Protocol for Verification and Validation of High-pressure High-temperature Equipment

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Standards referenced herein may be replaced by other international or national standards that can be shown to meet or exceed the requirements of the referenced standard.

Suggested revisions are invited and should be submitted to the Standards Department, API, 1220 L Street, NW, Washington, DC 20005, standards@api.org.

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1 Scope

1.1 Purpose

This report focuses on an evaluation process for high-pressure high-temperature (HPHT) equipment in the petroleum and natural gas industries which includes design verification analysis, design validation, material selection considerations, and manufacturing process controls necessary to ensure the equipment is fit-for-service in the applicable HPHT environment. HPHT environments are intended to mean that one or more of the following well conditions exist:

a) the completion of the well requires completion equipment or well control equipment assigned a temperature rating greater than 350 °F or a pressure rating greater than 15,000 psig;

b) the maximum anticipated surface pressure or shut-in tubing pressure is greater than 15,000 psig on the seafloor for a well with a subsea wellhead or at the surface for a well with a surface wellhead; or

c) the flowing temperature is greater than 350 °F on the seafloor for a well with a subsea wellhead or on the surface for a well with a surface wellhead.

NOTE In high-temperature, low-pressure applications, not all methodologies presented in this document may apply.

The design verification process focuses on the analytical methods to achieve design verification by calculating the performance limits of a design (system, subsystems, and components), including its service life and material selection. The design validation process focuses on evaluating the potential failure modes of the equipment, the effects/consequences of the failures and defining the appropriate test methods to evaluate the reliability of the equipment against the identified failure modes including validation of material performance. The material section defines the required input parameters for the verification process and recommends the procedures necessary to evaluate the material fitness-for-service in the service environment. Functional testing procedures specific to HPHT equipment are also included in this document.

The design verification and validation protocols in this report should be used as a guide by the various API subcommittees to develop new and revised standards on equipment specifications for HPHT service. This report is not intended to replace existing API equipment specifications but to supplement them by illustrating accepted practices and principles that may be considered in order to maintain the safety and integrity of the equipment. This report is intended to apply to the following equipment: wellheads, tubing heads, tubulars, packers, connections, seals, seal assemblies, production trees, chokes, and well control equipment. It may be used for other equipment in HPHT service.

Annexes to this report provide additional information on the following:

— Annex A provides example HPHT material property data,

— Annex B is a compendium of published metallurgical-related field failures,

— Annex C provides a detailed explanation of the failure mode and effect analysis (FMEA) process,

— Annex D contains technical information on the considerations for the selection of castings and forgings,

— Annex E provides information on the important elements of a quality management system for manufacturers of HPHT equipment.

1.2 Existing Designs and In-service Equipment

Previous standards exist for equipment designed for HPHT conditions. These include API and ASME publications and date back to such documents as AWHEM Std 6 (June 1957), *AWHEM Specification for Ring Joint Flanges for Drilling and Production Service for 15,000 psi Working Pressure*. Existing practices have resulted in successful, field proven equipment. Further enhancements to these specifications may include additional analytical and testing techniques referenced in this document. This document does not imply that existing equipment is unsatisfactory for use or should be replaced, or that additional components could not be made to the same existing design. Where the existing design, analysis processes, and procedures used in the design and manufacture of equipment fall fully within the scope of an existing API standard, the equipment is deemed to be fit-for-service. Changes in the functional specifications require reevaluation of the existing design. New or revised standards for equipment used in HPHT service should consider the history of equipment manufactured to prior standards and address future use of that equipment as well as new equipment made to the same design. Additional documentation of selected industry experience in HPHT well completions is available in the Bibliography.

Requirements for existing HPHT equipment are covered in many existing API standards. A listing of the standards that cover requirements for existing HPHT equipment as well as some standards that do not address HPHT requirements but are frequently invoked are provided in Table 1.

1.3 Applicability

This technical report describes an evaluation process for HPHT equipment to ensure the equipment is fit-for-service in the applicable HPHT environment. This report does not supersede current API standards but discusses additional or alternative methods of design verification and validation.

2 Terms and Definitions

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

2.1
corrosion resistant alloy
Nonferrous-based alloy in which any one or the sum of the specified amount of the elements titanium, nickel, cobalt, chromium, and molybdenum exceeds 50 % (mass fraction) (API 6A).

2.2
critical crack depth
Crack dimension at which unstable crack propagation is predicted to occur based on fracture mechanics calculations.

NOTE 1 Crack depth for a given load at which the stress intensity factor equals the plane strain fracture toughness (K_{IC}).

NOTE 2 Crack depth is that depth at which the combination of load ratio and toughness ratio are at the limit on the failure assessment diagram.

2.3
design margin
The ratio of the structural capacity of a system to the applied loads or design loads.

Table 1—API References for Equipment

Product Category	Products	Specifications
Surface wellheads/trees	Wellheads	API 6A [a]
	Tubing heads	API 6A [a]
	Valves, chokes, check valves	API 6A [a]
	Flanges and metal gaskets	API 6A [a], API 6AF1 [a], API 6AF2 [a]
	Surface trees	API 6A [a]
Tubular conduits	Tubulars	API 5CT [a], API 5DP [a], API 5CRA [a], API TR5C3 [a]
	Threaded connections	API 5C5 [a]
	Risers and piping	API 16F [a], API 16Q [a], API 16R [a], API 2RD [a], API 17G
Wellbore isolation	Production packers	API 11D1 [a]
	Seals (elastomeric and metal–metal)	API 6A, Annex F [a]
	Seal assemblies	
Subsea wellheads/trees	Wellheads	API 17D
	Subsea tubing heads	API 17D
	Subsea trees	API 17D
	Clamp hub/swivel flanges	API 17D
	Flexible pipe	API 17J
	Umbilicals	API 17E
	Control systems	API 17F
	Manifolds and through flowline	API17P
	High integrity pressure protection systems	API 17O [a]
	Clamp hubs and connections	API 16A [a]
Well control equipment	Production valves and chokes	API 6A [a], API 16C [a]
	Blowout preventers (BOPs)	API 16A [a]
	Drilling valves (choke and kill)	API 16A [a]
	Surface-controlled subsurface safety valves (SCSSVs)	API 14A [a]

[a] Includes requirements for HPHT equipment.

2.4
design validation
Process of proving a design by testing to demonstrate conformity of the product to design requirements (API Q1).

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.

2.5
design verification
Process of examining the result of a given design or development activity to determine conformity with specified requirements (API Q1).

NOTE Design verification activities include 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 independent of design and development review,
c) comparing new designs to similar proven designs.

2.6
elastic-plastic analysis
An analysis considering both the applied loading and deformation characteristics of the component.

2.7
field repairs
Repairs made to equipment outside of a normal service center.

2.8
fracture toughness
Property of a material which measures the resistance to failure due to crack propagation.

2.9
functional specification
Document that describes the features, characteristics, process conditions, boundaries and exclusions defining the performance and use requirements of the product, process, or service (ISO 13879).

2.10
limit load analysis
Calculations performed to determine a lower bound to the structural failure of a component (ASME *BPVC*, *Section VIII*, *Division 2* and *Division 3*).

2.11
load cycle
Series of loads applied to an assembly or component that generates stresses (ASME *BPVC*, *Section VIII*, *Division 2* and *Division 3*).

2.12
plastic collapse
Load that causes overall structural instability; the onset of gross plastic deformation.

NOTE 1 Plastic collapse load is calculated with elastic-plastic material properties.

NOTE 2 Plastic collapse is calculated using methods such as ASME *BPVC, Section VIII, Division 2*, Paragraph 5.2.4 or ASME *BPVC, Section VIII*, *Division 3*, Paragraph KD-230 using a true stress–strain material model.

2.13
post-yield
Material state characterized by having experienced permanent deformation.

2.14
pressure-containing
Part whose failure to function as intended results in a release of wellbore fluid to the environment (API 6A).

2.15
pressure-controlling
Part intended to control or regulate the movement of pressurized fluids (API 6A).

2.16
primary stress
Normal or shear stress developed by the imposed loading which is necessary to satisfy the laws of equilibrium of external and internal forces and moments (ASME *BPVC*, *Section VIII*, *Division 2*, Paragraph 5.12).

NOTE The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses that considerably exceed the yield strength will result in failure or at least in gross distortion. A general primary membrane stress is one that is distributed in the structure such that no redistribution of load occurs as a result of yielding.

2.17
rated working pressure
Maximum internal or external pressure that the equipment is designed to contain and/or control.

NOTE The rated working pressure should be defined in terms of applicable loading and environmental conditions.

2.18
secondary stress
Normal stress or a shear stress developed by the constraint of adjacent parts or by self-constraint of a structure (ASME *BPVC*, *Section VIII*, *Division 2*, Paragraph 5.12).

NOTE The basic characteristic of a secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur and failure from one application of the stress is not to be expected.

2.19
stainless steel
Steel containing more than 11 % chromium (mass fraction) to render the steel corrosion-resistant. (API 6A).

NOTE Other elements may be added to secure special properties.

2.20
stress relaxation
Time-dependent decrease in stress under sustained strain.

2.21
system
Combination of interacting elements organized to achieve one or more stated purposes (ISO 15288).

EXAMPLE Air transportation system.

2.22
technical specification
Document that describes technical requirements to be fulfilled by the product, process, or service in order to comply with the functional specification (ISO 13880).

2.23
thermal ratcheting
Progressive incremental inelastic deformation or strain that can occur in a component subjected to thermal cyclic loading.

NOTE Thermal ratcheting causes cyclic straining of the material due to thermal loads, which can result in failure by fatigue and/or cyclic incremental deformation of a structure.

2.24
thermal stress
Self-balancing stress produced by a nonuniform distribution of temperature through the cross section of a component.

NOTE Thermal stress may also be present when a constant temperature is applied to a composite of materials with differing coefficients of thermal expansion or to a material that is constrained from expanding or contracting in response to temperature changes.

2.25
user
user/purchaser
The company, organization or entity that purchases, installs, and/or uses equipment.

2.26
yield strength
Engineering stress at which, by convention, it is considered that plastic elongation of the material has commenced (ASTM E6).

