

High-pressure High-temperature Design Guidelines

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Introduction

This technical report serves as a design guideline for high-pressure high-temperature (HPHT) equipment, specifically for subsea applications.

This document is not intended to be a stand-alone specification or standard. Rather it is presented as a technical guidance document so that specifications, standards, and recommended practices may reference this document, in component or in total, to augment their operating scope greater than 15,000 psi (103.5 MPa) and/or greater than 350 °F (177 °C) wellbore conditions as proffered by API 1PER15K-1.

It is necessary that users of this technical report be aware that additional or different requirements that can better suit the demands of a particular service environment, the regulations of a jurisdictional authority, or other scenarios not specifically addressed in this technical report, may be applied as required. This document is a technical report, and it is not intended to replace sound engineering judgment.

The main topics for this technical report are categorized as follows.

- 1) **Design Verification**—The design verification process focuses on analytical methods. The specified requirements include verification of the mechanical integrity, life cycle, and other service requirements.
- 2) **Materials for HPHT Equipment**—The material section defines the required input parameters for the design verification process and recommends the procedures necessary to evaluate the material's properties for the intended service environment.
- 3) **Seals and Bolting/Fasteners**—The seals and bolting/fasteners sections provide guidance on these specific elements of the design as they impact or are impacted by the HPHT designs.
- 4) **Design Validation**—The design validation section focuses on demonstrating the integrity of the equipment's design and includes defining the appropriate validation methods to analyze and mitigate the failure modes identified from the failure modes, effects, and criticality analysis.
- 5) **Hydrostatic Test for HPHT Equipment**—The hydrostatic test sections provide guidance on the applicable hydrostatic test pressure based on the design standard selected.

Revision History

The intended scope of this technical report has not changed since its inception and through its two subsequent revisions. As a technical report, this document is intended to be a design guideline, highlighting the novel design methods and material characteristic changes associated with structural and pressure integrity of components working at elevated pressures and/or temperatures. It continues to serve as a guide for other standards and specifications to cite and use for their specific scopes operating in an HPHT realm. The second and now third editions are a reflection of what has been learned and refined about HPHT in terms of:

- clarifying intent and use of this technical report as a design guideline;
- identifying events (normal, extreme, survival), and refinement of various design and assessment methodologies with respect to these events, such as listing design factors associated with combined loads during these events;
- clarifying fatigue assessment design methodology and material characterization protocols;
- providing informational annexes on instrumentation and small bore tubing design.

The third edition also makes editorial changes to specific product specification and PR levels of referenced API documents that recognize HPHT.

Application

The scope of this technical report is limited to equipment and components identified in API documents that focus on subsea production equipment while addressing one or a combination of the following loading conditions:

- internal and external pressure;
- ambient and elevated operating temperatures;
- static and dynamic mechanical loads;
- other loadings.

This technical report is intended to provide design guidelines for pressure-containing components, seals, and fastener components that come in contact with or are immediately adjacent to wellbore fluids operating at HPHT conditions. Intra-field piping systems (for example, steel flowline and pipeline jumpers, manifold piping, valving, connectors, and tubing hanger) and intervention riser equipment are within the scope of this technical report.

The design methodology referenced in this technical report may also be applied to pressure-controlling components if the design methodology can appropriately assess the applicable failure mode(s).

This technical report does not cover the following:

- flexible pipes (bonded and unbonded);
- oil-country tubular goods for drilling or completing wells;
- downstream pipeline or production riser designs;
- downhole component hardware that may be subject to additional application-related design constraints;
- equipment covered by other API publications that specifically address HPHT applications;
- structural members or ancillary equipment associated with HPHT hardware but not working in close proximity to the HPHT environment;
- brittle materials (i.e. essentially no plastic deformation prior to failure, etc.).

High-pressure High-temperature Design Guidelines

1 Scope

The scope of this technical report is to provide design guidelines for oil and gas subsea equipment utilized in high-pressure high-temperature (HPHT) environments (see 3.1.24). For the purpose of the technical report, HPHT environments are intended to be one or a combination of the following well conditions:

- 1) the completion of the well requires completion equipment or well control equipment assigned a pressure rating greater than 15,000 psia (15 ksi, 103.5 MPa) or a temperature rating greater than 350 °F (177 °C);
- 2) the maximum anticipated surface pressure including shut-in tubing pressure is greater than 15,000 psia (15 ksi, 103.5 MPa) on the seafloor for a well with a subsea wellhead or at the surface for a well with a surface wellhead; or
- 3) the flowing temperature is greater than 350 °F (177 °C) on the seafloor for a well with a subsea wellhead or at the surface for a well with a surface wellhead.

NOTE There is no upper limit on service pressure ratings within the scope of this technical report. Service temperature ratings above 550 °F (288 °C) are outside the scope of this technical report.

This technical report is intended to serve as a general design guideline for HPHT application. Other subsea task groups and subcommittees may elect to adopt a portion or all of the presented guidelines for HPHT application, subject to their component hardware and application-related design constraints.

It is necessary that users of this technical report be aware of regulations from a jurisdictional authority that may impose additional or different requirements that better suit the demands of a particular service environment. This technical report provides additional considerations in HPHT equipment designs.

2 Normative References

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

API Specification 6A, *Specification for Wellhead and Tree Equipment*

API Specification 17D, *Specification for Subsea Wellhead and Tree Equipment*

API Standard 17G, *Design and Manufacture of Subsea Well Intervention Equipment*

API Specification 20B, *Open Die Shaped Forgings for Use in the Petroleum and Natural Gas Industry*

API Specification 20C, *Closed Die Forgings for Use in the Petroleum and Natural Gas Industry*

API Specification 20E, *Alloy and Carbon Steel Bolting for Use in the Petroleum and Natural Gas Industries*

API Specification 20F, *Corrosion-resistant Bolting for Use in the Petroleum and Natural Gas Industries*

API Standard 6X, *Design Calculations for Pressure-containing Equipment*

ANSI/ASME B1.1 ^{1,2}, *Unified Inch Screw Threads (UN, UNR, and UNJ Thread Forms)*

¹ American National Standards Institute, 1899 L Street, NW, Washington, DC 20036, <https://ansi.org>.

² American Society of Mechanical Engineers, Two Park Avenue, New York, New York 10016, www.asme.org.

ASME Boiler and Pressure Vessel Code, Section II—Materials

ASME Boiler and Pressure Vessel Code, Section VIII—Rules for Construction of Pressure Vessels, Division 2—Alternative Rules

ASME Boiler and Pressure Vessel Code, Section VIII—Rules for Construction of Pressure Vessels, Division 3—Alternative Rules for Construction of High Pressure Vessels

NACE MR0175/ISO 15156^{3,4}, Petroleum and Natural Gas Industries—Materials for Use in H₂S-containing Environments in Oil and Gas Production—Parts 1, 2, and 3

3 Terms, Definitions, Acronyms, Abbreviations, and Symbols

3.1 Terms and Definitions

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

3.1.1

assembly (or subsystem)

A group of components forming a self-contained, independently mounted unit that performs a defined function.

3.1.2

autofrettage

Process for producing a system of favorable residual stresses in a thick-wall pressure-containing body by pressurizing to produce plastic deformation in part or all of the wall thickness.

NOTE Autofrettage typically refers to a phenomenon where the material at the internal bore of a pressurized vessel experiences localized stresses exceeding the material's yield strength (S_{MYS}) while material further away from the bore is stressed below the yield strength.

3.1.3

barrier

A component or assembly that forms a pressure-containing or pressure-controlling envelope that is designed to prevent unintentional flow of produced or injected fluids, particularly to the external environment.

3.1.4

barrier element

A component or assembly that serves as part of a pressure-containing or pressure-controlling barrier's envelope.

3.1.5

barrier envelope

Series of barrier elements that, when linked together, act as a pressure-containing vessel or envelope, preventing leakage of well fluids.

3.1.6

cast or heat analysis

[ladle analysis (obsolete)]

Chemical analysis as representative of a heat of metal as reported to the purchaser and determined by analyzing a test sample obtained from the molten metal or product of remelted ingot, for the elements designated in a specification.

³ Association for Materials Protection and Performance, 15835 Park Ten Place, Houston, Texas 77084, www.ampp.org.

⁴ International Organization for Standardization, Chemin de Blandonnet 8, CP 401 – 1214 Vernier, Geneva, Switzerland, www.iso.org.

3.1.7**check analysis**

Limits of acceptability of the chemical composition of a material when the analysis is over or under the maximum or minimum specified value of an element; performed on a finished or semi-finished component and is not used by the producer for heat analysis acceptance testing.

3.1.8**chemical analysis**

Analysis of the semi-finished or finished product, usually for the purpose of determining conformance to the specification requirements.

NOTE The range of the specified composition applicable to product analysis is normally greater than that applicable to heat analysis in order to take into account deviations associated with analytical reproducibility and the heterogeneity of the metal.

3.1.9**corrosion-resistant alloy****CRA**

Nonferrous-based alloy for which any one or the sum of the specified amount of the elements—titanium, nickel, cobalt, chromium, and molybdenum—exceeds 50 % mass fraction.

NOTE This definition follows API 6A and API 6ACRA, which is different from that in NACE MR0175/ISO 15156 (see Part 2).

