and nitrogen contents particularly when feed changes have reduced sulfur (low sulfur feeds or hydroprocessed feeds) or increased nitrogen ^[44].

2.C.2.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the ACSCC DF are provided in [Table 2.C.2.1](#).

2.C.2.5 Basic Assumptions

The main assumption in determining the DF for ACSCC is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. cold work, welding and heat treatment). A severity index is assigned based on the susceptibility parameter

If cracks are detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.2.6 Determination of the DF

2.C.2.6.1 Overview

A flow chart of the steps required to determine the DF for ACSCC is shown in [Figure 2.C.2.1](#). The following sections provide additional information and the calculation procedure.

2.C.2.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for ACSCC. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FG](#), [Table 2.FG.89.24](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.2.6.3 Calculation of the DF

The following procedure may be used to determine the DF for ACSCC; see [Figure 2.C.2.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.2.1](#) and [Table 2.C.2.2](#) based on the pH of the water, and CO₃ concentration, and knowledge of whether the component has been PWHT'd.

NOTE a High susceptibility should be used if cracking is confirmed to be present.
- b) STEP 2—Based on the susceptibility in STEP 1, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- c) STEP 3—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 10.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- e) STEP 5—Determine the base DF for ACSCC, D_{fB}^{ACSCC} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Calculate the escalation in the DF based on the time in service since the last inspection using the *age* from STEP 3 and [Equation \(2.C.1\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{ACSCC} = \min\left(D_{fB}^{ACSCC} \cdot (\max(\text{age}, 1.0))^{1.1}, 5000\right) \quad (2.C.1)$$

2.C.2.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{ACSCC} is the DF for ACSCC

D_{fB}^{ACSCC} is the base value of the DF for ACSCC

S_{VI} is the Severity Index

2.C.2.8 References

See References [10], [13], [34], [36], [39], [40], [41], [42] (see Appendix D), [43], [44], and [45] in [Part 2, Section 2.2](#).

2.C.2.9 Tables

Table 2.C.2.1—Data Required for Determination of the DF—ACSCC

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section. This type of cracking may be sporadic and may grow rapidly depending on subtle changes in the process conditions. Periodic monitoring of process pH and CO_3^{2-} in FCC alkaline waters should be done to determine cracking susceptibility.
Presence of water (Yes or No)	Determine whether free water is present in the component. Consider not only normal operating conditions but also start-up, shutdown, process upsets, etc.
Presence of H ₂ S in the water (Yes or No)	Determine whether H ₂ S is present in the water phase in this component. If analytical results are not readily available, it should be estimated by a knowledgeable process engineer.
pH of water	Determine the pH of the water phase. If analytical results are not readily available, it should be estimated by a knowledgeable process engineer.
CO_3^{2-} concentration in water	Determine the carbonate ion concentration of the water phase present in this component. If analytical results are not readily available, it should be estimated by a knowledgeable process engineer.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
PWHT	Effective heat treatment to minimize residual stresses of carbon and low alloy steel weldments.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.2.2—Susceptibility to Cracking—ACSCC

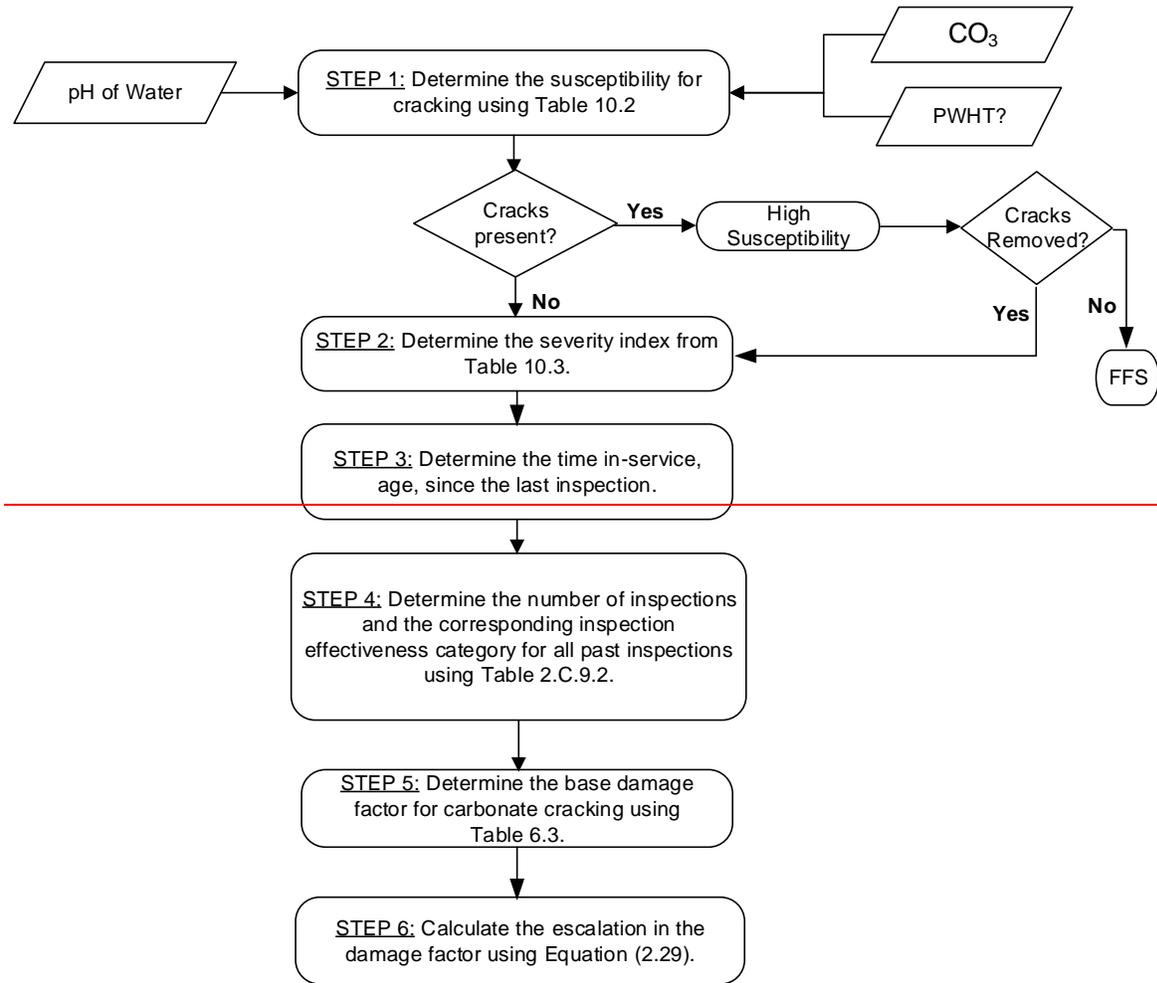
pH	Susceptibility to Cracking as a Function of Residual Stress and CO_3^{2-} Concentration in Water ¹				
	Effective PWHT	Unknown or Ineffective PWHT and/or Possible Cold Working			
	$CO_3^{2-} \leq 10,000$ ppm ^[2]	$CO_3^{2-} < 10$ ppm	$10 \leq CO_3^{2-} < 100$ ppm	$100 \leq CO_3^{2-} < 1,000$ ppm	$CO_3^{2-} \geq 1,000$ ppm ²
≤ 7.5	None	None	None	None	None
7.5 – 8.0	None	None	None	Low	Low
8.0 – 8.5	None	None	Low	Medium	High
8.5 – 9.0	None	Low	Medium	High	High
9.0 – 9.5	None	Medium	High	High	High
> 9.5	None	High	High	High	High

NOTE 1: Traditional alkalinity titration methods (PM alkalinity) are not effective for measurement of CO_3^{2-} in sour water.

NOTE 2: In refinery processes, the concentration of CO_3^{2-} is typically less than 10,000 ppm.

NOTE 3: These values were developed based upon industry survey which did not include a standardized means of determining the carbonate ion concentration. The owner-operator and corrosion specialist should exercise caution when selecting these values.

2.C.2.10 Figures



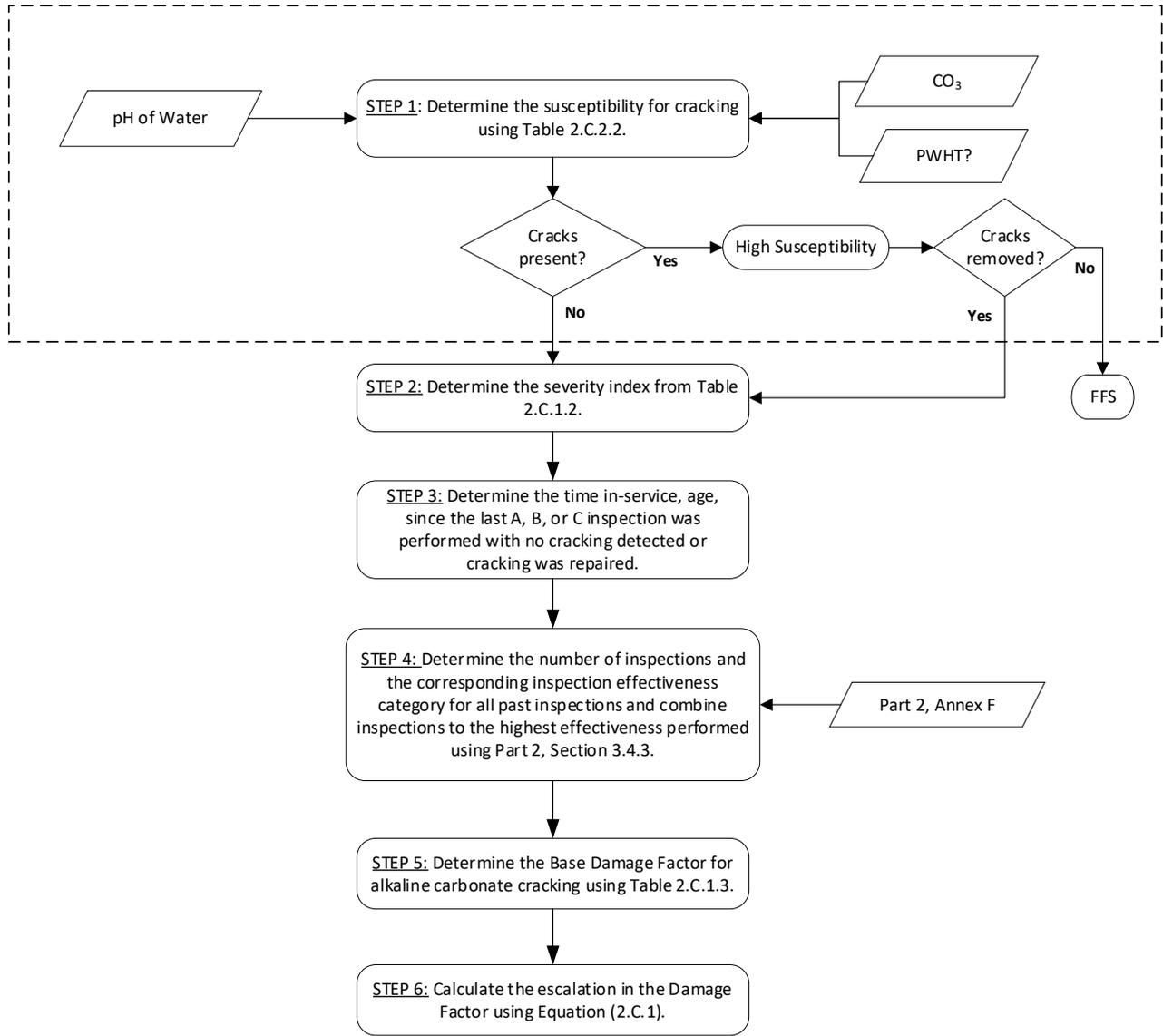


Figure 2.C.2.1—Determination of the ACSCC DF

2.C.3 SCC DF—Amine Cracking

2.C.3.1 Scope

The DF calculation for components subject to amine cracking is covered in this section.

2.C.3.2 Description of Damage

Amine cracking is defined as cracking of a metal under the combined action of tensile stress and corrosion in the presence of an aqueous alkanolamine solution at elevated temperature. The cracking is predominately intergranular in nature and typically occurs in carbon steels as a network of very fine, corrosion-product-filled cracks. Low alloy ferritic steels are also susceptible to amine cracking. Amine cracking is typically observed in amine treating units that use aqueous alkanolamine solutions for removal of acid gases such as H₂S and CO₂ from various gas or liquid hydrocarbon streams.

Four available parameters are used to assess the susceptibility of steel fabrications to amine cracking. They are the type of amine, amine solution composition, metal temperature, and level of tensile stress.

Results of a NACE survey indicate that amine cracking is most prevalent in monoethanolamine (MEA) and diisopropanolamine (DIPA) units and to a somewhat lesser extent in diethanolamine (DEA) units. Cracking is much less prevalent in methyldiethanolamine (MDEA), sulfinol, and diglycolamine (DGA) units.

Studies have concluded that the cracking occurs in a narrow range of electrochemical potential, which is very dependent upon the amine solution composition. Carbonate is a critical solution contaminant, and other contaminants such as chlorides, cyanides, etc. have been shown to affect cracking susceptibility. Despite this mechanistic understanding, the electrochemical potential of in-service components may not be readily available. Amine concentration is a factor in cracking susceptibility in MEA solutions, where cracking susceptibility has been shown to be higher in the 15 % to 35 % concentration range. There is not sufficient understanding of this relationship in other amine solutions, but it is noteworthy that cracking susceptibility is lower in MDEA and sulfinol units that typically utilize higher concentration amine solutions.

With regard to the amine solution composition, cracking typically occurs in the lean alkanolamine solution that is alkaline and contains very low levels of acid gases. Amine cracking does not occur in fresh amine solutions, i.e. those that have not been exposed to acid gases. Amine cracking is not likely to occur in rich alkanolamine solutions, which contain high levels of acid gases. In rich amine solutions, other forms of cracking are far more prevalent.

Amine cracking susceptibility is generally higher at elevated temperatures. A key consideration is the actual metal temperature and not just the normal process temperature. Cracking has occurred in components that normally operate at low temperatures, but were heat traced or steamed out prior to water washing to remove residual amine solution.

As-welded or cold worked carbon and low alloy steel fabrications are susceptible to amine cracking because of the high level of residual stress remaining after fabrication by these methods. Application of a post-fabrication stress-relieving heat treatment (e.g. PWHT) is a proven method of preventing amine cracking. A heat treatment of about 1150 °F (621 °C) for 1 hour per inch of thickness (1 hour minimum) is considered an effective stress-relieving heat treatment to prevent amine cracking of carbon steel.

It should be noted that other forms of cracking have been reported in amine units. In most cases, cracking occurred in components exposed to rich alkanolamine solutions and have typically been forms of hydrogen damage such as SSC, HIC, and SOHIC. These are not included here but are dealt with in other sections of this Part.

2.C.3.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the process environment contains acid gas treating amines (MEA, DEA, DIPA, MDEA, etc.) in any concentration, then the component should be evaluated for susceptibility to amine cracking.

2.C.3.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the amine cracking DF are provided in [Table 2.C.3.1](#).

2.C.3.5 Basic Assumptions

The main assumption in determining the DF for amine cracking is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

If cracking is detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks or arrays of cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.3.6 Determination of the DF

2.C.3.6.1 Overview

A flow chart of the steps required to determine the DF for amine cracking is shown in [Figure 2.C.3.1](#). The following sections provide additional information and the calculation procedure.

2.C.3.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting amine cracking. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FE, Table 2.FE.89.1](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.3.6.3 Calculation of the DF

The following procedure may be used to determine the DF for amine cracking; see [Figure 2.C.3.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.3.1](#).