NOTE This stress may be specified in terms of

a) a specified deviation from a linear stress–strain relationship,
b) a specified total extension attained, or
c) maximum or minimum engineering stresses measured during discontinuous yielding.

EXAMPLE In API 6A, yield strength values are the 0.2 % offset yield strengths determined from tests conducted in accordance with ASTM A370. In API 5CT, the stress occurs at specified strains (0.5 %, 0.65 %, etc.).

3 Abbreviations and Symbols

3.1 Abbreviations

For the purposes of this document, the following abbreviations apply.

BOP blowout preventer

CRA corrosion resistant alloy

DCB double-cantilever bend

FAT factory acceptance testing

FMEA failure mode and effect analysis (see ISO TS 16949)

FPB four-point bend

HPHT	high-pressure high-temperature
IMP	integrity management program
ITP	inspection and testing plan
MPS	manufacturing process specification
NDE	nondestructive examination
SCC	stress corrosion cracking
SCSSV	surface-controlled subsurface safety valve
SMYS	specified minimum yield strength
SSC	sulfide stress cracking
SSRT	slow strain rate testing
TPN	test priority number
UT	ultrasonic testing
UTS	ultimate tensile strength

3.2 Symbols

For the purposes of this document, the following symbols apply.

da/dN	fatigue crack growth rate
E	Young's modulus
J_{IC}	fracture toughness measured using the J-integral method in accordance with ASTM E1820
K_{I}	stress intensity factor
K_{IC}	material plane strain fracture toughness (material critical stress intensity factor)
K_{ISSC}	threshold stress intensity factor for sulfide stress cracking (see NACE TM0177)
K_{IEAC}	threshold stress intensity factor for environmentally assisted cracking appropriate for the environment
R	inside radius of component under pressure
S_{y}	minimum specified material yield strength at room temperature
s	time in seconds
t	wall thickness
ΔK	change in stress intensity factor

4 Functional Specification

4.1 Responsibility

The user/purchaser (hereinafter called user) should provide a complete basis of design for the equipment with sufficient detail for the supplier/manufacturer (hereinafter called manufacturer) to conduct a complete analysis in accordance with the guidelines in this document. The basis of design should include, but not necessarily be limited to:

a) environmental conditions including corrosion, corrosion/erosion allowance requirements, service temperatures, fluid composition (including any solids);

b) required loads and characteristics including handling, installation, temporary test conditions, possible cyclical loading conditions and changes to and combinations of those parameters over the operating life, thermal gradients, external loadings, etc.;

c) life cycle requirements;

d) applicable industry standards and/or regulatory requirements.

Guidance on developing a functional specification may be found in ISO 13879. Possible combinations of various design criteria should be specified in the form of a desired operating envelope for the product if applicable. Every effort should be made to determine a complete set of requirements that include the operating life.

4.2 Environmental Conditions

4.2.1 Temperature

The effect of temperatures, both steady state and transient, relevant to the performance of the product should be considered in the service condition requirements. When the occurrence of different temperatures during operation is predicted for different zones of the equipment, the design of the different zones can be based upon their predicted temperatures. In equipment exposed to repeated fluctuations of temperature in normal operation, the design should be based on the material properties at the appropriate temperatures.

4.2.2 Exposed Fluid

The evaluation of the equipment should consider exposure of fluids, liquids, and gases, which contact the equipment surfaces. As an example, these fluids may be seawater, drilling fluids, both oil-based and water-based, completion brines, well stimulation fluids, or produced fluids. The pH, acidity, or alkalinity of the fluid should also be considered.

4.2.3 Corrosion/Erosion Allowance Requirements

If corrosion or corrosion/erosion allowances are included in the design, the design verification and validation should consider those allowances.

4.2.4 Operational Environment

The user should specify how the equipment is going to be used, how the well is going to be operated, and how these actions affect the equipment.

4.3 Specified Loads and Characteristics

4.3.1 General

The following sections define the service conditions and loading requirements to be considered in the design verification analysis. The design documentation should also define when the extreme conditions occur and if they can or cannot occur simultaneously.

4.3.2 Pressure

The pressure requirements are the required maximum and the minimum rated working pressures, both internal and external. Differential pressure effects should be evaluated when appropriate in the design basis and when allowed. The rating for internal pressure capacity should not be increased due to external hydrostatic pressure unless specifically included in the analysis and documented.

4.3.3 Thermal Loads

Temperature effects on equipment performance, both steady state and transient, should be considered in load calculations. In equipment exposed to repeated fluctuations of temperature in normal operation, the design calculations should consider the following:

a) the highest temperature (e.g. yield strength degradation) for structural analysis,

b) the lowest temperature (e.g. impact strength) for failure due to brittle fracture,

c) the maximum temperature differential (e.g. thermal stresses) during both steady state and transient operation.

The possibility of stress or strain changes as a result of temperature changes should be considered in load calculations. Pressure changes due to heating or cooling of confined fluids should also be considered.

4.3.4 External Loads

External loading relevant to the performance of the product should be considered in the service condition requirements. This will include tension, torsion, compression, and bending loads. The external loads may also include the hydrostatic sea head pressure for subsea equipment. The source of external loading and cycle requirements should be considered (calculations, experimental methods, computer analysis, etc.) and documented.

EXAMPLE For a typical subsea wellhead, Christmas tree, and BOP stack, the loading should include external loading as well as the internal loading. The external loading should consider, as a minimum, installation loads, the hydrostatic sea head pressure at installation depth, the effective riser tension load on the equipment, and the bending moment generated from the riser offset angle, the rotational stiffness of the flex joint at the riser angle of pull, and the stresses generated from thermal gradients. The internal loading should consider the internal pressure, the end loads resulting from internal pressure, and the loads generated from thermal gradients.

4.3.5 Thermal Gradients

Thermal stresses are due to service temperature conditions that produce thermal gradients or due to differential thermal expansion from temperature changes in the absence of a thermal gradient. Thermal gradients are strain-controlled loads and should be evaluated for thermal stresses and functional effects on components. A thermal analysis should be conducted to determine the temperature distribution throughout the equipment such that thermal stresses and thermal distortion can be evaluated.

4.3.6 Temporary Conditions

Temporary loading conditions that contribute to the loading history on the equipment should be considered. Of special importance are temporary loading conditions that may stress the equipment at levels higher than operating conditions. Temporary loading conditions may include but are not limited to assembly loading, factory acceptance testing (FAT), and installation loading.

4.3.7 Internal Loads

Pressure imposed on the equipment should be considered for the service conditions. This includes pressure imposed upon the equipment after a complete surface nondestructive examination (NDE) inspection. The pressure associated with factory hydrostatic pressure testing, wellbore pressure testing, and system testing should also be considered. The source of loading should be considered (calculations, experimental methods, computer analysis, etc.) and documented.

4.3.8 Cyclic Loading

4.3.8.1 Pressure

Pressure cycles relevant to the performance of the product to be imposed on the equipment should be considered in the service condition requirements. The pressure cycles associated with factory hydrostatic pressure testing, wellbore pressure testing, and system testing should also be considered in the service cycle life. The source of loading and cycle requirements should be considered (calculations, experimental methods, computer analysis, etc.) and documented.

4.3.8.2 External Loads

External loading cycles relevant to the performance of the product should be considered in the service condition requirements. This will include tension, compression, and bending loads, such as riser loading. The source of external loading and cycle requirements should be considered (calculations, experimental methods, computer analysis, etc.) and documented.

4.3.8.3 Thermal Cycles

Thermal stresses that are associated with distortion of the equipment should be considered. Progressive distortion may result from thermal cycling due to thermal stresses and/or load redistribution, i.e. thermal cycles may reduce preload or result in gasket leakage. Successive thermal cycling may result in incremental distortion and an assessment should be made of thermal stresses to prevent thermal ratcheting. Fatigue life may be affected by thermal stresses and fatigue analysis should consider loading conditions including thermal cycling.

4.3.9 Combined Loading

Combinations of loads which occur simultaneously and which are relevant to the performance of the product should be evaluated. This may include internal pressure, external pressure, external loads, thermal loads, etc.

4.3.10 System Analysis and Integration

4.3.10.1 General

System integration brings together the component subsystems into one system and ensures that the subsystems function together as a system. Attention should be paid not only to the loads generated from other components in the system but also the defined conditions and load combinations.

For this document, systems approach will be defined as the loads or combination of loads along the length of the well. Generally, these loads are the result of pressure, tension, bending, and compression loads (both dynamic and static) on the components that will be transferred from component to component as these components are connected in the well configuration. These loads generally are transferred to the earth at the shoe through a cemented shoe joint, along the cemented casing and at the wellhead.

In identifying the functional specifications, the overall system from the reservoir to the wellhead to the surface system that is pressure-containing should be considered. Below the wellhead, there are three subsystems that should be considered (see Figure 1):

— the wellhead/BOP and the loads on the surface,

— the casing and tubing with completion and/or drilling equipment,

— the reservoir below any pressure-containing seal.

This document is intended for pressure-containing components. The design methodology may also be applied to pressure-controlling components.

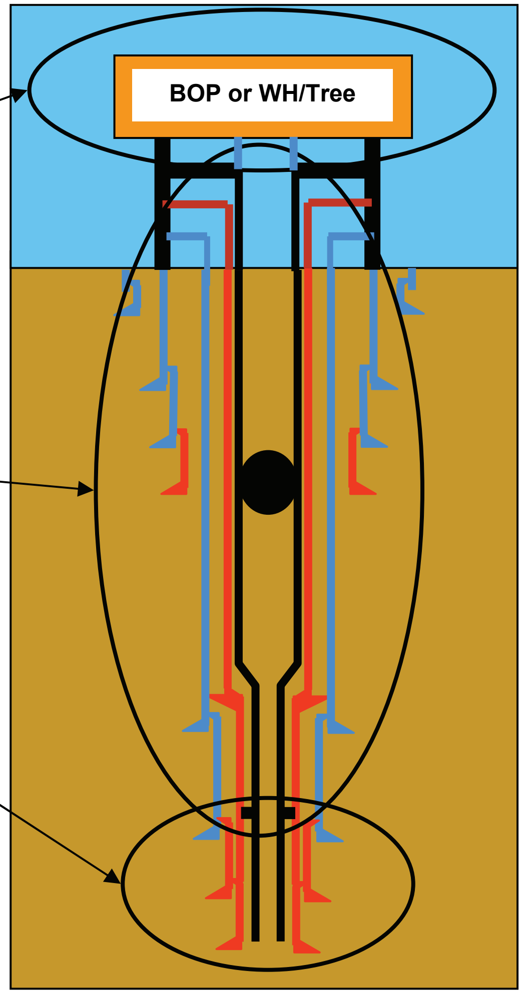


Figure 1—System Analysis Specification Breaks (Completion)

Generally, there are three subsystems above the wellhead (see Figure 2):

— the surface choke and kill system (all pressure-containing components),

— the riser or pressure-containing equipment,

— the tree/BOP and the loads directly above the wellhead.

