PART 2, ANNEX E CONTENTS

Risk-Based Inspection Methodology
Part 2—Probability of Failure Methodology
Annex 2.E—Mechanical and Metallurgical Damage Mechanisms

2.E.1 Overview

2.E.1.1 Determination of Mechanical and Metallurgical Damage Susceptibilities

Mechanical and Metallurgical damage susceptibilities should be based on assignments for each potential mechanism using this document or as estimated by a corrosion specialist.

Screening questions are used to determine if the mechanical and metallurgical damage mechanism sections apply. The applicable sections are used to determine conservative susceptibilities for potential damage mechanisms. The screening questions listed in Table 2.E.1.1 are used to select the applicable mechanisms.

2.E.1.2 Tables

Table 2.E.1.1—Screening Questions for Mechanical and Metallurgical Damage

Screening Questions	Action
HTHA 1. Carbon steel, C-½ Mo, or a Cr-Mo low alloy steel (such as ½ Cr-½ Mo, 1 Cr-½ Mo, 1¼ Cr-½ Mo, 2¼ Cr-1 Mo, 3 Cr-1 Mo, 5 Cr-½ Mo, 7 Cr-1 Mo, and 9 Cr-1 Mo)? 2. Operating temperature > 350 °F (177 °C)? 3. Operating hydrogen partial pressure > 50 psia (0.345 MPa)?	If Yes to all, proceed to Section 2.E.2
Brittle Fracture 1. Carbon or low alloy steel? 2. Minimum design metal temperature or minimum allowable temperature is unknown or below operating or upset temperature?	If Yes to both, proceed to Section 2.E.3
Low Alloy Steel Embrittlement 1. 1Cr-0.5Mo, 1.25Cr-0.5Mo, 2.25Cr-1Mo, or 3Cr-1 Mo low alloy steel? 2. Operating temperature between 650 and 1,070 °F (343 and 577 °C)?	If Yes to both, proceed to Section 2.E.4
885 °F Embrittlement 1. High chromium (≥12 % Cr) ferritic steel? 2. Operating temperature between 700 and 1,050 °F (371 and 566 °C)?	If Yes, proceed to Section 2.E.5
Sigma Phase Embrittlement 1. Austenitic stainless steel? 2. Operating temperature between 1,100 and 1,700 °F (593 and 927 °C)?	If Yes, proceed to Section 2.E.6
Mechanical Fatigue (Piping) 1. Component piping? 2. History of fatigue failures, visible/audible shaking or a source of cyclic vibration (continuous or intermittent) within approximately 50 ft (15.24 m) that is connected (directly or indirectly via structure)?	If Yes, proceed to Section 2.E.7

2.E.2 High Temperature Hydrogen Attack (HTHA) DF

2.E.2.1 Scope

The DF calculation for carbon steel, C-½ Mo, and Cr-Mo low alloy steel components subject to HTHA is covered in this section.

2.E.2.2 Description of Damage

HTHA occurs in carbon steel, C-½ Mo, and Cr-Mo low alloy steels exposed to a high partial pressure of hydrogen at elevated temperatures. It is the result of atomic hydrogen diffusing through the steel and reacting with carbides in the microstructure. There are two reactions associated with HTHA. First the hydrogen molecule, H_2, must dissociate to form atomic hydrogen, H, which can diffuse through steel.

$$H_2 \Leftrightarrow 2H \qquad \text{(hydrogen dissociation)}$$

The reaction to form atomic hydrogen occurs more readily at higher temperatures and higher hydrogen partial pressures. As a result, as both the temperature and hydrogen partial pressure are increased, the driving force for HTHA increases. The second reaction that occurs is between atomic hydrogen and the metal carbides.

$$4H + MC \Leftrightarrow CH_4 + M$$

Damage due to the HTHA can possess two forms:

1) internal decarburization and fissuring from the accumulation of methane gas at the carbide matrix interface;

2) surface decarburization from the reaction of the atomic hydrogen with carbides at or near the surface where the methane gas can escape without causing fissures.

Internal fissuring is more typically observed in carbon steel, C-½ Mo steels, and in Cr-Mo low alloy steels at higher hydrogen partial pressures, while surface decarburization is more commonly observed in Cr-Mo steels at higher temperatures and lower hydrogen partial pressures.

HTHA can be mitigated by increasing the alloy content of the steel and thereby increasing the stability of the carbides in the presence of hydrogen. As a result, carbon steel that only contains Fe_3C carbides has significantly less HTHA resistance than any of the Cr-Mo low alloy steels that contain Cr and Mo carbides that are more stable and resistant to HTHA.

Historically, HTHA resistance has been predicted based on industry experience that has been plotted on a series of curves for carbon steel and Cr-Mo low alloy steels showing the temperature and hydrogen partial pressure regime in which these steels have been successfully used without damage due to HTHA. These curves, which are commonly referred to as the Nelson curves, are maintained based on industry experience in API 941.

2.E.2.3 Current Status of HTHA Investigations and Inspection

In 2010, an incident within the refining industry led to an investigation where HTHA was identified as the damage mechanism that led to the failure of a heat exchanger. The refining industry has been examining the findings published in the Chemical & Safety Board report, along with new information from the industry concerning HTHA damage.

At the time of API 581, Third Edition release, API Recommended Practice 941, Seventh Edition—*Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants*—is being revised. Technology for investigating HTHA susceptibility and inspection methods for detection and assessment of HTHA damage is being developed. The Third Edition of API 581 includes a conservative screening criterion that allows the owner–~~user~~operator to flag components potentially affected by HTHA (see Section 2.E.2.4) until a more quantitative risk assessment is developed based on a later edition of API 941. Additionally, the most current edition of API 941 should be consulted for guidance on investigation, inspection, and replacement.

This document does not:

a) prescribe changes in materials of construction for components that exceed limits defined in Section 2.E.2.4;

b) provide guidance for assessing HTHA damage.

This document provides a screening criteria to identify potentially susceptible components for a thorough investigation. It is the owner–~~user~~operator's responsibility to:

a) review, investigate, and determine the actual status regarding HTHA, including documenting the procedures, assessment results, and conclusions;

b) conduct a thorough investigation and evaluate options for continued operation or replacement if HTHA is detected in the component during an inspection.

2.E.2.4 Screening Criteria for Carbon and C-½ Mo and Cr-Mo Low Alloy Steels

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

a) The material is carbon steel, C-½ Mo, or a Cr-Mo low alloy steel (such as Mn-0.5 Mo, ½ Cr-½ Mo, 1 Cr-½ Mo, 1¼ Cr-½ Mo, 1¼ Cr-½ Mo-V, 2¼ Cr-1 Mo, 3 Cr-1 Mo, 5 Cr-½ Mo).

b) The operating temperature is greater than 350 °F (177 °C).

c) The operating hydrogen partial pressure is greater than 50 psia (0.345 MPa).

2.E.2.5 Required Data

The basic data required for analysis are provided in Part 2, Table 4.1, and the specific data required for determination of the DF for HTHA are provided in Table 2.E.2.1.

2.E.2.6 Determination of the Damage Factor

2.E.2.6.1 Overview

A flow chart of the steps required to determine the DF for HTHA is shown in Figure 2.E.2.2. The following sections provide additional information and the calculation procedure.

2.E.2.6.2 Inspection Effectiveness

Currently there is no level of inspection effectiveness (LoIE) for HTHA damage.

2.E.2.6.3 Calculation of the Damage Factor

The following procedure may be used to determine the DF for HTHA; see Figure 2.E.2.2.

a) STEP 1—Determine the material of construction, exposure temperature, T, and the exposure hydrogen partial pressure, P_{H_2}.

b) STEP 2—Has HTHA damage historically been observed in the component?

— If yes and component has not been replaced, assign susceptibility to Damage Observed and skip to STEP 4.

— If yes and the component has been replaced in kind, assign susceptibility to High and skip to STEP 4.

— If a component has been replaced with an upgrade in the materials of construction, the component shall be re-evaluated in STEP 1 for the susceptibility based on the new material of construction.

c) STEP 3—Assign component susceptibility to HTHA as outlined below.

1) For Carbon and C-½ Mo Alloy Steels.

a) If the exposure temperature is > 350 °F (177 °C) and the exposure hydrogen partial pressure is > 50 psia (0.345 MPa), assign a high susceptibility to HTHA.

b) If exposure temperature is ≤ 350 °F (177 °C) and the exposure hydrogen partial pressure is ≤ 50 psia (0.345 MPa), assign HTHA susceptibility to None.

2) For All Other Cr-Mo Low Alloy Steels.

a) If the exposure temperature is > 350 °F (177 °C) and exposure hydrogen partial pressure is > 50 psia (0.345 MPa), calculate ΔT proximity to the API 941 curve using T and P_{H_2} from STEP 1. Assign HTHA susceptibility using Figure 2.E.2.1.

NOTE the approach used in Figure 2.E.2.1 is an example guideline using 50 °F (27.7 °C) increments. The 50 °F (27.7 °C) increments were used to represent relative changes in susceptibility. It is the owner–~~user~~operator's responsibility to customize the values to represent their practice for determining HTHA susceptibility.

d) STEP 4—Determine the DF for HTHA, D_f^{HTHA}, using Table 2.E.2.2 based on the susceptibility from STEP 2 or STEP 3.

2.E.2.6.4 Consideration of Susceptibility

The time in service of component significantly affects susceptibility to HTHA and should be considered during the HTHA review. Additionally, steels fabricated prior to 1970 may contain impurities and/or inclusions that were introduced during fabrication. As these steels age, they may become more susceptible to HTHA for similar process conditions compared to steels fabricated in 1980 or later. As a result, the owner–~~user~~operator may choose more conservative guidelines by increasing the susceptibilities in Table 2.E.2.2.

2.E.2.7 Nomenclature

D_f^{HTHA} is the DF for HTHA

P_{H_2} is the hydrogen partial pressure, MPa (psia)

T is the operating temperature, °F (°C)

2.E.2.8 References

2.E.2.9 Tables

Table 2.E.2.1—Data Required for Determination of Susceptibility to HTHA

Required Data	Comments
Material of construction	The component generic construction material (e.g. carbon steel, C-½ Mo, 2 ¼ Cr-1 Mo).
Hydrogen partial pressure, MPa (psia)	Determine the hydrogen partial pressure, which is equal to the product of the mole fraction of hydrogen and the total pressure (absolute).
Temperature, °F (°C)	The temperature of exposure.

Table 2.E.2.2—DF—HTHA

Susceptibility	DF
Damage Observed	5,000
High Susceptibility	5,000
Medium Susceptibility	2,000
Low Susceptibility	100
No Susceptibility	0