NOTE a High susceptibility should be used if cracking is confirmed to be present.

- b) STEP 2—Based on the susceptibility in STEP 3, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- c) STEP 3—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 7.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).

- e) STEP 5—Determine the base DF for amine cracking, D_{fB}^{amine} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Calculate the escalation in the DF based on the time in service since the last inspection using the *age* from STEP 3 and [Equation \(2.C.2\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{amine} = \min\left(D_{fB}^{amine} \cdot (\max(\text{age}, 1.0))^{1.1}, 5000\right) \quad (2.C.2)$$

2.C.3.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{amine} is the DF for amine cracking

D_{fB}^{amine} is the base value of the DF for amine cracking

S_{VI} is the Severity Index

2.C.3.8 References

See References [23], [24], [25], [26], [27], [28], and [29] in [Part 2, Section 2.2](#).

2.C.3.9 Tables

Table 2.C.1—Data Required for Determination of the DF—Amine Cracking

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Amine solution composition	Determine what amine solution composition is being handled in this component. Fresh amine has not been exposed to H ₂ S or CO ₂ . Lean amine contains low levels of H ₂ S or CO ₂ . Rich amine contains high levels of H ₂ S or CO ₂ . For components exposed to both lean and rich amine solutions (i.e. amine contactors and regenerators), indicate lean.
Maximum process temperature, °F (°C)	Determine the maximum process temperature in this component.
Steam out? (Yes or No)	Determine whether the component has been steamed out prior to water flushing to remove residual amine.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

2.C.3.10 Figures

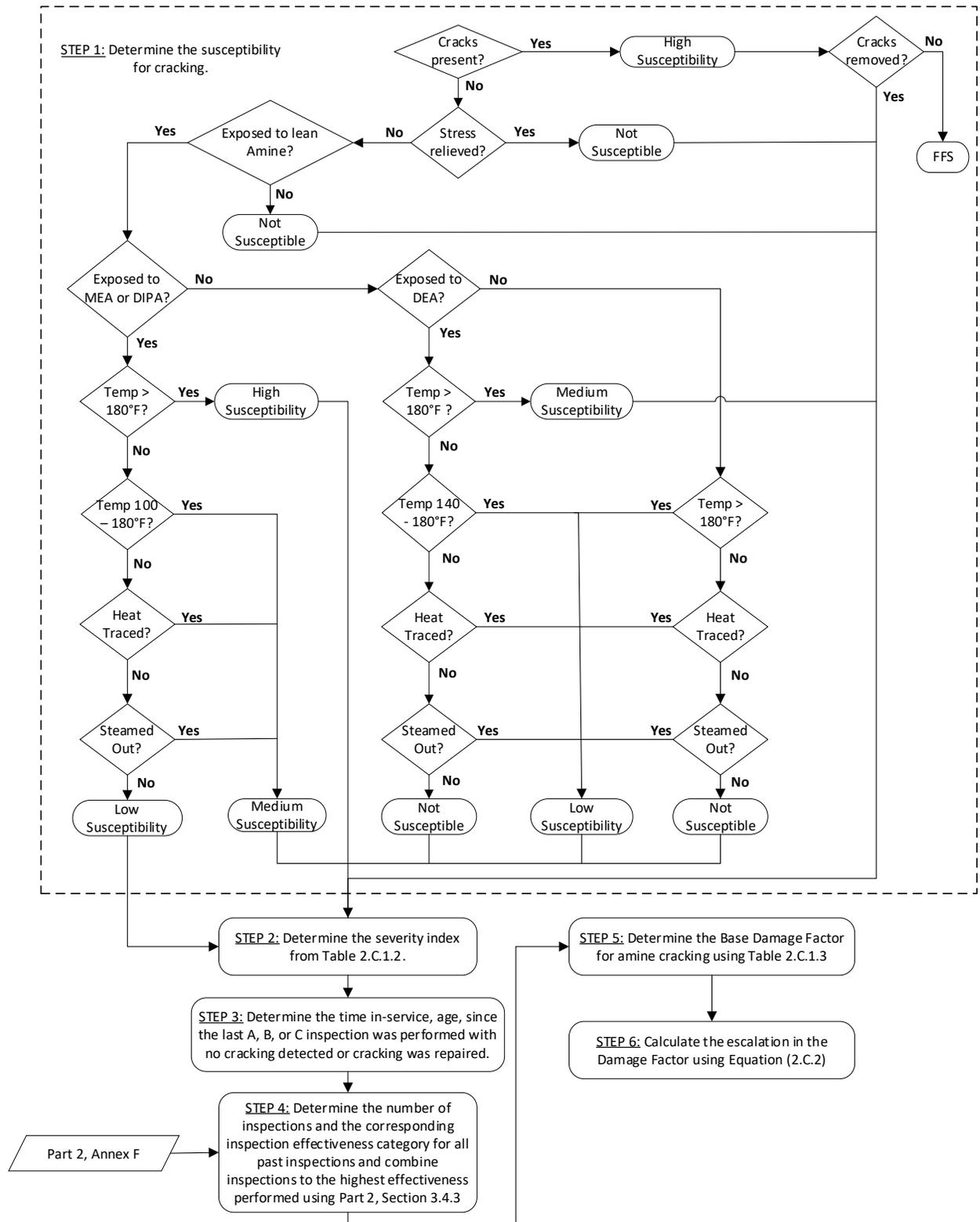


Figure 2.C.1—Determination of the Amine Cracking DF

2.C.4 Stress Corrosion Cracking (SCC) DF—Caustic Cracking

2.C.4.1 Scope

The DF calculation for components subject to caustic cracking is covered in this section.

2.C.4.2 Description of Damage

Caustic cracking is defined as the cracking of a material under the combined action of tensile stress and corrosion in the presence of sodium hydroxide (NaOH) at elevated temperature. The cracking is predominantly intergranular in nature and typically occurs as a network of fine cracks in carbon steels. Low alloy ferritic steels have similar cracking susceptibility.

There are three key parameters that determine susceptibility of steel fabrications to caustic cracking. They are caustic concentration, metal temperature, and level of tensile stress. Industry experience indicates that some caustic cracking failures occur in a few days, while many require prolonged exposure of one or more years.

Increasing the caustic concentration or metal temperature accelerates the cracking rate. The susceptibility to caustic cracking of carbon steel is shown in [Figure 2.C.4.1](#). Caustic cracking of carbon steel is not anticipated at metal temperatures less than about 115 °F (46 °C). In the 115 °F to 180 °F (46 °C to 82 °C) range, cracking susceptibility is a function of the caustic concentration. Above 180 °F (82 °C), cracking susceptibility is a function of the caustic concentration. Above 180 °F (82 °C), cracking is highly likely for all concentrations above about 5 wt %. Although cracking susceptibility is significantly lower in caustic solutions with less than 5 % concentration, presence of high temperatures (approaching boiling) can cause locally higher concentrations that would increase cracking susceptibility. Notable case histories of this phenomenon include caustic cracking of distillation columns when caustic is added to the column for pH control, and caustic cracking of boiler feed water components or piping bolts when gasket leaks expose the bolts to feed water.

With regard to temperature, the key consideration is the actual metal temperature, and not just the normal process temperature. There are many case histories of caustic cracking of components operating at ambient temperature that were heat traced or subject to a steam out while still containing caustic. As-welded or as-bent carbon and low alloy steel assemblies are susceptible to caustic cracking because of the high level of residual stress remaining after fabrication by these methods.

Application of a post-fabrication stress-relieving heat treatment (e.g. PWHT) is a proven method of preventing caustic cracking. A heat treatment of about 1150 °F (621 °C) for 1 hour per inch of thickness (1 hour minimum) is considered an effective stress-relieving heat treatment to prevent caustic cracking of carbon steel.

2.C.4.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the process environment contains caustic in any concentration, then the component should be evaluated for susceptibility to caustic cracking.

2.C.4.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the caustic cracking DF are provided in [Table 2.C.4.1](#).

2.C.4.5 Basic Assumptions

The main assumption in determining the DF for caustic cracking is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the

susceptibility parameter, a Severity Index is assigned that is a measure of the susceptibility of the component to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

A high susceptibility should be assigned if cracking was detected during a previous inspection whether the crack was repaired or left in place based upon FFS evaluation. The high susceptibility should be maintained until subsequent inspections of adequate effectiveness reveal no cracking detected. Cracking susceptibility can then be reassigned by a corrosion specialist. Cracks or arrays of cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.4.6 Determination of the DF

2.C.4.6.1 Overview

A flow chart of the steps required to determine the DF for caustic cracking is shown in [Figure 2.C.4.2](#). The following sections provide additional information and the calculation procedure.

2.C.4.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting caustic cracking.

Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FE, Table 2.FE.89.3](#). The number and category of the highest effective inspection will be used to determine the DF.

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.4.6.3 Calculation of the DF

The following procedure may be used to determine the DF for caustic cracking; see [Figure 2.C.4.2](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.4.2](#).

NOTE: High susceptibility should be used if cracking is confirmed to be present.

- b) STEP 2—Based on the susceptibility in STEP 1, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- c) STEP 3—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 6.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- e) STEP 5—Determine the base DF for caustic cracking, $D_{fB}^{caustic}$, using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Calculate the escalation in the DF based on the time in service since the last inspection using the *age* from STEP 3 and [Equation \(2.C.3\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{caustic} = \min\left(D_{fB}^{caustic} \cdot (\max(\text{age}, 1.0))^{1.1}, 5000\right) \quad (2.C.3)$$

2.C.4.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

$DF_f^{caustic}$ is the DF for caustic cracking

$DF_{fB}^{caustic}$ is the base value of the DF for caustic cracking

S_{VI} is the Severity Index

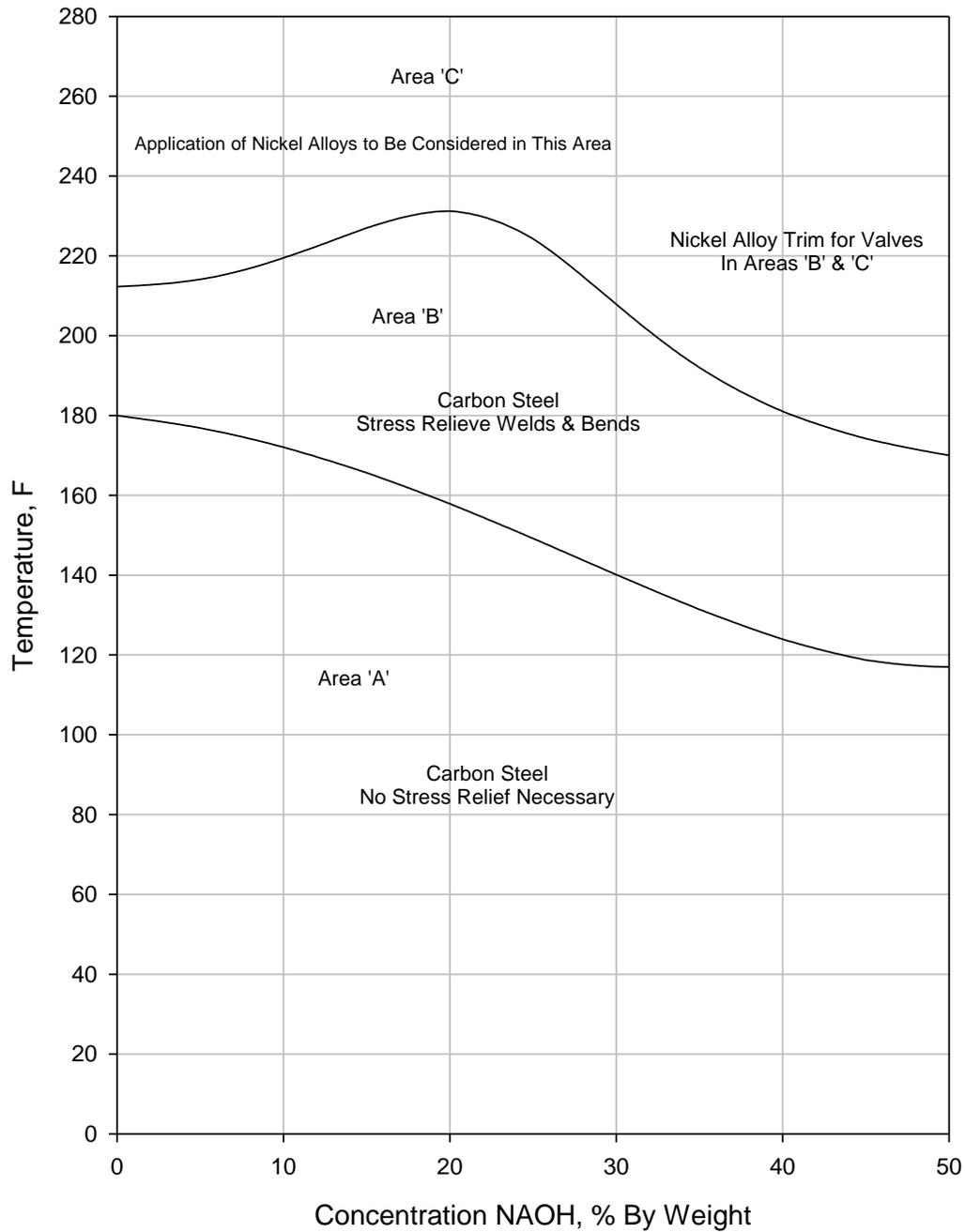
2.C.4.8 References

See References [19], [20] (pp. 583–587), [21], and [22] in [Part 2, Section 2.2](#).