3.1.10**corrosion-resistant material****CRM**

Ferrous or nonferrous alloy that is more corrosion resistant than low-alloy steels.

NOTE This term includes CRAs, duplex, austenitic, and martensitic stainless steels.

3.1.11**closure bolting**

Threaded fasteners used to assemble wellbore pressure-containing components or join end or outlet connections.

EXAMPLE Studs, nuts, bolts, and cap screws, etc.

3.1.12**component (or part)**

Identifiable portion of an assembly (or subsystem) that cannot be disassembled further and performs a defined function.

3.1.13**critical bolting**

Threaded fasteners and closure bolting, identified as high-risk components (i.e. loss of structural integrity or pressure containment).

EXAMPLE Studs, nuts, bolts, and cap screws, etc.

3.1.14**design validation**

Process of proving a design by testing to demonstrate conformity of the product to design requirements.

NOTE Design validation includes one or more of the following:

- a) prototype tests;
- b) functional and/or operational tests of production products;
- c) tests specified by industry standards and/or regulatory requirements;
- d) field performance tests and reviews.

3.1.15

design verification

Process of examining the result of a given design or development activity to determine conformity with specified requirements.

NOTE Design verification includes one or more of the following:

- a) confirming the accuracy of design results through the performance of alternative calculations;
- b) review of design output documents;
- c) comparing new designs to similar proven designs.

3.1.16

elevated temperature

Highest temperature of the pressure-contained fluids within a component's pressure-containing cavity for the range of rated working temperatures specified for a component.

NOTE 1 Actual elevated temperature at a particular location within the component may be at or somewhat lower than the elevated temperature due to thermal conduction/convection to a cooler environment temperature and use of insulation surrounding the component. These lower temperatures may be cited to address design life or suitability of use of a material at that location, provided that environmental conditions are a part of the design documented and reasonably match actual use conditions.

NOTE 2 S_{YST} and S_{UTST} are defined using test data or using the yield strength reduction ratios listed in API 6MET, or ASME *Boiler and Pressure Vessel Code (BPVC)* Section II, Part D. Elevated temperature should be at the upper limit of the expected environment or the specified temperature class. Elevated temperature may be referred in some codes and standards as "design temperature."

3.1.17

environmental assisted cracking

Cracking of a material wherein an interaction with its environment is a causative factor in conjunction with tensile stress, often resulting in brittle fracture of an otherwise ductile material.

EXAMPLE Environmental cracking is a general term that includes the following: chloride stress corrosion cracking, hydrogen embrittlement, hydrogen stress cracking, stress corrosion cracking, and sulfide stress cracking.

3.1.18

equipment (or system)

A group of components or assemblies connected in a particular configuration or order to meet an additional set of defined functions.

3.1.19

event, extreme

Occurrence that produces operating conditions that exceed normal operating conditions and include the unavoidable but predictable load conditions due the environmental and operating scenarios; rated working pressure or temperature is not exceeded during the event.

3.1.20

event, normal

Occurrence that produces operating conditions that include all loads, individual and combined, as defined by operational criteria up to extreme event conditions; rated working pressure or temperature is not exceeded during the event.

3.1.21

event, survival

Occurrence that produces operating conditions that exceed extreme conditions and include the unplanned, unavoidable, and unpredictable load conditions due to the environmental, operating, or any other scenarios; rated working pressure or temperature is not exceeded during the event.

NOTE 1 A survival event of a component means that the component does not structurally fail, but it can present one or more kinds of degradations that may impact its specified performance or service life.

NOTE 2 Survival event may be referred to as an “accidental event.”

3.1.22

fracture toughness

Property of a material that measures the resistance to failure resulting from crack propagation.

3.1.23

functional specifications

Document generated by the user/purchaser that specifies the design parameter requirements and operating conditions, as appropriate.

NOTE Functional specifications may also be referred to as “functional requirements.”

3.1.24

high-pressure high-temperature

Reference to wells with a potential pressure greater than 15,000 psia (103.5 MPa), or with an elevated temperature greater than 350 °F (177 °C), up to 550 °F (288 °C), measured at the mudline.

3.1.25

operational cycle

Initiation and establishment of new conditions, from both internal and external operational loads, followed by a return to the conditions that prevailed at the initiation of the cycle.

3.1.26

plastic collapse load

Load that causes overall structural instability; in numerical analysis, this point is indicated by the inability to achieve an equilibrium solution for a small increase in load (for example, a FEA solution will not converge).

3.1.27

pressure absolute (psia)

Pressure measured relative to absolute zero pressure; the internal pressure that the equipment is designed to contain and/or control, measured in “psia.”

3.1.28

pressure-containing

Component whose failure to function as intended results in a release of wellbore fluid to the environment.

3.1.29

pressure-controlling

Component that is intended to control or regulate the movement of pressurized fluids.

3.1.30

primary barrier

First component that prevents flow from a source.

3.1.31

ratcheting

Progressive incremental inelastic deformation or strain that can occur in a component that is subjected to variations of mechanical stress, thermal stress, or both.

3.1.32

secondary barrier

Second component that prevents flow from a source.

3.1.33**shakedown**

Phenomenon caused by cyclic loads or cyclic temperature distributions that produce plastic deformations in some regions of the component when the loading or temperature distribution is applied, but upon removal of the loading or temperature distribution, only elastic primary and secondary stresses are developed in the component, except in small areas associated with local stress (strain) concentrations.

3.1.34**stainless steel**

Steel containing more than 11 % mass fraction chromium to render the steel a corrosion-resistant material (CRM).

NOTE Other elements may be added to secure specific properties.

3.1.35**stress cycle(s)**

Condition in which the stress fluctuates between a minimum and maximum value, about a mean or initial value.

NOTE A single operational cycle may result in one or more stress cycles.

3.1.36**tensile strength (ultimate)**

Maximum load before failing or breaking divided by the original cross-sectional area.

NOTE Specified minimum ultimate tensile strength (S_{MUTS}) is measured at room temperature (between 50 °F to 100 °F [10 °C to 38 °C], in accordance with ASTM A370, E8).

3.1.37**yield strength**

Stress level, measured at room temperature and elevated temperature, at which material plastically deforms and does not return to its original dimensions when the load is released.

NOTE 1 Yield strengths specified in this technical report are the 0.2 % offset yield strength in accordance with ASTM A370 or ISO 6892-1.

NOTE 2 Specified minimum yield strength (S_{MYS}) is measured at room temperature (between 50 °F to 100 °F [10 °C to 38 °C], in accordance with ASTM A370, E8).

3.2 Acronyms and Abbreviations

ADCP	acoustic Doppler current profiler
BPVC	<i>Boiler and Pressure Vessel Code</i>
BSL	bolt specification level
CLC	cyclic load counting
CP	cathodic protection
CRA	corrosion-resistant alloy
CRM	corrosion-resistant material

CS	carbon steel
CTOD	crack tip opening displacement
CUF	cumulative usage factor
CVN	Charpy V-notch
ε -N	strain-cycle (strain-life curve)
EHE	external hydrogen embrittlement
ET	eddy current testing
FCGR	fatigue crack growth rate
FEA	finite element analysis
FM	fracture mechanics
FMEA	failure modes and effects analysis
FMECA	failure modes, effects, and criticality analysis
FT	fracture toughness
FUM	fatigue usage monitoring
HIC	hydrogen-induced cracking
HISC	hydrogen-induced stress cracking
HP	high pressure
HPHT	high-pressure high-temperature
HT	high temperature
HRC	hardness Rockwell C
ITP	inspection and test plan
LAS	low-alloy steel
LAST	lowest anticipated service temperature
LMP	load monitoring program
LRFD	load and resistance factor design
MDMT	minimum design material temperature
MPS	manufacturing procedure specification
MT	magnetic particle testing (also referred to as MPI)

NDE	nondestructive examination
PMI	positive material identification
PoD	probability of detection
PR	performance requirements (validation)
PREN	pitting resistance equivalent number
PSL	product specification level
PT	penetrant (dye) testing
PWHT	post-weld heat treatment
QA	quality assurance
QC	quality control
QTC	qualification test coupon
RGD	rapid gas decompression
ROV	remotely operated vehicle
RT	radiographic testing
RWP	rated working pressure
SCC	stress corrosion cracking
S-N	stress-cycle (stress-life curve)
SSC	sulfide stress cracking
SSRT	slow-strain rate test
UNS	unified numbering system (for alloy designation)
UT	ultrasonic testing
VME	von Mises equivalent (stress)

3.3 Symbols

da/dN	fatigue crack growth rate
D_i	inside diameter
D_o	outside diameter
D_X	is the suspension or external loads (i.e. casing loads, external riser or piping loads, installation loads [running], etc.)
e_pR	plastic elongation ratio (%)