2.E.2.10 Figures

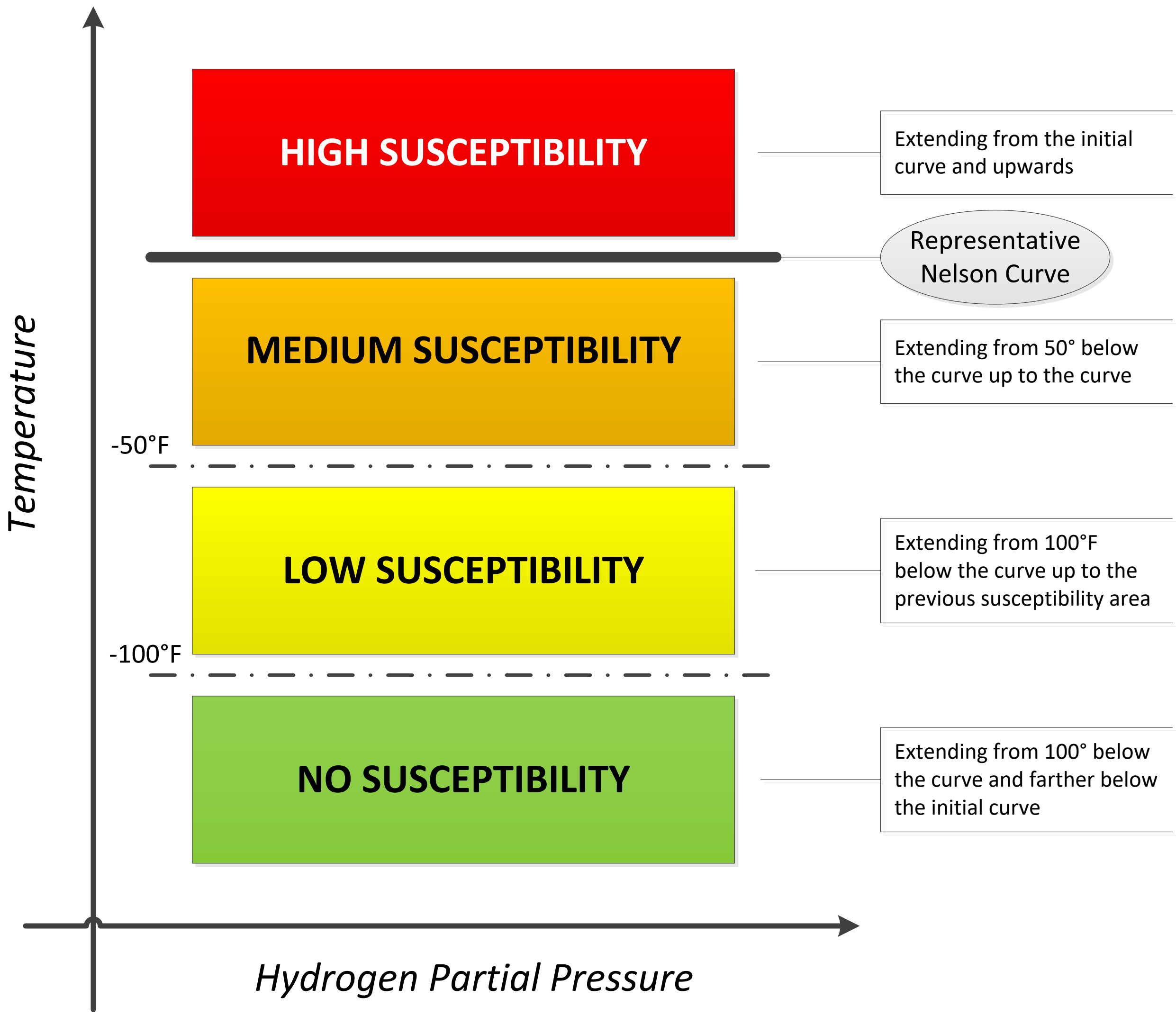
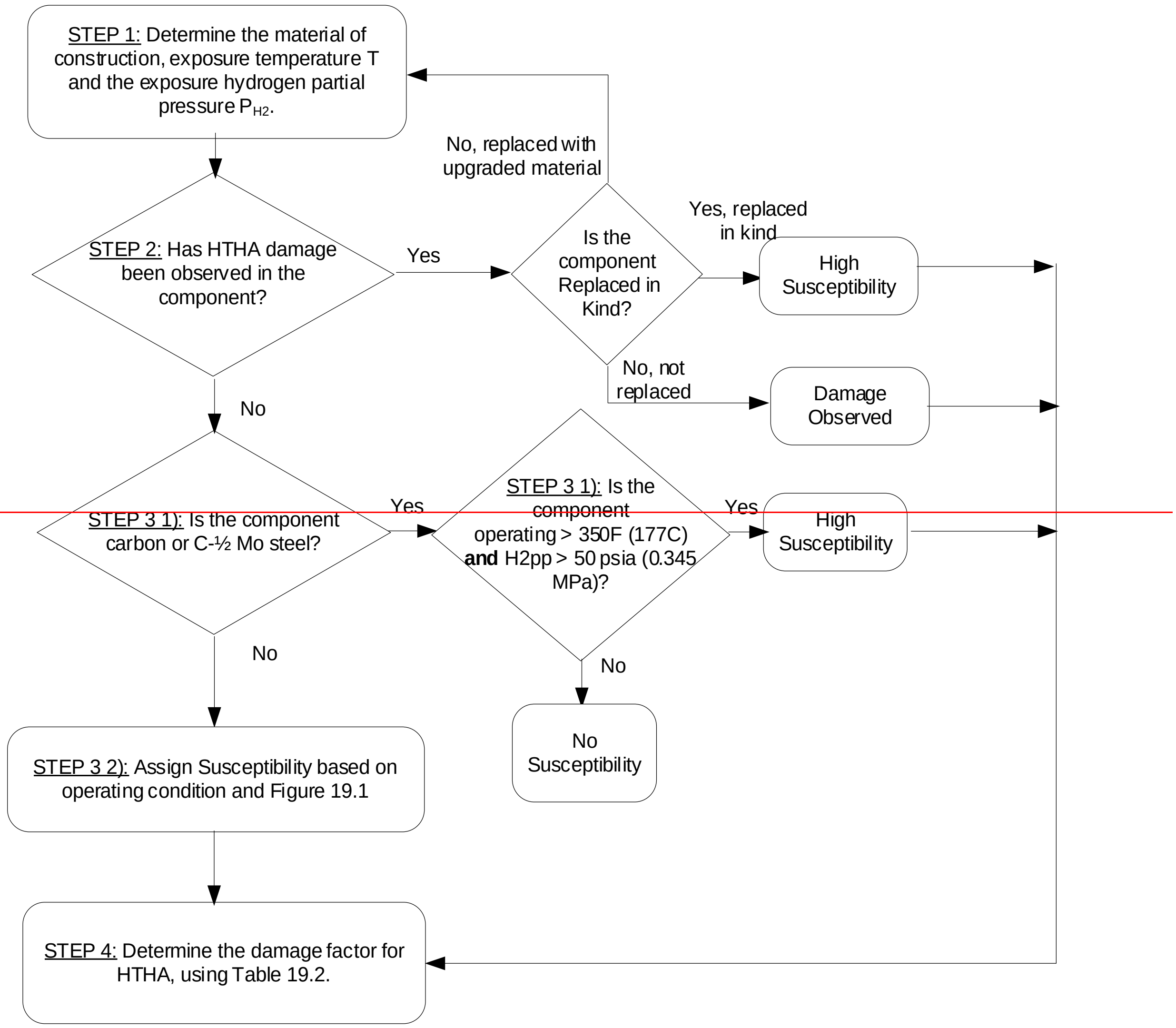


Figure 2.E.2.1—Example of HTHA Susceptibility Rankings for Cr-Mo Low Alloy Steels


STEP 1: Determine the material of construction, exposure temperature T and the exposure hydrogen partial pressure P_{H2}.
STEP 2: Has HTHA damage been observed in the component?
Yes
Is the component Replaced in Kind?
No, replaced with upgraded material
Yes, replaced in kind
High Susceptibility
No, not replaced
Damage Observed
No
STEP 3 1): Is the component carbon or C-½ Mo steel?
Yes
STEP 3 1): Is the component operating > 350F (177C) and H2pp > 50 psia (0.345 MPa)?
Yes
High Susceptibility
No
No
No Susceptibility
STEP 3 2): Assign Susceptibility based on operating condition and Figure 19.1
STEP 4: Determine the damage factor for HTHA, using Table 19.2.

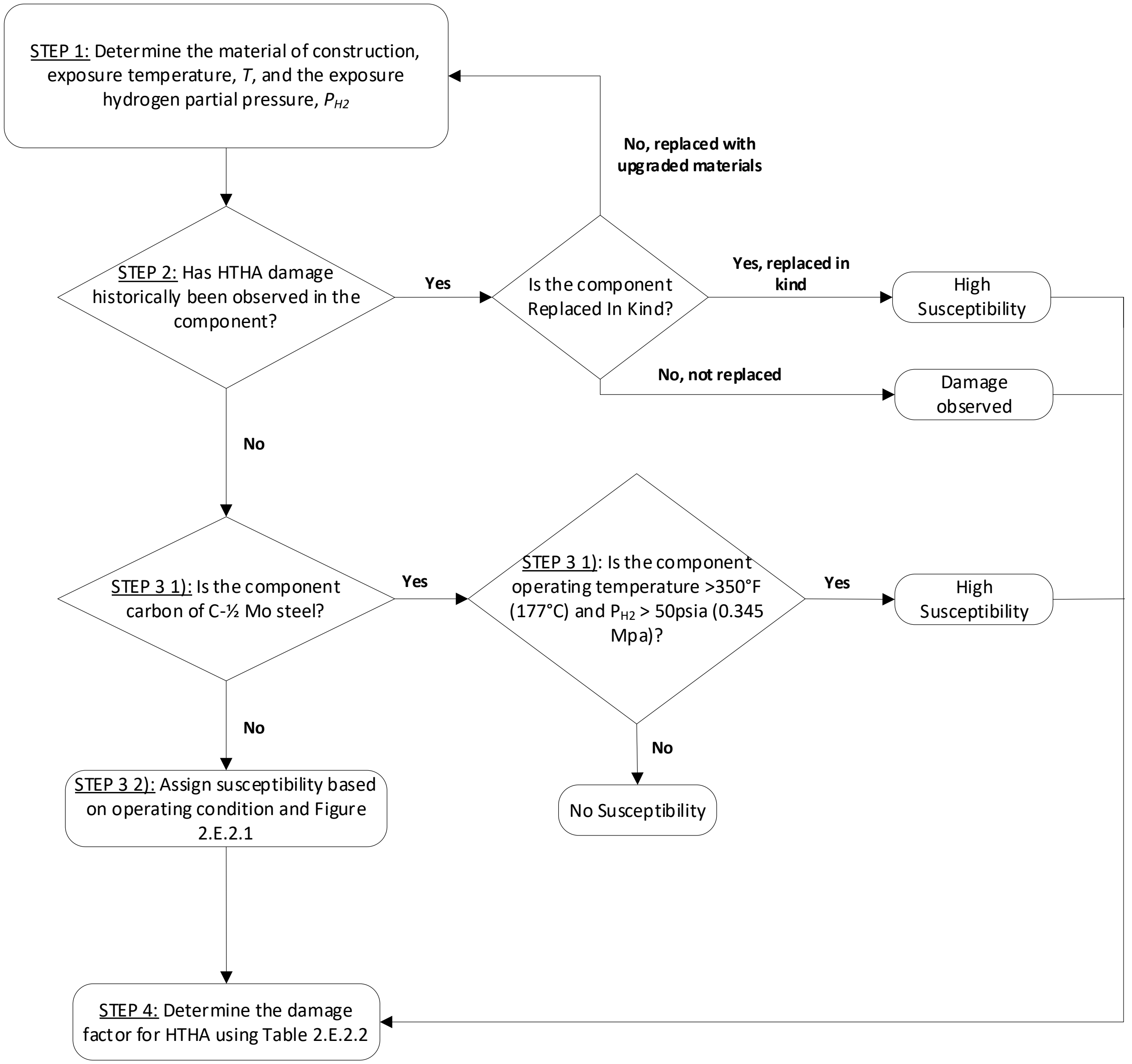


Figure 2.E.2.2—Determination of the HTHA DF

2.E.3 Brittle Fracture DF

2.E.3.1 Scope

The DF calculation for ferritic components subject to brittle fracture due to low-temperature operation is covered in this section. Low alloy steels subject to embrittlement at relatively high temperature are not part of the scope in this section and are covered in Section 2.E.4.

2.E.3.2 Description of Damage

Brittle fracture due to low temperature operation or relatively low toughness is the sudden failure of a structural component, usually initiated at a crack or defect. This is an unusual occurrence because design stresses are normally low enough to prevent such an occurrence. However, some older equipment with thick walls, equipment that might see low temperatures due to an upset, or equipment that has been modified could be susceptible to varying degrees.

Low temperature/low toughness fracture of steel is affected by the following.

a) The applied loads. Brittle fracture is less likely at low applied loads.

b) The material specification. Some materials are manufactured to have good fracture properties or toughness properties. Materials are often “qualified” for use by performing an impact test. This test measures the energy needed to break a notched specimen.

c) Temperature. Many materials (especially ferritic steels) become brittle below some temperature called the brittle-ductile transition temperature or reference temperature. Brittle fracture is typically not a concern above 300 °F (149 °C).

d) Weld residual stresses and PWHT.

e) Thickness of the component.

The goal of the low temperature/low toughness fracture assessment is to rank components by their relative POF with respect to fracture. This assessment will take into account the thickness, the material type, the PWHT, and temperatures.

2.E.3.3 Screening Criteria

If both of the following are true, then the component should be evaluated for susceptibility to brittle fracture.

a) The material is carbon steel or a low alloy steel; see Table 2.E.3~~2~~.1.

b) If minimum design metal temperature (MDMT), T_{MDMT} , or minimum allowable temperature (MAT), T_{MAT} , is unknown, or the component is known to operate at or below the MDMT or MAT under normal or upset conditions.

2.E.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 DF for brittle fracture are provided in Table 2.E.3~~2~~.2.

2.E.3.5 Basic Assumption

Brittle fracture requires the coincident presence of a crack-like defect, application of sufficient stress, and a susceptible material. The susceptibility to failure by brittle fracture can change due to in-service conditions.

2.E.3.6 Determination of the DF

2.E.3.6.1 Overview

A flow chart of the steps required to determine the DF for brittle fracture is shown in Figure 2.E.3~~2~~.1. The following sections provide additional information and the calculation procedure.

2.E.3.6.2 Inspection Effectiveness

Low temperature/low toughness fracture is prevented by a combination of appropriate design and operating procedures. When low temperature/low toughness fracture does occur, it almost invariably initiates at some pre-existing crack-like defect. From the initiation point, a crack will grow unstable, resulting in a serious leak or sometimes complete catastrophic rupture of the component. Theoretically, an inspection to locate and remove such pre-existing defects would reduce the POF. However, the initiating defect can be very small and need not be exposed to the surface where it could be found. For this reason, inspection for such defects is generally not considered to be an effective method for prevention of brittle fracture.

If existing records of a component do not indicate if it is constructed of normalized plate, then a metallurgical examination may help resolve this. In some cases, it may be possible to remove samples of the material large enough for testing to determine the toughness, which can also improve the accuracy of the prediction of low temperature/low toughness fracture likelihood.

For this damage mechanism, credit is not given for inspection. However, the results of metallurgical testing together with impact testing can be used to update the inputs to the DF calculation that may result in a change in this value.