2.C.4.9 Tables

Table 2.C.4.1—Data Required for Determination of the DF—Caustic Cracking

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
NaOH concentration (%)	Determine the concentration of the caustic solution being handled in this component. Take into account whether heating or flashing of water produces higher concentration.
Maximum process temperature, °F (°C)	Determine the maximum process temperature in this component. Consider local heating due to mixing if at a caustic injection point.
Steam out? (Yes or No)	Determine whether the component has been steamed out prior to water flushing to remove residual caustic.
Time since last SCC inspection (years)	Use inspection history to determine years since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

2.C.4.10 Figures**Figure 2.C.4.1—Susceptibility of Caustic Cracking in Carbon Steel**

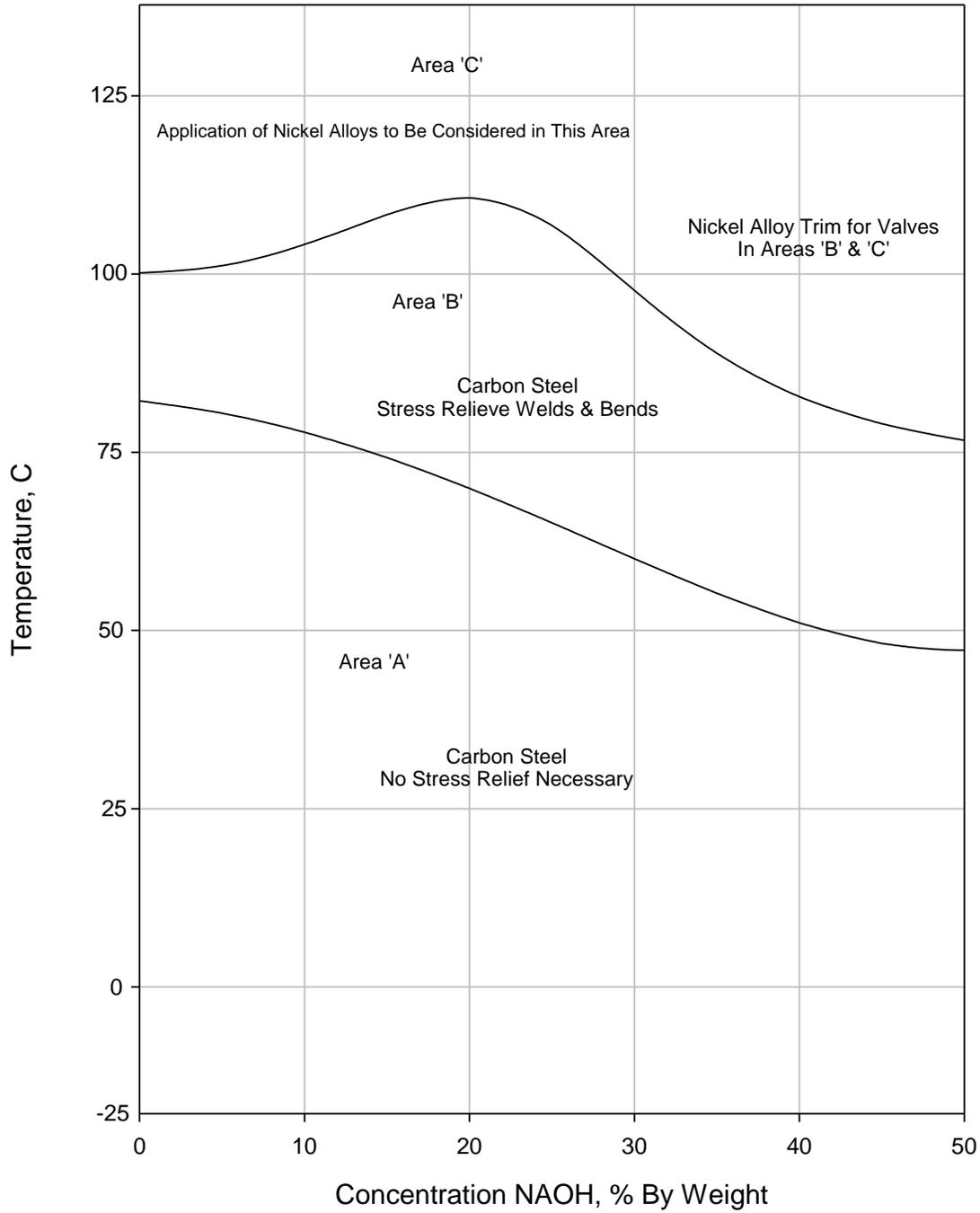
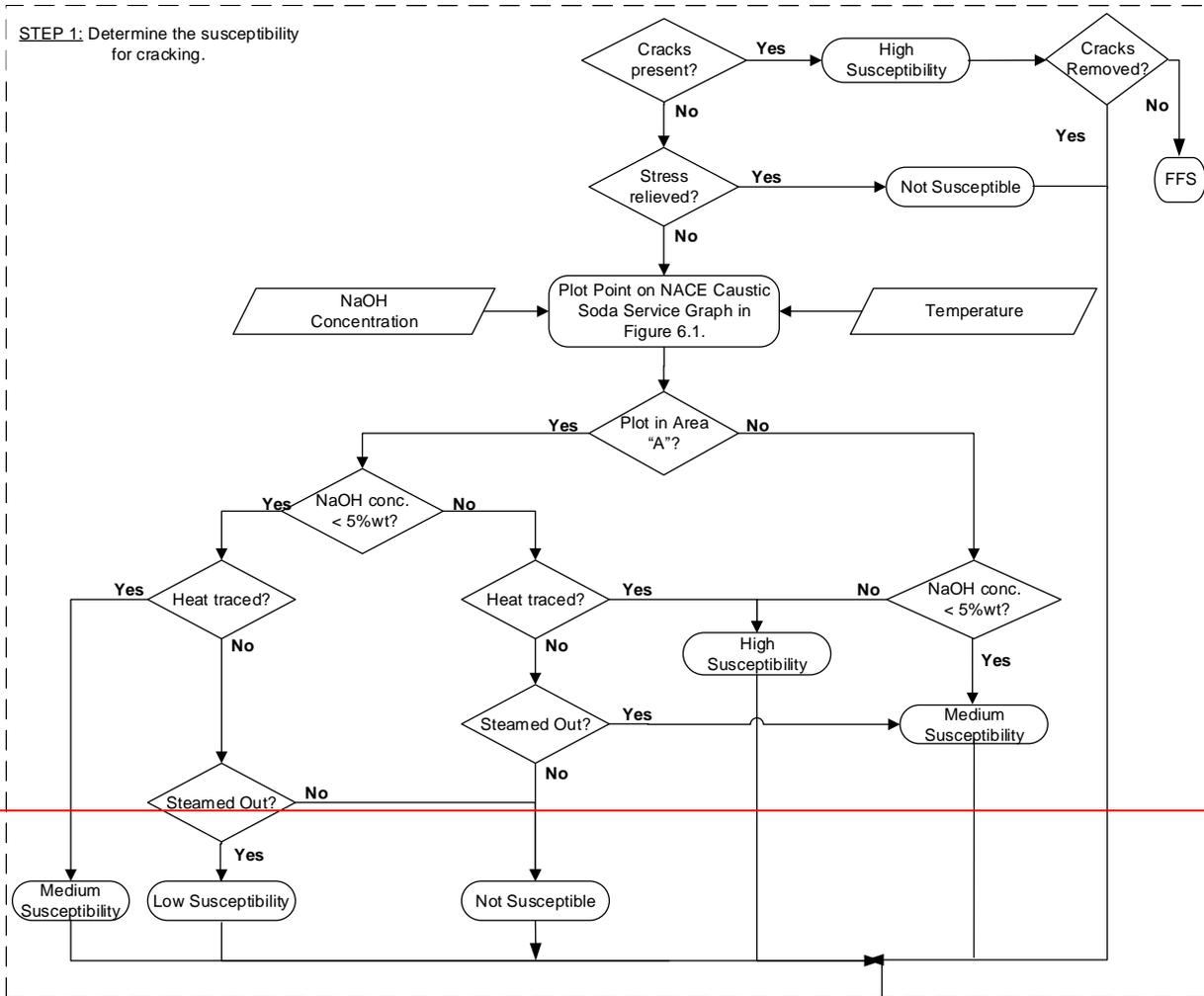


Figure 2.C.4.1M—Susceptibility of Caustic Cracking in Carbon Steel



STEP 2: Determine the severity index from Table 6.2.

STEP 3: Determine the time in-service, age, since the last inspection.

STEP 4: Determine the number of inspections and the corresponding inspection effectiveness category for all past inspections using Table 2.C.9.3.

STEP 5: Determine the base damage factor for caustic cracking using Table 6.3.

STEP 6: Calculate the escalation in the damage factor using Equation (2.25).

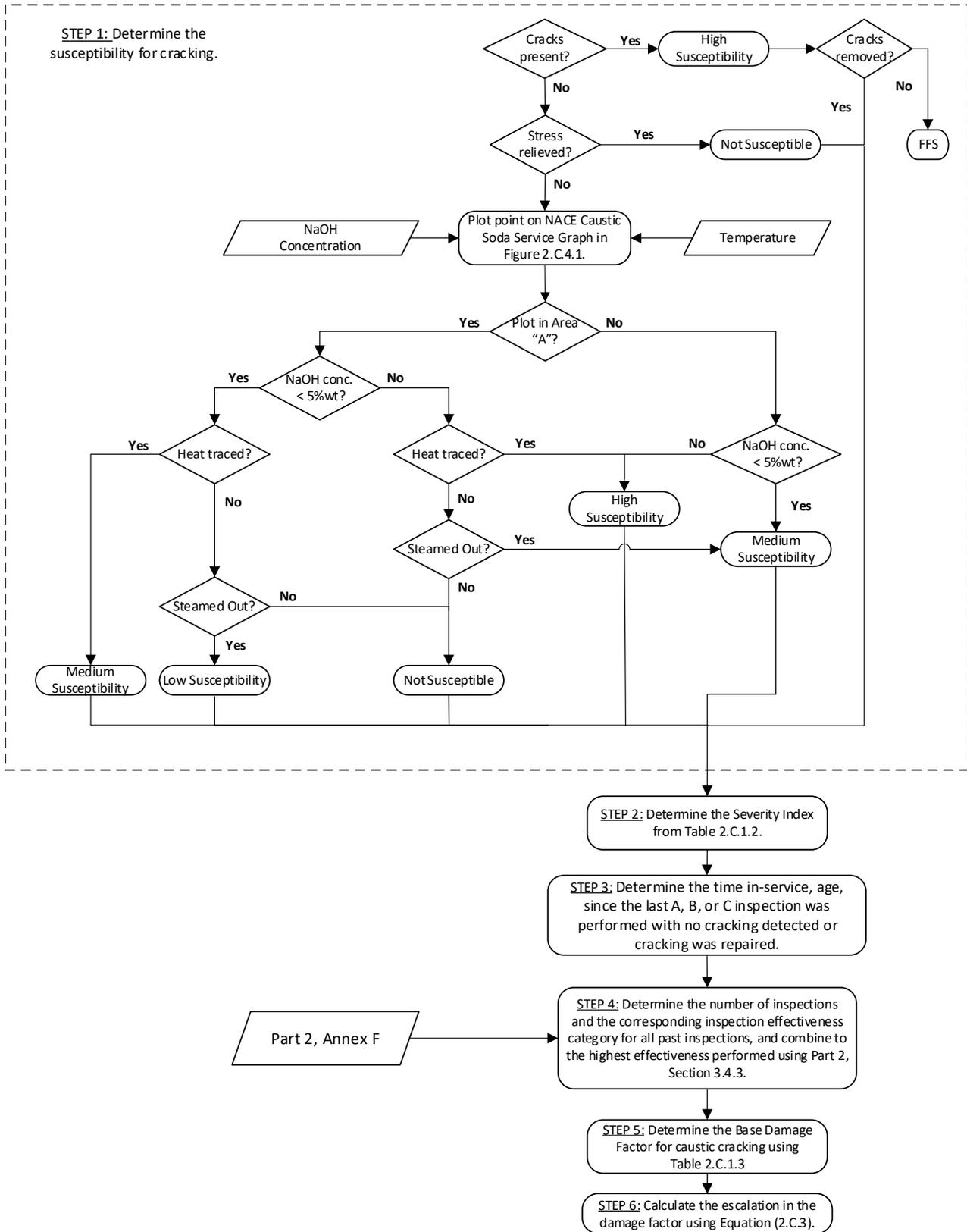


Figure 2.C.4.2—Determination of the Caustic Cracking DF

2.C.5 SCC DF—Chloride Stress Corrosion Cracking (CISCC)

2.C.5.1 Scope

The DF calculation for components subject to CISCC is covered in this section.

2.C.5.2 Description of Damage

CISCC of austenitic stainless steels can occur in a chloride-containing aqueous environment. The susceptibility to CISCC is dependent on the concentration of the chloride ions, the temperature, and other factors outlined in the basic data in [Table 2.C.5.1](#). It should be emphasized that the chloride concentration in water within wetting and drying conditions can be higher than the concentration measured in the bulk solution due to partial water vaporization. Such vaporization can increase CISCC susceptibility. CISCC is more likely to occur at metal temperatures above 66 °C (150 °F).

Chlorides are found in many processes. The following factors are major influences on the probability of chloride-containing solutions to cause CISCC.

- a) Aqueous conditions are present.
- b) pH and temperature are the most influential factors in CISCC.
- c) Below a temperature of 77°F (25°C), cracking is virtually unknown. But extremes of Cl concentration, stress, and/or pH can cause cracking.
- d) CISCC is more likely to occur at metal temperatures above 140°F (60°C).
- e) Above 302°F (150°C), it has been generally accepted that liquid water is not present unless the system is under pressure.
- f) Below a pH of 2.5, the material corrodes/pits rather than cracking as the cause of failure.
- g) Above a pH of 10.5, only extremely high Cl concentrations in the presence of with oxidizers and elevated stress and temperature may experience cracking. In these conditions, cracking may be better characterized as caustic cracking.
- h) In industrial processes, chlorides may concentrate even in low bulk process Cl ppm concentrations.
- i) In laboratory tests, concentrations of 10 ppm Cl are sufficient to influence cracking in higher temperature solutions at pH of 6 and below. Oxidizers may also increase the susceptibility to CISCC in these regions.
- j) Higher chloride content can influence the tendency toward cracking in the less extreme regions of pH and temperature.
- k) In the High susceptibility region of pH and temperature, a very low concentrations of chlorides may result in Cl cracking. Austenitic stainless steels should not be used in this region.

Examples of common sources of chlorides in refineries and petrochemical plants are as follows.

- 1) Chloride salts from crude oil, produced water, and ballast water.
- 2) Water condensed from a process stream (process water).
- 3) Boiler feed water and stripping system.
- 4) Catalyst.
- 5) Insulation.
- 6) Residue from hydrotest water and other manufacturing operations.
- 7) Fumes from chemicals containing either organic or inorganic chlorides.

CISCC may occur during in-service or shutdown periods, if chloride-containing solutions are present at temperatures greater than 140 °F (60 °C). In addition, internal CISCC may occur as a result of exposure to wash water or fire water.

CISCC is typically transgranular and branched. The greatest susceptibility to CISCC is exhibited by austenitic stainless steels with an 8% Ni content (300 series stainless steel). Greater resistance to CISCC is experienced in material with lower or higher 8% Ni contents. Duplex stainless steels with low nickel contents are more resistant to CISCC, as are alloys with greater than 42% Ni.

2.C.5.3 Screening Criteria

If all of the following are true, then the component should be evaluated for susceptibility to CISCC.

- a) The component's material of construction is an austenitic stainless steel.
- b) The component is exposed or potentially exposed to chlorides and water. Also consider upsets, hydrotest water remaining in component, and cooling tower drift (consider both under insulation and process conditions).
- c) The presence of aqueous conditions.
- d) The operating temperature is between 75°F (23.90 °C) and 345°F (173.90 °C) and a pH > 2.5 and ≤ 10.5 (If pH is ≤ 2.5, go to HCl corrosion for damage rate determination).

2.C.5.4 Required Data

The basic component data required for analysis are given in [Table 2.C.1.1](#), and the specific data required for determination of the CISCC DF are provided in [Table 2.C.5.1](#).

2.C.5.5 Basic Assumptions

The main assumption in determining the DF for CISCC is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

If cracks are detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.5.6 Determination of the DF

2.C.5.6.1 Overview

A flow chart of the steps required to determine the DF for CISCC is shown in [Figure 2.C.5.1](#). The following sections provide additional information and the calculation procedure.

2.C.5.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for CISCC.

Examples of inspection activities that are both intrusive (requires entry into the equipment) and non-intrusive (can be performed externally) are provided in [Annex 2.FG](#), [Table 2.FG.89.46](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.5.6.3 Calculation of the DF

The following procedure may be used to determine the DF for CISCC; see [Figure 2.C.5.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.5.1](#) and [Table 2.C.5.2](#). If cracking is confirmed to be present, set the susceptibility to High and skip to STEP 4. If cracking is present and was not removed, a FFS evaluation is recommended to ensure that the component is suitable for continued service.
- b) STEP 2—Determine the susceptibility using [Table 2.C.5.2](#) or [Figure 2.C.5.1](#).
- c) STEP 3—Modify the base susceptibility in STEP 2 with the susceptibility modifier from [Table 2.C.5.3](#).
- d) STEP 4—Determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#) using susceptibility from STEP 1 (if cracking is present) or STEP 3.
- e) STEP 5—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- f) STEP 6—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 12.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- g) STEP 7—Determine the base DF for CISCC, D_{fB}^{CISCC} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 6 and the Severity Index, S_{VI} , from STEP 4.
- h) STEP 8—Calculate the escalation in the DF based on the time in service since the last inspection using the *age* from STEP 5 and [Equation \(2.C.4\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{CISCC} = \min\left(D_{fB}^{CISCC} \cdot (\max(\text{age}, 1.0))^{1.1}, 5000\right) \quad (2.C.4)$$

2.C.5.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{CISCC} is the DF for CISCC

D_{fB}^{CISCC} is the base value of the DF for CISCC

S_{VI} is the Severity Index

2.C.5.8 References

See References [10], [58], [59], [60], [61], [62], [63], and [64] in [Part 1, Section 2.2](#).