4.3.10.2 Responsibilities

It is the user's responsibility to provide the functional specifications. The user should perform a system design analysis of the well system over the life cycle of the well, including defined conditions and load combinations. This analysis should include interface loading between well equipment and/or sections of the well, e.g. completion equipment, wellhead casing and tubing, and equipment above the wellhead. The equipment used in the system shall be verified and validated as fit-for-service and suitable for the load and environmental conditions using industry accepted techniques.

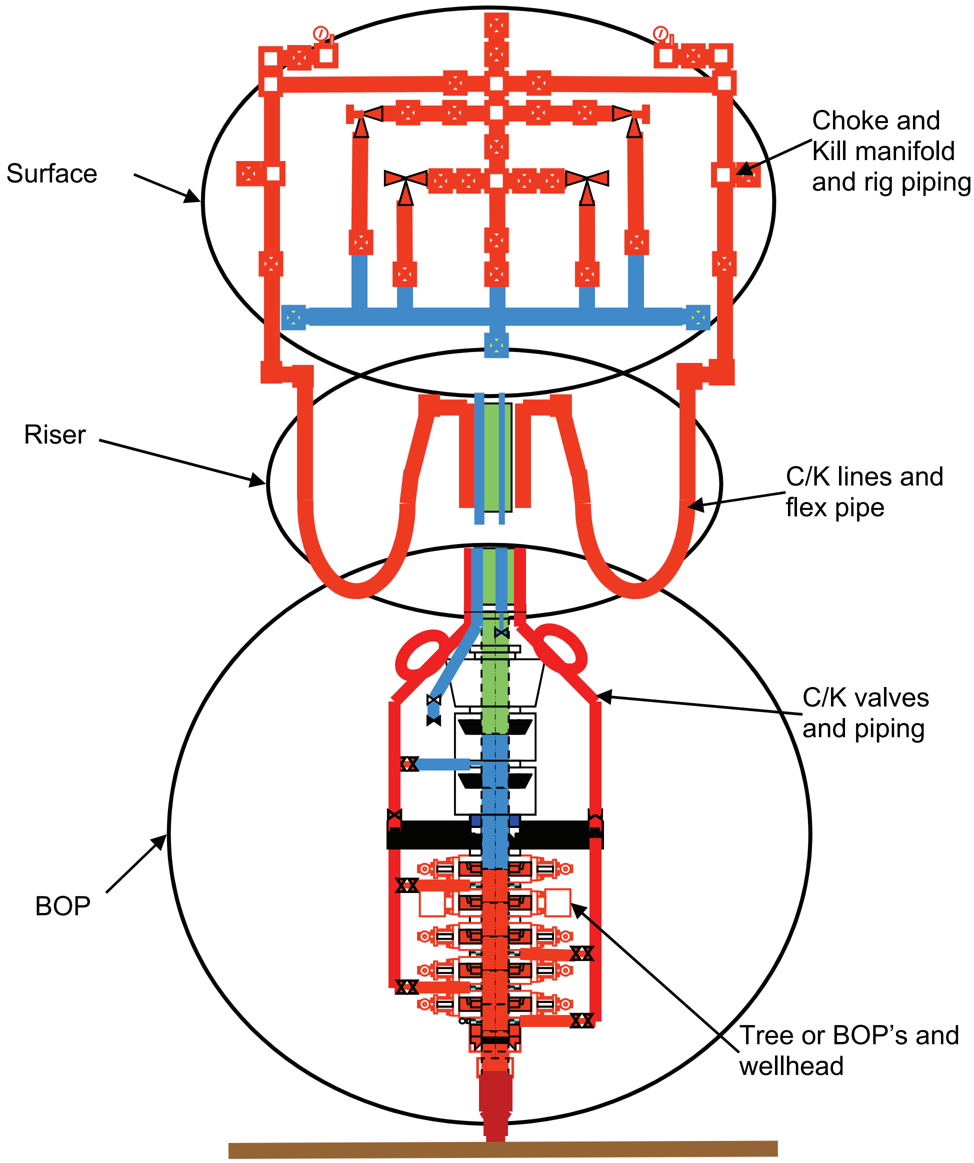


Figure 2—System Analysis Specification Breaks (Drilling)

A set of comprehensive functional specifications from the user facilitates design analysis and verification for the equipment to be supplied. This may require an iterative process whereby existing equipment capabilities are compared to functional and performance requirements. Considerations may include but are not limited to the following:

a) interfaces and/or geometry changes that may result in an irregular distribution of loads and stresses;

b) avoidance of damage or wall losses, which may result in a progressive failure;

c) the loads for the component/subcomponent during its life cycle;

d) interface reconciliation of load transfers;

e) loadings during the installation, running and handling, and operations of the equipment;

f) integrity management is based on a risk assessment of the system (redundancy and reliability);

g) system integrity considers the operational plan such as pressure testing the casing or wellhead after installation;

h) requirements and designs are checked by a review process;

i) objective evidence is presented when defining the loads on the system;

j) deterministic or reliability-based characterization of product performance may be utilized.

4.3.10.3 Load Types and Considerations

Systems load integration should be divided into subsystem sections and the load types considered. Different loading conditions will also have different design margins. Risk-based integrity assessment/inspection may be necessary to determine remaining life after extreme or survival design load conditions are exceeded. Additional inspection may be required at periodic intervals.

NOTE Consider that some load cases will not occur simultaneously. See ISO 13624-1 and API 2RD for system load considerations and load type examples.

Load transfer between components should be detailed. A tabular representation of the loading conditions should be used to communicate where possible (see example in API 5C5). Alternately, a combined loading operating envelope may be used to illustrate combined loading conditions [see example in Figure 3 from API 11D1] or a combined loading capacity chart may be used (see example in Figure 4 from API 6AF1).

For new equipment designs, the user should provide the functional specifications and the manufacturer should design the equipment to conform to those specifications.

For existing equipment designs, the manufacturer should state the capacity of the equipment and the user should verify that it satisfies the system loads and functional specifications.

4.4 Life Cycle Loading

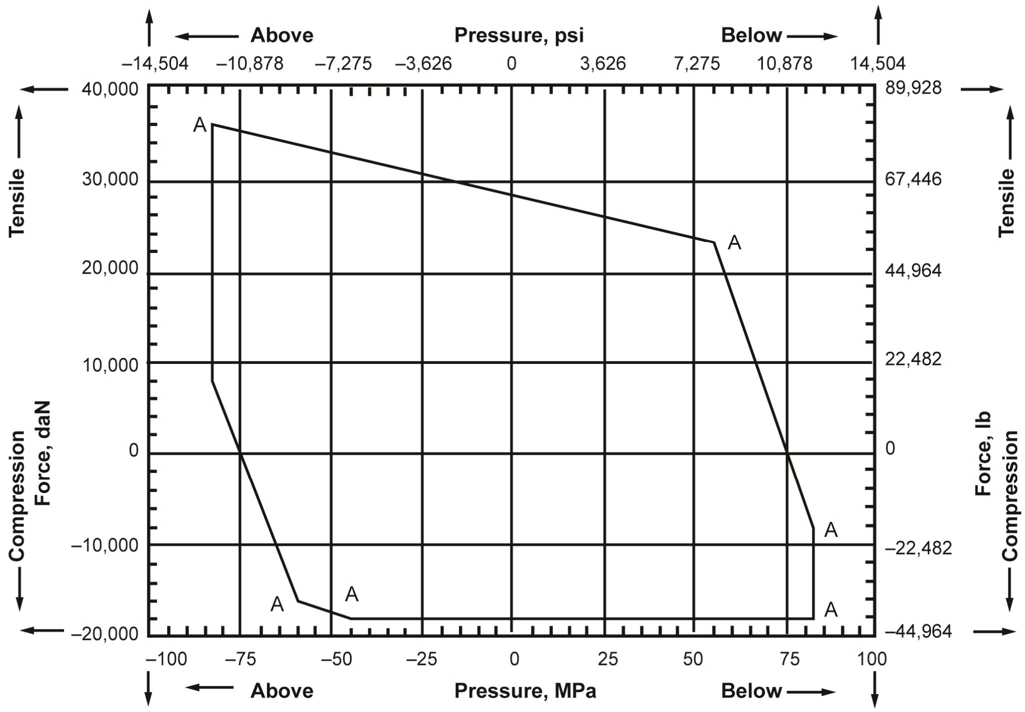
The user and the manufacturer should collectively define the service load cycle and data retention requirements prior to procurement of the equipment. Loading relevant to the performance of the product should be considered, including pressure stresses, thermal stresses, discontinuity stresses, residual stresses, and combined loading.

4.5 Applicable Industry Standards and/or Regulatory Requirements

4.5.1 Standards for equipment designed for higher pressures and higher temperatures have been in the industry for years. These include API and ASME publications and date back to such documents as AWHEM Std 6 (June 1957), *AWHEM Specification for Ring Joint Flanges for Drilling and Production Service for 15,000 psi Working Pressure*. See the Bibliography for a list of other standards.

4.5.2 Federal regulatory authorities include the Bureau of Safety, and Environmental Enforcement (BSEE) and the Bureau of Land Management (BLM). The BLM is responsible for federal lands while the BSEE regulates offshore drilling, completions and production. Other international regulatory agencies such as the Norwegian Petroleum Directorate or HSE (UK) may have requirements for HPHT equipment.

4.5.3 State regulatory authorities regulate through the state oil and gas commissions of their respective states. These agencies regulate the oil and gas industry in each of their respective jurisdictions. HPHT wells will require operators to meet their rules.