2.E.3.6.3 Calculation of the DF

The following procedure may be used to determine the DF for brittle fracture; see Figure 2.E.~~2~~3.1.

a) STEP 1—Determine if administrative or process controls exist that will prevent the component from being fully pressurized below some temperature. If so, use this temperature for critical exposure temperature, CET, and go to STEP 3.

b) STEP 2—Determine the CET that the component may be subjected to during operation, using the guidance of Part 3, API 579-1/ASME FFS-1.

c) STEP 3—Determine the reference temperature, T_{ref}, using the material yield strength, YS, from Table 2.E.~~2~~3.3 and ASME Exemption Curve from Table 2.E.~~2~~3.1, in accordance with API 579-1/ASME FFS-1 [10].

d) STEP 4—Determine $CET - T_{ref}$ from STEP 1 or STEP 2, as applicable; T_{ref} is from STEP 3.

e) STEP 5—Determine the base DF, D_{fB}^{brit}, using the component thickness, t, and Table 2.E.3~~2~~.4 or Table 2.E.3~~2~~.5 based on the component PWHT condition and $CET - T_{ref}$ from STEP 4.

f) STEP 6—Determine the DF, D_f^{brit}, using Equation (2.E.1).

$$D_f^{brit} = D_{fb}^{brit} \cdot F_{SE} \qquad (2.E.1)$$

In general, the adjustment factor for service experience is 1 or F_{SE} = 1.00. However, this factor is reduced to F_{SE} = 0.01 if the component under assessment has a thickness less than or equal to 0.5 in. (12.7 mm) or meets all of the following criteria.

1) It is fabricated from P-1 and P-3 steels where the design temperature is less than or equal to 650 °F (343 °C).

2) The equipment satisfied all requirements of a recognized code or standard at the time of fabrication.

3) The nominal operating conditions have been essentially the same and consistent with the specified design conditions for a significant period of time, and more severe conditions (i.e. lower temperature and/or higher stress) are not expected in the future.

4) The CET at the MAWP is greater than or equal to −20 °F (−29 °C) if it is a pressure vessel or −155 °F (−104 °C) if it is a piping circuit.

5) The nominal uncorroded thickness is not greater than 2 in. (50.8 mm).

6) Cyclic service, fatigue, or vibration service is not a design requirement per design code.

7) The equipment or circuit is not subject to environmental cracking.

8) The equipment or circuit is not subject to shock chilling (see API 579-1/ASME FFS-1 for a definition of shock chilling).

   This adjustment is based on the grandfathering concept permitted in API 579-1/ASME FFS-1, Part 3, Level 2, Method C.

2.E.3.7 Nomenclature

CET is the critical exposure temperature as defined in API 579-1/ASME FFS-1, °F (°C)

D^{brit} is the DF for brittle fracture

D_{fB}^{brit} is the base DF for brittle fracture

F_{SE} is the DF adjustment for service experience

t is the component thickness, mm (in.)

T_{MAT} is the MAT as defined in API 579-1/ASME FFS-1, °F (°C)

T_{MDMT} is the MDMT as defined by construction code, °F (°C)

T_{ref} is the reference temperature as defined in API 579-1/ASME FFS-1, °F (°C)

YS is the material yield strength, ksi (MPa)

2.E.3.8 References

2.E.3.9 Tables

Table 2.E.~~2~~3.1—Assignment of Materials to the Material Temperature Exemption Curves

Curve	Material [1, 2, 6]
A	1. All carbon and all low alloy steel plates, structural shapes, and bars not listed in Curves B, C, and D below. 2. SA-216 Grades WCB and WCC if normalized and tempered or water-quenched and tempered; SA-217 Grade WC6 if normalized and tempered or water-quenched and tempered. 3. The following specifications for obsolete materials: A7, A10, A30, A70, A113, A149, A150. [3] 4. The following specifications for obsolete materials from the 1934 edition of the ASME Code, Section VIII: S1, S2, S25, S26, and S27. [4] 5. A201 and A212 unless it can be established that the steel was produced by a fine-grain practice. [5]
B	1. SA-216 Grade WCA if normalized and tempered or water-quenched and tempered. SA-216 Grades WCB and WCC for thicknesses not exceeding 2 in. if produced to a fine-grain practice and water-quenched and tempered. SA -217 Grade WC9 if normalized and tempered. SA-285 Grades A and B. SA-414 Grade A. SA-442 Grade 55 > 1 in. if not to fine-grain practice and normalized. SA-442 Grade 60 if not to fine-grain practice and normalized. SA-515 Grades 55 and 60. SA-516 Grades 65 and 70 if not normalized. SA-612 if not normalized. SA-662 Grade B if not normalized. 2. Except for cast steels, all materials of Curve A if produced to fine-grain practice and normalized that are not listed for Curves C and D below. 3. All pipe, fittings, forgings, and tubing not listed for Curves C and D below. 4. Parts permitted from paragraph UG-11 of the ASME Code, Section VIII, Division 1, shall be included in Curve B even when fabricated from plate that otherwise would be assigned to a different curve. 5. A201 and A212 if it can be established that the steel was produced by a fine-grain practice.
C	1. SA-182 Grades 21 and 22 if normalized and tempered. SA-302 Grades C and D. SA-336 Grades F21 and F22 if normalized and tempered. SA-387 Grades 21 and 22 if normalized and tempered. SA-442 Grade 55 < 1 in. if not to fine-grain practice and normalized. SA-516 Grades 55 and 60 if not normalized. SA-533 Grades B and C. SA-662 Grade A. 2. All material of Curve B if produced to fine-grain practice and normalized and not listed for Curve D below.

Table 2.E.3.1—Assignment of Materials to the Material Temperature Exemption Curves (Continued)

Curve	Material [1, 2, 6]
D	SA-203. SA-442 if to fine-grain practice and normalized. SA-508 Class 1. SA-516 if normalized. SA-524 Classes 1 and 2. SA-537 Classes 1 and 2. SA-612 if normalized. SA-662 if normalized. SA-738 Grade A.

NOTE 1 When a material class or grade is not shown, all classes or grades are included.

NOTE 2 The following apply to all material assignment notes.

a. Cooling rates faster than those obtained in air, followed by tempering, as permitted by the material specification, are considered equivalent to normalizing and tempering heat treatments.

b. Fine-grain practice is defined as the procedures necessary to obtain a fine austenitic grain size as described in SA-20.

NOTE 3 The first edition of the *API Code for Unfired Pressure Vessels* (discontinued in 1956) included these ASTM carbon steel plate specifications. These specifications were variously designated for structural steel for bridges, locomotives, and rail cars or for boilers and firebox steel for locomotives and stationary service. ASTM A149 and A150 were applicable to high-tensile-strength carbon steel plates for pressure vessels.

NOTE 4 The 1934 edition of Section VIII of the ASME Code listed a series of ASME steel specifications, including S1 and S2 for forge welding; S26 and S27 for carbon steel plates; and S25 for open-hearth iron. The titles of some of these specifications are similar to the ASTM specifications listed in the 1934 edition of the *API Code for Unfired Pressure Vessels*.

NOTE 5 These two steels were replaced in strength grades by the four grades specified in ASTM A515 and the four grades specified in ASTM A516. Steel in accordance with ASTM A212 was made only in strength grades the same as Grades 65 and 70 and has accounted for several known brittle failures. Steels in conformance with ASTM A201 and A212 should be assigned to Curve A unless it can be established that the steel was produced by fine-grain practice, which may have enhanced the toughness properties.

NOTE 6 No attempt has been made to make a list of obsolete specifications for tubes, pipes, forgings, bars, and castings. Unless specific information to the contrary is available, all of these product forms should be assigned to Curve A.

Table 2.E.3.2—Data Required for Determination of the DF—Brittle Fracture

Required Data	Comments
Administrative controls for upset management (Yes/No)	Are there controls and or awareness training to prevent the coincident occurrence of low temperatures (upset) at or near design pressures?
Minimum operating temperature under normal or upset conditions, °F (°C)	Can be entered by the user. The temperature may be set to the atmospheric boiling point of the fluid in the component if the fluid is a liquid.
Service life of equipment (years)	How long has the equipment been in the specified service?
Inspection and testing history accuracy factor	Accuracy and attainability of previous inspection history. Frequency of inspections, data points available. Previous metallurgical analysis and mechanical testing (impact test).

Table 2.E.3.3—Reference Temperature

Carbon Steels—20 joule or 15 ft-lb Transition Temperature for Each ASME Exemption Curve				
Minimum Yield Strength (ksi)	ASME Exemption (°F)			
	Curve A	Curve B	Curve C	Curve D
30	104	66	28	2
32	97	59	21	−5
34	91	53	15	−11
36	86	48	10	−16
38	81	43	5	−21
40	78	40	2	−24
42	74	36	−2	−28
44	71	33	−5	−31
46	68	30	−8	−34
48	66	28	−10	−36
50	63	25	−13	−39
Low Alloy Steels—27 joule or 20 ft-lb Transition Temperature for Each ASME Exemption Curve				
Minimum Yield Strength (ksi)	ASME Exemption (°F)			
	Curve A	Curve B	Curve C	Curve D
30	124	86	48	22
32	115	77	39	13
34	107	69	31	5
36	101	63	25	−1
38	96	58	20	−6
40	92	54	16	−10
42	88	50	12	−14
44	85	47	9	−17
46	81	43	5	−21
48	79	41	3	−23
50	76	38	0	−26
52	73	35	−3	−29
54	71	33	−5	−31
56	69	31	−7	−33
58	67	29	−9	−35
60	65	27	−11	−37
62	63	25	−13	−39
64	62	24	−14	−40
66	60	22	−16	−42
68	58	20	−18	−44
70	57	19	−19	−45
72	56	18	−20	−46
74	54	16	−22	−48
76	53	15	−23	−49
78	52	14	−24	−50
80	51	13	−25	−51

Table 2.E.3.3M—Reference Temperature

Carbon Steels—20 joule or 15 ft-lb Transition Temperature for Each ASME Exemption Curve				
Minimum Yield Strength (MPa)	ASME Exemption (°C)			
	Curve A	Curve B	Curve C	Curve D
200	42	21	0	−15
210	38	17	−4	−18
220	36	15	−7	−21
230	33	1	−9	−23
240	31	10	−11	−26
260	27	6	−15	−29
280	24	3	−18	−32
300	22	1	−21	−35
320	19	−2	−23	−37
340	17	−4	−25	−39
360	15	−6	−27	−41
Low Alloy Steels—27 joule or 20 ft-lb Transition Temperature for Each ASME Exemption Curve				
Minimum Yield Strength (MPa)	**ASME Exemption (°C)**			
	Curve A	**Curve B**	**Curve C**	**Curve D**
200	55	33	12	−2
210	50	29	8	−7
220	46	25	4	−11
230	43	22	1	−14
240	40	19	−2	−16
250	38	17	−4	−19
260	36	15	−6	−21
270	34	13	08	−23
280	32	11	−10	−24
290	31	10	−11	−26
300	30	8	−13	−27
310	28	7	−14	−28
320	27	6	−15	−30
330	26	5	−16	−31
340	25	4	−17	−32
360	23	2	−19	−34
380	21	0	−21	−36
400	19	−2	−23	−37
420	18	−3	−24	−39
440	16	−5	−26	−40
460	15	−6	−27	−42
480	14	−7	−28	−43
500	13	−8	−29	−44
520	12	−9	−30	−45
540	11	−10	−31	−46
560	10	−11	−32	−47

Table 2.E.3.4—DF, Component Not Subject to PWHT—Brittle Fracture

$CET - T_{ref}$ (°F)	DF As a Function of Component Thickness (in)								
	0.25	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
100	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.1	1.2
80	0.0	0.0	0.0	0.8	1.1	2	3	4	6
60	0.0	0.0	1.0	2	4	9	19	36	60
40	0.0	0.7	2	9	29	69	133	224	338
20	0.1	1.3	10	49	143	296	500	741	1008
0	0.9	3	39	175	424	759	1142	1545	1950
−20	1.2	7	109	405	850	1366	1897	2415	2903
−40	2	16	220	697	1317	1969	2596	3176	3703
−60	2	30	350	988	1740	2479	3160	3769	4310
−80	3	46	474	1239	2080	2873	3581	4203	4746
−100	4	61	579	1436	2336	3160	3883	4509	5000

Table 2.E.3.4M—DF, Component Not Subject to PWHT—Brittle Fracture

$CET - T_{ref}$ (°C)	DF As a Function of Component Thickness (mm)								
	6.4	**12.7**	**25.4**	**38.1**	**50.8**	**63.5**	**76.2**	**88.9**	**101.6**
56	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.1	1.2
44	0.0	0.0	0.0	0.8	1.1	2	3	4	6
33	0.0	0.0	1.0	2	4	9	19	36	60
22	0.0	0.7	2	9	29	69	133	224	338
11	0.1	1.3	10	49	143	296	500	741	1008
−0	0.9	3	39	175	424	759	1142	1545	1950
−11	1.2	7	109	405	850	1366	1897	2415	2903
−22	2	16	220	697	1317	1969	2596	3176	3703
−33	2	30	350	988	1740	2479	3160	3769	4310
−44	3	46	474	1239	2080	2873	3581	4203	4746
−56	4	61	579	1436	2336	3160	3883	4509	5000