J_{IC}	fracture toughness measured using the J-integral method in accordance with ASTM E1820
ΔK	stress intensity factor range
K_I	Mode I stress intensity factor
K_{IC}	Mode I critical stress intensity factor
K_{IEAC}	Mode I stress intensity factor measured in service environment
K_{th}	threshold stress intensity factor
L	fluid dynamic loading (i.e. slugging, water hammer, flow-induced vibration, wave and current loading, vortex-induced vibration, etc.)
N_f	number of design cycles
P	internal or external specified pressure at temperature
P_T	hydrostatic body test pressure
R	inside radius
S	design allowable stress
S_{INT}	stress intensity
S_{MYS}	specified minimum material yield strength at room temperature (between 50 °F to 100 °F [10 °C to 38 °C], reference ASTM A370, E8)
S_{MUTS}	specified minimum material ultimate tensile strength at room temperature (between 50 °F to 100 °F [10 °C to 38 °C], reference ASTM A370, E8)
S_{PL}	allowable limit on local primary membrane and local primary membrane plus bending stress categories
S_{PS}	allowable primary plus secondary stress at elevated temperature
S_{UTST}	material ultimate tensile strength at elevated temperature
S_{YST}	material yield strength at elevated temperature
NOTE S_{YST} and S_{UTST} defined as the upper limit of the expected environment or specified temperature class using test data or using the yield strength reduction ratios listed in API 6MET, or ASME BPVC Section II, Part D.	
t	wall thickness
T	self-restraining loads (i.e. thermal loads, thermal expansions, installation misalignment loads, or applied displacements, etc.)
W_A	assembly loads (for example, sealing preload, bolt preloads, connector preloads)

4 Addressing Issues Posed in API 1PER15K-1

4.1 General

API 1PER15K-1 takes a system-level approach to the review of the entire well system exposed to HPHT conditions. API 1PER15K-1 does not offer analysis tools or design processes for the verification or validation of specific hardware. For that reason, the intent of this technical report is to provide guidance on analysis tools and design processes to address the applications cited in API 1PER15K-1 for the design verification and validation of subsea production hardware and systems.

4.2 High-pressure Effects, High-temperature Effects, and High-pressure High-temperature Effects

4.2.1 High-pressure Effects

4.2.1.1 General

A broad range of pressure-containing oilfield equipment design is based on the definitions and formulae found in API 6X or the ASME *BPVC* Section VIII, Division 2: 2021 Edition (hereafter ASME Div. 2). There are limited data available on the use of 30 ksi rated working pressure (RWP) equipment based on API 6AB (withdrawn) and on 20 ksi RWP equipment based on API 6A in production conditions above 15 ksi, both derived from ASME Div. 2 design methodology. The design practice from ASME for equipment with design pressure greater than 10 ksi suggests that the equipment designer should consider ASME *BPVC* Section VIII, Division 3: 2021 Edition (hereafter ASME Div. 3). This is the ASME recommendation, but not its requirement. It should be noted that ASME Div. 2 does not specify a limitation on the pressures for which it can be used. For very high pressures (HPs) (for example, 20 ksi, 25 ksi, 30 ksi), additional considerations to design and manufacturing practices should be applied to meet the design principles and manufacturing practices to subsea equipment with such pressure ratings.

API documentation continued to reference ASME Div. 2 where this was not in conformance with ASME's current edition. This was an underlying intent in the development of API 6X where referencing the ASME documents is minimized, and API equipment designs will not be subject to unnecessary changes due to revision to the ASME documents.

4.2.1.2 Analytical Methods

With reference to the 2021 edition of ASME Div. 2 and ASME Div. 3, it should be noted that the design practices and analytical methods (linear-elastic, elastic-plastic) are similar in principle between these two codes; however, they have different load factors against the plastic collapse load (for example, ASME Div. 2 = 2.4 and ASME Div. 3 = 1.8) and minimum hydrostatic body test pressures. Both design codes utilize the analytical methods referenced therein to verify that the pressure equipment has adequate protection against typical failure modes (such as global plastic collapse, local strain damage limits, etc.).

Additionally, ASME Div. 3 implements the use of fracture mechanics (FM) analysis to address the potential fast-fracture failure of pressure vessels from material flaws and/or imperfections in critically stressed locations where flaws may occur randomly in manufacture (i.e. structural discontinuities, notches, sharp corners, etc.). ASME Div. 2 references the traditional stress-cycle fatigue curves (S-N curves) to address fatigue/life-cycle estimation if the equipment is identified to be fatigue sensitive from the screening process.

4.2.1.3 Thin-wall and Thick-wall Designs

The transition from 15 ksi to higher RWPs can change designs from thin-wall to thick-wall pressure vessel designs, where thick-wall is the result of the vessel inside radius to vessel wall thickness ratio equal to or less than "4" ($R/t \leq 4$: ASME Div. 2: 2007 and later) or an outside-to-inside diameter ratio equal to or greater than "1.25" ($D_o/D_i \geq 1.25$: ASME Div. 3: 2010 and later). Two fundamental changes are occurring when transitioning from thin-wall to thick-wall pressure vessel designs.

- a) The internal bore yielding (from internal pressure leading to inner wall plastic deformation), typically referred to as an “autofrettage” effect (see 3.1.2).
- b) The pressure vessel's possible susceptibility to cyclic loads could theoretically lead to either a fatigue failure or a fast-fracture failure at areas of highly localized stress. This phenomenon is typically associated with stress concentrations on the inside at sharp corners, such as bore intersections, seal pockets, or abrupt changes in bore diameters, as autofrettage is experienced. Assessment of cyclic loading effects on stress concentrations has been a long-standing practice for fatigue analysis utilizing S-N curves for predicting when and/or where materials may fail from the applied loads. However, the potential fatigue failure can now occur inside as well as outside the structure from imperfections or flaws at highly stressed locations from HP loads or mechanical cyclic loads. Another fatigue assessment method is following the FM methodology to predict or estimate life cycle from inherent flaws growing or propagating within the elevated stress field until the flaws grow to a point where the material's resistance to microstructure crack growth is compromised, resulting in a fast-fracture failure of the component's wall.

Since its inception, the API 17TR8 task group has contemplated defining guidelines for determining where oilfield equipment designs change from thin-wall to thick-wall, and given the service history of equipment with existing API specifications, providing corresponding direction for use of existing practices (thin-wall/linear-elastic analysis), or adoption of a new design regimen (thick-wall/elastic-plastic analysis). Either way, practical applications are difficult to manufacture, fabricate, or handle (heavy lift) for practical applications and are difficult to maintain uniform material strength over the wall sections of manufactured equipment (through-wall properties). By reducing the design margins and test pressure, designing products can be more manageable in terms of weight and size, whereas safety and reliability of equipment is maintained by simultaneously applying more rigorous analysis, validation, and additional quality assurance (QA).

4.2.1.4 Analysis Principles

Traditionally, the standard practice is to rely on API 6X, API 17D, or the ASME *BPVC* to provide design guidance when the equipment's structural requirements go beyond the defined boundaries of the API specifications/standards. However, the problem then arises as to “how much of the ASME *BPVC* does one follow”: 1) exact to the “letter”; 2) using portions of the code that are applicable to the particular design; or 3) following a parallel path using the ASME *BPVC* methods but developing another set of design margins applicable to oilfield applications. Oilfield equipment is of complex geometry and is far from a simple cylindrical pressure vessel or piping union design. It is typically subjected to a variety of extreme external loading conditions, and many relevant loadings are explicitly addressed in ASME *BPVC*. Additionally, some loadings that are explicitly addressed in ASME *BPVC*, such as snow and wind loads, may not be relevant to subsea equipment. Therefore, the recommended approach for API 17TR8 is “Design by Analysis” and *not* “Design by Rules” (Part 4 of Div. 2 or KD-220 of Div. 3). The equipment designer must rely on sound engineering practices and judgment, accompanied by unique validation prototype testing programs.

As a result, this document recognizes that equipment with 15 ksi RWP (or lower) with high-temperature (HT) effects should continue with the simpler, traditional linear-elastic analysis in the existing API specifications and within the scope of the governing standards, as this has yielded robust and field-proven designs.

For RWP from 15 ksi up to and including 20 ksi, there is a transitional zone where both linear-elastic and elastic-plastic design methodologies can be utilized, but with additional considerations. Traditional design practice of linear-elastic analysis can be followed with additional considerations or the more advanced, rigorous elastic-plastic design method of ASME Div. 2 may be applied for this pressure rating range, by using more accurate material model/properties (true-stress/true-strain). Either way, higher design margins, hydrostatic body test pressures, and accurate material properties are required where complicated or unknown loading conditions exist. It should be noted that this conservatism may not eliminate failure modes related to the autofrettage, stress concentrations, and mechanical cyclic loads for more complicated geometries. Therefore, design check-gates (rectangular boxes illustrated in the flowchart of Figure 1) have been added to alert the equipment designer when simpler design methods or more complicated geometries/load paths may mask a less stable design result.

For RWP greater than 20 ksi, elastic-plastic design methodology of ASME Div. 3 is recommended. It is also recommended that the accuracy of material properties and model construction be verified, and high level of quality control (QC) be imposed in the manufacture.

In summary, there are three analytical design paths that can be applied to HPHT designs.

- For equipment up to and including 15 ksi RWP with HT effects, the traditional or existing linear-elastic analysis in API 6X and API 17D, in conjunction with material properties at operating temperature, is appropriate.
- For RWP greater than 15 ksi, up to and including 20 ksi, the recommended design practices of ASME Div. 2 through linear-elastic analysis (with the design check-gates) or elastic-plastic analysis should be used to accurately assess the inclusive nature of pressure, temperature, and mechanically induced loads.
- For RWP greater than 20 ksi, the elastic-plastic design methodology of ASME Div. 3 is recommended, as the internal bore yielding effect becomes more pronounced.