2.C.5.9 Tables

Table 2.C.5.1—Data Required for Determination of the DF—CISCC

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Cl ⁻ concentration of process water (ppm)	Determine the bulk Cl ⁻ concentration of the water phase. If unknown, the default value for ppm is >1000. Consider Cl ⁻ content of any water present in system (i.e. hydrotest, boiler feed, steam). Also, consider the possibility of concentration of Cl ⁻ by evaporation or upset conditions.
Operating temperature, °F (°C)	Determine the highest operating temperature expected during operation (consider normal and non-normal operating conditions).
pH of process water	Determine pH of the process water. High pH solutions with high chlorides generally are not as susceptible to cracking as low pH solution with chlorides.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.5.2 – Susceptibility to CISCC

Temperature, (°F)	Susceptibility to Cracking as a Function of pH																			
	< 2.5 ⁵	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	≥ 11.0	
< 30	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
30 - 52.5	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
52.5 - 75	None	Low	Low	Low	Low	None	None	None	None											
75 - 97.5	None	Medium	Medium	Medium	Low	None	None	None	None	None										
97.5 – 120	None	High	High	Medium	Low	Low	Low	Low	None	None	None	None	None							
120 - 142.5	None	High	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	None	None						
142.5 - 165	None	High	Medium	Low	Low	None														
165 - 187.5	None	High	Low	Low	None															
187.5 - 210	None	High	Low	Low	None															
210 - 232.5	None	High	Low	Low	None															
232.5 - 255	None	High	Low	Low	None															
255 - 277.5	None	High	Low	Low	None															
277.5 - 300	None	High	Low	Low	None															
300 - 322.5	None	High	Low	Low	None															
322.5 - 345	None	High	Low	Low	None															
>345	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None

Notes:
 NOTE 1: Decrease one susceptibility category if chloride concentration is < 10 ppm
 NOTE 2: Decrease one susceptibility category if oxygen concentration is < 90 ppb
 NOTE 3: Increase one susceptibility category if chloride concentration is > 100 ppm
 NOTE 4: Increase one susceptibility category if deposits are present where chlorides may concentrate
 NOTE 5: No cracking susceptibility, go to HCl corrosion to determine corrosion rate

Table 2.C.5.2M – Susceptibility to CISCC

Temperature, (°C)	Susceptibility to Cracking as a Function of pH																			
	< 2.5 ¹	2.5	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	≥ 11.0	
< -1.1	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
-1.1 - 11.39	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None
11.39 - 23.89	None	Low	Low	Low	Low	None	None	None	None											
23.89 - 36.39	None	Medium	Medium	Medium	Low	None	None	None	None	None										
36.39 - 48.89	None	High	High	Medium	Low	Low	Low	Low	Low	None	None	None	None							
48.89 - 61.39	None	High	Medium	Medium	Medium	Medium	Low	Low	Low	Low	Low	Low	None	None						
61.39 - 73.89	None	High	Medium	Low	Low	None														
73.89 - 86.39	None	High	Low	Low	None															
86.39 - 98.89	None	High	Low	Low	None															
98.89 - 111.39	None	High	Low	Low	None															
111.39 - 123.89	None	High	Low	Low	None															
123.89 - 136.39	None	High	Low	Low	None															
136.39 - 148.89	None	High	Low	Low	None															
148.89 - 161.39	None	High	Low	Low	None															
161.39 - 173.89	None	High	Low	Low	None															
>173.89	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None	None

NOTE 1: Decrease one susceptibility category if chloride concentration is < 10 ppm
 NOTE 2: Decrease one susceptibility category if oxygen concentration is < 90 ppb
 NOTE 3: Increase one susceptibility category if chloride concentration is > 100 ppm
 NOTE 4: Increase one susceptibility category if deposits are present where chlorides may concentrate
 NOTE 5: No cracking susceptibility, go to HCl corrosion to determine corrosion rate

Table 2.C.5.3— Determination of the Susceptibility Modifier for CISCC

Environmental Variable	Susceptibility Modifier
Cl < 10 ppm	-1
Oxygen < 90 ppb	-1
Cl > 100 ppm	+1
Deposits	+1

NOTE: CISCC susceptibility value is determined by adjusting the base susceptibility with the susceptibility modifiers.

2.C.5.10 Figures

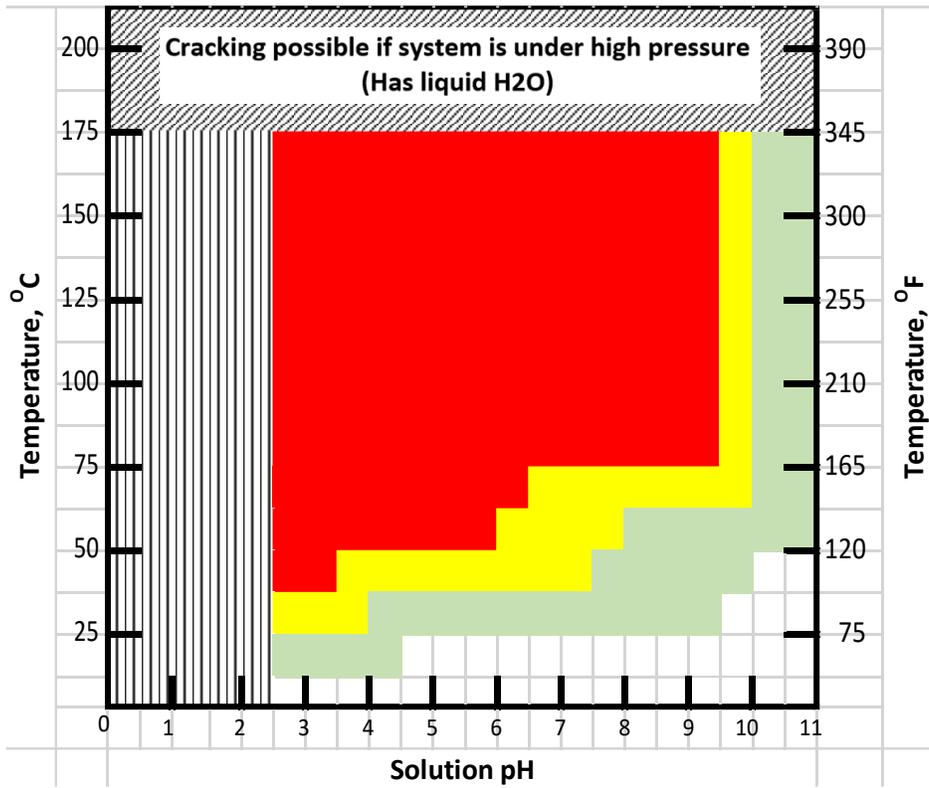
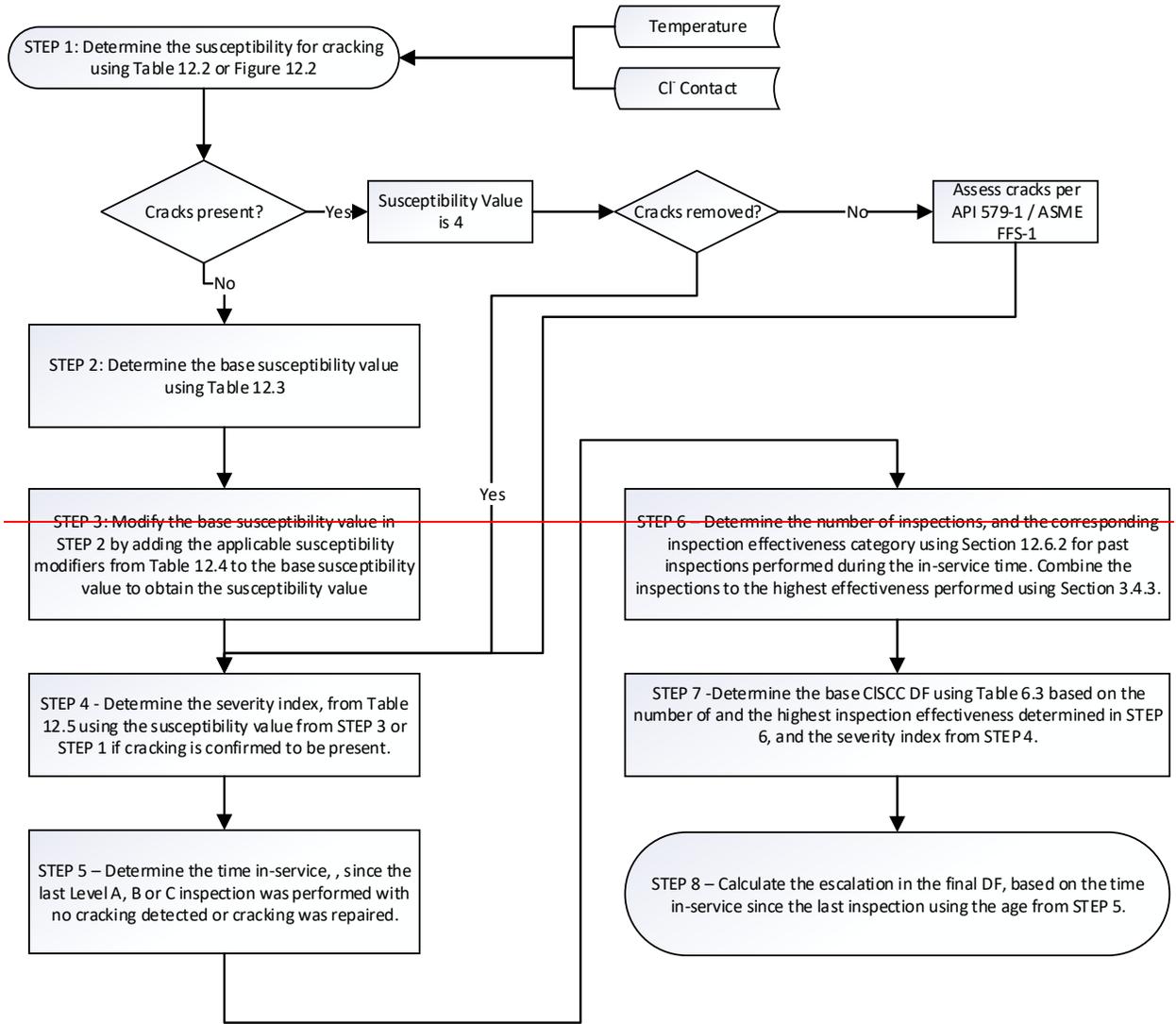


Chart Key

Base Susceptibility for CISCC
None
Low
Medium
High
Pitting Corrosion - Go to HCl corrosion

Figure 2.C.5.1 Determination of CISCC Susceptibility



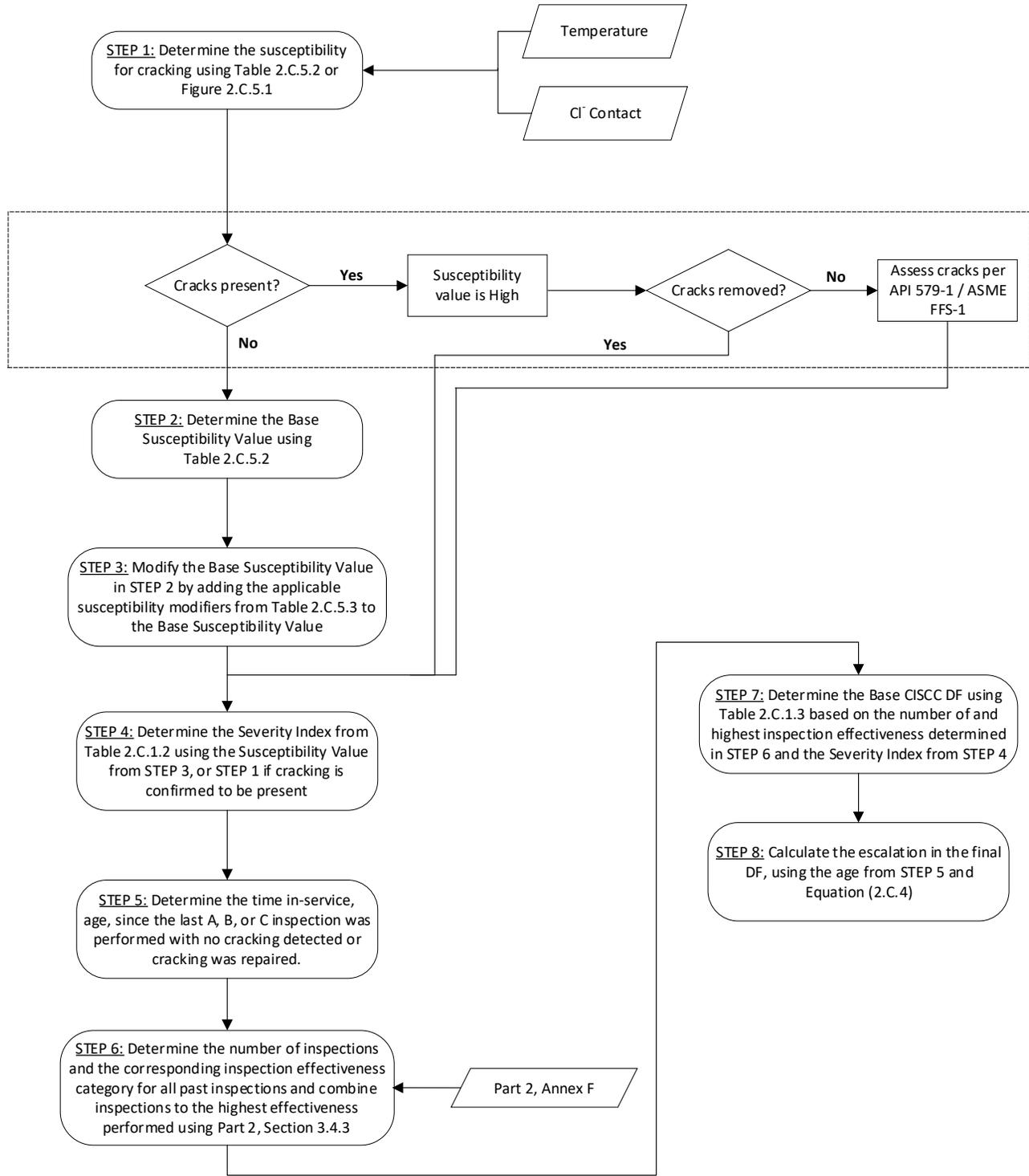


Figure 2.C.5.2—Determination of the CISCC DF

2.C.6 SCC DF—Hydrogen-induced Cracking and Stress-oriented Hydrogen-induced Cracking in Hydrofluoric Acid Services (HIC/SOHIC-HF)

2.C.6.1 Scope

The DF calculation for components subject to HIC/SOHIC-HF is covered in this section.

2.C.6.2 Description of Damage

HIC is defined as stepwise internal cracks that connect adjacent hydrogen blisters on different planes in the metal or to the metal surface. No externally applied stress is needed for the formation of HIC. The driving force for the cracking is high stress at the circumference of the hydrogen blisters caused by buildup of internal pressure in the blisters. Interaction between these high stress fields tends to cause cracks to develop that link blisters on different planes in the steel.