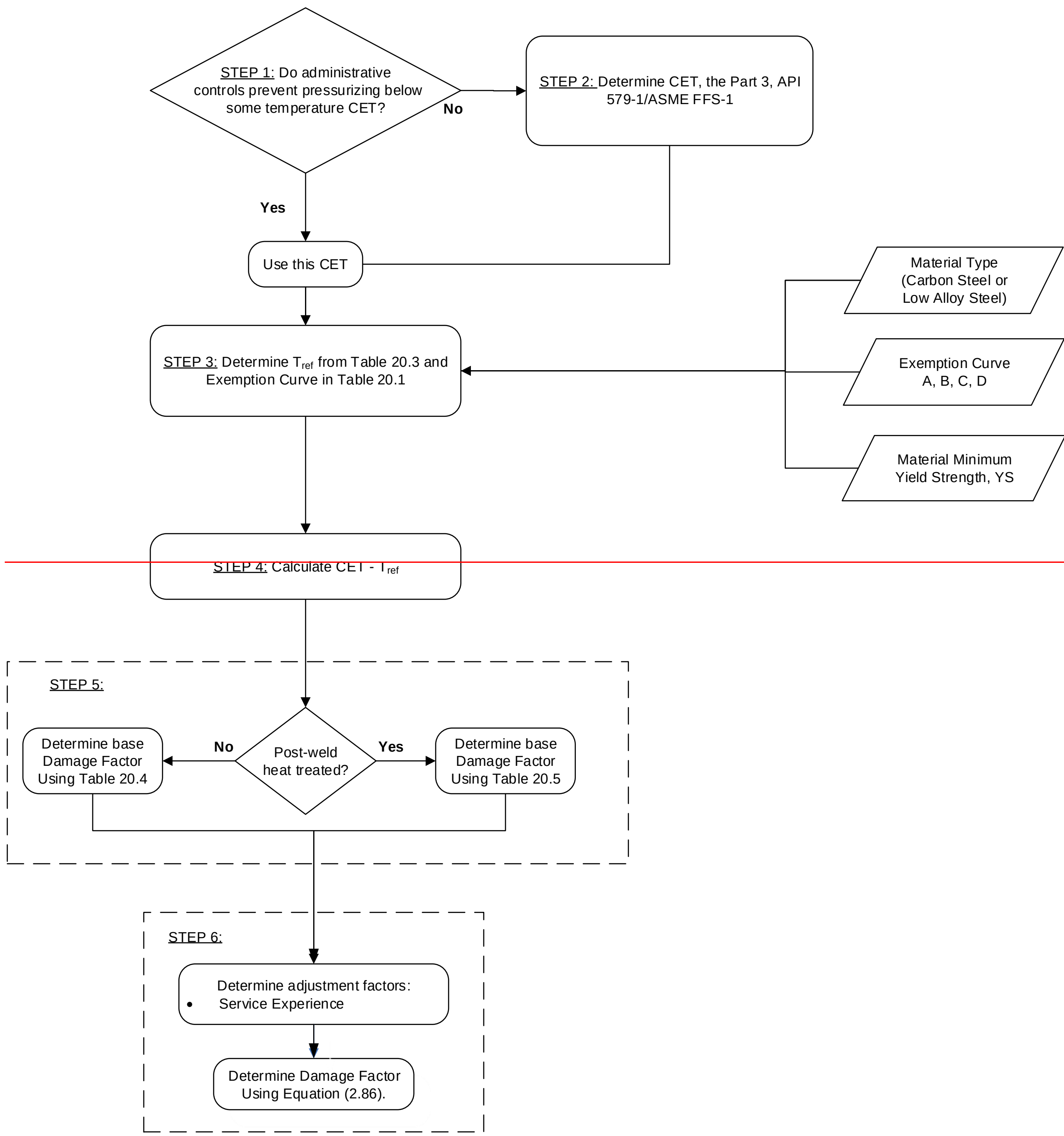
Table 2.E.3.5—DF, Component Subject to PWHT—Brittle Fracture

$CET - T_{ref}$ (°F)	DF As a Function of Component Thickness (in)								
	0.25	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0
100	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
80	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
60	0.0	0.0	0.0	0.0	0.0	0.5	0.9	1.1	1.3
40	0.0	0.0	0.0	0.5	1.1	1.3	2	3	4
20	0.0	0.0	0.6	1.2	2	4	7	13	23
0	0.0	0.0	1.1	2	6	14	29	53	88
−20	0.0	0.4	2	5	17	41	83	144	224
−40	0.0	0.9	3	12	38	90	171	281	416
−60	0.0	1.1	5	22	68	153	277	436	623
−80	0.0	1.2	7	34	102	219	382	582	810
−100	0.0	1.3	9	46	133	277	472	704	962

Table 2.E.3.5M—DF, Component Subject to PWHT—Brittle Fracture

$CET - T_{ref}$ (°C)	DF As a Function of Component Thickness (mm)								
	6.4	12.7	25.4	38.1	50.8	63.5	76.2	88.9	101.6
56	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
33	0.0	0.0	0.0	0.0	0.0	0.5	0.9	1.1	1.3
22	0.0	0.0	0.0	0.5	1.1	1.3	2	3	4
11	0.0	0.0	0.6	1.2	2	4	7	13	23
−0	0.0	0.0	1.1	2	6	14	29	53	88
−11	0.0	0.4	2	5	17	41	83	144	224
−22	0.0	0.9	3	12	38	90	171	281	416
−33	0.0	1.1	5	22	68	153	277	436	623
−44	0.0	1.2	7	34	102	219	382	582	810
−56	0.0	1.3	9	46	133	277	472	704	962

2.E.3.10 Figures



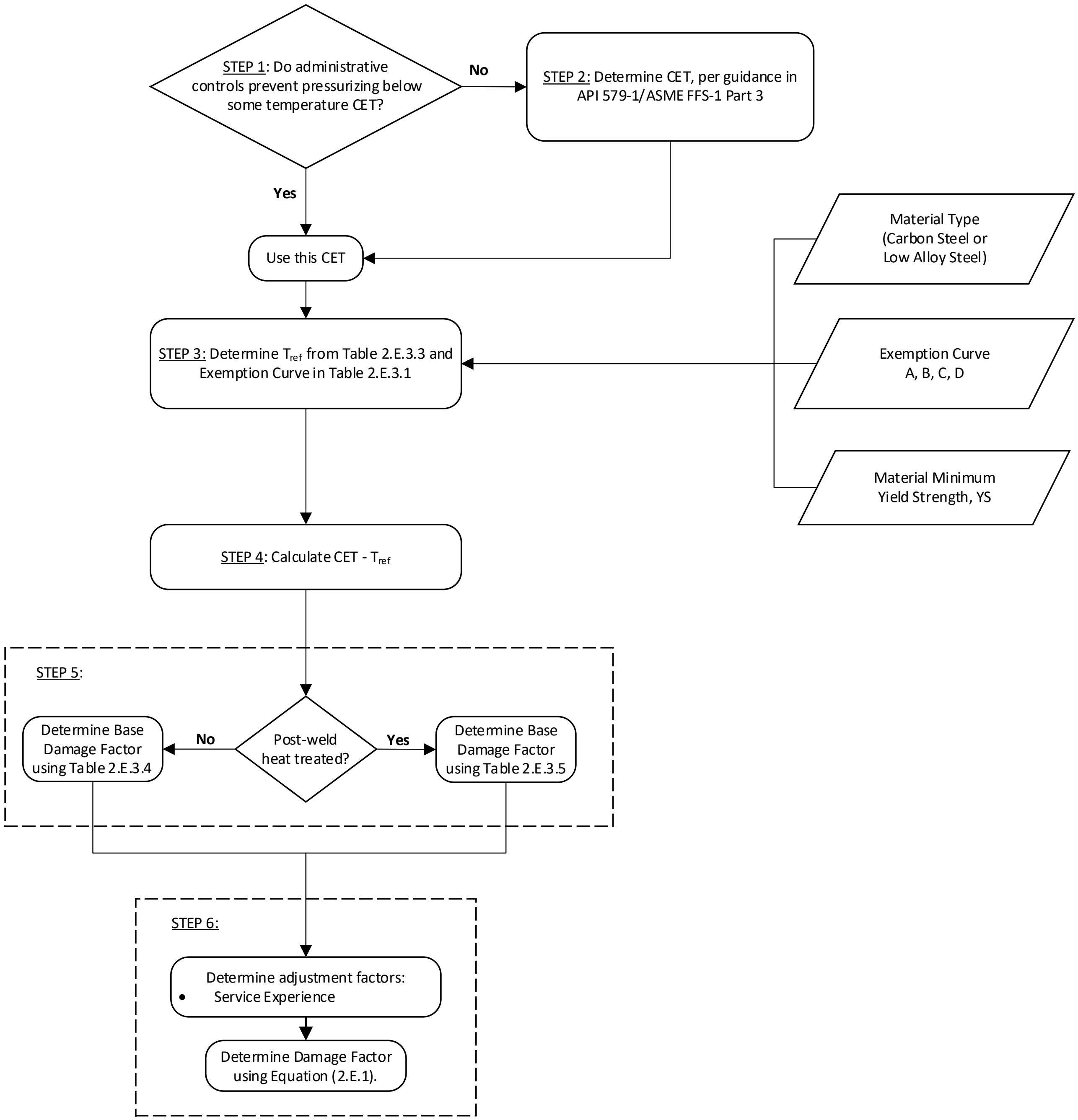


Figure 2.E.3.1—Determination of the Brittle Fracture DF

2.E.4 Low Alloy Steel Embrittlement Damage Factor

2.E.3.1 Scope

The DF calculation for low alloy Cr-Mo steel components subject to embrittlement is covered in this section.

2.E.3.2 Description of Damage

The toughness of some low alloy or Cr-Mo steels is reduced by a phenomenon called embrittlement after extended exposure to temperatures in the range of 650 °F to 1070 °F (343 °C to 577 °C). Of particular interest to the refining and petrochemical industries is the embrittlement of Cr-Mo steels used in operations within the temperature range for embrittlement. The reduction in fracture toughness only affects the material at the lower temperatures experienced during start-up and shutdown of equipment. Industry practice to avoid brittle fracture has been to reduce the operating pressure to one-fourth of the design pressure when the vessel temperature is less than some minimum process temperature. Typical industry practice for this minimum temperature is 300 °F to 350 °F (149 °C to 177 °C) for older vintage low alloy steels, or lower temperatures for more modern steels.

The embrittlement is caused by segregation of tramp elements and alloying elements along grain boundaries in the steel. The phosphorous and tin content of the steel are of particular importance in 2.25 Cr-1Mo and 3 Cr-1Mo alloys, and their effect is made worse by manganese and silicon, which are important alloying elements, while in 1.25Cr-0.5Mo and 1Cr-0.5Mo alloys, phosphorus, arsenic, and antimony are also of particular importance. A J-factor based on composition is typically specified to control the susceptibility to low alloy steel embrittlement in 2.25Cr-1Mo alloys and 3Cr-1Mo alloys. The J-factor and X-bar factor are calculated using Equation (2.E.2) and Equation (2.E.3). Laboratory and long-term field studies have confirmed fair correlation between the J-factor and the amount of low alloy steel embrittlement in 2.25Cr-1Mo and 3Cr-1Mo alloys, and between X-bar factor and embrittlement of 1.25Cr-0.5Mo and 1Cr-0.5Mo alloys.

$$\text{J-factor} = (\%Si + \%Mn) \cdot (\%P + \%Sn) \cdot 10^4 \tag{2.E.2}$$

$$\text{X-bar} = (10\%P + 5\%Sb + 4\%Sn + \%As) \cdot 100 \tag{2.E.3}$$

One very important aspect of embrittlement is the tendency of weld metal and HAZs to show increased susceptibility to embrittlement vs the wrought base material. A few studies have shown that 2.25Cr-0.5Mo and 3Cr-1Mo are particularly susceptible. It is debatable whether or not 1.25Cr-0.5Mo and 1Cr-0.5Mo steels are also susceptible to temper embrittlement but are susceptible to in-service loss of toughness; therefore, these materials have been included in the DF calculations in this section.

2.E.3.3 Screening Criteria

If all of the following are true, then the component should be evaluated for susceptibility to low alloy steel embrittlement.

a) The material is 1Cr-0.5Mo, 1.25Cr-0.5Mo, 2.25Cr-1Mo, or 3Cr-1 Mo low alloy steel.

b) The operating temperature is between 650 °F and 1070 °F (343 °C and 577 °C).

2.E.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 DF for low alloy steel embrittlement are provided in Table 2.E.3.1.

2.E.3.5 Basic Assumption

Low alloy steel embrittlement is evaluated in the same way as brittle fracture (see Section 2.E.2) except that a shift in the reference temperature is made to account for embrittlement.

2.E.3.6 Determination of the Damage Factor

2.E.3.6.1 Overview

A flow chart of the steps required to determine the DF for low alloy steel embrittlement is shown in Figure 2.E.3.1. The following sections provide additional information and the calculation procedure.

2.E.3.6.2 Inspection Effectiveness

For this damage mechanism, credit is not given for inspection. However, the results of metallurgical testing together with impact testing can be used to update the inputs to the DF calculation that may result in a change in this value.

2.E.3.6.3 Calculation of the Damage Factor

The following procedure may be used to determine the DF for low alloy steel embrittlement; see Figure 2.E.3.1.

a) STEP 1—Determine if administrative or process controls exist that will prevent the component from being fully pressurized below some temperature. If so, use this as the minimum pressurization temperature, T_{MPT} , and go to STEP 3.

b) STEP 2—Determine the T_{MPT} that the component may be subjected to during operation, using the lowest of the following.

   1) The minimum design temperature, T_{MDT} .

   2) The T_{MDT} as estimated by the process engineer, including upsets.

c) STEP 3—Determine the reference temperature, T_{ref} , from Table 2.E.2.3 using material yield strength, YS , and the material specification from Table 2.E.2.1 [10].

d) STEP 4—Determine $\Delta FATT$. If $\Delta FATT$ is not known it may be estimated by one of the following methods, listed in decreasing order of accuracy.