Regardless of the design path taken, these thick-wall designs should culminate with a fatigue screening assessment of its susceptibility to cyclic loads leading to possible fatigue or fast-fracture failures. Cyclic load screening becomes a part of the design regimen, not just a consideration.

Detailed guidance on the appropriate applications of these design analysis methodologies is provided in Section 5. Additionally, Section 6 provides guidance on the material properties and material models associated with these design analysis methodologies.

4.2.1.5 High-pressure Effects on Materials

HPs can affect produced fluids interactions with materials. For example, the partial pressure of H_2S will go up as the design pressure increases even if the concentration remains the same. Therefore, a well that can use FF trim at 10,000 psi may require HH trim at 20,000 psi (see API 6A or API 17D for material classes).

4.2.2 High-temperature Effects

4.2.2.1 General

The HT effects on materials in HPHT application are understood well qualitatively. They can be well understood quantitatively through an appropriate material testing program and have been documented in API 6MET, and for nonmetallic material, refer to API 6J1. Derated values for material strength (S_{YST} , S_{UTST}) used in design verification analyses shall be at the designated elevated temperature.

4.2.2.2 High-temperature Effects on Material Properties

The effects of elevated temperature on materials in a corrosive environment are not well documented. Different materials adjacent to each other may be functionally suited for each component, but each component in the assembly could expand or contract at different coefficients of expansion and Poisson's ratio, changing the geometry of seal pockets, glands, sliding clearances, etc. This effectively defeats the mechanism at elevated temperatures that otherwise work well at lower temperatures.

Most available data on material compatibility in severe environments are at room temperature. Severe environment effects should be considered at both temperature extremes. Elevated temperature typically accelerates localized corrosion and general corrosion rates. Elevated temperature also changes the material's fracture toughness (FT) values (i.e. da/dN , K_{IC} , etc.), thus changing the expected cyclic life of a component. More is known about FT data at room temperature and cold/arctic temperatures, but few data are available at elevated operating temperatures, especially for oilfield equipment.

NOTE 1 API 1PER15K-1 contains tables of commonly used oilfield equipment materials (Table 3, Table 4, and Table 5).

NOTE 2 API 17G suggests that materials should be examined for derating characteristics starting at 100 °F (38 °C).

In assessing HT (high [elevated] temperature) or severe environmental effects on material properties, the lack of available data is a concern. Some material properties may be inferred from data published for aerospace and nuclear applications where the operating temperatures are either significantly higher or lower than the typical temperature defined for HPHT environment, though it is often not the exact material grade and general corrosion rates. However, oilfield environments are far more active and corrosive than the other industries, making data interpolation less plausible. In this regard, this technical report provides detailed guidance on the types of material data/properties required for the design verification analysis at elevated temperature and with consideration to the environmental effects on the material properties (see Section 6).

4.2.2.3 High-temperature Effects on Seals

Materials that seal against a particular geometry (shape, surface finish, etc.) are another significant consideration with HT effects. Selection of seal material is a function of its geometry and material properties that should include a degree of pliability during assembly (or removal), longevity at temperature (ambient or elevated/operating), and resiliency to repeat cyclic expansion/contraction of surrounding components.

Nonmetallic seals have an additional concern with respect to temperature limits changing its molecular bond make-up or its physical properties. Nonmetallic components are often tested at elevated temperatures to discern a compound's operating life through accelerated aging tests (for example, API 6J1, ISO 23936-2).

NOTE Elastomers typically peak at 280 °F (138 °C) and thermoplastics peak at around 400 °F (204 °C) for nominal design life. Higher temperatures are possible but may be with a reduced design/operating life. Metal seals can be a viable solution for higher operating temperatures for extended periods. These temperature limits stated above are a general guide for differentiating between classes of nonmetallic sealing materials operating at prolonged elevated temperature. Specific materials or composite configurations may outperform these guidelines and should be thoroughly evaluated for specific use.

Additionally, the less pliable the seal material, the harder it becomes to assemble and maintain, often requiring a completely different seal and seal pocket configuration. Less pliability also leads to tighter tolerances between components and smoother surface finishes. Less pliable materials may also lead to less forgiveness to imperfections and dirt/debris, causing premature seal leakage or failure. Some less pliable seals may also require more elaborate sets of components to build around the seal to create the seal pocket. This added set of geometries may require additional length or width in assembled components, resulting in greater stack-up heights in assembled hardware. As a result, a proven HP design may be easily achievable at lower temperatures but may require a re-design for each added temperature regime, making scaling for size and different temperatures (for the same RWP) difficult to achieve.

Seals also have a specific problem with temperature range. If the temperature range is kept fairly narrow, components do not expand or contract nearly as much and the overall seal configuration remains fairly constant. As the range widens, less pliable materials need to be used for the upper end of the temperature range but become too rigid and stiff at the lower end. This often causes seal leakage at the other end of the temperature extreme. Furthermore, seal pocket geometry and tolerance (extrusion) gaps get wider or narrower, encouraging seal extrusion or pinching off (often called nibbling), damaging the seal and leading to premature failure. The wider temperature range could also encourage material fretting in metal seals due to the added movement between seal and seal pocket surfaces.

A subtler concern is stress relaxation, as observed by research conducted by Larson and Miller ^[1,3] and Orr, Sherby, and Dorn ^[2,3]. They observed that highly stressed components at elevated temperature experience a gradual redistribution of the stress in a component over time in a manner that lowers the residual stress in the component (similar to performing post-weld heat treatment [PWHT] process on weldments to allow the component to relieve some of the induced stress caused by welding and subsequent cooling). In pressure-containing and pressure-controlling components, this is not of significance at the temperatures addressed in this technical report. However, a change of even a few thousandths of an inch may result in loss of preload force in the retaining fasteners or a loss of bearing contact in a seal. For this reason, material testing standards for stress relaxation are addressed in this technical report to help define material requirements, for seals as well as fasteners (see Section 6 and Section 7).

4.2.3 Combined High-pressure High-temperature Effects

When combining HP and HT in an application, both temperature and pressure may affect working functionality in addition to pressure containment. HP and HT can change material properties and overall geometry, fit, concentricity, parallelism, make-up fit gap, etc. This results in additional degrees of freedom that then need to be addressed for each pressure and temperature combination to make sure moving components (as found in pressure-controlling components) continue to operate within the expanding and contracting external envelop of the pressure-containing body. This results in additional degrees of freedom that then need to be addressed for each pressure and temperature combination. As mentioned above, any change in the form, fit, or function may change the design and may require a new set of verification and validation tests for every combination.

The industry has been successful in developing HP equipment at lower than HT temperatures, below 350 °F (177 °C). The same has been true for HT equipment at relatively low-pressure ratings. However, HPHT permutation may potentially create a unique design, especially when a wide temperature range (high and low) is added to the functional requirements. Low-temperature (such as dormant shut-in conditions at environmental temperature) design solutions and material selection may be quite different than what is required for operating at HT (flowing wellbore conditions). The wider the gap between low and high temperatures may lead to two sets of design configurations working in close proximity to the other—one which works at the lower temperature, the second at higher temperature. For example, a lack of pliancy of an HT seal may impair the seal's ability to work at low temperature. Conversely, a low-temperature seal may degrade or age prematurely when exposed to prolonged HT conditions.

4.3 Loading Conditions—What Is Unique to Subsea?

In addition to the HPHT effects on equipment, the subsea environment poses several unique challenges to HPHT equipment designs, as related to loading conditions, including the following:

- The subsea/ocean environment:
 - a) external hydrostatic pressure: when, where, and how to apply appropriately;
 - b) constant cold temperature:
 - 1) massive heat sink;
 - 2) widens the temperature range (as compared to in-the-well downhole conditions);
 - c) seawater corrosion and cathodic protection (CP) effects on material properties.
- External loads:
 - a) cyclic loads imposed by intervention vessels;
 - b) cyclic loads imposed by metocean environment;
 - c) loads associated with extreme and survival events;
 - d) in situ hydrostatic pressure (due to water depth compared to in-air or factory operation or testing).
- Flow assurance considerations:
 - a) appropriate insulation to minimize heat sinks;
 - b) appropriate insulation to achieve temperature rating.
- Remoteness: remote monitoring vs restricted service life (with respect to periodic inspection for fatigue—life-cycle estimation).

Therefore, the equipment functional specifications and basis of design should address and/or include the loading conditions indicated above, as applicable (see 5.3).

4.4 Functional Requirements—Normal, Extreme, and Survival Conditions

Extreme and survival conditions are uncommon events, as defined in 5.4.6 and Table 1. The manufacturer's responsibility is to establish the equipment's load-carrying capacities related to normal, extreme, and survival events by verification analysis and validation where appropriate as defined in Table 1. The user/purchaser's responsibility is to identify and define the operating conditions with consideration of metocean conditions, so that the stress limits and capacities defined in Section 5 are not exceeded. The subsequent use of equipment subjected to the loads and pressures associated with these events requires inspection or other evaluation processes to consider it fit for continued operation(s).