The source of hydrogen in the steel is the corrosion reaction with either wet hydrogen sulfide (covered in [Section 2.C.9](#)) or HF. HF is used in HF alkylation units at concentrations in the range 96 % to 99 % and greater concentration of HF in water. Exposure of carbon steel to aqueous or anhydrous HF may result in HIC/SOHIC.

Hydrogen blisters are planar hydrogen-filled cavities formed at discontinuities in the steel (i.e. voids, inclusions, laminations, sulfide inclusions). Blisters most often occur in rolled plate steels with a banded microstructure resulting from elongated sulfide inclusions. Susceptibility to hydrogen blistering, and therefore HIC, is primarily related to the quality of the plate steel (i.e. the number, size, and shape of the discontinuities). In this regard, the sulfur content of the steel is a primary material parameter. Reducing the sulfur content of the steel reduces the susceptibility to blistering and HIC. Addition of calcium or REMs for sulfide inclusion shape control is generally beneficial.

SOHIC is defined as a stacked array of blisters joined by HIC that is aligned in the through-thickness direction of the steel as a result of high localized tensile stresses. SOHIC is a special form of HIC that usually occurs in the base material adjacent to the HAZ of a weld, where there are high residual stresses from welding. As with HIC, plate steel quality is a key parameter of SOHIC susceptibility. In addition, reduction of residual stresses by PWHT can reduce, but may not eliminate, the occurrence and severity of SOHIC.

2.C.6.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the component is exposed to HF in any concentration, then the component should be evaluated for susceptibility to HIC/SOHIC-HF.

2.C.6.4 Required Data

The basic component data required for analysis are given in [Table 2.C.1.1](#), and the specific data required for determination of the HIC/SOHIC-HF DF are provided in [Table 2.C.6.1](#).

2.C.6.5 Basic Assumptions

The main assumption in determining the DF for HIC/SOHIC-HF is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

Piping fabricated from wrought components of conventional steels [i.e. A53, A106, API 5L (not including 5LX), A234, A105, etc.] should be considered to have a low susceptibility to HIC/SOHIC-HF. For components fabricated from rolled and welded plate steel, the susceptibility should be determined using [Table 2.C.6.4](#). The susceptibility of the steel to blistering is directly related to the cleanliness of the steel. It should be recognized that blistering is not a damage mechanism that will lead to a leak path unless it is accompanied by HIC leading to the surface. Blistering does pose a danger to mechanical integrity particularly when it approaches a weld that contains sufficient residual stresses to drive the HIC to the surfaces. It is this last case, the most severe situation that is considered when determining the susceptibility to HIC/SOHIC-HF.

If cracks are detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.6.6 Determination of the DF

2.C.6.6.1 Overview

A flow chart of the steps required to determine the DF for HIC/SOHIC-HF is shown in [Figure 2.C.6.1](#). The following sections provide additional information and the calculation procedure.

2.C.6.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for HIC/SOHIC-HF. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FG](#), [Table 2.FG.89.9](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.6.6.3 Adjustment for On-line Monitoring

In addition to inspection, on-line monitoring using hydrogen probes and/or key process variables provides a better understanding of HIC/SOHIC-HF susceptibility. The advantage of on-line monitoring is that process changes affecting SCC susceptibility can be detected before significant cracking occurs. This earlier detection could permit more timely action to decrease the POF. For HIC/SOHIC-HF, an on-line monitoring factor of 2 is applied if either hydrogen probes or monitoring of key process variables are used. If both hydrogen probes and monitoring of key process variables are used, an on-line monitoring factor of 4 is applied.

2.C.6.6.4 Calculation of the DF

The following procedure may be used to determine the DF for HIC/SOHIC-HF; see [Figure 2.C.6.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.6.1](#) and [Table 2.C.6.2](#) based on the material of construction and knowledge of whether the component was subject to PWHT.

NOTE a High susceptibility should be used if cracking is confirmed to be present.

- b) STEP 2—Based on the susceptibility in STEP 1, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#). In determining the susceptibility, it should be noted that if HF is present in any concentration, then the component is potentially susceptible to HIC/SOHIC-HF.
- c) STEP 3—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.

- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 14.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- e) STEP 5—Determine the base DF for HIC/SOHIC-HF, $D_{fB}^{HIC/SOHIC-HF}$, using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Determine the on-line adjustment factor, F_{OM} , from [Table 2.C.6.2](#).
- g) STEP 7—Calculate the final DF accounting for escalation based on the time in service since the last inspection using the *age* from STEP 3 and [Equation \(2.C.5\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions. The equation also applies the adjustment factor for on-line monitoring.

$$D_f^{HIC/SOHIC-HF} = \min \left(\frac{D_{fB}^{HIC/SOHIC-HF} \cdot (\max(\text{age}, 1.0))^{1.1}}{F_{OM}}, 5000 \right) \quad (2.C.5)$$

2.C.6.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

$D_f^{HIC/SOHIC-HF}$ is the DF for HIC/SOHIC-HF

$D_{fB}^{HIC/SOHIC-HF}$ is the base value of the DF for HIC/SOHIC-HF

F_{OM} is the on-line monitoring adjustment factor

S_{VI} is the Severity Index

2.C.6.8 References

See References [10], [81], and [82] in [Part 2, Section 2.2](#).

2.C.6.9 Tables

Table 2.C.6.1—Data Required for Determination of the DF—HIC/SOHIC-HF

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Presence of HF (Yes or No)	Determine whether HF may be present in the component. Consider not only normal operating conditions but also upset conditions that may allow carryover of HF from other components.
Sulfur content of plate steel	Determine the sulfur content of the plate steel used to fabricate the component. This information should be available on the MTR in the equipment files. If not available, it can be estimated from the ASTM or ASME specification of the steel listed on the U-1 form in consultation with a materials engineer.
Steel product form (plate or pipe)	Determine what product form of steel was used to fabricate the component. Most components are fabricated from rolled and welded steel plates (e.g. A285, A515, A516, etc.), but some small-diameter components is fabricated from steel pipe and piping components. Most small-diameter piping is fabricated from steel pipe (e.g. A106, A53, API 5L, etc.) and piping components (e.g. A105, A234, etc.), but most large diameter piping (above approximately NPS 16 diameter) is fabricated from rolled and welded plate steel.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
On-line monitoring (hydrogen probes, process variables, or combination)	The type of proactive corrosion monitoring methods or tools employed such as hydrogen probes and/or process variable monitoring.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.6.2—Susceptibility to Cracking—HIC/SOHIC-HF

Weld Condition	Susceptibility to Cracking As a Function of Steel Sulfur Content		
	High Sulfur Steel ^a >0.01 % S	Low Sulfur Steel ≤0.01 % S	Product Form— Seamless/Extruded Pipe
Non-PWHT	High	High	Low
PWHT	High	Medium	Low

^a Typically includes A70, A201, A212, A285, A515, and most A516 before about 1990.

Table 2.C.6.3—On-line Monitoring Adjustment Factors for HIC/SOHIC-HF

On-line Monitoring Method	Adjustment Factors As a Function of On-line Monitoring—F_{OM}
Key process variables	2
Hydrogen probes	2
Key process variables and hydrogen probes	4
NOTE The adjustment factors shown above are estimates providing a measure of the relative effectiveness of various on-line monitoring methods. Factors based on the user's experience can be used as a substitute for the values presented in this table.	

2.C.6.10 Figures

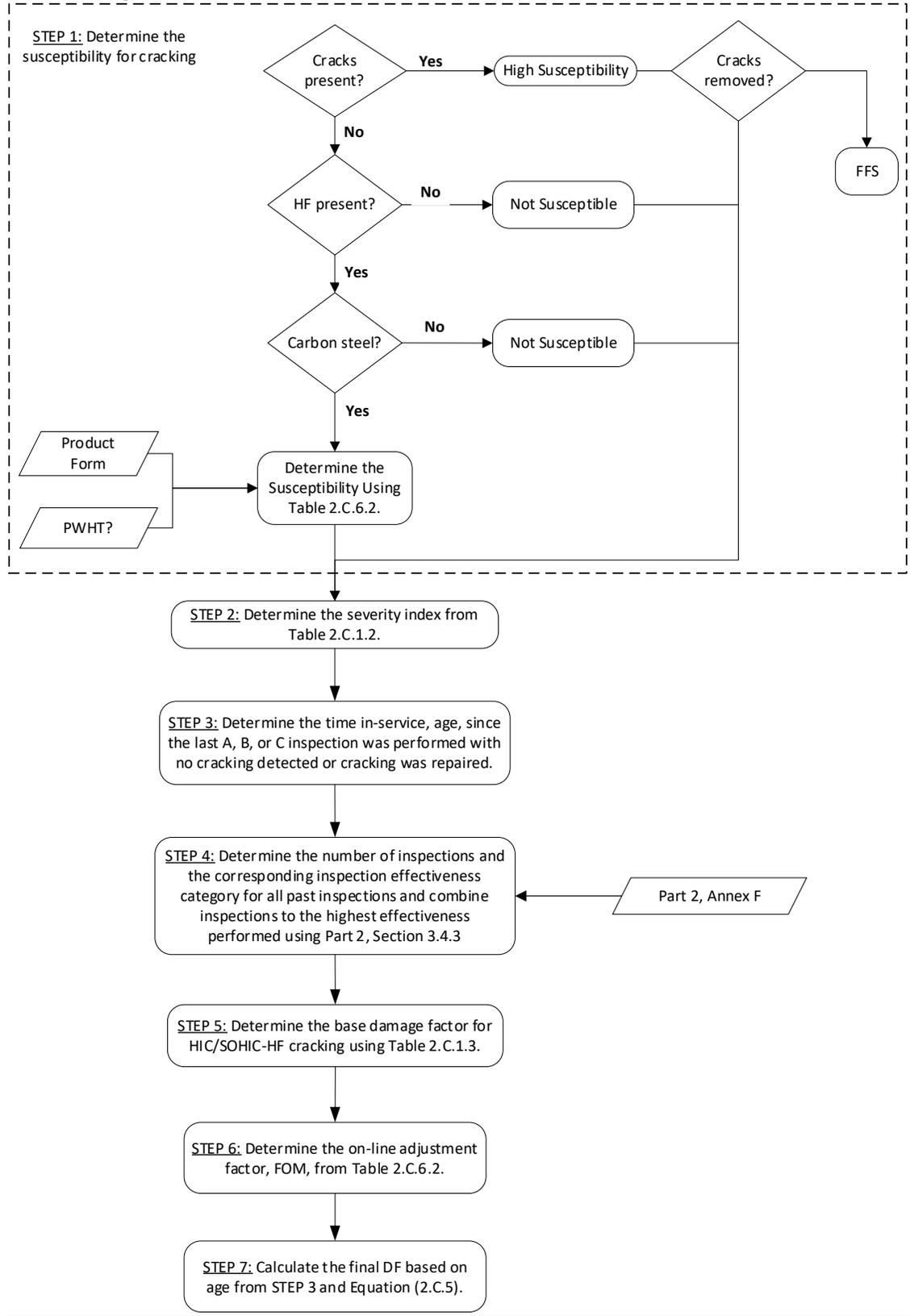


Figure 2.C.6.1—Determination of the HIC/SOHIC-HF Cracking DF**2.C.7 SCC DF—Hydrogen Stress Cracking in Hydrofluoric Acid (HSC-HF)****2.C.7.1 Scope**

The DF calculation for components subject to HSC-HF covered in this section.

2.C.7.2 Description of Damage

HSC is defined as cracking of a metal under the combined action of tensile stress and a corrosion mechanism that produces hydrogen that may diffuse into the metal. HSC may result from exposure to hydrogen sulfide (see [Section 2.C.10](#)) or from exposure to HF. HSC-HF occurs in high-strength (high hardness) steels or in hard weld deposits or hard HAZs of lower-strength steels. In addition, HSC-HF may occur in stressed Alloy 400 if oxygen or other oxidizers are present in the HF.

Concentrated HF is used as the acid catalyst in HF alkylation units. The usual HF-in-water concentrations are 96 % to 99+ % and the temperatures are generally below 66 °C (150 °F). Under these conditions a fully killed (deoxidized), low sulfur, clean soft carbon steel is the material of choice for most equipment except where close tolerances are required for operation (i.e. pumps, valves, instruments).

Where close tolerances are required and at temperatures over 150 °F (66 °C) to approximately 350 °F (178 °C), Alloy 400 is used. Corrosion in 80 % and stronger HF-in-water solutions is equivalent to corrosion in anhydrous hydrofluoric acid (AHF; <200 ppm H₂O) and reference to corrosion in AHF implies an HF-in-water concentration as low as 80 %. HF acid with a concentration lower than 80 % HF in water is considered aqueous. Both aqueous and anhydrous HF can cause hydrogen embrittlement of hardened carbon and alloy steels. To prevent hydrogen embrittlement in welded steel structures, the requirements of NACE RP0472 should be followed. Welds produced by all welding methods should be hardness tested.

Alloy steel fasteners have been a source of many failures in anhydrous HF service. ASTM A193 Grade B7 chromium molybdenum steel bolts are hard and will crack in the presence of HF. Grade B7M, the same steel tempered to a lower hardness of 201 to 235 Brinnell, may be a better choice if contact by HF cannot be avoided. However, B7M bolts will also crack if stressed beyond their yield point in an HF environment. Bolt torque may be difficult to control in field flange makeup. In this case, B7 bolts may be specified and replacement of any bolt that may have contacted HF as a result of flange leaks would be required.

2.C.7.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the component is exposed to HF in any concentration, then the component should be evaluated for susceptibility to HSC-HF.

2.C.7.4 Required Data

The basic component data required for analysis are given in [Table 2.C.1.1](#), and the specific data required for determination of the HSC-HF DF are provided in [Table 2.C.7.1](#).

2.C.7.5 Basic Assumptions

The main assumption in determining the DF for HSC-HF is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

If cracks are detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.7.6 Determination of the DF

2.C.7.6.1 Overview

A flow chart of the steps required to determine the DF for HSC-HF is shown in [Figure 2.C.7.1](#). The following sections provide additional information and the calculation procedure.

2.C.7.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for HSC. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally), are provided in [Annex 2.FG](#), [Table 2.FG.89.8](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.7.6.3 Calculation of the DF

The following procedure may be used to determine the DF for HSC-HF; see [Figure 2.C.7.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.7.1](#) and [Table 2.C.7.2](#) based on the maximum Brinnell hardness of weldments and knowledge of whether the component was subject to PWHT.

NOTE a High susceptibility should be used if cracking is confirmed to be present.

- b) STEP 2—Based on the susceptibility in STEP 1, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- c) STEP 3—Determine the time in service, age , since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 13.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- e) STEP 5—Determine the base DF for HSC-HF, D_{fB}^{HSC-HF} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Calculate the escalation in the DF based on the time in service since the last inspection using the age from STEP 3 and [Equation \(2.C.6\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{HSC-HF} = \min\left(D_{fB}^{HSC-HF} \cdot (\max(age, 1.0))^{1.1}, 5000\right) \quad (2.C.6)$$

2.C.7.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{HSC-HF} is the DF for HSC-HF

D_{fB}^{HSC-HF} is the base value of the DF for HSC-HF

S_{VI} is the Severity Index

2.C.7.8 References

See References [10], [81], and [82] in [Part 2, Section 2.2](#).