NOTE 1 Points labeled “A” are intersection points of two or more failure modes.

NOTE 2 From API 11D1.

Figure 3—Performance Envelope Example

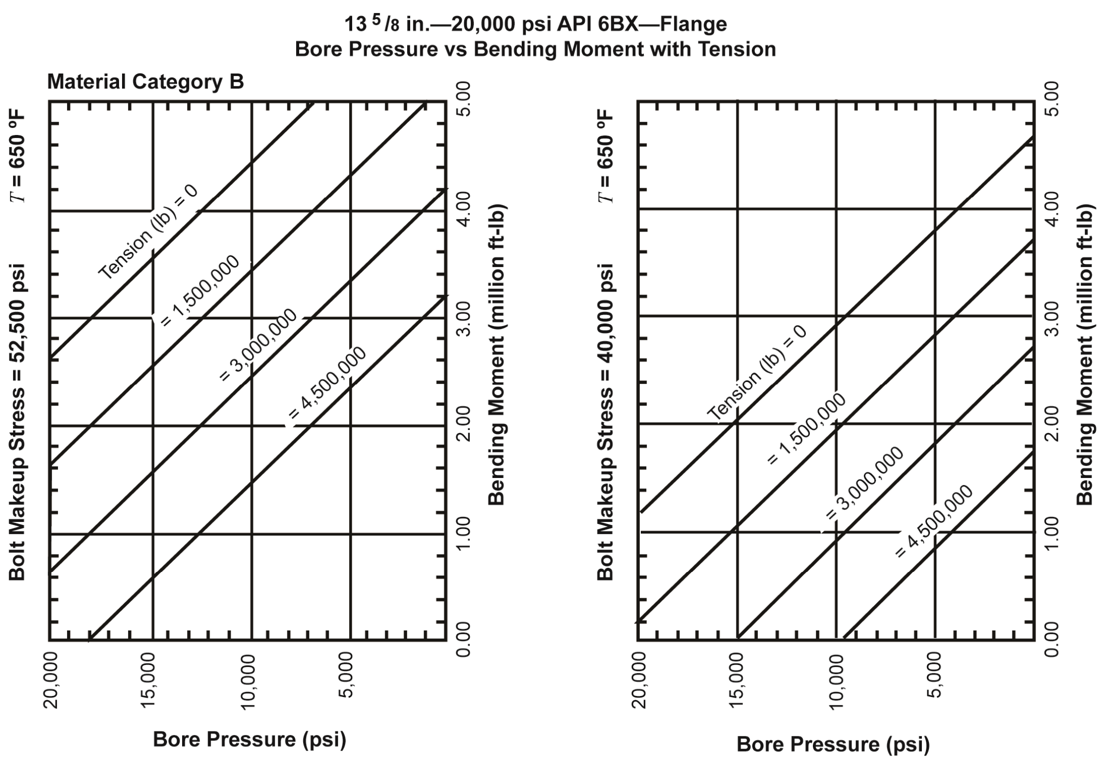


Figure 4—Combined Loading Capacity Chart from API 6AF1

4.5.4 Generally, all of these regulatory agencies provide rules for operations (drilling, completions and production). However, these rules do not dismiss the responsibility of the operator to operate in a prudent and safe manner and the manufacturer to provide fit-for-service equipment.

4.5.5 As a reference, the following organizations and committees that participate in the development of standards for the petroleum and natural gas industry are listed below. This is not intended to be a comprehensive list and does not imply compliance to standards developed by these organizations is mandatory.

a) API (American Petroleum Institute)—API is the only national trade association that represents all aspects of America's oil and natural gas industry. API standards are used throughout the oil and gas industry (www.api.org).

b) ASME International (formerly the American Society of Mechanical Engineers)—ASME is a nonprofit professional society that enables collaboration, knowledge sharing, and skill development across engineering disciplines, while promoting the vital role of the engineer in society. ASME codes and standards, publications, conferences, continuing education, and professional development programs provide a foundation for advancing technical knowledge and a safer world (www.asme.org).

c) ASTM International (formerly the American Society for Testing and Materials)—ASTM International is one of the largest voluntary standards development organizations in the world-a trusted source for technical standards for materials, products, systems, and services. Known for their high technical quality and market relevancy, ASTM International standards have an important role in the information infrastructure that guides design, manufacturing, and trade in the global economy (www.astm.org).

d) American National Standards Institute (ANSI)—ANSI empowers its members and constituents to strengthen the U.S. marketplace position in the global economy while helping to assure the safety and health of consumers and the protection of the environment. The Institute oversees the creation, promulgation, and use of thousands of norms and guidelines that directly impact businesses in nearly every sector including the energy sector. ANSI is also actively engaged in accrediting programs that assess conformance to standards—including globally-recognized cross-sector programs such as the ISO 9000 (quality) and ISO 14000 (environmental) management systems (www.ansi.org).

e) NACE International (formerly the National Association of Corrosion Engineers)—NACE provide standards for corrosion and hostile environments for material. These standards are used worldwide by the oil and gas industry (www.nace.org).

f) British Standards Institution (BSI)—Since its foundation in 1901 as the Engineering Standards Committee, BSI Group has grown into a leading global independent business services organization providing standard-based solutions in more than 120 countries (www.bsigroup.com).

g) Canadian Standards Association (CSA)—As a solutions-oriented organization, CSA works in Canada and around the world to develop standards that address real needs, such as enhancing public health and safety, advancing the quality of life, helping to preserve the environment and facilitating trade (www.csa.ca).

h) Deutsches Institut für Normung; in English, the German Institute for Standardization (DIN)—DIN is the German national organization for standardization and is that country's ISO member body (www.din.de).

i) International Organization for Standardization (ISO)—ISO is the world's largest developer and publisher of international standards (www.iso.org).

j) The Standards Council of Canada (SCC)—SCC facilitates the development and use of national and international standards and accreditation services to enhance Canada's competitiveness and social well-being (www.scc.ca).

k) Aerospace Industries Association/National Aerospace Standards (AIA/NAS)—The AIA standards provide engineers, designers, and others working for manufacturers and suppliers of aerospace and national defense systems with information designed to assure product quality and safety (www.aia-aerospace.org/standards).

l) (U.S. Department of Defense Standards (MIL-STDS)—These documents establish uniform engineering and technical requirements for military-unique or substantially modified commercial processes, procedures, practices, and methods. There are five types of defense standards: interface standards, design criteria standards, manufacturing process standards, standard practices, and test method standards. MIL-STD-962 covers the content and format for defense standards (http://dodssp.daps.dla.mil).

5 Technical Specifications

5.1 General

The technical specifications should show conformance to the functional specifications of Section 4, should include the design verification analysis, the validation program requirements, the performance capabilities, and should demonstrate the equipment is fit-for-service. The technical specification for the equipment should be documented and should be based on the experience, analyses, and/or capabilities of existing equipment, which form the basis for a fit-for-service assessment.

5.2 Responsibilities

The functional specification for the system provided by the user should be reviewed by the manufacturer to ensure required information has been provided (see 4.3.10.2).

The manufacturer is responsible for the design, development, design verification, design validation, and manufacture of the equipment. It is the responsibility of the manufacturer to document and have available for review the technical specification for the equipment provided. The user should review and accept the technical specification.

NOTE See ISO 13880 for guidance on preparing a technical specification.

5.3 Personnel Requirements

Design documentation should be reviewed and verified by a qualified individual ("the reviewer") other than the individual who created the design. The qualifications of the manufacturer's reviewer should be documented in accordance with 5.4.

NOTE Review by the user is addressed in 4.1.

5.4 Documentation

Technical design should be performed in conformance with API Q1, and documentation should include

— technical specifications and functional specifications, as defined in 5.5;

— design verification, as defined in 5.5.6;

— design validation results, as defined in 5.5.7; and

— design outputs.

The qualification, training, and experience of those responsible for design and development as well as qualification, training, and experience of the reviewer shall be documented and accessible to the user.

5.5 Response to Functional Specifications

5.5.1 Environmental Conditions

The manufacturer should assess the defined environmental conditions and history for the equipment that are anticipated to affect the serviceability and fitness-for-service of the equipment. This should consider relevant failure mechanisms due to the loading conditions and materials used in the design. The environmental conditions that are considered should be both external and internal to the pressure-containing boundary (i.e. hurricanes, seawater, production fluids, etc.).

5.5.2 Specified Loads and Characteristics

5.5.2.1 General

The manufacturer should have documentation of assumed design loads and characteristics supplied by the user in accordance with 4.3. For user-specific equipment, the loads provided by the user based on which the equipment was designed should be stated. In cases when an existing design is used, the manufacturer should demonstrate that equipment rated capacities determined by industry acceptable methods satisfy the loading requirements.

5.5.2.2 Thermal Gradients

Thermal analysis is dependent on having mechanical and physical material properties within the defined design or operating temperature ranges. Determining the thermal gradient requires a steady state and/or transient heat transfer analysis for thick wall equipment. Conduction, radiation, and convection should be included in the analysis as applicable.

Trapped fluids or gasses may contribute to the steady state temperature distribution and possible pressure increases. Given trapped fluids, it should be decided to what extent the calculation will account for the behavior of the fluids. The simplest approach is to account for the fluid as a change in conductivity from the surrounding metal parts. The more detailed approach captures the natural convection and its contribution to the heat transfer. Bolted connections require special attention because the bolts may experience a different temperature distribution than the connection. Additional requirements for thermal gradients should be considered for residual stresses in weldments when conducting fit-for-service assessments.

Thermal analysis should consider effects of stress relaxation and the resulting effects on structural and functional capacity of the equipment. The stress relaxation properties of the materials over the design life of the equipment at the design temperatures should be defined when performing this analysis.

5.5.3 Life Cycle Loading

The manufacturer should demonstrate through a technical specification accepted by the user that the product meets the life cycle requirements specified in 4.4. The life cycle evaluation, analysis, and/or testing should consider combined loads (see 4.3.10.3) and sequence of foreseen loads throughout the life of the product to demonstrate fit-for-service with appropriate design margins. Design margins applicable to various loading conditions may be different.

5.5.4 System Analysis

Component design should consider the effect of system loads as they propagate through the system as well as loads generated by other components. The design should consider how loads are transferred through interfaces throughout the life of the well.