   1) Determined by engineering analysis or actual impact testing of metal samples.

   2) Determined in a step cooling embrittlement test, SCE . The SCE can be related to the actual in-service $\Delta FATT$ using Equation (2.E.4) where age is the operating time in hours and SCE is the specified change in $FATT$.

$$\Delta FATT = 0.67 \cdot \left(\log\left(age\right) - 0.91\right) \cdot SCE \qquad (2.E.4)$$

3) Determined by chemical composition correlations. Use the chemical composition to determine the J-factor or X-bar factor using Equation (2.E.2) and Equation (2.E.3). The J-factor and X-bar factor may be correlated to the expected $\Delta FATT$ after long-term service. Based on long-term exposures, this is conservatively correlated to the J-factor and X-bar factor in Equation (2.E.5) and Equation (2.E.6), respectively.

$$\Delta FATT = -77.321 + (0.57570 \cdot \text{J-factor}) - (5.5147 \cdot (10^{-4}) \times (\text{J-factor}^2)) \quad (2.E.5)$$

$$\Delta FATT = -87.335 + (11.437 \cdot \text{X-bar}) - (0.1472 \cdot (\text{X-bar}^2)) \quad (2.E.6)$$

4) Determined by using conservative assumptions based on year of fabrication. A conservative value of can be assumed for the long term $\Delta FATT$ depending on the year of fabrication as follows:

— fourth generation equipment (after to 1988): 150 °F (66 °C);

— third generation equipment (1981 to 1987): 250 °F (121 °C);

— second generation equipment (1973 to 1980): 300 °F (149 °C);

— first generation equipment (1965 to 1972): 350 °F (177 °C).

e) STEP 5—Calculate $T_{ref} + \Delta FATT$ using T_{ref} from STEP 3 and $\Delta FATT$ from STEP 4.

f) STEP 6—Calculate the DF, D_f^{tempe}, using Table 2.E.2.4 or Table 2.E.2.5 based on the component PWHT condition and where $T_{ref} + \Delta FATT$ is from STEP 5.

NOTE Use $T_{MPT} - \left(T_{ref} + \Delta FATT\right)$ in place of $CET - T_{ref}$ with T_{MPT} from STEP 1 or STEP 2, as applicable.

2.E.3.7 Nomenclature

age is the in-service operating time, hours

D_f^{tempe} is the DF for low alloy steel embrittlement

SCE is the specified change in *FATT*

T_{MDT} is the minimum design temperature, °F (°C)

T_{MPT} is the minimum pressurization temperature, °F (°C)

T_{ref} is the reference temperature, °F (°C)

YS is the material yield strength

$\Delta FATT$ is the change in the fracture appearance transition temperature, °C for equations in this section

2.E.3.8 References

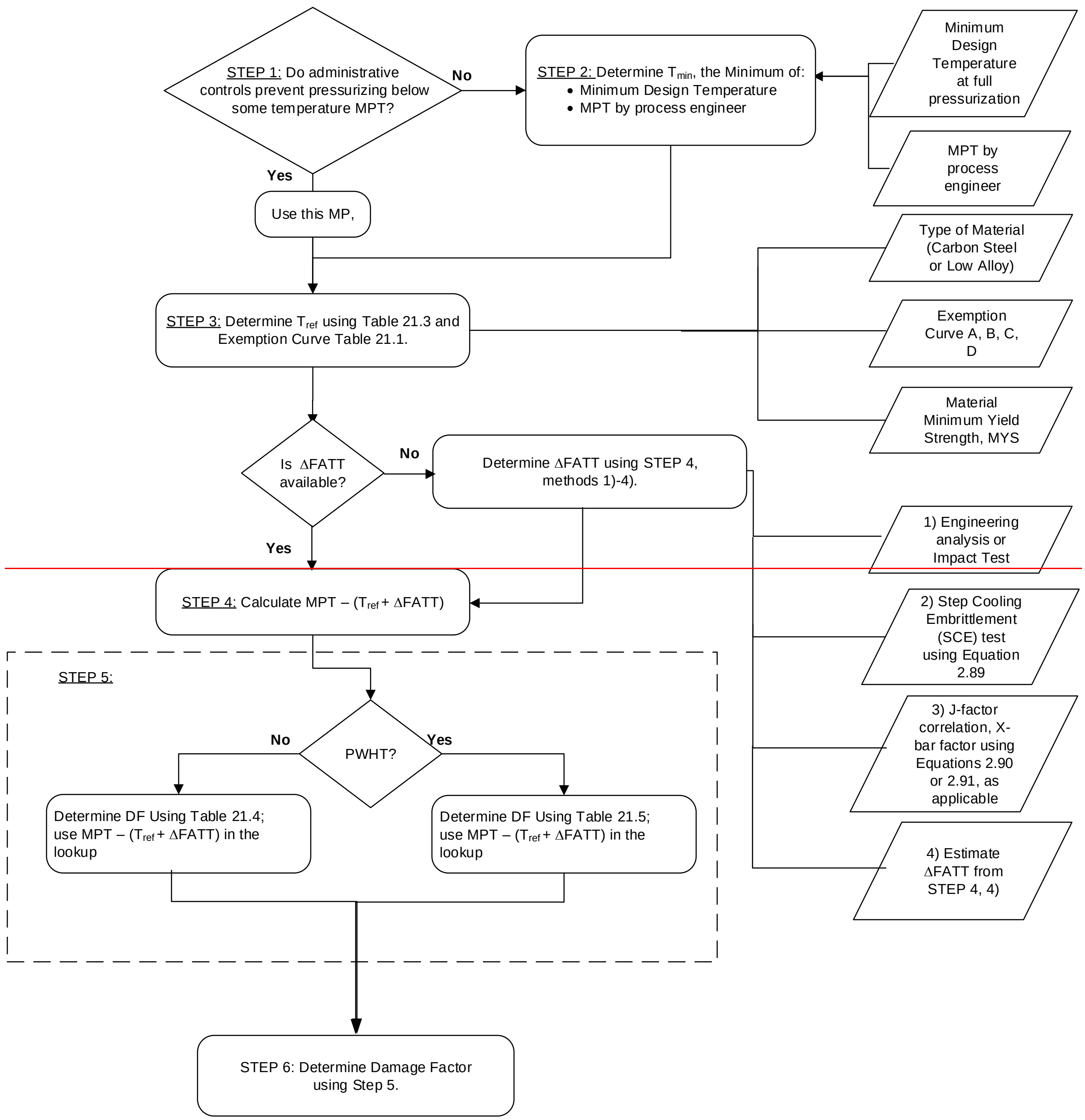
See References [76], [84], [85], [86], [87], [88], [89], and [90] in Part 2, Section 2.2.

2.E.3.9 Table

Table 2.E.3.1—Data Required for Determination of the DF—Low Alloy Steel Embrittlement

Required Data	Comments
Impact test temperature, °F (°C)	If impact tested. If this is unknown, it should be assumed that impact tests were not done.
Administrative controls for upset management (Yes/No)	Are there controls and or awareness training to prevent the coincident occurrence of low temperatures (upset) at or near design pressures?
Minimum operating temperature under normal, start-up/shutdown, or upset conditions, °F (°C)	For low alloy steel embrittlement, this may be the temperature below which the operating pressure is reduced for purposes of fracture control. If not known, the temperature should be set to the atmospheric boiling point of the fluid in the component if the fluid is a liquid.
Time in service, years	The number of years in service within the temperature range.
$\Delta FATT$, °F (°C)	The change in the fracture appearance transition temperature before and after embrittlement.
Chemical composition of steel (optional)	Specifically, the %Si, %Mn, %P, and %Sn for 2.25Cr-1Mo and 3Cr-1M0 steels and the %P, %Sb, %Sn, and %As for 1.25Cr-1Mo and 1Cr-1Mo steels, which contribute to the susceptibility to low alloy steel embrittlement. If not known, a transition shift will be assumed.
Screening of materials (Y/N)	Was the material used for the component screened for susceptibility to low alloy steel embrittlement by such methods as specifications for steel composition or specification of a transition temperature requirement in a step cooling embrittlement (SCE) test.
SCE specified delta temperature, °F (°C)	The delta temperature specified for SCE tests.

2.E.3.10 Figures



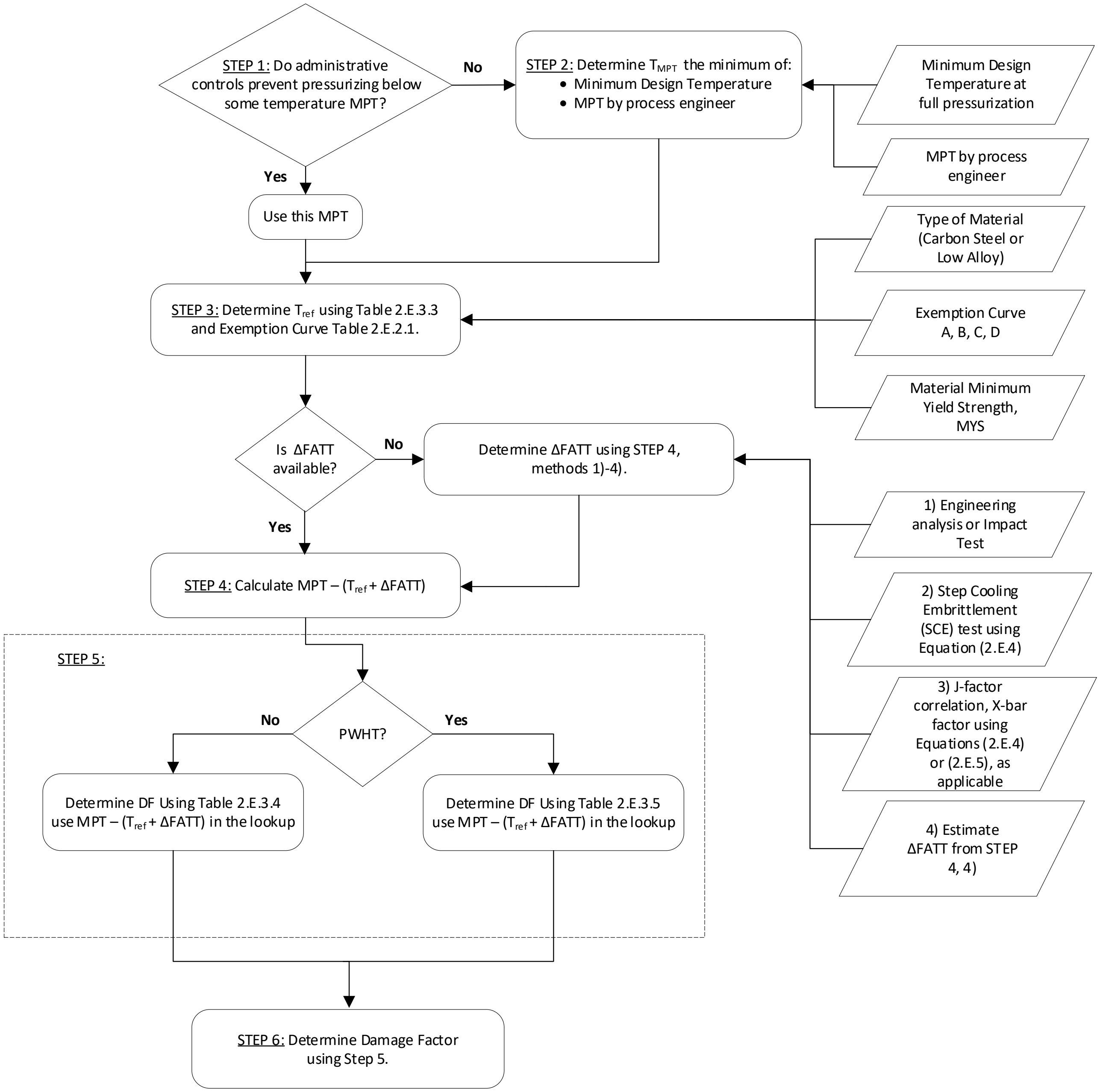


Figure 2.E.3.1—Determination of the Low Alloy Steel Embrittlement DF

2.E.5 885 °F Embrittlement DF

2.E.5.1 Scope

The DF calculation for components subject to 885 °F embrittlement is covered in this section.

2.E.5.2 Description of Damage

885 °F embrittlement is a reduction in toughness of ferritic stainless steels with a chromium content of greater than 13 %, after exposure to temperatures between 700 °F and 1000 °F (371 °C and 538 °C). The reduction in toughness is due to precipitation of a chromium-phosphorous intermetallic phase at elevated temperatures. As is the case with other mechanisms that result in a loss of toughness due to metallurgical changes, the effect on toughness is most pronounced not at the operating temperature, but at lower temperatures experienced during plant shutdowns or upsets.

The precipitation of the intermetallic phase is believed to occur most readily at a temperature around 885 °F (474 °C), hence the name for this mechanism. Steels with more than 27 % chromium are most severely affected, but these are not typically used in refinery or petrochemical processes. Martensitic stainless steels such as Type 410 are normally considered to be immune to this problem. Type 405 is a ferritic stainless steel that is subject to the problem if it contains chromium levels at the high end of its composition range.

The existence of 885 °F embrittlement can reveal itself by an increase in hardness in affected areas. Physical testing of samples removed from service is the most positive indicator of a problem.