2.C.7.9 Tables

Table 2.C.7.1—Data Required for Determination of the DF—HSC-HF

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Presence of HF (Yes or No)	Determine whether HF may be present in the component. Consider not only normal operating conditions but also upset conditions that may allow carryover of HF from other components.
Brinnell hardness of steel weldments	Determine the maximum Brinnell hardness actually measured at the weldments of the steel component. Readings should be made and reported using Brinnell scale, not converted from micro-hardness techniques (e.g. Vicker, Knoop, etc.). If actual readings are not available, use the maximum allowable hardness permitted by the fabrication specification.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.7.2—Susceptibility to Cracking—HSC-HF

As-welded Max Brinnell Hardness			PWHT Max Brinnell Hardness		
<200	200 to 237	>237	<200	200 to 237	>237
Low	Medium	High	None	Low	High

2.C.7.10 Figures

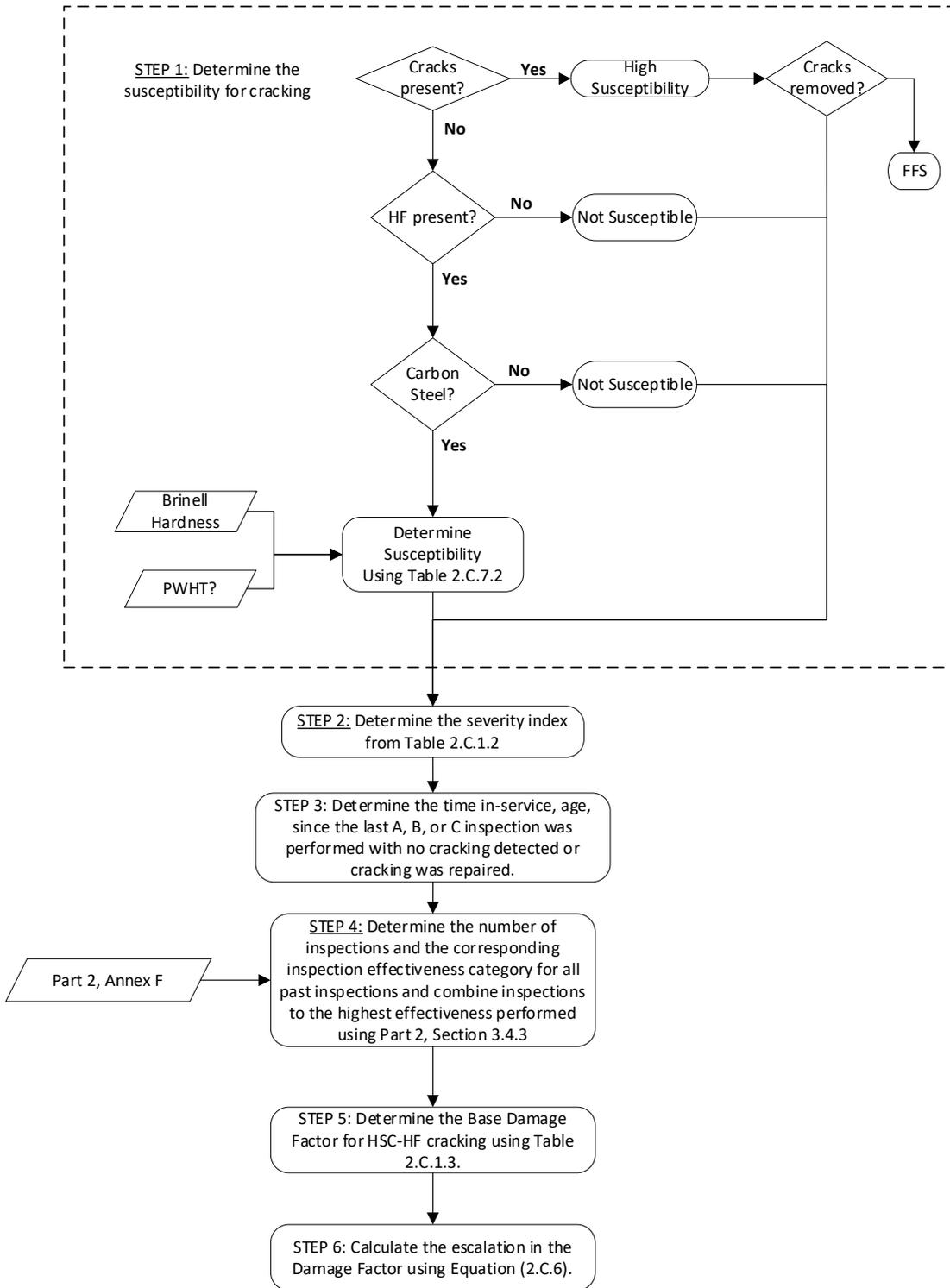


Figure 2.C.7.1—Determination of the HSC-HF Cracking DF

2.C.8 SCC DF—Polythionic Acid Stress Corrosion Cracking (PASCC)

2.C.8.1 Scope

The DF calculation for components subject to PASCC is covered in this section.

2.C.8.2 Description of Damage

PA and sulfurous acid are major considerations in the petroleum-refining industry, particularly in catalytic cracking, desulfurizer, hydrocracker, and catalytic reforming processes. These complex acids typically form in sulfide containing deposits during shutdown (or ambient) conditions when the component is exposed to air and moisture. The acid environment, combined with susceptible materials of construction in the sensitized or as-welded condition, results in rapid intergranular corrosion and cracking. Preventive measures to reduce or eliminate PASCC include flushing the component with alkaline or soda ash solution to neutralize sulfides immediately after shutdown and exposure to air or purging with dry nitrogen during the shutdown to prevent air exposure, according to recommended practices established by NACE (RP0170).

PA and sulfurous acid will cause SCC in sensitized austenitic stainless steels and nickel base alloys. Cracking is always intergranular and requires relatively low tensile stresses for initiation and propagation. As-welded, regular, and high carbon grade stainless steels, such as Types 304/304H and 316/316H, are particularly susceptible to SCC in the weld HAZ. Low-carbon steels (i.e. C < 0.03 %) are less susceptible at temperatures less than 800 °F (427 °C). Chemically stabilized stainless steel grades, such as Types 321 and 347 are less susceptible to PASCC, particularly if they are thermally stabilized. Susceptibility of alloys and chemically or thermally stabilized materials to PASCC can be determined by laboratory corrosion testing according to ASTM G35.

2.C.8.3 Screening Criteria

If the component's material of construction is an austenitic stainless steel or nickel-based alloy and the component is exposed to sulfur bearing compounds, then the component should be evaluated for susceptibility to PASCC.

2.C.8.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the PASCC DF are provided in [Table 2.C.8.1](#).

2.C.8.5 Basic Assumptions

The main assumption in determining the DF for PASCC is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

If cracks are detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.8.6 Determination of the DF

2.C.8.6.1 Overview

A flow chart of the steps required to determine the DF for PASCC is shown in [Figure 2.C.8.1](#). The following sections provide additional information and the calculation procedure.

2.C.8.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for PASCC. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally), are provided in [Annex 2.FE](#), [Table 2.FC.89.5](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.8.6.3 Calculation of the DF

The following procedure may be used to determine the DF for PASCC; see [Figure 2.C.8.1](#).

- a) STEP 1—Determine the susceptibility for cracking using [Figure 2.C.8.1](#) and [Table 2.C.8.2](#) based on the operating temperature and material of construction.

NOTE a High susceptibility should be used if cracking is confirmed to be present.

- b) STEP 2—Based on the susceptibility in STEP 1, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- c) STEP 3—Determine the time in service, age , since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- d) STEP 4—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 12.9.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- e) STEP 5—Determine the base DF for PASCC, D_{fB}^{PASCC} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 4 and the Severity Index, S_{VI} , from STEP 2.
- f) STEP 6—Calculate the final DF using [Equation \(2.C.7\)](#).

NOTE: escalation of the DF with time is not applicable for PASCC.

$$D_f^{PASCC} = \min\left(D_{fB}^{PASCC}, 5000\right) \quad (2.C.7)$$

2.C.8.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{PASCC} is the DF for PASCC cracking

D_{fB}^{PASCC} is the base value of the DF for PASCC cracking

S_{VI} is the Severity Index

2.C.8.8 References

See References [10], [46], [47], [48], [49], [50], [51], [52], [53], [54], [55], [56], and [57] in [Section 2.2](#).

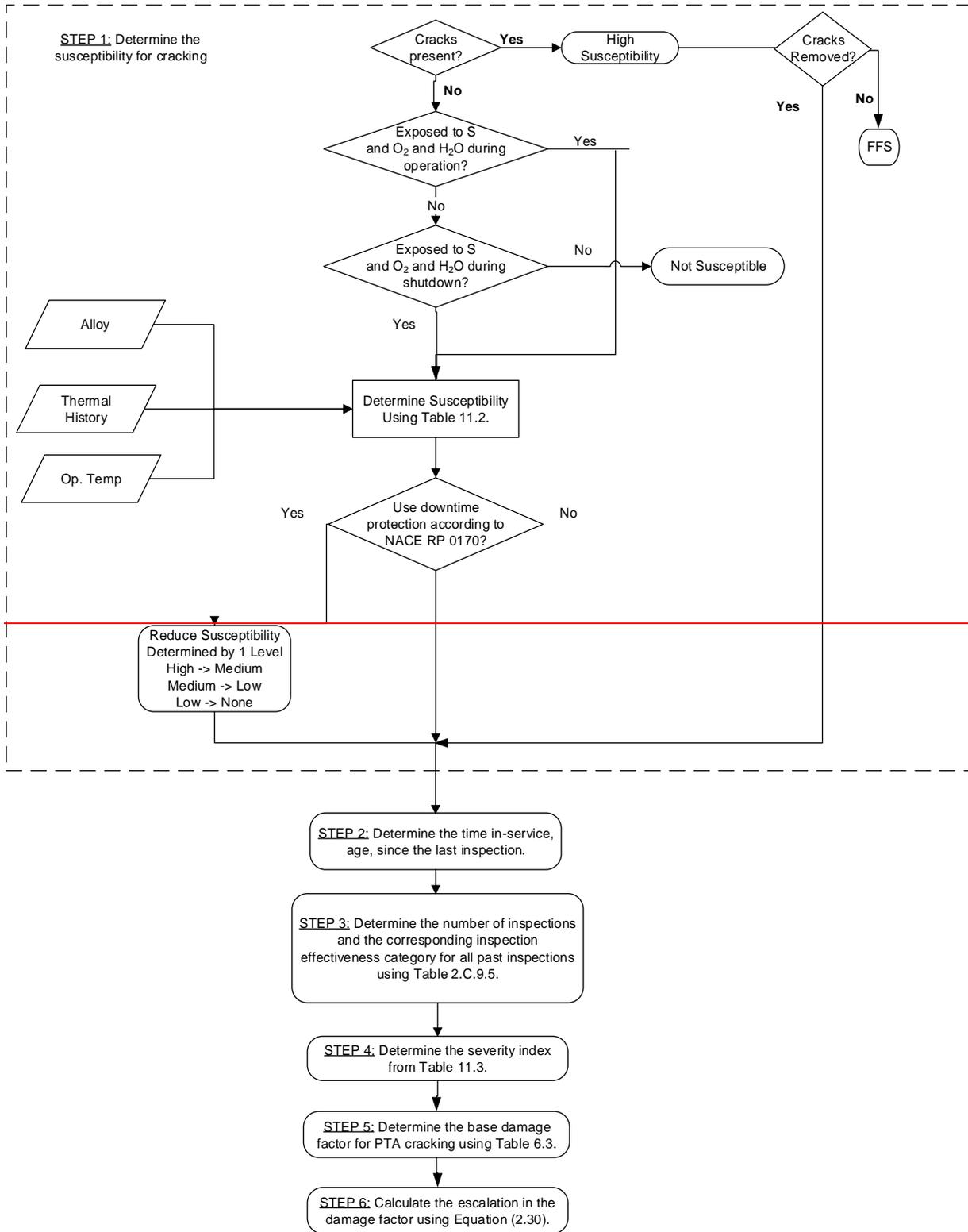
2.C.8.9 Tables**Table 2.C.8.1—Data Required for Determination of the DF—PASCC**

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Thermal history (solution annealed, stabilized before welding, stabilized after welding)	Determine the thermal history of the material. Consider especially whether thermal stabilization heat treatment was performed after all welding.
Maximum operating temperature, °F (°C)	Determine the maximum operating temperature of the component. Consider any high temperature exposure such as during decoking.
Presence of sulfides, moisture, and oxygen: During operation? (Yes or No) During shutdown? (Yes or No)	Determine whether these constituents are present in the component. If uncertain, consult with a process engineer. Consider whether high-temperature component in sulfidic service is opened to environment during shutdown.
Downtime protection used?(Yes or No)	Determine whether downtime protection for PASCC has been provided per NACE RP0170. This may include soda ash washing, nitrogen blanketing, or dehumidification.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.8.2—Susceptibility to Cracking—PASCC

Operating Temperatures < 800 °F (427 °C)			
Material	Susceptibility to Cracking As a Function of Heat Treatment		
	Solution Annealed (default)	Stabilized Before Welding	Stabilized After Welding
All regular 300 series SS and Alloys 600 and 800	Medium	—	—
H Grade 300 series SS	High	—	—
L Grade 300 series SS	Low	—	—
321 SS	Medium	Medium	Low
347 SS, Alloy 20, Alloy 625, all austenitic weld overlay	Low	Low	Low
Operating Temperatures ≥ 800 °F (427 °C)			
Material	Susceptibility to Cracking As a Function of Heat Treatment		
	Solution Annealed (default)	Stabilized Before Welding	Stabilized After Welding
All regular 300 series SS and Alloys 600 and 800	High	—	—
H Grade 300 series SS	High	—	—
L Grade 300 series SS	Medium	—	—
321 SS	High	High	Low
347 SS, Alloy 20, Alloy 625, all austenitic weld overlay	Medium	Low	Low
NOTE If the process operating temperature is less than 800 °F (427 °C), then sensitization is present in the as-welded condition only. If the process operating temperature is greater than or equal to 800 °F (427 °C), then sensitization can occur during operation.			

2.C.8.10 Figures



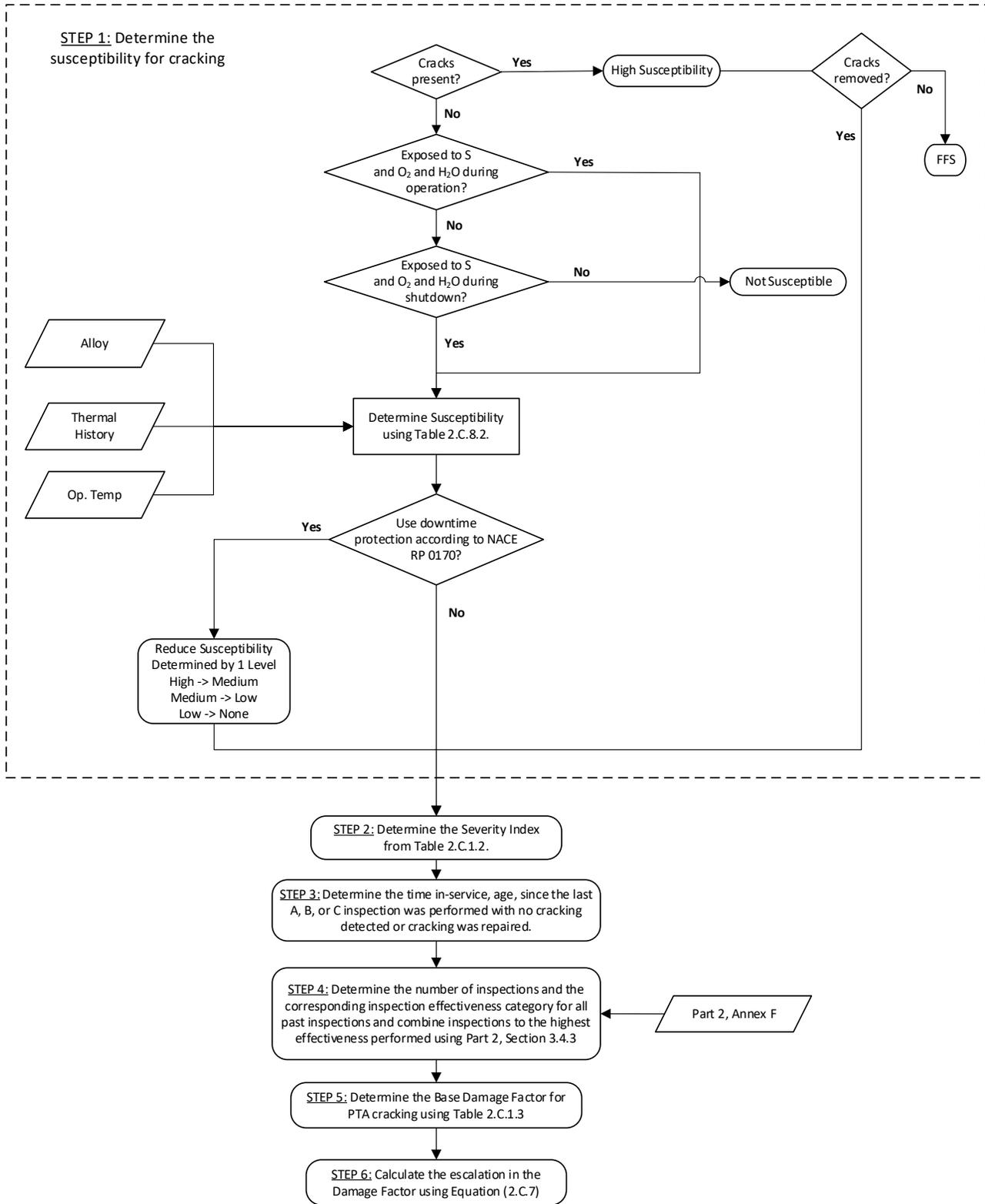


Figure 2.C.8.1—Determination of the PASCC DF

2.C.9 SCC DF—Wet H₂S Hydrogen-induced Cracking and Stress-oriented Hydrogen-induced Cracking (HIC/SOHIC-H₂S)

2.C.9.1 Scope

The DF calculation for components subject to HIC/SOHIC-H₂S is covered in this section.