5.5.5 Applicable Industry Standards and/or Regulatory Requirements

The manufacturer should demonstrate that the product meets the applicable industry and/or regulatory requirements referenced in 4.5.

5.5.6 Design Verification

Each new product model should go through a design verification analysis to confirm that the design meets the requirements specified in the technical specification. If the environment and/or application changes for a product model, the design verification process should be repeated to verify conformance to the new requirements. The design verification analysis should be reviewed and verified by a qualified individual(s) other than the individual(s) who did the original analysis. See 6.2 for additional guidelines on design verification.

Where verification and/or validation and sufficient industry experience exists, design verification and validation documentation may be completed and approved by a qualified person to meet the functional and technical specifications and acceptance criteria. This should include a detailed field history of successful performance of the same size, type and model in an environment similar to that of the functional specifications.

5.5.7 Design Validation

Each new product model should go through a design validation test program to confirm that the design meets the requirements specified in the technical specification. If the environment and/or application changes for a product model, the design validation testing should be reviewed, repeated, or supplemented to verify conformance to the new requirements.

5.5.8 Manufacturing Process Specification (MPS)

The manufacturer should prepare a written MPS as well as a written inspection and testing plan (ITP). The MPS should describe in detail the individual steps or actions required to manufacture or fabricate each piece of equipment that is produced under this specification. Likewise, the ITP should describe each inspection or test that will be performed on the equipment “in process” and for final acceptance. The ITP should show the acceptable ranges for dimensions, materials properties, and other equipment characteristics that are required at each stage of the manufacturing process. It should also indicate hold points in the manufacturing and inspection/testing plans and whether each inspection or test is to be reviewed, monitored, or witnessed by authorized representatives of the manufacturer, the user, or third party.

The MPS and ITP should be submitted to the user for review and modified as necessary, prior to the commencement of manufacturing or fabrication.

The user should conduct a timely review of the MPS and ITP and should signify acceptance of the MPS and ITP in writing.

The MPS and ITP should not be changed following acceptance, except by written agreement between the manufacturer and the user.

5.5.9 Quality Assurance

A quality management system should be applied to assist in compliance with the requirements of this document. Certification by an external body of the quality management system to an established industry standard is recommended. The manufacturer is responsible for complying with the applicable requirements of this document. The user should be allowed to make any investigation necessary in order to assure compliance by the manufacturer and to reject any material, documentation, or process that does not comply with these requirements.

NOTE API Q1 provides sector-specific guidance on quality management systems.

5.6 Fit-for-service Basis

The foregoing functional and technical specifications define fit-for-service requirements. The user and manufacturer should agree upon and document the basis for accepting the equipment design. Acceptance may be based on the following:

a) proven exploration and production experience or technology,

b) proven alternative industry experience or technology,

c) verification and validation requirements (including any advanced design development techniques),

d) a combination of the previous elements.

5.7 Aftermarket Activities

5.7.1 General

After a product has been sold or transferred to the user, some activities by the manufacturer may still be required to keep the product operational. These may include initial installation, service during use, inspection during, between, or after use, and repair and maintenance of the product to prepare it for its next usage. Guidance about these activities is given in the following sections.

5.7.2 Installation

Installation of the product should follow the original equipment manufacturer's documented procedures and work methods and/or the applicable API standard for the product. This should be done and supervised by personnel who have been trained and deemed competent to carry out the work. Local safety precautions, permits, and regulations pertaining to the installation should be followed.

5.7.3 Service and Inspection During Use

Periodic inspection and maintenance of HPHT equipment may be necessary. Each product (as applicable) should be inspected and/or tested at specified regular intervals as established by the recommendations of the product manufacturer, field experience, user’s policy, and governmental regulations according to a documented integrity management program (IMP). Any product service needed during use should follow the original equipment manufacturer’s documented procedures and work methods by qualified personnel. Records of such repairs including any component replacement should be documented.

The IMP requires individual users to develop programs to systematically identify and address risks to the segments of their HPHT equipment that could affect “high consequence areas” where a leak or rupture would have the greatest impact, including highly populated or environmentally sensitive areas (see 49 *CFR* 192).

An IMP should consist of the following:

a) demonstrated knowledge and understanding of the equipment and its function,

b) identification of the threats to the equipment (these should be included as modes of failure if appropriate),

c) an evaluation and ranking of the risk,

d) identification of measures to mitigate these risks,

e) measurements of the performance of these mitigation measures,

f) creation of a continuous improvement methodology to periodically update the IMP,

g) records and records retention of relevant product data and life cycle history.

5.7.4 Repair and Remanufacture

Repair and remanufacture of HPHT equipment should follow the applicable requirements of the product specification to which the product was manufactured. Modifications to the product that affect the integrity of the product should be evaluated in accordance with the equipment technical specification, verification analysis, and validation testing previously conducted. This should be completed by qualified personnel with complete documentation of the work performed. Field repairs of HPHT equipment should be performed according to design documentation.

5.7.5 Life Extension

The original service life of a product may be extended. Consideration should be given to crack growth and crack growth rate, actual loading conditions vs design load capabilities, erosion/corrosion of wall thickness, and long-term environmental effects on the materials.

6 Best Practices and Guidance

6.1 Materials

6.1.1 General

6.1.1.1 Materials selection and the associated fabrication and service conditions are an important part of the design of reliable drilling and production equipment that are fit-for-service. This section is intended to highlight the material and mechanical properties that design engineers should consider in designs of greater than 15,000 psi pressure or greater than 350 °F temperature; ensuring a fit-for-service design is achieved. The design includes resistance to loading, response/performance and corrosion behavior of engineered materials.

6.1.1.2 This section steps through properties required by the design codes and practices that address the chosen design methods. Also, a high-level overview is provided of materials and mechanical properties, the effects of the environment on these properties, and current industry standards for materials testing.

6.1.1.3 Of importance is a listing of property data available in the literature. A summary of the status of a literature survey is provided in the following.

a) API 6A and an American Well Head Equipment Manufacturers (AWHEM) study provides data on derating of yield strength for low-alloy steel, stainless steel, and corrosion resistant alloy (CRA) materials as a function of temperature.

b) Various manufacturers of CRA, particularly the highly alloyed austenitic stainless steels, nickel-based cold-worked alloys, and precipitation-hardened nickel-based alloys have generated proprietary temperature derating data specific to their alloys and manufacturing processes. Some of these data are published and included in this document.

c) For CRA, data are available to determine the effect of the environment on properties through mechanisms such as stress corrosion cracking but not necessarily under cyclic conditions. These data are not included in this report but are available through various publications.

d) ASME *BPVC, Section VIII*, *Division 2* and *Division 3* contain some stress cyclic fatigue data that takes into account the effect of temperature,

e) ASME *BPVC, Section II*, Part D gives derating of material properties with temperature.

f) API 579-1/ASME FFS-1 contains some fracture mechanics data that take into account the effect of temperature.

6.1.2 Organization of Materials

6.1.2.1 Materials for completions may be both metallic alloys and nonmetallics intended for seals, which are discussed in 6.1.7. All other sections are devoted to metal alloys.

6.1.2.2 References for industry standards available for the testing of metallic alloys are in 6.1.6. These test methods would be the basis for deriving data listed in Table 2.

HPHT design standards are listed in Table 2 with their cited mechanical properties for high-pressure and high-temperature applications. Some of the typical alloys that have been used in HPHT equipment are listed in Table 3 and Table 4 and indicate what alloys (not an exclusive list) can be used to manufacture various types of equipment. The alloys are classified as:

— carbon steel and low-alloy steels (see Table 3),

— stainless and CRAs (Table 4).

In Table 3 and Table 4, squares filled in with an "X" indicate the alloy typically used for the component.

Examples of the effect of temperature on material properties are found in Annex A.

The data for various alloy families is found in Annex A and is arranged according to alloy families in Table 3 and Table 4. Information on various alloy families is provided at the beginning of each section of an alloy family.

6.1.2.3 Information on nonmetallics is in 6.1.7.

6.1.2.4 Published equipment failures that provide lessons learned for future projects are in Annex B.

6.1.3 Typical Material Applications

Table 5 lists materials that are typically used in surface and subsurface applications. Bolting materials are not addressed but should be included in the analysis of the design.

6.1.4 General Background on Material Property Limitations Due to Temperature

6.1.4.1 General

Temperature effects require additional considerations for static, fatigue, and fracture toughness properties. In addition, it may introduce concerns for time-dependent creep properties.

6.1.4.2 Low Temperature

Temperatures below room temperature generally cause an increase in strength properties of metallic alloys. Ductility, fracture toughness, and elongation usually decrease.

Table 2—Material Properties Cited by Design Standards

Reference Standard	Yield Strength	Ultimate Strength	Modulus	K_{IC} in Air	J_{IC} in Air	K_{IEAC}	Fatigue Crack Growth Rate in Air	Fatigue Crack Growth Rate	True Stress Strain Curve	Impact (Charpy)		Thermal Conductivity	Coeff of Thermal Expansion
										QA	For Material Properties		
API 6A	X	X	X							X			
API 17D	X	X	X								X		
API 16A	X	X	X										
API 16C	X	X	X				X	X					
ASME *BPVC*, *Sec VIII*, *Div 2*	X	X	X					X	X		X	X	X
ASME *BPVC*, *Sec VIII*, *Div* 3	X	X	X	X	X	X	X	X	X		X	X	X
BS7608							X	X					
API 579/ASME FFS-1	X	X	X	X	X	X	X	X	X		X	X	X
BS7910	X	X	X	X		X	X	X	X		X		
API 2RD	X	X	X	X	X					X			
API 1111	X	X	X	X	X				X	X			
ISO 12108				X									
API 5C3/ISO TR10400	X	X	X	X		X [a]				X			
RMA Handbook, molded, extruded, and plate cut products: ASTM D2000, SAE J200, ASTM D1056, SAE J18		X	X									X	X

a See API 5C3 for discussion on the use of K_{IMAT}.