NOTE Determining whether equipment is fit-for-service and may be returned to field use after an extreme or survival event should be based on sound engineering judgment between the manufacturer and the user/purchaser on a case-by-case basis.

The results of the design verification and validation of the components at extreme and survival events should define any limitations in the ability to use the equipment (assemblies) for continued operation(s). The ability to continue operation of equipment should be proven by relevant design verification and validation testing. Validation should include some measures of equipment functionality after an extreme or survival event (such as being able to operate a valve or unlock a subsea connector after an event as suggested in API 17G).

Guidance on load factors for extreme and survival events is provided in Table 1.

Given the limitations of inspection for permanently installed equipment of subsea systems, the use of equipment subjected to survival events shall be limited to operations focused on (re)gaining well control.

For any event (normal, extreme, or survival), the pressure shall not exceed the defined RWP of the exposed equipment.

5 Design Verification

5.1 General

The objective for design verification is to confirm that the HPHT equipment design is in conformance with its functional specifications and serviceability criteria, and the equipment has adequate protection against failure modes identified for HPHT equipment.

The loads obtained from the functional specifications form the design basis for the HPHT equipment and shall include the applicable operating pressure, temperature, and external loads as well as the corresponding cyclic loadings (loading histogram) for significant events that are applied to the equipment.

In this regard, Figure 1 illustrates various processes for the design verification, including design validation, for HPHT equipment that requires the equipment designer to:

- identify the scope of the component or equipment design rating (for example, pressure, temperature) for appropriate application of HPHT design flowchart and verification path (see 5.2);
- define the input parameters for design analysis (see 5.3);
- perform the design analysis (see 5.4);
- perform the fatigue assessment/life-cycle estimation, as necessary (see 5.5);
- perform the design validation (see Section 8).

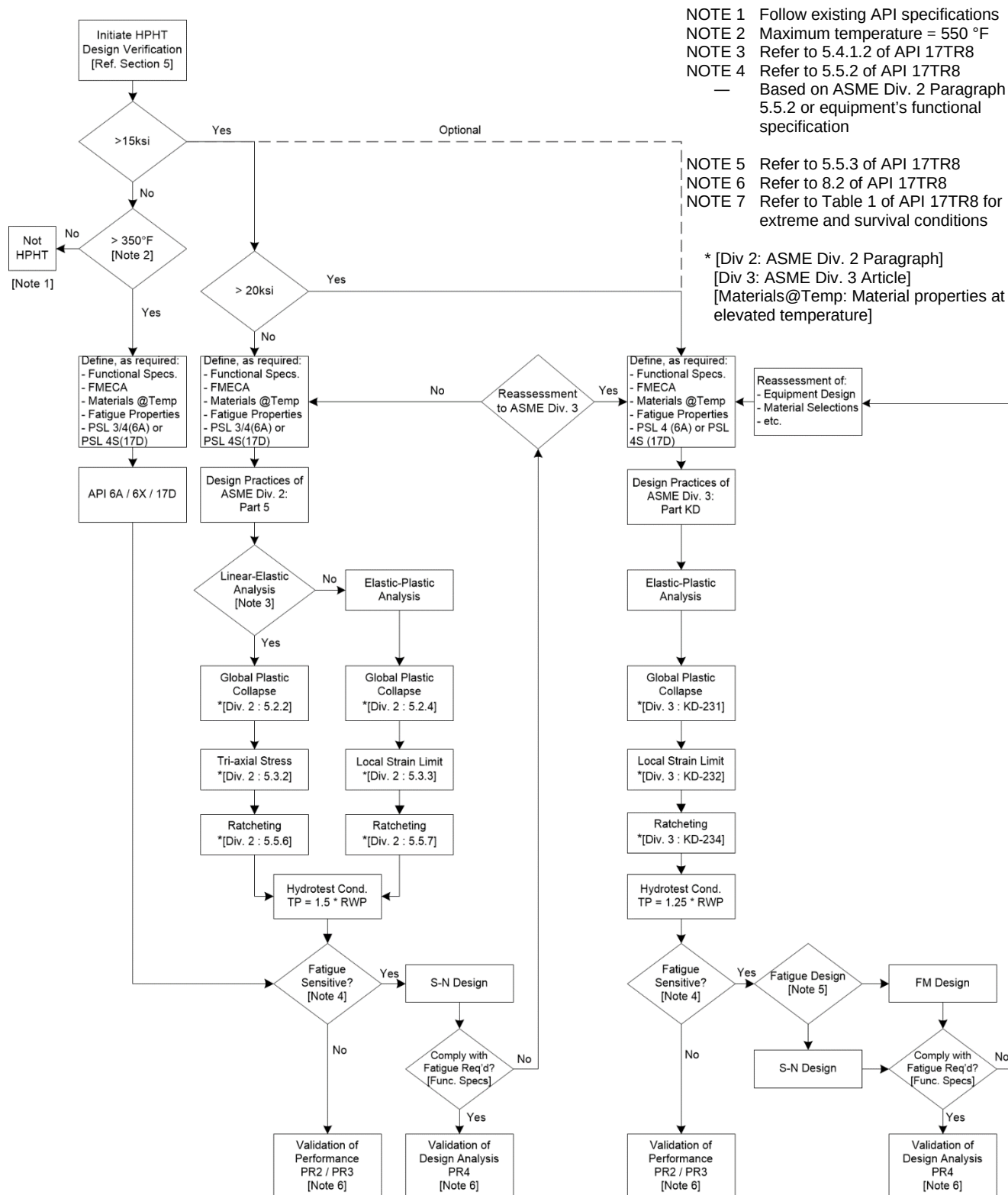


Figure 1—High-pressure High-temperature Design Flowchart

Detailed procedures for these design flowchart processes are provided in the following sections of this technical report.

5.2 High-pressure High-temperature Design Flowchart

5.2.1 General

The HPHT design flowchart is a recommended methodology for pressure-containing components. The design methodology referenced therein may also be applied to pressure-controlling components if the design methodology can assess the failure modes. Failure modes for pressure-controlling components are typically identified as deflection and/or leakage. For pressure-controlling components, the applicable API design standards remain the governing requirements.

The application of Figure 1 is based on one or a combination of conditions indicated in Section 1 and depicts the equipment design and temperature rating criteria for HPHT application.

The HPHT design flowchart provides several analytical paths for the design verification of HPHT equipment for protection against identified failure modes. Each respective path initiates by addressing the required design input parameters, the existing API specifications, with progression to incorporate the design practices provided in ASME Div. 2 or ASME Div. 3. Considerations are given to the following:

- existing API documents: API 6A, API 6X, API 17D, API 17G;
- additional requirements for thick-wall equipment analyzed with linear-elastic analysis of ASME Div. 2;
- recognition of advancements in design analysis methodology of elastic-plastic analysis of ASME Div. 2 and ASME Div. 3;
- fatigue screening to determine whether a fatigue assessment is necessary to be performed;
- fatigue assessment (life-cycle estimation).

Current API product specifications (for example, API 6X, API 17D) commonly use thin-walled linear-elastic analysis design practices with defined design margins based on the material's yield strength adjusted (derated) for elevated temperature. These existing industry practices have resulted in successful, field-proven equipment. However, the increased design pressures and design temperatures defined for HPHT applications result in higher stresses and strains for pressure-containing components and, therefore, may require the use of thick-wall components. This may require additional assessment and/or advanced methodology for accuracy.

The HPHT design flowchart (see Figure 1) permits the use of API 6A and API 6X or API 17D design verification methodology for equipment with a pressure rating of 15 ksi or lower for use in HT conditions, and within the scope of the applicable governing design standards. API 6X may not be fully appropriate for handling of external loads that some subsea equipment may be subjected. To ensure the equipment fit for intended service, the equipment designer may also elect to utilize the linear-elastic analysis of ASME Div. 2, or elastic-plastic analysis of ASME Div. 2 with progression to ASME Div. 3, as necessary.

Whereas selective application of various API and ASME design practices can provide equivalent levels of safety, design of HPHT complex thick-wall, pressure-containing components requires analysis methods for structural and functional integrity to comply with design life-cycle requirements with proper safety margins. Additionally, the material properties and nondestructive examination (NDE) should be defined that they are accurately aligned with the structural and failure assessments.

Utilizing thick-wall assemblies/systems for HPHT application results in some technical challenges (for example, additional weight, uncertainty in through-wall material properties for thick-wall equipment,

additional manufacturing considerations, and optimization of the design to ensure integrity). Thick-wall equipment may also impact the equipment-supporting infrastructure requirements (i.e. handling, lifting, supports, etc.). Additionally, HPHT assemblies/systems may exhibit additional failure modes (for example, cyclic loadings, ratcheting, or brittle fracture) in which characteristics should be addressed through advanced design methodology.

Therefore, advanced analytical techniques utilizing detailed numerical analysis methods such as finite element analysis (FEA), linear-elastic or elastic-plastic evaluations of ASME Div. 2 or ASME Div. 3 should be utilized in HPHT equipment design, along with more advanced material testing, NDE inspection, and acceptance criteria. Application of these techniques provides an accurate prediction of material stress and strain conditions, which can be used for verification of the design for both structural and functional capacities. Those evaluations provide a more thorough understanding of the material's behavior in the plastic zone and provide a more accurate assessment of the HPHT equipment against its mechanical integrity and life-cycle requirements.