2.C.9.2 Description of Damage

HIC is defined as stepwise internal cracks that connect adjacent hydrogen blisters on different planes in the metal or to the metal surface. An externally applied stress is not required for the formation of HIC. The driving force for the cracking is high stresses at the circumference of the hydrogen blisters caused by buildup of internal pressure in the blisters. Interactions between these high stress fields tend to cause cracks to develop that link blisters on different planes in the steel.

The buildup of pressure in the blisters is related to the hydrogen permeation flux in the steel. The source of the hydrogen in the steel is the corrosion reaction with wet hydrogen sulfide. Water must be present for this corrosion reaction to occur, and the resultant hydrogen flux is primarily associated with two environmental parameters, pH and the H₂S content of the water. Typically, the hydrogen flux in steels has been found to be lowest in near neutral pH solutions, with increasing flux at both lower and higher pH values. Corrosion at low pH values is caused by H₂S, whereas corrosion at high pH values is caused by high concentrations of the bisulfide ion. Presence of cyanides at elevated pH can further aggravate the hydrogen penetration into the steel. Hydrogen permeation is known to increase with H₂S content, e.g. H₂S partial pressure in the gas phase or H₂S content of the water phase. The presence of 50 ppm of H₂S in the water has been sufficient to cause HIC.

Hydrogen blisters are planar hydrogen-filled cavities formed at discontinuities in the steel (e.g. voids, inclusions, laminations, sulfide inclusions). Blisters most often occur in rolled plate steels, especially those with a banded microstructure resulting from elongated sulfide inclusions. Susceptibility to hydrogen blistering, and therefore HIC, is primarily related to the quality of the plate steel, i.e. the number, size, and shape of the discontinuities. In this regard, the sulfur content of the steel is a key material parameter. Reducing the sulfur content of the steel reduces the susceptibility to blistering and HIC. Additions of calcium or rare earth minerals (REMs) that control sulfide inclusion shape control are generally beneficial.

The susceptibility of the steel to blistering is directly related to the cleanliness of the steel, which is measured by sulfur content. It should be recognized that blistering is not a damage mechanism that will lead to a leak path unless it is accompanied by HIC leading to the surface. Blistering does pose a danger to mechanical integrity when it approaches a weld that contains sufficient residual stresses to drive the HIC to the surfaces. It is in this last case, the most severe situation that is considered when determining the susceptibility to HIC/SOHIC-H₂S.

SOHIC is defined as a stacked array of blisters joined by HIC that is aligned in the through-thickness direction of the steel as a result of high localized tensile stresses. SOHIC is a special form of HIC that usually occurs in the base material, adjacent to the HAZ of a weld, where stresses are highest due to the additive effect of applied stress (from internal pressure) and the residual stresses from welding. As with HIC, plate steel quality is a key parameter for SOHIC susceptibility. In addition, reduction of residual stresses by PWHT can reduce, but may not eliminate, the occurrence and severity of SOHIC.

The level of applied stress also influences the occurrence and severity of SOHIC. Although HIC/SOHIC is much more prominent in plate steel fabrications, it has been observed to a limited extent in steel pipe fabrications, usually in the more severe hydrogen charging environments.

Environmental conditions known to cause HIC/SOHIC-H₂S damage are carbon and low alloy steels in process environments containing an aqueous phase (liquid water) and any of the following, as outlined ANSI/NACE MR0103/ISO 17945^[58]:

- a. >50 ppmw total sulfide content in the aqueous phase;
- b. ≥ 1 ppmw total sulfide content in the aqueous phase and $\text{pH} < 4$;
- c. ≥ 1 ppmw total sulfide content and ≥ 20 ppmw free cyanide in the aqueous phase, and $\text{pH} > 7.6$;
- d. > 0.3 kPa absolute (0.05 psia) partial pressure H₂S in the gas phase associated with the aqueous phase (including liquid water condensation from streams shown as 100% vapor when at or close to saturation).
- e. Rich and lean aqueous H₂S removal solvent (amine, e.g.) services when the gas or liquid being treated contains H₂S.

All sustained operation conditions should be considered when assigning service severity level. Start up, shut down, or other anomalous transient conditions do not need to be considered. Condensation of vapor streams should be considered when the vapor phase is close to saturation, along with process upset events that are known to have sustained conditions.

2.C.9.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the process environment contains water and H₂S in any concentration, then the component should be evaluated for susceptibility to HIC/SOHIC-H₂S cracking.

2.C.9.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the HIC/SOHIC-H₂S cracking DF are provided in [Table 2.C.9.1](#).

2.C.9.5 Basic Assumptions

The main assumption in determining the DF for HIC/SOHIC-H₂S cracking is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a leak.

If SOHIC is detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Known blisters or cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.9.6 Determination of the DF

2.C.9.6.1 Overview

A flow chart of the steps required to determine the DF for HIC/SOHIC-H₂S cracking is shown in [Figure 2.C.9.1](#). The following sections provide additional information and the calculation procedure.

2.C.9.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting for HIC/SOHIC-H₂S. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FG, Table 2.FG.89.79](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.9.6.3 Adjustment for On-line Monitoring

In addition to inspection, on-line monitoring using hydrogen probes and/or key process variables provides a better understanding of HIC/SOHIC-H₂S susceptibility. The advantage of on-line monitoring is that process changes affecting SCC susceptibility can be detected before significant cracking occurs. This earlier detection could permit more timely action to decrease the POF. For HIC/SOHIC-H₂S, an on-line monitoring factor of 2 is applied if either hydrogen probes or monitoring of key process variables are used. If both hydrogen probes and monitoring of key process variables are used, an on-line monitoring factor of 4 is applied.

2.C.9.6.4 Calculation of the DF

The following procedure may be used to determine the DF for HIC/SOHIC-H₂S cracking; see [Figure 2.C.9.1](#).

- a) STEP 1—Determine the environmental severity (potential level of hydrogen flux) for cracking based on the H₂S content of the water and its pH using [Table 2.C.9.2](#).

NOTE a High environmental severity should be used if cracking is confirmed to be present.

- b) STEP 2—Determine the susceptibility for cracking using [Figure 2.C.9.1](#) and [Table 2.C.9.3](#) based on the environmental severity from STEP 1, the sulfur content of the carbon steel, product form, and knowledge of whether the component was subject to PWHT.
- c) STEP 3—Based on the susceptibility in STEP 2, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- d) STEP 4—Determine the time in service, age , since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- e) STEP 5—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 9.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).
- f) STEP 6—Determine the base DF for HIC/SOHIC-H₂S cracking, $D_{fB}^{HIC/SOHIC-H_2S}$, using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 5 and the Severity Index, S_{VI} , from STEP 3.
- g) STEP 7—Determine the on-line adjustment factor, F_{OM} , from [Table 2.C.9.4](#).
- h) STEP 8—Calculate the final DF accounting for escalation based on the time in service since the last inspection using the age from STEP 4 and [Equation \(C.2.8\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions. The equation also applies the adjustment factor for on-line monitoring.

$$D_f^{HIC/SOHIC-H_2S} = \min \left(\frac{D_{fB}^{HIC/SOHIC-H_2S} \cdot (\max(age, 1.0))^{1.1}}{F_{OM}}, 5000 \right) \quad (C.2.8)$$

2.C.9.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

$D_f^{HIC/SOHIC-H_2S}$ is the DF for HIC/SOHIC-H₂S cracking

$D_{fB}^{HIC/SOHIC-H_2S}$ is the base value of the for HIC/SOHIC-H₂S cracking

F_{OM} is the on-line monitoring adjustment factor

S_{VI} is the Severity Index

2.C.9.8 References

See References [30], [31], [32], [33], [34], [35], [36], [37], [38] and [144] in [Part 2, Section 2.2](#).

2.C.9.9 Tables

Table 2.C.9.1—Data Required for Determination of the DF—HIC/SOHIC-H₂S Cracking

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Presence of water (Yes or No)	Determine whether free water is present in the component. Consider not only normal operating conditions but also start-up, shutdown, process upsets, etc.
H ₂ S content of water	Determine the H ₂ S content of the water phase. If analytical results are not readily available, it can be estimated using the approach of Petrie & Moore ^[30] .
pH of water	Determine the pH of the water phase. If analytical results are not readily available, it should be estimated by a knowledgeable process engineer.
Presence of cyanides (Yes or No)	Determine the presence of cyanide through sampling and/or field analysis. Consider primarily normal and upset operations but also start-up and shutdown conditions.
Sulfur content of plate steel	Determine the sulfur content of the steel used to fabricate the component. This information should be available on material test reports (MTRs) in equipment files. If not available, it can be estimated from the ASTM or ASME specification of the steel listed on the U-1 form in consultation with materials engineer.
Steel product form (plate or pipe)	Determine what product form of steel was used to fabricate the component. Most components are fabricated from rolled and welded steel plates (e.g. A285, A515, A516, etc.), but some small-diameter components is fabricated from steel pipe and piping components. Most small-diameter piping is fabricated from steel pipe (e.g. A106, A53, API 5L, etc.) and piping components (e.g. A105, A234, etc.), but most large diameter piping (above approximately NPS 16 diameter) is fabricated from rolled and welded plate steel.
Age (years)	Use inspection history to determine the time since the last SCC inspection.
Inspection effectiveness category	The effectiveness category that has been performed on the component.
On-line monitoring (hydrogen probes, process variables, or combination)	The type of proactive corrosion monitoring methods or tools employed such as hydrogen probes and/or process variable monitoring.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.9.2—Environmental Severity—HIC/SOHIC-H₂S Cracking

pH of Water	Environmental Severity as a Function of H ₂ S Content of Water				
	< 0.05 psia	≥ 0.05 psia Partial Pressure H ₂ S			
	All ppm H ₂ S	1 to 50 ppm	> 50 to 1,000 ppm	> 1,000 to 10,000 ppm	>10,000 ppm
< 3.5	None	Low	Low	Moderate	High
3.5 to 4.5	None	Low	Low	Moderate	High
4.5 to 5.5	None	None	Low	Low	Moderate
5.5 to 6.5	None	None	Low	Low	Moderate
6.5 to 7.6	None	None	Low	Low	Moderate
7.6 to 8.3	None	None ¹	Moderate ¹	Moderate ¹	Moderate ¹
8.4 to 8.9	None	None ¹	Moderate ¹	Moderate ¹	High
> 9.0	None	None ¹	Moderate ¹	Moderate ¹	High

NOTE If > 20 ppmw free cyanides are present, increase the susceptibility to HIC/SOHIC-H₂S one category for pH > 7.6 and H₂S concentrations greater than 1 ppm.

Table 2.C.9.3—Susceptibility to Cracking—HIC/SOHIC-H₂S

Environmental Severity	Susceptibility to Cracking as a Function of Steel Sulfur Content					
	High Sulfur Steel ^a >0.01 % S		Low Sulfur Steel ≤0.01 % S		Product Form— Seamless/Extruded Pipe	
	As-welded	PWHT	As-welded	PWHT	As-welded	PWHT
High	High	High	High	Medium	Medium	Low
Moderate	High	Medium	Medium	Low	Low	Low
Low	Medium	Low	Low	Low	Low	Low

^a Typically includes A70, A201, A212, A285, A515, and most A516 before about 1990.

Table 2.C.9.4—On-line Monitoring Adjustment Factors for HIC/SOHIC-H₂S

On-line Monitoring Method	Adjustment Factors as a Function of On-line Monitoring— <i>F_{OM}</i>
Key process variables	2
Hydrogen probes	2

2.C.9.10 Figures

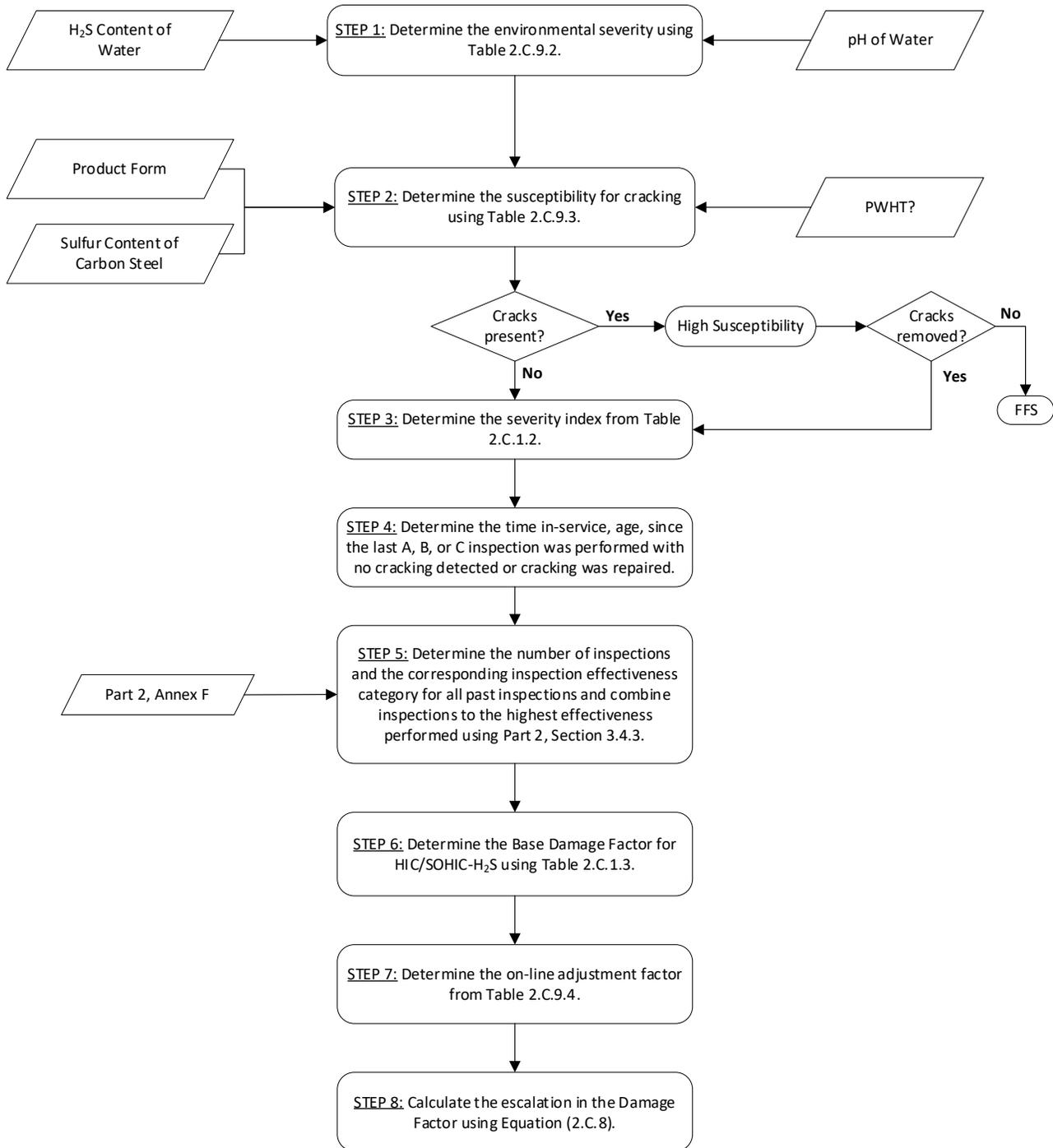


Figure 2.C.9.1—Determination of the HIC/SOHIC-H₂S DF

2.C.10 SCC DF—Sulfide Stress Cracking (SSC)

2.C.10.1 Scope

The DF calculation for components subject to SSC is covered in this section.