Table 3—Typical Carbon and Low-alloy Steels for HPHT Use
(T > 350 °F or P > 15,000 psi)

Alloys Families	Alloy Designations	Equipment of Components										
		Wellheads	Tubing Heads	Tubulars	Threaded Connectors [a]	Packers [b]	Seals [c]	Seal Assemblies	Production Trees	Chokes	Well Control Equipment	SCSSVs
Carbon steel	A707	X	X						X			
Low-alloy steel	C90 [d]			X	X	X		X				X
	C95 [d]			X	X	X		X				X
	T95 [d]			X	X	X		X				X
	P110 [d]			X	X	X		X				X
	C-110 [d]			X	X	X		X				X
	Q125 [d]			X	X	X		X				X
	8630 modified	X	X	X	X	X		X	X	X	X	X
	4130/4140/4145 mod	X	X	X	X	X		X	X	X	X	X
	F22	X	X	X	X	X		X	X	X	X	X

[a] Includes crossovers, pup joints, nipples, etc.

[b] Includes PBRs.

[c] Seals are typically nonmetallic items.

[d] From API 5CT/ISO 11960, Tables C.5 and E.5.

Table 4—Stainless Steel and Corrosion Resistant Alloys for HPHT Use (T > 350 °F or P > 15,000 psi)

Alloys Families	UNS Number	Common Alloy Designation	Equipment of Components										
			Wellheads	Tubing Heads [a]	Tubulars	Threaded Connectors [b]	Packers [c]	Seals [d]	Seal Assemblies	Production Trees	Chokes	Well Control Equipment	SCSSVs
Martensitic	S41425				X	X	X		X				X
	S41427				X	X	X		X				X
	S41426	13CrS/HP2			X	X	X		X				X
	S41000	410	X	X			X		X	X	X		X
	S41500	F6NM	X	X			X		X	X	X		X
Duplex SS	S31803	22Cr		X	X	X	X		X	X	X		X
	S31260	25Cr		X	X	X	X		X	X	X		X
Super duplex	S32760 S39274 S39277	25CrW		X	X	X	X		X	X	X		X
	S32750	26-6-3			X	X	X		X				X
Austenitic Fe-based	S31600	316		X	X	X	X		X	X	X		X
	N08028	28Cr			X	X	X		X				X
	N08535	25Cr			X	X	X		X				X
	N08135	2035			X	X	X		X				X
	N08020	20Cb3®			X	X	X		X				X
Austenitic Ni-based	N08825	Alloy 825			X	X	X		X				X
	N04400	Alloy 400						X					X
	N06007	Hastelloy® G			X	X	X		X				X
	N06985	G-3			X	X	X		X				X
	N06950	INCONEL® Alloy 050			X	X	X		X				X
	N06255 N06975	G-2			X	X	X		X				X
	N10276	Hastelloy® C-276			X	X	X		X				X

Table 4—Stainless Steel and Corrosion Resistant Alloys for HPHT Use (T > 350 °F or P > 15,000 psi) (Continued)

Alloys Families	UNS Number	Common Alloy Designation	Equipment of Components										
			Wellheads	Tubing Heads [a]	Tubulars	Threaded Connectors [b]	Packers [c]	Seals [d]	Seal Assemblies	Production Trees	Chokes	Well Control Equipment	SCSSVs
Precipitation hardening Ni-based	N07718	Alloy 718		X			X		X	X	X		X
	N07716	Custom Age 625PLUS®		X			X		X	X	X		X
	N09925	INCOLOY® Alloy 925™		X			X		X	X	X		X
	N07725	INCONEL® Alloy 725™		X			X		X	X	X		X
	N09935	Alloy 935		X			X		X	X	X		X
	N09945	Alloy 945		X			X		X	X			X
	N09945	Alloy 945X		X			X		X	X			X
Ti-based	R56400	Ti-6-4			X	X							X
	R53400	Ti 12						X					
	R56260	Ti 6246	X		X	X	X	X	X				X
Co-based	R30035	MP35N®											X

NOTE 1 The use of registered trademark names does not constitute an endorsement of these products by API.

NOTE 2 These alloys are listed for information purposes only; API does not require the use of proprietary or patented products.

a Includes tubing hanger.

b Includes crossovers, pup-joints, nipples, etc.

c Includes PBRs.

d Seals are typically nonmetallic items.

Table 5—List of Typical Materials

Minimum Yield ksi	Wellhead and Above Use	Down-hole Use
75/80/85	F22	9Cr-1Mo
	13 Cr	410
	F6NM	13Cr
	8630M	4130/4140/4145 mod
	4130/4140	
90	F22	410
	4130/4140	4130/4140
	F6NM	
	8630M	
110	UNS N09925	UNS N09925
	UNS N07718	S17400
	UNS N09935	UNS N09935
		4130mod/4140
120/125	UNS N09945	UNS N09945
	UNS N07718	UNS N07718
	UNS N07725	UNS N07725
	UNS N07716	UNS N07716
		4130mod/4140
140	UNS N07718	UNS N07718
	UNS N07716	UNS N09945
	UNS N09945	UNS N07716

6.1.4.3 Temperature Effects

Strength properties of metallic alloys usually decrease with increasing temperature. This strength decrease is dependent on many factors, such as temperature and the time of exposure, which may degrade the heat treatment condition or cause a metallurgical change. Because of the variable effect of elevated temperature on strength, ductility, and fracture toughness, it is emphasized that the elevated temperature properties in this report should be used for information only.

The effect of temperature on static mechanical properties is shown by a series of graphs or tables of property (as percentages of the room temperature property) vs temperature. Data used to construct these graphs were obtained from tests conducted over a limited range of strain rates. Caution should be exercised in using these static property curves at very high temperatures, particularly if the strain rate intended in design is much less than that stated with the graphs. The reason for this concern is that at very low strain rates or under sustained loads, plastic deformation or creep deformation may occur to the detriment of the intended structural use.

Between –65 °F and 160 °F, the stability of most structural metallic alloys is relatively independent of exposure time. Some API standards allow operation to 250 °F without derating. However, as temperature is increased, the degradation of material properties becomes increasingly time-dependent. The factor of exposure time should be considered in design when applicable.

6.1.4.4 Creep and Stress Rupture Properties

Creep is defined as a time-dependent deformation of a material while under an applied load. It is usually regarded as an elevated temperature phenomenon, although some materials creep at room temperature. If permitted to continue indefinitely, creep may terminate in rupture. Creep in service is usually typified by complex conditions of loading and temperature. Creep data for general design use are usually obtained under conditions of constant uniaxial loading and constant temperature in accordance with ASTM E139. Creep data are sometimes obtained under conditions of cyclic uniaxial loading and constant temperature or constant uniaxial loading and variable temperatures. At temperatures when creep appears likely to occur, it may be necessary to test under simulated service conditions. Creep damage is cumulative, similar to plastic strain resulting from multiple static loadings. This damage may involve effects on most alloys with the initiation and growth of cracks or subsurface voids within a material. Additional information can be found in ASME *BPVC, Section XI*.

6.1.4.5 Environmental Effects

Carbon and low-alloy steel equipment exposed to oil and gas production can corrode when wetted by water. The corrosion rate is a function of the environment and fluid flow. Variables influencing corrosion rate include water chemistry (in situ pH, chlorides, salts, and organic acids), temperature, production velocity, flow regimes and wall shear stresses. Both CO_2 and H_2S contribute to corrosion through separate mechanisms. Various models are available, coupled with field data, to predict when corrosion control is necessary for equipment to reach design life without failure.

In addition to controlling corrosion, materials should be selected to prevent failure due to environmental stress corrosion cracking in sour, H_2S-containing, production environments. The industry best practice for choosing materials (metal alloys only—not nonmetallics) in sour service is NACE MR0175/ISO15156 (all parts). The guidelines in this international standard provide environmental limits for alloys to prevent cracking. Metallurgical properties and manufacturing requirements are recommended for alloys within these environmental limits. Nonmetallics are not covered. The standard is not a warranty against cracking and cautions the user that alloys are not necessarily immune under all service."

Carbon and low-alloy steels are most likely to fail due to sulfide stress cracking (SSC), which NACE MR0175/ISO15156 defines as: "cracking of metal involving corrosion and tensile stress (residual and/or applied) in the presence of water and H_2S." Strength or hardness control may be necessary. Welding procedures should be qualified to NACE MR0175/ISO 15156. SSC sensitivity decreases with increasing temperature.

Stainless and CRAs are used for completion and production equipment when the corrosion rate for carbon and low-alloy steels is considered unacceptable for desired project life. Stainless and CRAs in the presence of H_2S are susceptible to stress corrosion cracking (SCC), which NACE MR0175/ISO15156 defines as 'cracking of metal involving anodic processes of localized corrosion and tensile stress (residual and/or applied) in the presence of water and H_2S." Chlorides and oxidants increase alloy sensitivity to cracking. Increasing temperature increases the susceptibility of alloys to cracking in the presence of water, although some alloys such as the martensitic stainless steels (12/13 % Cr) and the duplex stainless steels (22 % Cr/25% Cr) may also have low and intermediate temperature susceptibilities because of sensitivity to SSC.

Some alloys, such as the 300 series stainless steels, used for control line tubing and instrument tubing can stress corrosion crack at higher temperatures even when H_2S is not present.

NACE MR0175/ISO15156 prescribes laboratory testing procedures that can qualify alloys for general use in all environments or as fit-for-service testing for a project specific environment. The environmental variables that should be defined in the production environment are: the minimum in situ water pH, the maximum chloride concentration, the maximum partial pressure of H_2S in the gas phase, minimum and maximum temperatures, and the presence of solid elemental sulfur. It is critical to consider both the immediate short-term environment and changes that may occur longer term, such as increases in the partial pressure of H_2S due to reservoir souring from water injection.

Production test environments are detailed in NACE TM0177. The following are acceptable specimens and test procedures:

a) smooth tensile bars (ultrasonic testing [UT]), NACE TM0177, Method A;

b) C-rings (CR), NACE TM0177, Method C;

c) four-point bends (FPB), EFC Publication 17;

d) double-cantilever bend specimens (DCB), NACE TM0177, Method D.

The UT, CR, and FPB specimens are nominally stressed to a percentage of yield stress, depending upon the alloy and the environment, to determine a threshold stress for cracking. Tests are run for a minimum of 30 days with some companies specifying tests up to 6 months. The DCB is a fracture mechanics specimen that will determine a threshold stress intensity factor, K_{IEAC}, for crack arrest. Carbon and low-alloy steels are tested at ambient temperature, or lower for project specific environments, while stainless and CRAs are tested at both ambient and maximum temperatures. Galvanic coupling tests of stainless and CRAs to carbon steel can be required.