885 °F embrittlement is reversible by appropriate heat treatment to dissolve precipitates, followed by rapid cooling. Heat treatment temperature is typically in the range of 1400 °F to 1500 °F (760 °C to 816 °C), so this may not be practical for many components.

2.E.5.3 Screening Criteria

If both of the following are true, then the component should be evaluated for susceptibility to 885 °F embrittlement.

a) The material is a high chromium (>12 % Cr) ferritic steel.

b) The operating temperature is between 700 °F and 1050 °F (371 °C and 566 °C).

2.E.5.4 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 DF for 885 °F embrittlement are provided in Table 2.E.5.1.

2.E.5.5 Basic Assumption

Since 885 °F embrittlement may occur in a relatively short period of time, it is assumed in the development of the DF that any of the ferritic materials listed in Table 2.E.5.2 that have been exposed to temperatures in the 700 °F to 1,000 °F (371 °C to 538 °C) range are affected.

API 579-1/ASME FFS-1 [10] recommends that for embrittled materials, the toughness should be determined by the K_{Ir} (fracture arrest) curves, truncated at 100 °F (38 °C). It is further recommended that for severely embrittled materials, 50 % of this value should be used. The ductile-to-brittle transition temperatures for ferritic stainless steels (400 series) typically are in the 50 °F to 100 °F (10 °C to 38 °C) range.

2.E.5.6 Determination of the Damage Factor

2.E.5.6.1 Overview

A flow chart of the steps required to determine the DF for 885 °F embrittlement is shown in Figure 2.E.5.1. The following sections provide additional information and the calculation procedure.

2.E.5.6.2 Inspection Effectiveness

For this damage mechanism, credit is not given for inspection. However, the results of metallurgical testing can be used to update the inputs to the DF calculation that may result in a change in this value.

2.E.5.6.3 Calculation of the DF

The following procedure may be used to determine the DF for 885 °F embrittlement; see Figure 2.E.5.1.

a) STEP 1—Determine if administrative or process controls exist that will prevent the component from being fully pressurized below some temperature. If so, use this temperature for T_{min} and go to STEP 3.

b) STEP 2—Determine the minimum temperature, T_{min}, that the component may be subjected to during operation, using the lowest of the following:

   1) the minimum design temperature;

   5) the minimum temperature as estimated by the process engineer, including upsets.

c) STEP 3—Determine the reference temperature. Use T_{ref} = 28 °C (80 °F) unless the actual ductile to brittle transition temperature is known.

d) STEP 4—Determine $T_{min} - T_{ref}$, where T_{min} is from STEP 1 or STEP 2, as applicable, and T_{ref} is from STEP 3.

e) STEP 5—Determine the DF, D_f^{885F}, using Table 2.E.5.3 based on $T_{min} - T_{ref}$ from STEP 4.

2.E.5.7 Nomenclature

D_f^{885F}	is the DF for 885 °F embrittlement
T_{min}	is the minimum temperature, °F (°C)
T_{ref}	is the reference temperature, °F (°C)

2.E.5.8 References

See References [65], [66], [67], and [68] in Part 2, Section 2.2.

2.E.5.9 Tables

Table 2.E.5.1—Data Required for Determination of the DF—885 °F Embrittlement

Required Data	Comments
Administrative controls for upset management (Yes/No)	Are there controls and or awareness training to prevent the coincident occurrence of low temperatures (upset) at or near design pressures?
Minimum operating temperature under normal, start-up/shutdown, or upset conditions, °C (°F)	This may be the temperature below which the operating pressure is reduced for purposes of fracture control. If not entered, the temperature will be set to the atmospheric boiling point of the fluid in the component if the fluid is a liquid.
T_{ref}, °F (°C)	The original transition temperature.

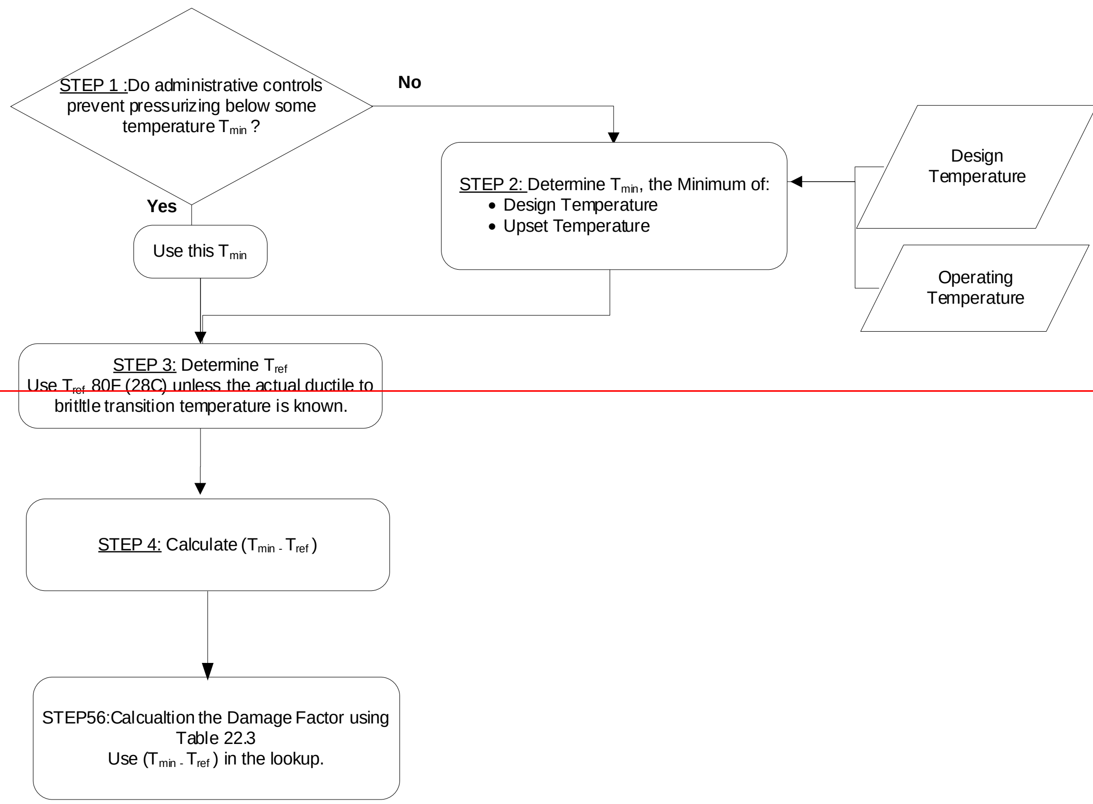
Table 2.E.5.2—Materials Affected by 885 °F Embrittlement

AISI Designation	% Chromium
Type 405	11.5 to 14.5
Type 430	16 to 18
Type 430F	16 to 18
Type 442	18 to 23
Type 446	23 to 27

Table 2.E.5.3—DF—885 °F Embrittlement

$T_{min} - T_{ref}$		DF
°C	°F	
>56	>100	0
56	100	2
44	80	8
33	60	30
22	40	87
11	20	200
-0	0	371
−11	−20	581
−22	−40	806
−33	−60	1022
−44	−80	1216
−56	−100	1381

2.E.5.10 Figures



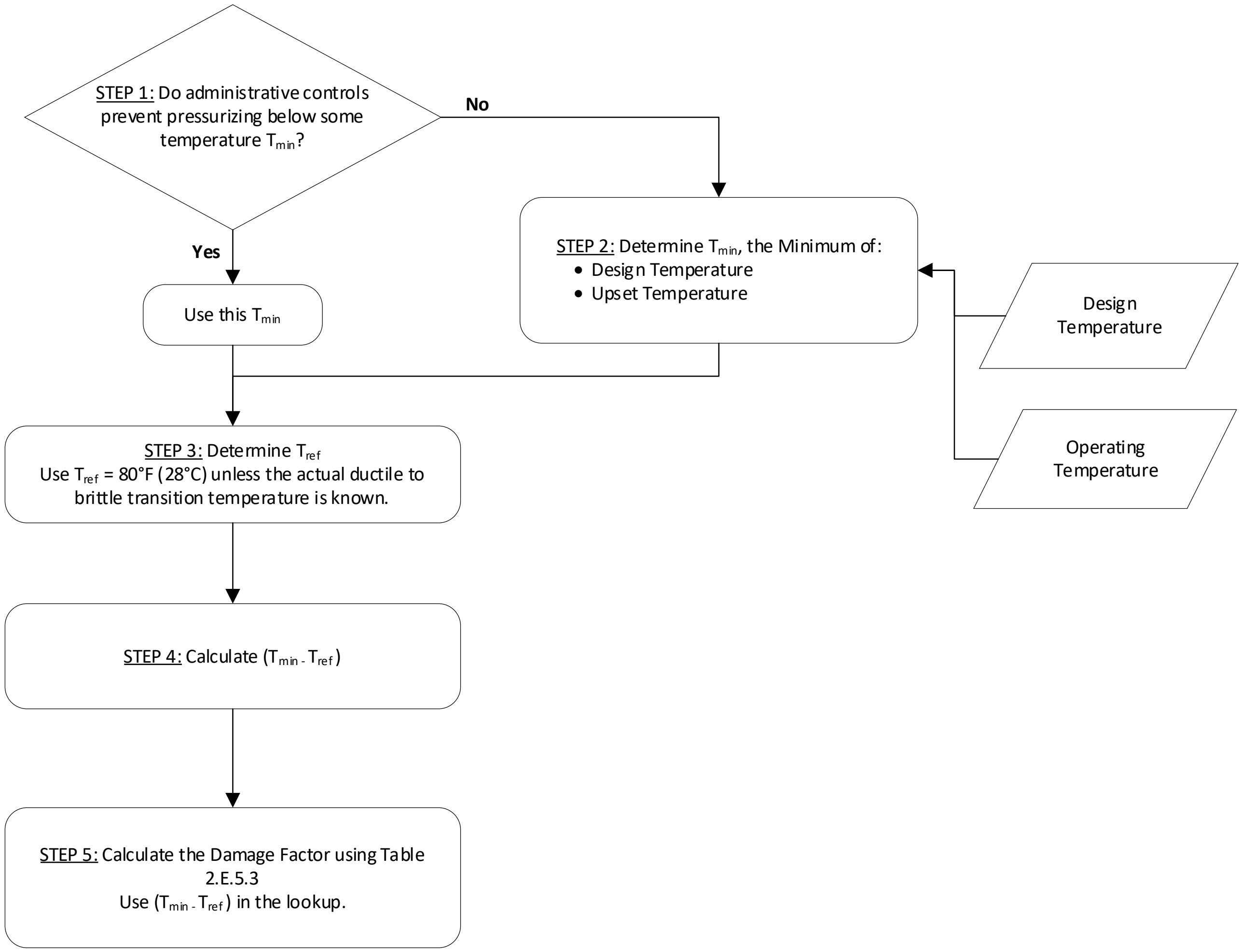


Figure 2.E.5.1—Determination of the 885 °F Embrittlement DF

2.E.6 Sigma Phase Embrittlement DF

2.E.6.1 Scope

The DF calculation for components subject to sigma phase embrittlement is covered in this section.

2.E.6.2 Description of Damage

Sigma phase is a hard, brittle intermetallic compound of iron and chromium with an approximate composition of $FE_{0.6}Cr_{0.4}$. It occurs in ferritic (Fe-Cr), martensitic (Fe-Cr), and austenitic (Fe-Cr-Ni) stainless steels when exposed to temperatures in the range of 1,100 °F to 1,700 °F (593 °C to 927 °C). The rate of formation and the amount of sigma formed are dependent on chemical composition of the alloy and prior cold work history. Ferrite stabilizers (Cr, Si, Mo, Al, W, V, Ti, Nb) tend to promote sigma formation, while austenite stabilizers (C, Ni, N, Mn) tend to retard sigma formation. Austenitic stainless steel alloys typically exhibit a maximum of about 10 % sigma phase, or less with increasing nickel. However, other alloys with a nominal composition of 60 % Fe, 40 % Cr (about the composition of sigma) can be transformed to essentially 100 % sigma. A transformation vs time curve for such a Fe-Cr alloy showed 100 % conversion to sigma in 3 hours at 1377 °F (747 °C). Conversion to sigma in austenitic stainless steels can also occur in a few hours, as evidenced by the known tendency for sigma to form if an austenitic stainless steel is subjected to a PWHT at 1275 °F (691 °C). Sigma is unstable at temperatures above 1650 °F (899 °C), and austenitic stainless steel components can be de-sigmatized by solution annealing at 1950 °F (1066 °C) for 4 hours followed by a water quench.

Mechanical properties of sigmatized materials are affected depending upon both the amount of sigma present and the size and shape of the sigma particles. For this reason, prediction of mechanical properties of sigmatized material is difficult.

The tensile and yield strength of sigmatized stainless steels increases slightly compared with solution annealed material. This increase in strength is accompanied by a reduction in ductility (measured by % elongation and reduction in area) and a slight increase in hardness.

The property that is most affected by sigma formation is the toughness. Impact tests show decreased impact energy absorption, and decreased percent shear fracture sigmatized stainless steels vs solution annealed material. The effect is most pronounced at temperatures below 1,000 °F (538 °C) although there may be some reduction in impact properties at higher temperatures as well. However, because austenitic stainless steels exhibit such good impact properties in the solution annealed condition, then even with considerable degradation, the impact properties may be comparable to other steels used in the process industries. A draft FFS report from the Materials Properties Council recommends default fracture toughness values of $150\ ksi\sqrt{in}$ and $90\ ksi\sqrt{in}$ for base and weld material, respectively, for thermally embrittled austenitic stainless steels.