Following the design analysis for pressure containment integrity, equipment that may undergo cyclic operations (i.e. pressure, temperature, external loads, etc.) shall be subjected to a fatigue screening. Further discussion on fatigue assessment is provided in 5.5). Evaluation of the pressure-containing component using the fatigue screening methods of this technical report determines if fatigue analysis is required to calculate its life-cycle characteristics for conformance with the functional specifications. If fatigue analysis is not required based on the screening criteria, this should be documented within the manufacturer's technical specifications with technical justification.

Results of a fatigue screening and/or assessment may indicate that more rigorous evaluation is required using the design practices involving the S-N fatigue curves (S-N design), FM design, and fatigue crack growth rate (FCGR), as defined in ASME Div. 3, API 579-1/ASME FFS-1, or BS 7910.

5.2.2 Recommended Path for Design Verification

Operators/manufacturers of HPHT equipment may initiate the design verification process by following the traditional design practices of linear-elastic analysis in accordance with API 6X or ASME Div. 2, as applicable. This approach has historically been relatively straightforward for equipment pressure rating ≤ 20 ksi, yielding robust designs that can satisfy functional specifications and life-cycle requirements with limited or no need for post-manufacture or "in-service" re-evaluation.

The HPHT design flowchart (see Figure 1) introduces the application of linear-elastic analysis in accordance with ASME Div. 2. Although the linear-elastic analysis methodologies of API 6X and ASME Div. 2 are similar, consideration to the loading conditions (i.e. external loads, combined loads, etc.) varies between these standards. Therefore, the equipment designer shall address the loading conditions as specified in the equipment's functional specifications through the appropriate selection of these referenced design standards. Additional requirements for using linear-elastic analysis of ASME Div. 2 for HPHT equipment are specified in 5.4.1.3 to verify protection against local strain failure mode.

Additionally, for pressure rating greater than 15 ksi, the equipment designer is recommended to use the more advanced elastic-plastic analysis of ASME Div. 2 or ASME Div. 3 for benefits as stated previously.

5.2.3 Alternate Path for Design Verification

The HPHT design flowchart (see Figure 1) offers an alternate direct path to the use of ASME Div. 3 design practices for HPHT equipment, with elastic-plastic analysis and FM design for cyclic fatigue analyses. Additionally, this technical report recommends that ASME Div. 3 be applied for HPHT equipment with pressure ratings greater than 20 ksi.

Operators/manufacturers of HPHT equipment may choose to go directly to the design practices of ASME Div. 3 to capture potential benefits listed above related to weight, improve certainties in through-wall material properties and optimization of design integrity, or simply to acquire a more thorough understanding of the

material's behavior in its plastic zone and a more accurate assessment of the HPHT equipment characteristics against its mechanical integrity and life-cycle requirements.

While the use of ASME Div. 3 design practices for HPHT equipment designs can offer certain advantages (for example, it specifies a lower design margin than the design practices of ASME Div. 2), it may also require more rigorous constraints on static and cyclic loading identifications, material testing and inspection, manufacturing, and life-cycle load monitoring to confirm that predicted cyclic loading conditions have not been exceeded. Manufacturers may elect to go directly to the design practices of ASME Div. 3 for design verification and should clearly identify and value-assess the benefits and constraints, including life-cycle/load monitoring requirements associated with the direct ASME Div. 3 approach.

5.3 Input Parameters for Design Analysis

5.3.1 Functional Specifications

The design verification process starts with the equipment's functional specifications. The user/purchaser should provide a complete functional specification as the basis of design for the equipment using a life-cycle approach with sufficient details for the manufacturer to conduct the design analysis or design verification in accordance with HPHT design flowchart (see Figure 1) and the guidelines of this technical report.

The functional specifications should include, but not be limited to, the following:

- well pressure and temperature (bottom hole and at wellhead during flowing conditions) over the life of the well;
- well fluid properties or compositions (H_2S , CO_2 , etc.);
- mechanical/structural loads (external loads);
- environmental and/or metocean conditions (external load effects);
- cyclic loading/life-cycle requirements (i.e. pressure cycles, temperature cycles, flow-induced loads, external loads, etc.);
- corrosion, corrosion/erosion requirements;
- specified loads and characteristics including temporary test conditions, possible cyclic loading conditions, and changes to those parameters over the operating life, thermal gradients, external loadings, etc.;
- storage conditions;
- transportation and installation conditions;
- applicable industry standards and/or regulatory requirements.

Guidance on developing a functional specification can be found in ISO 13879. API 1PER15K-1 provides additional guidance on elements of the functional specifications. API 1PER15K-1 also provides guidance on HPHT equipment service criteria.

5.3.2 Failure Modes, Effects, and Criticality Analysis

A failure modes, effects, and criticality analysis (FMECA) should be performed at an early stage of the design process. When performed in the early design phase, FMECA can assist in mitigating any identified risks where modifications to the design are feasible options. Component-level FMECA analysis should be performed by the manufacturer to identify failure modes and manage/mitigate the risk of failure within the confines of the component's design envelope. Higher systems-level FMECAs should be performed by the

user/purchaser unless the “where-used” aspect of the assembly (incorporated within a larger (higher level) assembly or fabrication) and its intended use is known to the manufacturer.

FMECA is an extension of an FMEA (failure modes and effects analysis) process where a criticality assessment, “C,” is identified. The functional specification should be used to inform the loading, operational, and environmental factors addressed in the FMECA. Criticality assessment should consider the role of equipment as it relates to well control envelopes or its failure (by proximity) adversely affecting the performance of adjacent components/equipment. This may be based on the barrier philosophy of primary barrier and/or secondary barrier. Examples of criticality assessment may be as follows.

- Where loss of containment (failure point) occurs in a primary barrier envelope and cannot be contained within a secondary barrier envelope or isolated by a barrier element, this may be considered as high criticality.
- Where loss of containment occurs away from the primary barrier envelope, in a secondary barrier envelope where source of the loss can be retained by the primary barrier envelope or isolated by a barrier element, this may be considered as a lower criticality.

FMECA should be performed to identify failure modes, resulting hazards affecting the component/equipment, and the component's criticality to a complete equipment. API 1PER15K-1 provides additional guidance on the FMEA process and API 17N provides guidance on the FMECA process. A primary output of the FMECA should be the development of a documented design validation program.

An additional objective of the FMECA analysis, in the context of this technical report, is to identify any additional validation testing requirements associated with the equipment's performance requirements (PR), specifically for PR3 and PR4, and they should be based on identified failure mode(s) or event(s), as applicable. The definitions, validation testing requirements, and considerations for PR3 and PR4 are provided in 8.2.

5.3.3 Material Properties

Applicable material properties (for example, yield strength, tensile strength, modulus of elasticity) and fatigue properties (for example, S-N curves, FT, FCGR) shall be identified and/or generated in accordance with the temperature and environmental parameters specified in the equipment's functional specifications and 4.2, for the design analysis of HPHT equipment.

Section 6 provides detailed guidance on the material requirements and testing protocols for HPHT application. General guidance on material selection is provided in Annex B. Guidance on material QC is provided in Annex C. Guidance on material characterization is provided in Annex D.

5.3.4 Product Specification Level

The product specification levels (PSL) provide varying levels of quality control and assurance related to material quality and properties. PSL levels for HPHT equipment are based on their governing API 6A and API 17D product standards, and they are associated with API 6A/API 6X and ASME Div. 2 design practices.

The design flowchart cites PSL 4 (API 6A) and PSL 4S (API 17D) for QA processes (in accordance with API 6A or API 17D).

NOTE 1 Guidance is also provided in ASME Div. 3, Article KM-2 (Mechanical Property Test Requirements for Metals) Fabrication Requirements), Article KF-1 (General Fabrication Requirements), Article KF-2 (Supplemental Welding Fabrication Requirements), Article KE-2 (Requirements for Examination and Repair of Material), Article KE-4 (Final Examination of Vessels).

NOTE 2 Obtaining material coupons (such as 1/4T—as prescribed by PSL 4 or PSL 4S) from QTCs or prolongations may be inadequate for determining through-thickness properties for some materials or forging geometries. Refer to Annex C for additional details.

5.4 Design Analysis

5.4.1 General

5.4.1.1 Design Verification Guidance

For the design analysis of HPHT equipment in accordance with Figure 1, this technical report provides the following guidance to be applied for the design verifications. Normal, extreme, and survival events shall not include situations where the RWP or operating temperature (range) is exceeded.

Elevated temperature should be at the upper limit of the expected environment or the specified temperature class.

5.4.1.2 Design by Analysis

This technical report recommends design-by-analysis based on the use of numerical stress and/or thermal analysis (for example, FEA) for HPHT equipment. Methodologies associated with design-by-analysis should be 1) linear-elastic or 2) elastic-plastic analysis. These design verification methodologies are identified in Figure 1 to their respective applications. Figure 1 is intended to provide guidance to the applicable verification methods within ASME Div. 2 or ASME Div. 3 design path for the evaluation of HPHT components. Subsection 6.3 advises on the material models and material properties required for these design analysis methodologies.