NACE MR0175/ISO15156 also recognizes two years of properly documented field experience as an alternative to lab testing.

6.1.5 Metals

6.1.5.1 General

One of the major factors contributing to the general utility of steels is the wide range of mechanical properties which can be achieved by several routes. One route is heat treatment. For example, softness and good ductility may be required during fabrication of a part and very high strength during its service life. Both sets of properties are obtainable in the same material. All steels can be softened to a greater or lesser degree by annealing, depending on the chemical composition of the specific steel. Annealing is achieved by heating the steel to an appropriate temperature, holding, and then cooling it at the proper rate.

Another route to achieving strength is cold working. It is the method used to strengthen low-carbon unalloyed steels, highly alloyed austenitic stainless steels, and nickel based alloys. Austenitic or Ni-based alloys can be cold worked to quite high strength levels, or tempers. These are commonly supplied to specified minimum strength levels. Steels can be hardened or strengthened by means of cold working, heat treating, or a combination of these.

Heat treating is the principal method for strengthening steel. The heat treatment of steel may be of three types: martensitic hardening, age hardening, and austempering. Carbon and alloy steels are martensitic-hardened by heating to a high temperature, or austenitizing, and cooling at a recommended rate, often by quenching in oil, water, or water-based polymers. This is followed by tempering, which consists of reheating to an intermediate temperature to relieve internal stresses and to improve toughness. The maximum hardness of carbon and alloy steels, quenched rapidly to avoid the nose of the continuous cooling transformation curve, is a function, in general, of the alloy content, particularly the carbon content.

Both the maximum thickness for complete hardening and the depth to which an alloy will harden under specific cooling conditions and the distribution of hardness can be used as a measure of a material's hardenability.

Some Ni-based alloys can be strengthened by age hardening. This heat treatment is designed to dissolve certain constituents in the alloy and then precipitate them in some preferred particle size and distribution. Since both the martensitic-hardening and the age-hardening treatments are relatively complex, specific details may be presented where applicable to an alloy.

Steel bars, billets, forgings, and thick plates, especially when heat treated to high-strength levels, exhibit variations in mechanical properties with location and direction. In particular, elongation, reduction of area, toughness, and notched strength are likely to be lower in either of the transverse directions than in the longitudinal direction. This lower ductility and/or toughness results from both the grain boundary variation caused by metal flow and from nonmetallic inclusions, which tend to be aligned with the direction of primary flow. Such anisotropy can be minimized by careful control of melting practices (including degassing and vacuum-arc remelting) and of hot-working practices. In applications where transverse properties are critical, requirements should be discussed with the steel supplier and properties in critical locations should be substantiated by appropriate testing.

6.1.5.2 Obtaining High Temperature Data

6.1.5.2.1 General

Testing requires attention to the section thickness, where the test specimens are taken, and whether the orientation conforms to that of the part in design. Also, the alloy composition is a variable. The exact blend of alloying elements can affect the hardenability of the alloy. These variables should be controlled by the manufacturer in conjunction with the designer. One way to get a general idea of what alloys will do at certain temperatures is to look at available data from similar products that have been tested to generate high temperature behavior. The following are four sources of data:

a) API 6MET [30];

b) MMPDS-01, *Metallic Materials Properties Development and Standardization* handbook [107];

c) BSEE Technology Assessment and Research Project No. 583 [126];

d) alloy manufacturer's data.

NOTE The above list is not inclusive. Other data may be available including testing of actual materials at elevated temperatures.

6.1.5.2.2 API 6MET Technical Report

API funded a project to examine mechanical properties of metallic materials used for API 6A and 17D wellhead equipment for service above 250 °F. A total of eleven different alloys meeting API 6A, PSL 3 conditions were supplied "in condition" by a variety of suppliers. Materials in this test program included alloys common to the oil and gas industry. The alloys tested included low-alloy steels, martensitic, precipitation hardened and duplex stainless steels, and nickel alloys. See Table A.2 and Table A.5 for a summary.

6.1.5.2.3 *Metallic Materials Properties Development and Standardization Handbook* (MMPDS-01)

The handbook is an accepted source for metallic material and fastener system allowables for the Federal Aviation Administration (FAA), all departments and agencies of the Department of Defense (DoD), and the National Aeronautics and Space Administration (NASA). It provides information that may not be found in other places. Although it provides information on the effect of temperature, it is aimed at aerospace and may not have direct applicability to the oilfield. A case in point is alloy 718. The melting, forging, and heat treatment for 718 is covered by API 6A718 and is different from that for aerospace applications. The detailed information on the effect of temperature shown in the handbook may not apply to 718 alloy used in oilfield equipment. The general trend of the temperature effect on the materials properties may be correct, but the detail of the property may not apply. Therefore, the 718 data is not shown here since no information on melt practice, heat treatment, or forging ratio is provided. The same is true for the low-alloy steels, i.e. the trends hold, but the details of the data may not.

6.1.5.2.4 BSEE Technology Assessment and Research Project No. 583

Lab tests were run on three forged and heat treated blocks of F22M 2 $^{1}/_{4}$Cr-1Mo alloy with temperature derating up to 350 °F. Fracture mechanics fatigue crack growth data was obtained at ambient temperature in air and also in the environments of seawater with cathodic protection, and with H_2S. Some of these crack growth data are summarized in A.2.4.

6.1.5.2.5 Alloy Manufacturers

Data from alloy manufacturers is provided since this data is aimed for oilfield use and is available in publications. Again, it is provided for information and guidance as to the effect of temperature on properties. A case in point is for duplex alloys. Manufacturers have provided derating factors for duplex production tubing. Information that may be needed is tubing wall thickness and grade, but the information is provided here to show the effect of temperature on properties for this alloy family.

6.1.6 Testing for Mechanical Properties

6.1.6.1 General

6.1.6.1.1 This section discusses the various mechanical testing protocols for metallic components that can be used to provide the information required by design engineers for the design of HPHT equipment in accordance with Table 2. It does not include qualification testing of production material. HPHT conditions require that design engineers be cognizant of the effects of temperature and the environment on the mechanical properties of metallic components regardless of design methodology used. HPHT temperatures are sufficiently high to require that an allowance be made for the decrease in strength that occurs in metals at the maximum design temperature compared to the room temperature properties. Ductility and toughness should be considered for minimum design temperature, but additional consideration should be made for high temperature. Normally these properties would be expected to increase as design temperatures go into the high temperature range, but environmental interactions may actually cause a decrease to occur. The fatigue resistance of metallic parts may be altered by high temperature and environmental interactions and thus require testing. Testing may be required to characterize the thermophysical properties (thermal expansion, etc.) of specific materials at the maximum design temperature.

6.1.6.1.2 The test protocols described in this section are not intended for the routine qualification of production materials. Some of these tests are quite involved and time consuming. They are, rather, to characterize the parameters needed by the design engineer for a specific alloy in the appropriate section size and heat-treat condition. Consideration should be given to the number of tests required to develop confidence that the results will be representative. This may require testing multiple heats or testing at extreme material conditions (high and low strength, high and low alloying content, etc.). Whenever characterizing material for a specific parameter, tensile, hardness, and impact testing should be repeated for the test material to correlate it to the production material.

6.1.6.1.3 Where welding is used in fabrication and/or repair of HPHT equipment, weldments (weld metal and heat affected zones of base materials) should be included in the test protocols. The properties of weldments may vary considerably by the type of weld metal, the welding process, heat input, stress relief temperature, size of wire, etc. Weld overlays used for corrosion and/or erosion resistance should be included in the test protocol if the overlay is part of the design minimum wall thickness. It may be necessary to include weld overlays in the test protocol even if they are not part of the minimum design thickness of the design methodology. The evaluation of crack initiation and growth in the cladding should be evaluated. Testing should be done on material in the as-heat treated condition as well as the heat treated followed by postweld heat-treated condition.

6.1.6.2 Materials Characterization Testing

Materials of interest for a given part can be tensile tested at the maximum design temperature and at room temperature so that a yield or tensile strength reduction factor for the maximum design temperature can be determined. The specified minimum yield strength (SMYS) at room temperature can then be adjusted upwards by an equal amount so that the required minimum at temperature is assured.

EXAMPLE Assume that a gate valve body requires a material with a 75 ksi minimum yield strength. Further assume the alloy of choice is F22 low-alloy steel and the maximum service temperature is 400 °F. This alloy undergoes a reduction of yield strength of 10 % at the higher temperature. The SMYS for a room temperature tensile test should be 75 ksi/0.90 = 83.3 ksi. By ordering material to a SMYS of 83.3 ksi at room temperature, running elevated temperature tensile tests may be avoided while still ensuring that the material meets 75 ksi at the maximum design temperature.

6.1.6.3 Elevated Temperature Tensile Tests on Production Material

Elevated temperature tensile tests may be run at the maximum design temperature as part of the production material qualification to ensure that the minimum material yield strength required by the design is met. It is also good practice to run a room temperature tensile test along with it for information. The hardness range specified in the material specification should correspond to the room temperature properties of the material as hardness testing on production parts will be done at ambient temperature.

6.1.6.4 Impact Properties

6.1.6.4.1 It is natural to focus on elevated temperature properties of materials when designing HPHT equipment, but the designer should also consider the properties at the minimum design temperature. HPHT equipment may be subject to low ambient temperatures during installation, shut-in periods, and during maintenance. The toughness, as measured by a Charpy V-notch impact test, at the minimum design temperature may be a limiting factor for a candidate HPHT material. Impact toughness of a given forging is highly dependent on the orientation of the test specimen in relationship to the direction of greatest hot work, the degree of hot work, and the microstructure of the material. These parameters are not homogenous throughout a large forging but will vary depending upon forging practice, the hardenability of the alloy, location within a given cross section, and the specific heat treatment. It may thus be important to test in different locations with different test specimen orientations in order to ensure that the impact toughness is completely characterized. Consideration should be given to testing in worst case locations from a metallurgical standpoint (typically heaviest cross sections) and in critical engineering locations (typically highest stressed areas).