Tests performed on sigmatized stainless steel samples from FCC regenerator internals showed that even with 10 % sigma formation, the Charpy impact toughness was 39 ft-lb at 1200 °F (53 joules at 649 °C). This would be considered adequate for most steels, but is much less than the 190 ft-lb (258 joules) obtained for solution annealed stainless steel. In this specimen, the impact toughness was reduced to 13 ft-lb at room temperature, a marginal figure but still acceptable for many applications. The percent of shear fracture is another indicator of material toughness, indicating what percent of the Charpy impact specimen broke in a ductile fashion. For the 10 % sigmatized specimen referenced above, the values ranged from 0 % at room temperature to 100 % at 1200 °F (649 °C). Thus, although the impact toughness is reduced at high temperature, the specimens broke in a 100 % ductile fashion, indicating that the material is still suitable. The lack of fracture ductility at room temperature indicates that care should be taken to avoid application of high stresses to sigmatized materials during shutdown, as a brittle fracture could result. Table 2.E.6.2 summarizes impact property data found for Type 304 and 321 stainless steels.

2.E.6.3 Screening Criteria

If both of the following are true, then the component should be evaluated for susceptibility to sigma phase embrittlement.

a) The material an austenitic stainless steel.

b) The operating temperature between 1,100 °F and 1,700 °F (593 °C and 927 °C).

2.E.6.4 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 DF for sigma phase embrittlement are provided in Table 2.E.6.1.

2.E.6.5 Basic Assumption

Since data is scarce and exhibits considerable scatter, it is assumed that sigmatized austenitic stainless steels will behave in a brittle fashion similar to ferritic steels. The data available showed a reduction in properties, but not the original properties. It is assumed that in the calculation of the DF, the original impact toughness of austenitic stainless steels is about $330\ MPa\sqrt{m}\ (300\ ksi\sqrt{in})$.

The references were searched for additional test data, which were scarce and exhibited considerable scatter. The test data found are shown in Table 23.2. The data in this table were used to construct property trend lines of Low Sigma (1 % and 2 %), High Sigma (10 %), and Medium Sigma (Average of Low and High).

2.E.6.6 Determination of the DF

2.E.6.6.1 Overview

A flow chart of the steps required to determine the DF for sigma phase embrittlement is shown in Figure 2.E.6.1. The following sections provide additional information and the calculation procedure.

2.E.6.6.2 Inspection Effectiveness

For this damage mechanism, credit is not given for inspection. However, the results of metallurgical testing can be used to update the inputs to the DF calculation that may result in a change in this value.

2.E.6.6.3 Calculation of the DF

The following procedure may be used to determine the DF for sigma phase embrittlement; see Figure 2.E.6.1.

a) STEP 1—Determine the evaluation temperature T_{min}. The material may be evaluated at normal operating conditions or at a lower temperature such as shutdown or upset temperature.

b) STEP 2—Determine the estimated % sigma in the material. This can be made through comparisons with materials in similar service or via metallographic examination of a sample.

c) STEP 3—Determine the DF, D_f^{sigma}, using Table 2.E.6.3 based on T_{min} from STEP 1 and the estimated % sigma from STEP 2.

2.E.6.7 Nomenclature

D_f^{sigma} is the DF for sigma phase embrittlement

T_{min} is the minimum temperature, °F (°C)

2.E.6.8 References

See References [66], [67], [68], [69], [70], [72], [73], [74], [75], [76], and [77], in Part 2, Section 2.2.

2.E.6.9 Tables

Table 2.E.6.1—Data Required for Determination of the DF—Sigma Phase Embrittlement

Required Data	Comments
Administrative controls for upset management (Yes/No)	Are there controls and or awareness training to prevent the coincident occurrence of low temperatures (upset) at or near design pressures?
Minimum operating temperature under normal, start-up/shutdown, or upset conditions, °F (°C)	This may be the temperature below which the operating pressure is reduced for purposes of fracture control. If not known, the temperature should be set to the atmospheric boiling point of the fluid in the component if the fluid is a liquid.
Amount of sigma	Estimate of the amount of sigma phase present. Low (>1 %, <5 %) Medium (≥5 %, <10 %) High (≥10 %)

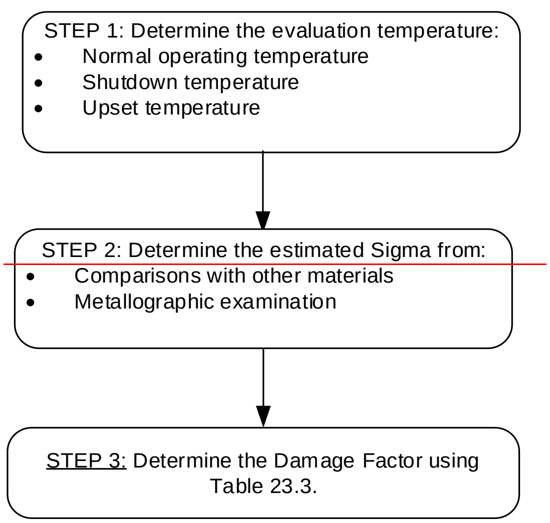
Table 2.E.6.2—Data for Property Trends of Toughness vs Temperature—Sigma Phase

Test Temperature		304 SS 2 % SIGMA		321 SS 10 % SIGMA		304 SS 1 % SIGMA		304 SS 2 % SIGMA		347 SS 1 % SIGMA	
°C	°F	% of Impact	% Shear	% of Impact	% Shear	% of Impact	% Shear	% of Impact	% Shear	% of Impact	% Shear
21	70	21	0	7	0	—	—	21	10	50	90
260	500	38	25	10	20	—	—	—	—	100	100
482	900	44	50	15	40	20	10	—	—	100	100
649	1200	63	100	21	60	71	90	77	90	100	100

Table 2.E.6.3—DF—Sigma Phase

T_{min} Evaluation Temperature		DF As a Function of Sigma Content		
(°C)	**(°F)**	**Low Sigma**	**Medium Sigma**	**High Sigma**
649	1200	0.0	0.0	18
538	1000	0.0	0.0	53
427	800	0.0	0.2	160
316	600	0.0	0.9	481
204	400	0.0	1.3	1333
93	200	0.1	3	3202
66	150	0.3	5	3871
38	100	0.6	7	4196
10	50	0.9	11	4196
−18	0	1.0	20	4196
−46	−50	1.1	34	4196

2.E.6.10 Figures



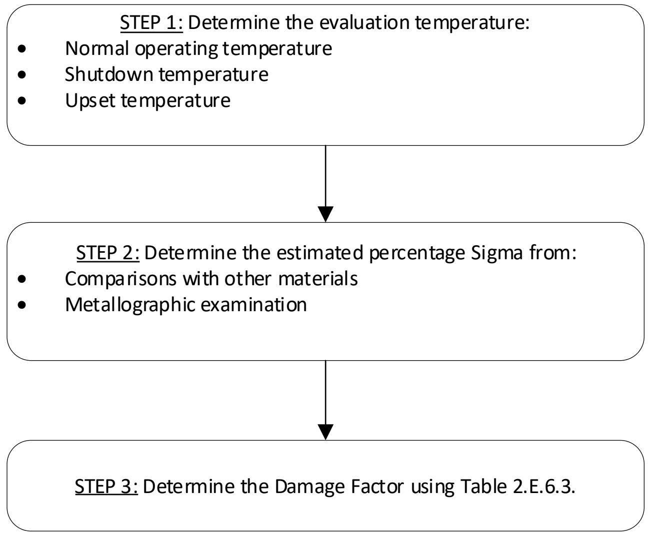


Figure 2.E.6.1—Determination of the Sigma Phase Embrittlement DF

2.E.7 Piping Mechanical Fatigue DF

2.E.7.1 Scope

The DF calculation for piping components subject to mechanical fatigue is covered in this section.

2.E.7.2 Description of Damage

Fatigue failures of piping systems present a very real hazard under certain conditions. Properly designed and installed piping systems should not be subject to such failures, but prediction of vibration in piping systems at the design stage is very difficult, especially if there are mechanical sources of cyclic stresses such as reciprocating pumps and compressors. In addition, even if a piping systems are not subject to mechanical fatigue in the as-built condition, changing conditions such as failure of pipe supports, increased vibration from out of balance machinery, chattering of relief valves during process upsets, changes in flow and pressure cycles, or adding weight to unsupported branch connections (pendulum effect) can render a piping system susceptible to failure. Awareness of these influences incorporated into a management of change program can reduce the POF.

2.E.7.3 Screening Criteria

If both of the following are true, then the component should be evaluated for susceptibility to mechanical fatigue.

a) The component is pipe.

b) There have been past fatigue failures in this piping system or there is visible/audible shaking in this piping system or there is a source of cyclic vibration within approximately 15.24 m (50 ft) and connected to the piping (directly or indirectly via structure). Shaking and source of shaking can be continuous or intermittent. Transient conditions often cause intermittent vibration.

2.E.7.4 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 DF for mechanical fatigue are provided in Table 2.E.7.1.

2.E.7.5 Basic Assumption

Properly designed piping has a low tendency for mechanical fatigue failure due to the low period of vibration or low stress amplitude. The period is determined by the piping diameter, thickness, mass, support spacing, and support type.

Based on input from plant engineers and inspectors from several disciplines, the following key indicators of a high POF were identified.

a) Previous failures due to fatigue.

b) Audible, visible, or otherwise noticeable piping vibration (including small branch connections) that is greater than typical plant piping systems.

c) Connection to reciprocating machinery, extreme cavitation through let-down or mixing valves, or relief valve chatter.

The presence of any or all of the above indicators determines the base susceptibility, which is then modified by various adjustment factors.

2.E.7.6 Determination of the DF

2.E.7.6.1 Overview

A flow chart of the steps required to determine the DF for mechanical fatigue is shown in Figure 2.E.7.1. The following sections provide additional information and the calculation procedure.

2.E.7.6.2 Inspection Effectiveness

For this damage mechanism, credit is not given for inspection. However, the results of metallurgical testing can be used to update the inputs to the DF calculation that may result in a change in this value.

Mechanical fatigue failures in piping are not that common. Unfortunately, when failures occur, they can be of high consequence. In addition, traditional nondestructive testing techniques are of little value in preventing such failures. The reason that crack detection techniques are not by themselves adequate are as follows.

a) Most of the time to failure in piping fatigue is in the initiation phase, where a crack in the process of forming has formed but is so small that it is undetectable.

b) By the time a crack has reached a detectable size, the crack growth rate is high, and failure will likely occur in less than a typical inspection frequency.

c) Cyclic stresses in vibrating piping tend to have a fairly high frequency, which increases the crack growth rate.

d) Cracks form and grow in locations that are typically difficult to inspect, such as at fillet weld toes, the first unengaged thread root, and defects in other welds.

e) The initiation site for crack growth is not necessarily on the outside of the pipe; in fact, a crack can grow from an embedded defect undetectable from either side without special techniques.

Therefore, inspection for mechanical fatigue in piping systems depends heavily on detection and correction of the conditions that lead to susceptibility. Such techniques include the following.

1) Visual examination of pipe supports to assure that all supports are functioning properly (i.e. they are actually supporting the pipe).

2) Visual examination of any cyclic motion of the pipe. If the pipe can be seen to be vibrating or moving in a cyclic manner, the pipe should be suspected of mechanical fatigue failure.

3) Visual examination of all fillet welded supports and attachments to piping. Fillet welds are especially susceptible to failure by fatigue, and these may provide an early warning of problems if cracks or failures are found.

4) As a general rule, small branch connections with unsupported valves or controllers on them are highly susceptible to failure. Examine these for signs of motion, and provide proper support for all such installations.

5) Surface inspection methods [penetrant testing (PT), MT] can be effective in a focused and frequent inspection plan.

6) Manually feeling the pipe to detect vibration. This requires experience, but normally process plant piping will not vibrate any more severely than a car engine at idle speed.

7) Measurement of piping vibration using special monitoring equipment. There are no set values of vibration that will be acceptable or nonacceptable under all conditions, so experience with using and interpreting vibration data is required.

8) Visual inspection of a unit during transient conditions and different operating scenarios (e.g. start-ups, shutdowns, upsets, etc.) looking for intermittent vibrating conditions.

9) Checking for audible sounds of vibration emanating from piping components such as control valves and fittings.

2.E.7.6.3 Calculation of the DF

The following procedure may be used to determine the DF for mechanical fatigue; see Figure 2.E.7.1.

a) STEP 1—Determine the number of previous failures that have occurred, and determine the base DF D_{fB}^{PF} based on the following criteria.

   1) None—D_{fB}^{PF} = 1.

   2) One—D_{fB}^{PF} = 50.

   3) Greater than one—D_{fB}^{PF} = 500.

b) STEP 2—Determine the amount of visible/audible shaking or audible noise occurring in the pipe, and determine the base DF D_{fB}^{AS} based on the following criteria.

   1) Minor—D_{fB}^{AS} = 1.

   2) Moderate—D_{fB}^{AS} = 50.