5.4.1.3 Linear-elastic Analysis Applied for Thick-wall Equipment

The traditional application of linear-elastic analysis (in accordance with ASME Div. 2) may result in nonconservative designs from the stress classification procedures (refer to the Hopper diagram of ASME Div. 2, Figure 5.1) to demonstrate structural integrity for thick-wall pressure-containing components (" $R/t \leq 4$ " or " $D_o/D_i \geq 1.25$ "), especially around structural discontinuities, or notches. This is due to variations in the stress distribution within the wall thickness.

Therefore, linear-elastic analysis may be used for the design analysis of thick-wall pressure-containing assemblies, in addition to the requirements specified in Figure 1, when the von Mises equivalent (VME) stress does not exceed the material's yield strength through more than 5 % of component thickness in the maximum defined loading scenario/combinations for normal event load conditions. It should be noted that the ASME Div. 2 Paragraph 4.1.6.2(a) should be evaluated for hydrostatic test conditions.

For the ASME Div. 2 linear-elastic design path, the API allowable stress criteria should be used, where $S = 2/3 \times S_{YST}$, $S_{PL} = S_{YST}$, and $S_{PS} = 2 \times S_{YST}$, where S_{YST} = specified minimum yield strength adjusted for elevated temperature.

Mesh sensitivity analysis should be performed to validate the FEA and ensure that the mesh density variations do not affect the stress distribution (within 5 % variance) through the component thickness.

NOTE Elastic-perfectly plastic or limit-load (limit state) design analysis is an acceptable method provided results meet ASME Div. 2 global collapse acceptance criteria, plus adequately meeting strain limit and cyclic loading life requirements. Limit-load analysis also requires that the geometry and materials of construction are sufficiently ductile and have sufficient FT resulting only in ductile failure modes.

The applicability of limit-load analysis shall be validated for geometry and materials modeled as described in Section 6, 8.8, and Annex D.

5.4.1.4 Load and Resistance Factor Design

The HPHT design flowchart specifies ASME Div. 2 and ASME Div. 3 as design practices for HPHT component designs. Within these design standards, ASME specifies the load and resistance factor design (LRFD) analysis method in accordance with ASME Div. 2 or ASME Div. 3, which is considered one of the more accurate analysis methods. This method requires design-by-analysis (for example, FEA) with applied

load factors to verify that a pressure-containment component design has adequate margin as protection against the identified failure modes (for example, plastic collapse, rupture).

There are differences in the specified load factors between ASME Div. 2 (2.4 on plastic collapse load) and ASME Div. 3 (1.8 on plastic collapse load). ASME Div. 3 cites lower load factors, which would be beneficial to maintain HP equipment with reasonable wall thickness. However, the lower load factors require additional input and verification by the equipment designers or user/purchaser as described in 5.2.3.

5.4.1.5 Stress Components and Equivalent Stresses

The calculated stress components derived from detailed numerical analysis can be combined as a VME stress or a stress intensity (S_{INT}). The VME stress failure theory is considered a more accurate predictor for the onset of yielding in ductile materials. These two methods can produce different results based on the magnitudes of the underlying stress components. The use of stress intensity (S_{INT}) or VME stress is recognized by API 6X for linear-elastic methods. VME stress is recognized in recent editions of ASME Div. 2 and Div. 3.

5.4.1.6 Load Descriptions

ASME Div. 2—Table 5.2 and ASME Div. 3—Table KD-230.2 provide descriptions of the loads that are analyzed using these codes. These loads may not directly correspond to the loadings required to be analyzed for API HPHT equipment. The following is the correlation between loads typically experienced in the oil and gas equipment and loads identified in ASME Div. 2 and ASME Div. 3. The defined loads do not identify all loading cases, but provide guidance on load categorization between ASME and API requirements:

- P is the internal or external specified pressure at temperature;
- P_T is the hydrostatic body test pressure (see Section 9);
- D_X is the suspension or external loads (i.e. casing loads, external riser or piping loads, installation loads [running], etc.) for normal, extreme, and survival events (D_{NORMAL} , $D_{EXTREME}$, $D_{SURVIVAL}$, respectively);
- L is the fluid dynamic loading (i.e. slugging, water hammer, flow-induced vibration, wave and current loading, vortex-induced vibration, etc.);
- T is the self-restraining loads (i.e. thermal loads, thermal expansions, installation misalignment loads, or applied displacements, etc.); this load case does not typically affect the collapse load, but should be considered in cases where elastic follow-up causes stresses that do not relax sufficiently to redistribute the load without excessive deformation;
- W_A is the assembly loads (for example, sealing preload, bolt preloads, connector preloads).

An additional loading consideration for oilfield equipment is the load-bearing interface between components within an assembly. This loading consideration can be applied as an equivalent pressure-end load, as applicable.

With consideration to the above, the following sections outline the design analysis process in accordance with the HPHT design flowchart (see Figure 1) to verify protection against the identified failure modes for HPHT equipment.

5.4.2 Global Plastic Collapse

The design verification for protection against plastic collapse can be accomplished through linear-elastic analysis, where permitted by 5.4.1.3, or elastic-plastic analysis.

- 1) Linear-elastic Analysis—API 6X and applicable sections of ASME Div. 2, specify linear-elastic analysis for global plastic collapse load. Nevertheless, the equipment designer is cautioned to ensure appropriate utilization of the linear-elastic analysis methodology, as this approach has the potential for nonconservative results from thick-wall stress distribution theory, and/or stress categorization difficulties due to complex geometry associated with HPHT equipment. Subsection 5.4.1.3 should be considered when linear-elastic methodology is utilized for thick-wall (" $R/t \leq 4$ " or " $D_o/D_i \geq 1.25$ ") pressure-containing component analysis.

The API allowable stress criteria should be used, where $S = 2/3 \times S_{YST}$, $S_{PL} = S_{YST}$, and $S_{PS} = 2 \times S_{YST}$, where S_{YST} = specified minimum yield strength adjusted for elevated temperature.

- 2) Elastic-plastic Analysis—Elastic-plastic analysis provides better accuracy in the assessment of protection against global plastic collapse of a component relative to the linear-elastic analysis method, as the elastic-plastic stress analysis simulates actual material behavior calculated by factoring the plastic collapse load. The maximum allowable working load is calculated by applying the applicable load factors to the internal or external pressure, hydrostatic head loads, and dead weight loads to verify that these loads do not exceed the component's plastic collapse load (load at which unbounded plastic deformation occurs). Strain hardening effects shall be included in elastic-plastic analysis using true-stress/true-strain material characteristics. Alternatively, the maximum allowable working loads may be calculated by factoring the component's plastic collapse load by the applicable load factors. The designer should verify the deformation and plasticity at the rated capacities to ensure functionality. For additional guidance on serviceability requirements, refer to 5.4.7. The elastic-plastic analyses, with the applicable load factors, are to be performed and comply with the global plastic criteria of Table 1 (Global Criteria 1 and Global Criteria 2) for ASME Div. 2 or ASME Div. 3, as applicable.

Subsequent postprocessing of FEA results can be retrieved for the verifications of other applicable failure modes (i.e. local strain limit damage, ratcheting effects, fatigue, etc.). The material properties used for these analyses are to be in accordance with 6.3.

NOTE Elastic-perfectly plastic analysis is an acceptable method only for ratcheting analysis. Limit-load (limit state) design analysis is an acceptable method only when considering hydrostatic pressure testing to meet ASME Div. 3.

Table 1—Global Plastic Collapse Design Margins/Load Factors

Load Conditions	Linear-elastic (Membrane) See API 17G/17D ^a	Elastic-plastic (LRFD) See ASME Section VIII, Div. 2 ^{b,c,d}		Elastic-plastic (LRFD) See ASME Section VIII, Div. 3 ^{b,c,d}	
		Global Criteria 1 $LRFD \times (P + D_x) + W_A$	Global Criteria 2 $LRFD \times (P + D_x + T) + W_A$	Global Criteria 1 $LRFD \times (P + D_x) + W_A$	Global Criteria 2 $LRFD \times (P + D_x + T) + W_A$
Normal	$0.67 \times S_{YST}$	2.40	2.10	1.80	1.58
Extreme	$0.80 \times S_{YST}$	2.00	1.75	1.50	1.32
Survival	$1.00 \times S_{YST}$	1.60	1.40	1.20	1.05

^a Refer to API 17G/17D for design factors for stress categories other than membrane stress. S_{YST} = specified minimum yield strength derated for elevated temperature.

^b Material properties at elevated temperature shall be applied for all LRFD analyses.

^c Refer to 5.4.1.6 for a description of load types.

^d To ensure protection against global plastic collapse, the designer must select LRFD factors for extreme and survival events based on a risk assessment of the equipment design or further validation testing.

A summary of these design margins for the linear-elastic method and load factors for the elastic-plastic method can be found in Table 1. If other loads are applicable, refer to ASME Div. 2 or Div. 3. Refer to 9.2 and 9.3 for hydrostatic body test pressure (P_T) conditions.