2.C.10.2 Description of Damage

SSC is defined as cracking of a metal under the combined action of tensile stress and corrosion in the presence of water and hydrogen sulfide. SSC is a form of HSC resulting from absorption of atomic hydrogen that is produced by the sulfide corrosion process on the metal surface. SSC usually occurs more readily in high strength (high hardness) steels in hard weld deposits or hard heat-affected zones (HAZs) of lower-strength steels. Susceptibility to SSC is related to the hydrogen permeation flux in the steel, which is primarily associated with two environmental parameters, pH and H₂S content of the water. Typically, the hydrogen flux in steels has been found to be lowest in near neutral pH solutions, with increasing flux at both lower and higher pH values. Corrosion at low pH values is caused by H₂S, whereas corrosion at high pH values is caused by high concentrations of the bisulfide ion. Presence of cyanides at elevated pH can further aggravate the hydrogen penetration into the steel. SSC susceptibility is known to increase with H₂S content, e.g. H₂S partial pressure in the gas phase or H₂S content of the water phase. The presence of as little as 1 ppm of H₂S in the water has been found to be sufficient to cause SSC.

Susceptibility to SSC is primarily related to two material parameters, hardness and stress level. High hardness of the steel increases its susceptibility to SSC. SSC has not generally been a concern for carbon steel base materials typically used for refinery pressure vessels and piping in wet hydrogen sulfide service because these steels have sufficiently low strength (hardness) levels. However, weld deposits and HAZs may contain zones of high hardness and high residual stresses from welding. High residual tensile stresses associated with welds increases susceptibility to SSC. PWHT significantly reduces residual stresses and also tempers (softens) weld deposits and HAZs. A PWHT of about 621 °C (1150 °F) for 1 hour per inch of thickness (1 hour minimum) is considered effective for carbon steel. Somewhat higher temperatures are required for low alloy steels. Control of hardness and reduction of residual stresses are recognized methods for preventing SSC as outlined in NACE RP0472.

Environmental conditions known to cause SSC damage are carbon and low alloy steels in process environments containing an aqueous phase (liquid water) and any of the following, as outlined in ANSI/NACE MR0103/ISO 17945^[58]:

- a. >50 ppmw total sulfide content in the aqueous phase;
- b. ≥1 ppmw total sulfide content in the aqueous phase and pH < 4;
- c. ≥1 ppmw total sulfide content and ≥20 ppmw free cyanide in the aqueous phase, and pH > 7.6;
- d. >0.3 kPa absolute (0.05 psia) partial pressure H₂S in the gas phase associated with the aqueous phase (including liquid water condensation from streams shown as 100% vapor when at or close to saturation).
- e. Rich and lean aqueous H₂S removal solvent (amine, e.g.) services when the gas or liquid being treated contains H₂S.

All sustained operation conditions should be considered when assigning service severity level. Start up, shut down, or other anomalous transient conditions do not need to be considered. Condensation of vapor streams should be considered when the vapor phase is close to saturation, along with process upset events that are known to have sustained conditions.

2.C.10.3 Screening Criteria

If the component's material of construction is carbon or low alloy steel and the process environment contains water and H₂S in any concentration, then the component should be evaluated for susceptibility to SSC.

2.C.10.4 Required Data

The basic component data required for analysis are given in [Part 2, Table 4.1](#), and the specific data required for determination of the SSC DF are provided in [Table 2.C.10.1](#).

2.C.10.5 Basic Assumptions

The main assumption in determining the DF for SSC is that the damage can be characterized by a susceptibility parameter that is designated as High, Medium, or Low based on process environment, material of construction, and component fabrication variables (i.e. heat treatment). Based on the susceptibility parameter, a Severity Index is assigned that is a measure of the component susceptibility to cracking (or the probability of initiating cracks) and the probability that the crack will result in a loss of containment.

If cracking is detected in the component during an inspection, the susceptibility is designated as High, and this will result in the maximum value for the Severity Index. Cracks or arrays of cracks that are found during an inspection should be evaluated using FFS methods in API 579-1/ASME FFS-1 ^[10].

2.C.10.6 Determination of the DF

2.C.10.6.1 Overview

A flow chart of the steps required to determine the DF for SSC is shown in [Figure 2.C.10.1](#). The following sections provide additional information and the calculation procedure.

2.C.10.6.2 Inspection Effectiveness

Inspections are ranked according to their expected effectiveness at detecting SSC. Examples of inspection activities that are both intrusive (requires entry into the equipment) and nonintrusive (can be performed externally) are provided in [Annex 2.FG, Table 2.FG.89.66](#).

If multiple inspections of a lower effectiveness have been conducted during the designated time period, they can be equated to an equivalent higher effectiveness inspection in accordance with [Part 2, Section 3.4.3](#).

2.C.10.6.3 Calculation of the DF

The following procedure may be used to determine the DF for SCC; see [Figure 2.C.10.1](#).

- a) STEP 1—Determine the environmental severity (potential level of hydrogen flux) for cracking based on the H₂S content of the water and its pH using [Table 2.C.10.2](#).
- b) STEP 2—Determine the susceptibility for cracking using [Figure 2.C.10.1](#) and [Table 2.C.10.3](#) based on the environmental severity from STEP 1, the maximum Brinnell hardness of weldments, and knowledge of whether the component was subject to PWHT.

NOTE a High susceptibility should be used if cracking is confirmed to be present.

- c) STEP 3—Based on the susceptibility in STEP 3, determine the Severity Index, S_{VI} , from [Table 2.C.1.2](#).
- d) STEP 4—Determine the time in service, *age*, since the last Level A, B, or C inspection was performed with no cracking detected or cracking was repaired. Cracking detected but not repaired should be evaluated and future inspection recommendations based upon FFS evaluation.
- e) STEP 5—Determine the number of inspections and the corresponding inspection effectiveness category using [Part 2, Section 8.6.2](#) for past inspections performed during the in-service time. Combine the inspections to the highest effectiveness performed using [Part 2, Section 3.4.3](#).

- f) STEP 6—Determine the base DF for SCC, D_{fB}^{SSC} , using [Table 2.C.1.3](#) based on the number of inspections and the highest inspection effectiveness determined in STEP 5 and the Severity Index, S_{VI} , from STEP 3.
- g) STEP 7—Calculate the escalation in the DF based on the time in service since the last inspection using the *age* from STEP 4 and [Equation \(2.C.9\)](#). In this equation, it is assumed that the probability for cracking will increase with time since the last inspection as a result of increased exposure to upset conditions and other non-normal conditions.

$$D_f^{SSC} = \min\left(D_{fB}^{SSC} \cdot (\max(\text{age}, 1.0))^{1.1}, 5000\right) \quad (2.C.9)$$

2.C.10.7 Nomenclature

age is the component in-service time since the last cracking inspection or service start date

D_f^{SSC} is the DF for SSC

D_{fB}^{SSC} is the base value of the DF for SSC

S_{VI} is the Severity Index

2.C.10.8 References

See References [14], [19] (pp. 541–559), [29], [30], [31], [32] and [144] in [Part 2, Section 2.2](#).

2.C.10.9 Tables

Table 2.C.10.1—Data Required for Determination of the DF—SSC

Required Data	Comments
Susceptibility (Low, Medium, High)	The susceptibility is determined by expert advice or using the procedures in this section.
Presence of water (Yes or No)	Determine whether free water is present in the component. Consider not only normal operating conditions but also start-up, shutdown, process upsets, etc.
H ₂ S content of water	Determine the H ₂ S content of the water phase. If analytical results are not readily available, it can be estimated using the approach of Petrie & Moore [30].
pH of water	Determine the pH of the water phase. If analytical results are not readily available, it should be estimated by a knowledgeable process engineer.
Presence of cyanides (Yes or No)	Determine the presence of cyanide through sampling and/or field analysis. Consider primarily normal and upset operations but also start-up and shutdown conditions.
Max Brinnell hardness	Determine the maximum Brinnell hardness actually measured at the weldments of the steel components. Report readings actually taken as Brinnell, not converted from finer techniques (e.g. Vickers, Knoop, etc.). If actual readings are not available, use the maximum allowable hardness permitted by the fabrication specification.
Age (years)	Use inspection history to determine the time since the last SCC inspection.

Inspection effectiveness category	The effectiveness category that has been performed on the component.
Number of inspections	The number of inspections in each effectiveness category that have been performed.

Table 2.C.10.2—Environmental Severity—SSC

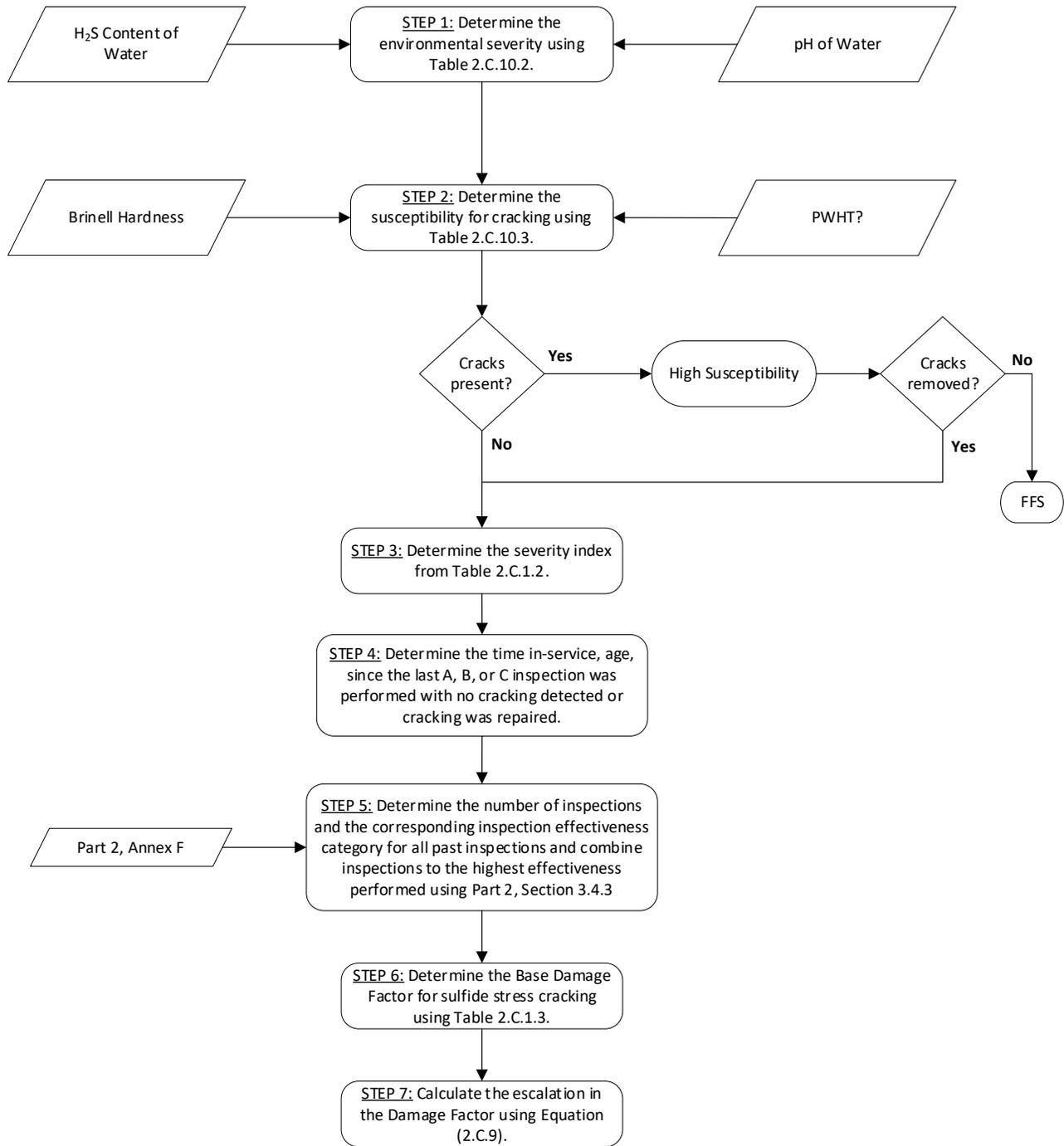
pH of Water	Environmental Severity as a Function of H ₂ S Content of Water				
	< 0.05 psia	≥ 0.05 psia Partial Pressure H ₂ S			
	All ppm H ₂ S	> 1 to 50 ppm	> 50 to 1,000 ppm	> 1,000 to 10,000 ppm	>10,000 ppm
< 3.5	None	Low	Low	Moderate	High
3.5 to 4.5	None	Low	Low	Moderate	High
4.5 to 5.5	None	None	Low	Low	Moderate
5.5 to 6.5	None	None	Low	Low	Moderate
6.5 to 7.6	None	None	Low	Low	Moderate
7.6 to 8.3	None	None ¹	Moderate ¹	Moderate ¹	Moderate ¹
8.4 to 8.9	None	None ¹	Moderate ¹	Moderate ¹	High
> 9.0	None	None ¹	Moderate ¹	Moderate ¹	High

NOTE If > 20 ppmw free cyanides are present, increase the susceptibility to SSC one category for pH > 7.6 and H₂S concentrations greater than 1 ppm.

Table 2.C.10.3—Susceptibility to SSC—SSC

Environmental Severity	Susceptibility to SSC As a Function of Heat Treatment					
	As-welded Max Brinnell Hardness ¹			PWHT Max Brinnell Hardness ¹		
	<200	200 to 237	>237	<200	200 to 237	>237
High	Low	Medium	High	Not	Low	Medium
Moderate	Low	Medium	High	Not	Not	Low
Low	Low	Low	Medium	Not	Not	Not

NOTE: Actually tested as Brinnell, not converted from finer techniques, e.g. Vickers, Knoop, etc.

2.C.10.10 Figures**Figure 2.C.10.1—Determination of the SSC DF**