   3) Severe—D_{fB}^{AS} = 500.

c) STEP 3—Determine the adjustment factor for visible/audible shaking based on the following criteria. This adjustment is based on observation that some piping systems may endure visible shaking for years. A repeated stress with a cycle of only 1 hertz (1/s) results in over 30 million cycles in a year. Most systems, if they were subject to failure by mechanical fatigue, would be expected to fail before reaching tens or hundreds of million cycles. One should note that intermittent cycles are cumulative.

   1) Shaking less than 2 weeks—F_{fB}^{AS} = 1.

   2) Shaking between 2 and 13 weeks—F_{fB}^{AS} = 0.2.

   3) Shaking between 13 and 52 weeks—F_{fB}^{AS} = 0.02.

d) STEP 4—Determine the type of cyclic loading connected directly or indirectly within approximately 15.24 m (50 ft) of the pipe, and determine the base DF, D_{fB}^{CF}, based on the following criteria.

1) Reciprocating machinery—D_{fB}^{CF} = 50.

2) PRV chatter—D_{fB}^{CF} = 25.

3) Valve with high pressure drop—D_{fB}^{CF} = 10.

4) None—D_{fB}^{CF} = 1.

e) STEP 5—Determine the base DF using Equation (2.76).

$$D_{fB}^{mfat} = \max\left[D_{fB}^{PF},\ \left(D_{fB}^{AS} \cdot F_{fB}^{AS}\right),\ D_{fB}^{CF}\right] \tag{2.76}$$

f) STEP 6—Determine the final value of the DF using Equation (2.77).

$$D_{f}^{mfat} = D_{fb}^{mfat} \cdot F_{CA} \cdot F_{PC} \cdot F_{CP} \cdot F_{JB} \cdot F_{BD} \tag{2.77}$$

The adjustment factors are determined as follows.

1) Adjustment for Corrective Action, F_{CA}—Established based on the following criteria.

— Modification based on complete engineering analysis—F_{CA} = 0.002.

— Modification based on experience—F_{CA} = 0.2.

— No modifications—F_{CA} = 2.

2) Adjustment for Pipe Complexity, F_{PC}—Established based on the following criteria.

— 0 to 5 total pipe fittings—F_{PC} = 0.5.

— 6 to 10 total pipe fittings—F_{PC} = 1.

— Greater than 10 total pipe fittings—F_{PC} = 2.

3) Adjustment for Condition of Pipe, F_{CP}—Established based on the following criteria.

— Missing or damaged supports, improper support—F_{CP} = 2.

— Broken gussets, gussets welded directly to the pipe—F_{CP} = 2.

— Good condition—F_{CP} = 1.

4) Adjustment for Joint Type or Branch Design, F_{JB}—Established based on the following criteria.

— Threaded, socket weld, saddle on—F_{JB} = 2.

— Saddle in fittings—$F_{JB} = 1$.

— Piping tee, weldolets—$F_{JB} = 0.2$.

— Sweepolets—$F_{JB} = 0.02$.

5) Adjustment for Branch Diameter, F_{BD}—Established based on the following criteria.

— All branches less than or equal to 2 NPS—$F_{BD} = 1$.

— Any branch greater than 2 NPS—$F_{BD} = 0.02$.

2.E.7.7 Nomenclature

D_{fB}^{AS}	is the base DF for shaking
D_{fB}^{CF}	is the base DF for cyclic loading type
D_{f}^{mfat}	is the DF for mechanical fatigue
D_{fB}^{mfat}	is the base DF for mechanical fatigue
D_{fB}^{PF}	is the base DF for previous failures
F_{BD}	is the DF adjustment for branch diameter
F_{CA}	is the DF adjustment for corrective action
F_{CP}	is the DF adjustment for condition of pipe
F_{JB}	is the DF adjustment for joint type
F_{PC}	is the DF adjustment for pipe complexity
F_{fB}^{AS}	is the adjustment factor for audible shaking

2.E.7.8 References

See Reference [75] in Part 2, Section 2.2.

2.E.7.9 Tables

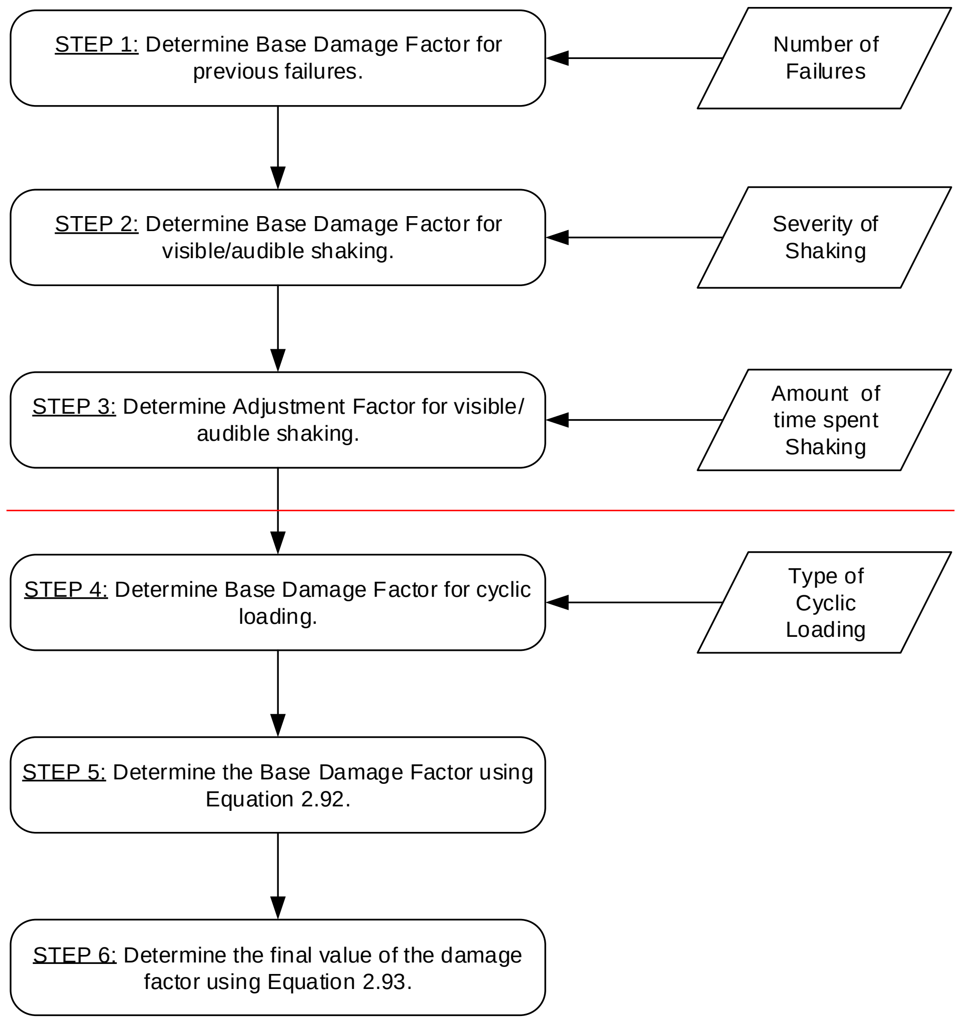
Table 2.E.7.1—Data Required for Determination of the DF—Mechanical Fatigue

Required Data	Comments
Number of previous fatigue failures: None, One, or >1	If there has been no history of fatigue failures and there have been no significant changes, then the likelihood of a fatigue failure is believed to be low.
Severity of vibration (audible or visible shaking): Minor, Moderate, or Severe	The severity of shaking can be measured in these subjective terms or can be measured as indicated at the bottom of this table in optional basic data. Examples of shaking are: Minor—no visible shaking, barely perceptible feeling of vibration when the pipe is touched; Moderate—little or no visible shaking, definite feeling of vibration when the pipe is touched; Severe—visible signs of shaking in pipe, branches, attachments, or supports. Severe feeling of vibration when the pipe is touched.
Number of weeks pipe has been shaking: 0 to 2 weeks, 2 to 13 weeks, 13 to 52 weeks	If there have been no significant recent changes in the piping system and the amount of shaking has not changed for years, or the amount of accumulative cycles is greater than the endurance limit, then it can be assumed that the cyclic stresses are below the endurance limit. (Most piping shaking will be at a frequency greater than 1 hertz. One hertz for 1 year is approximately 3×10^7 cycles, well beyond the endurance limit for most construction materials.)
Sources of cyclic stress in the vicinity of the item (e.g. within 50 ft): reciprocating machinery, PRV chatter, high-pressure drop valves (e.g. let-down and mixing valves), none	Determine to what cyclic source the piping is connected. The connections could be direct or indirect, e.g. through structural supports.

Table 2.E.7.1—Data Required for Determination of the DF—Mechanical Fatigue

Required Data	Comments
Corrective actions taken: modifications based on complete engineering analysis, modifications based on experience, no modifications	Credit is given for analysis work that shows that the shaking piping is not a fatigue concern.
Piping complexity: based on 15.24 m (50 ft) of pipe, choose: 0 to 5 branches, fittings, etc. 5 to 10 branches, fittings, etc. >10 branches, fittings, etc.	Determine the piping complexity in terms of the number of branched connections, number of fittings, etc.
Type of joint or branch design used in this piping: threaded, socket welded, saddle on, saddle in, piping tee, weldolet, sweepolet	Determine the type of joint or branch connection that is predominant throughout this section of piping that is being evaluated.
Condition of the pipe: missing/ damaged supports, unsupported weights on branches, broken gussets, gussets/supports welded directly to pipe, good condition	What is the condition of the piping section being evaluated in terms of support?

2.E.7.10 Figures



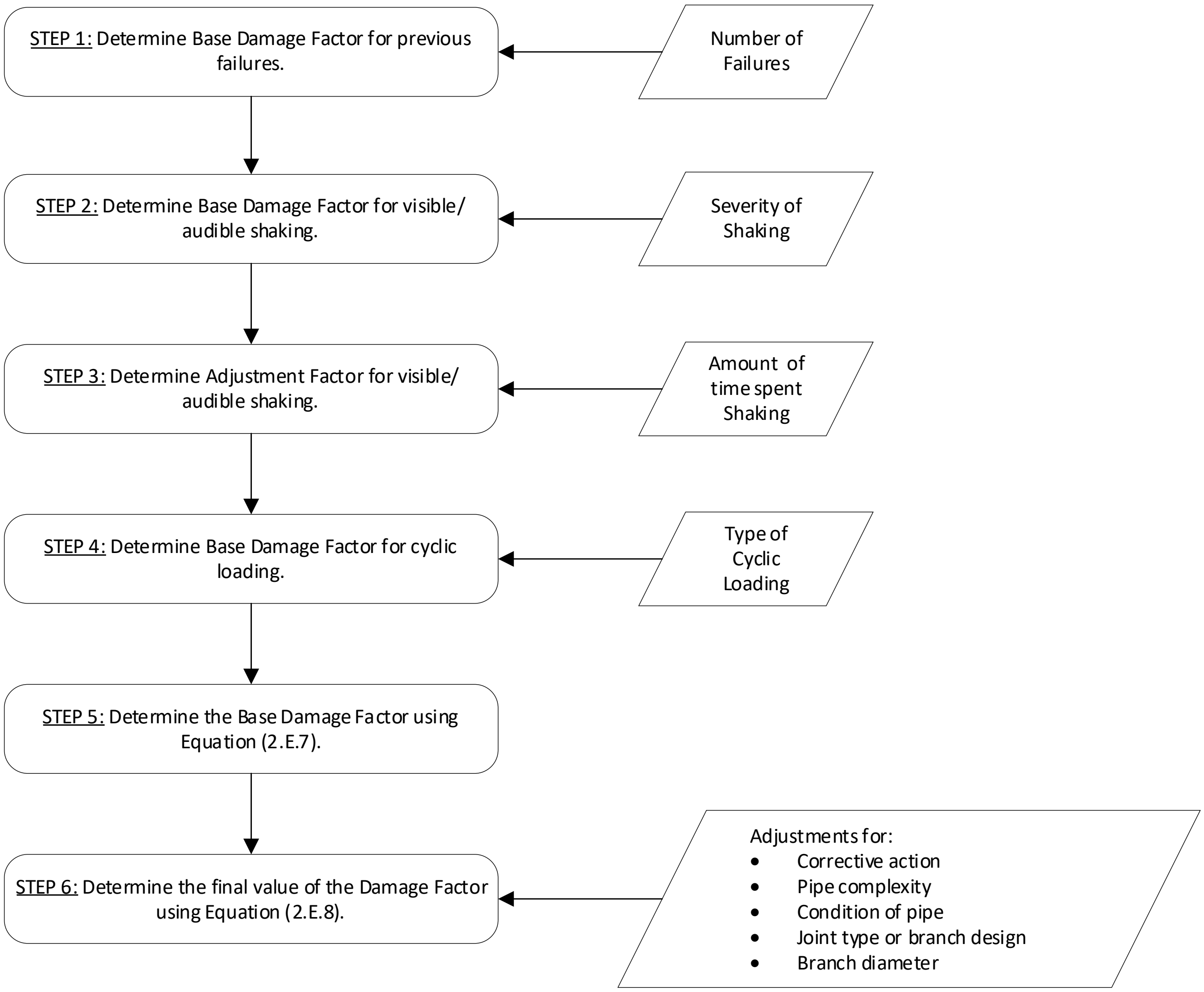


Figure 2.E.7.1—Determination of the Piping Mechanical Fatigue