5.4.3 Local Strain Limit

In addition to demonstrating protection against global plastic collapse, the applicable local strain limit failure criteria should be satisfied for HPHT equipment design. Areas of structural discontinuities are typical locations for high-stress risers (peak stress/strain) that may cause local plastic strain and potential initiation site for fatigue or crack initiation. Linear-elastic or elastic-plastic stress analysis method can be used for local stress or strain assessment for normal, extreme, and survival events.

- a) Linear-elastic Analysis—The linear-elastic analysis criteria to prevent local failure at peak strain locations (i.e. structural discontinuities, notches, etc.) or the triaxial-stress verification within the pressure-containing equipment are defined in ASME Div. 2 Paragraph 5.3.2, where $S = 2/3 \times S_{YST}$, where S_{YST} = specified minimum yield strength adjusted for elevated temperature.
- b) Elastic-plastic Analysis—The elastic-plastic analysis can also be used to define a limiting triaxial-strain at peak strain locations (i.e. structural discontinuities, notches, etc.) within the pressure-containing equipment. The local strain analysis should be performed for normal and extreme events, adjusted for environmental conditions, and comply with ASME Div. 2 Paragraph 5.3.3 or ASME Div. 3 Article KD-232.

5.4.4 Ratcheting Effects

Protection against ratcheting, where the repeated application, removal, and re-application of load that results in unsustainable stress-strain hysteresis, can be analyzed using either linear-elastic or elastic-plastic analysis.

- a) Linear-elastic Analysis—The linear-elastic analysis criteria to prevent ratcheting through the thickness of the pressure-containing component are defined in ASME Div. 2 Paragraph 5.5.6 and API 6X.
- b) Elastic-plastic Analysis—Elastic-plastic stress analysis can be used to ensure that the pressure vessel does not fail by ratcheting. The elastic-perfectly plastic material properties used for this analysis should be input at the material minimum specified yield strength adjusted (derated) for elevated temperature. The ratcheting assessment should be performed and comply with ASME Div. 2 Paragraph 5.5.7 or ASME Div. 3 Article KD-234.

5.4.5 Plastic Collapse under Hydrostatic Body Test Condition

Linear-elastic or elastic-plastic analysis can be used to ensure that the pressure-containing equipment does not exhibit plastic collapse under the hydrostatic body test pressure specified in Figure 1 and Section 9. The hydrostatic body test condition stress analysis should be performed in accordance with the applicable sections of API 6X, API 17D, ASME Div. 2 or ASME Div. 3.

For a linear-elastic analysis in ASME Div. 2, this condition shall be considered satisfied by evaluation of the hydrostatic body test pressure defined in Figure 1 and Section 9 relative to the applicable sections of API 6X, API 17D, ASME Div. 2 Paragraph 4.1.6.2(a).

For an elastic-plastic analysis utilizing ASME Div. 2, this condition is satisfied by evaluation of the hydrostatic body test conditions in ASME Div. 2—Table 5.5 for global, local, and any serviceability criteria (if applicable). It is recognized that the hydrostatic body test pressure is not used directly in this evaluation and the load factors from ASME Div. 2—Table 5.5 should be used for this evaluation.

For an elastic-plastic analysis utilizing ASME Div. 3, the global and serviceability criteria (if applicable) from ASME Div. 3—Table KD-230.4 should be used.

5.4.6 Extreme and Survival Events

5.4.6.1 Extreme Events

Extreme events include the unavoidable but predictable load conditions due the environmental and operating scenarios. Exceeding RWP or temperature is not allowed for extreme events. The allowable number of extreme event cycles should be determined based on the design life and combination of all loading. An extreme event is an event with a probability of occurring less than 10^{-1} and larger than 10^{-2} , based on appropriate risk assessment, for the period under consideration.

5.4.6.2 Survival Events

Survival events include the unplanned, unavoidable, and unpredictable load conditions due to the environmental, operating, or any other scenarios whatsoever. Exceeding rated working pressure or temperature (range) is not allowed for survival events. A survival event is an event with a probability of occurring less than that of an extreme event, based on appropriate risk assessment, for the period under consideration. Survival events are more severe than an extreme event (which may be unplanned) in which equipment, after exposure, is required to maintain critical safety functionality. Certain events, while even beyond the probability of the survival definition, may be required by the user/purchaser or regulatory bodies to be included within the design of the system [worst case discharge (WCD) may be an example of such a survival event].

5.4.7 Serviceability Criteria

The designer shall perform a serviceability check by verifying the deformation and plasticity at the rated capacities to ensure functionality.

NOTE The plastic collapse criteria may be satisfied, but the equipment may have excessive deformation at the rated design conditions. In this case, the rated design loads may have to be reduced based on deformation or other functional criteria. Examples of service criteria are limits on the rotation of a mating flange pair to avoid possible flange leakage concerns, and limits on plastic deformation or displacements that may limit functionality.

5.5 Fatigue Assessment/Life-cycle Estimation

5.5.1 General

Subsequent to the design verification for pressure containment integrity, HPHT equipment that may undergo cyclic operations (i.e. pressure, temperature, external loads, etc.) shall be subjected to a fatigue screening to determine if fatigue assessment is necessary to calculate its life-cycle estimation for conformance with its functional specifications.

There are two methods of evaluating fatigue assessment:

- S-N design based on alternating stress or strain amplitude;
- FM design based on material's fatigue crack growth data, da/dN vs ΔK , with alternating stress cycles that result in an alternating crack tip stress intensity.

Each method requires a detailed component or system level load histogram as input with appropriate material properties defined for the design verification. Both S-N design and FM design are defined in this technical report with guidance on appropriate applications.

Failure assessment due to fatigue cycling should be based on an effective alternating stress or alternating strain for a given number of cycles based on load histograms defined by the user/purchaser, including operating environments design life, extreme events, and inspection intervals, as applicable. In the absence of specific criteria, the manufacturer may assume a representative fatigue cycle histogram, environment design life, and inspection interval as the basis for standard product offerings. The equipment user/purchaser

should determine if the standard product design fatigue life, operating environment, and inspection intervals meet or exceed the expected or actual service conditions. The number of cycles should be adequate to satisfy the user/purchaser defined cycle life and functional specifications. The fatigue cycles should include applicable cyclic loadings for the life of the component, which includes factory testing, installation loadings, and operational loads.

Prior to a fatigue assessment, the global design verification process should identify the most highly stressed regions that are the most critical for fatigue crack initiation and/or fatigue crack propagation/growth. Then a determination should be made to the extent and location(s) where alternating or cyclic loading is taking place. When the FM design is used, the alternating stresses defining the path of crack growth should be based on the maximum principal stress range. The flaw is assumed to propagate in a plane perpendicular to the direction of the maximum principal stress. It should be noted that fatigue crack growth is load path dependent. Evaluation of load sequence to determine the load combinations that result in the least number of cycles to failure should be conducted.

The traditional S-N fatigue analysis assumes that the fatigue life of complex structures can be predicted by calculating the highest range of alternating principal stress at any location, then by determining an allowable number of design cycles from laboratory data obtained on strain-cycled, smooth, polished bars. If there are no significant fabrication flaws in the structure, this approach usually produces a conservative result. However, the fatigue life of a smooth, polished bar test specimen is the sum of the number of cycles required to initiate a flaw and the number of cycles to propagate the flaw through the thickness of the specimen. If a metallurgical or fabrication flaw exists at the high-stress location in a component's structure, initiation has already occurred, so the fatigue life of the component is only the number of cycles required for propagation to failure. This could theoretically give a nonconservative fatigue life, so the more accurate FM design should be selected for cases where a catastrophic loss of containment or fast fracture could result. However, the probability that the S-N design produces a nonconservative result in machined structures in practice is low for the following reasons.

- The probability that a flaw is located in the region of highest stress is very low.
- In low-cycle fatigue (< 10,000 cycles), the number of cycles required to propagate a flaw to failure in a component's structure after initiation is almost always greater than the number of cycles required for propagation of a flaw through the laboratory specimen because:
 - a) the general stress field at the crack tip in a component usually drops off as the crack grows beyond the highly stressed surface;
 - b) the maximum permitted flaw size in the component's structure is usually greater than the thickness of the laboratory fatigue specimen.
- The S-N fatigue is typically based on a high-stress concentration region where the principal stresses decline rapidly through the thickness.
- The S-N alternating stress is based on the localized high elastic principal surface stress and does not consider shakedown or elastic-plastic stress redistribution.

NOTE Shakedown areas exhibit a stable hysteresis loop, with no indication of progressive deformation. Further loading and unloading, or applications and removals of the temperature distribution, produces only elastic primary and secondary stresses.

The FM analysis starts with the assumption that a flaw exists at a high-cycle stress location. The size of this assumed flaw is the largest flaw deemed acceptable by the NDE criteria that are used in the manufacture of the component(s). It should be noted that it is possible for the fatigue life calculated using the FM approach to be greater than that calculated using the S-N approach, particularly in low-cycle fatigue (for example, a design life less than about 10,000 cycles). However, in high-cycle fatigue (for example, a design life greater than about 100,000 cycles), the FM approach results in a shorter life unless a very large stress intensification factor is used with the S-N approach or a very small initial flaw size can be justified for the FM approach.