6.1.6.4.2 Charpy V-notch impact testing is generally used as a quality control tool for verifying that a given production material is correctly processed and meets a minimum value of toughness that was empirically established based upon field experience. This type of quality control testing is covered in Section 6 of this document. There are, however, other reasons for performing Charpy V-notch testing as part of a materials characterization testing protocol. These will be discussed here.

6.1.6.4.3 Charpy V-notch impact testing over a range of test temperatures can be utilized to develop a transition curve that shows toughness as a function of temperature. Metals having a body centered cubic or BCC structure (such as carbon, low-alloy, and martensitic stainless steels) may undergo a precipitous drop in impact toughness with a small decrease in test temperature in the transition zone between the upper and lower shelves. It is important to consider where on a transition curve the proposed impact test temperature and specified minimum design temperature lie.

6.1.6.4.4 Charpy V-notch impact testing can be useful for evaluating the adequacy of hot work in a forging. This would typically be done on a first article basis. As previously mentioned, impact toughness is highly dependent on the orientation of the test specimen in relationship to the direction of greatest hot work. Impact values of specimens taken parallel to the direction of greatest hot work (the longitudinal orientation) will be higher than specimens taken perpendicular (the transverse orientation). The difference in toughness values will reflect the difference in hot working in different directions. A part machined from a bar forged just in a radial direction will have a much greater difference between longitudinal and transverse impact toughness values than a part machined from an open die forged bar with radial forging and an upset operation.

6.1.6.5 Fracture Toughness Testing

6.1.6.5.1 Fracture toughness testing or a valid correlation to Charpy V-notch results is necessary to support fracture mechanics analysis. It may be specified in conjunction with other design methodologies of Section 5 to provide the design engineer with the information necessary to evaluate defects. Fracture toughness testing is generally done in accordance with ASTM E1820 or BS 7448 in air at various temperatures. There are many test parameters that should be considered including test methodology (K_{IC}, J_{IC}, crack tip opening displacement), test specimen type (DCB, compact tension, etc.), test specimen size, test location within a part, orientation of the test specimen, test temperature, test environment, strain rate, etc. A set of three specimens is tested for each combination of test parameters. It may be necessary to test more than one combination of parameters in order to examine the fracture toughness on a worst case basis. The acceptance criteria for fracture toughness testing should be predicated on a fracture mechanics design methodology and nondestructive testing criteria that are realistic for the part size.

6.1.6.5.2 Fracture toughness values of a given material are strongly influenced by the material's strength and microstructure. As a consequence, fracture toughness may vary considerably throughout the cross section of a part depending on the alloy's hardenability and heat treatment. Fracture toughness values will also vary with the degree and direction of hot work. Consideration should be given to testing in worst case locations from a metallurgical standpoint (typically heaviest cross sections) and in critical engineering locations (typically highest stressed areas). In general, the orientation of the test specimen should be chosen such that crack growth in the test specimen is the same as the most likely direction of crack growth in the part. For most parts this will be through the wall in a radial direction. The corresponding fracture toughness test specimen orientation will be L-R (longitudinal then radial).

6.1.6.5.3 The test temperature for fracture toughness testing is typically the lowest minimum design temperature as this is a worst case from strictly a mechanical standpoint. Testing at higher temperatures may be warranted if the material being tested is known to be or suspected of becoming embrittled through interaction with its environment within the design temperature range. The test environment should be representative of the environments (both internal and external) that the material will be exposed to in service.

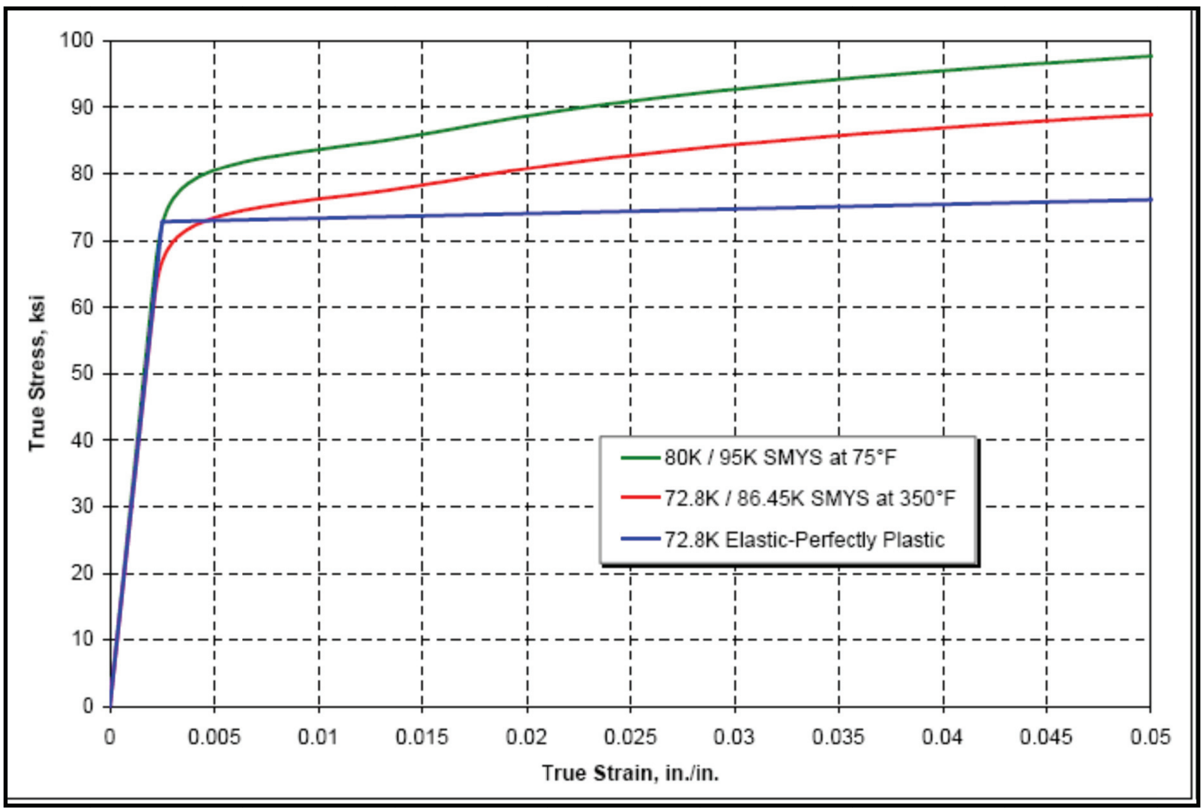
6.1.6.5.4 Fracture toughness testing is complex, expensive, and time consuming. As discussed in 6.4.3, it may be possible to develop a correlation between the Charpy impact toughness values and the fracture toughness values of a material. This relationship should be developed empirically for a given part made out of a specific material, heat treat condition, and manufacturing route. Published equations that convert impact values directly into fracture toughness may be inaccurate. Fracture toughness can be done on a first article basis, and after a correlation is made, the production forgings can be Charpy impact tested. Charpy impact testing should not be considered a substitute for fracture toughness testing when environmental effects are to be considered.

6.1.6.6 Slow Strain Rate Testing (SSRT)

If it is not known whether or not a material may become embrittled through interaction with a specific environment, consider slow strain rate testing the material in that environment. SSRT is covered in NACE TM0198. As the name implies, it basically involves running a tensile test at a slow strain rate (typically 1–4 × 10^{-6} s^{-1}) in a specified environment. The results of the environmental test are then compared against a control specimen tested in air at the same strain rate and test temperature. SSRT is a very rapid test for evaluating the environmental sensitivity of a material because any protective film on the surface of the specimen is disrupted as the specimen is strained in the environment. Environmental sensitivity is indicated if the time to failure, the elongation, or the reduction of area results of the environmental test are not within 80 % (or other agreed upon percentage) of those values from the control specimen tested in air. An alternate percentage may be used upon mutual agreement between the manufacturer and the user.

6.1.6.7 True Stress–True Strain Tensile Testing

Tensile testing at the maximum design temperature will provide information to the design engineer that is needed for a stress/strain based design methodology including yield and tensile strength, the modulus of elasticity, and data that characterize the material's behavior in the nonlinear elastic-plastic region. A true stress–true strain curve can be obtained via ASME *BPVC*, *Section VIII*, *Division 2*, Annex 3.D or ASME *BPVC*, *Section VIII*, *Division 3*, Paragraph KD-231.4. An example of the curve is shown in Figure 5. Other proven methods may be used.



NOTE Calculated in accordance with ASME *BPVC*, *Section VIII*, *Division 2*, Annex 3.D.

Figure 5—Example of True Stress for 2 1/4Cr-1Mo True Strain Curve

6.1.6.8 Physical Property of Materials

It may be necessary to provide physical property data (modulus of elasticity, Poisson's ratio, thermal coefficient of expansion, etc.) of a material at the maximum design temperature to a design engineer. Some of this data may be available in the literature, but such data should be used with caution. It is important to ensure that the data are based upon the same material type and in the same heat treat condition as the production part. Often, published data reflect an average value over a given temperature range. Do not assume that the actual value is constant over the specified temperature range: it may vary considerably from the average value. Published data should only be used if the maximum design temperature is relatively close to the maximum temperature in the temperature range of the published data.

EXAMPLE Suppose the maximum design temperature of a part is 450 °F and the design engineer should know the coefficient of thermal expansion for the part over the design temperature range. Using a published average value for a 0 °F to 1000 °F temperature range would be inappropriate without verification testing. Using a published average value for a 0 °F to 500 °F is acceptable.

6.1.6.9 Modulus of Elasticity

It is convenient to express the elasticity of a material with the ratio of stress to corresponding strain below the proportional limit, a parameter also termed the tensile elastic modulus or Young's modulus of the material. This is usually given the symbol E. Modulus data for alloys and temperatures can be found in ASME B31.3, Appendix C, Table C-6 or ASME *BPVC, Section II*, Part D.

6.1.6.10 Fatigue Testing

6.1.6.10.1 Fatigue testing may be necessary to examine the effects of cyclic loading on material. Cyclic loading may arise from external mechanical loading (due to currents, wave action, installation stresses), internal mechanical loading (due to pressure, operational factors), thermal cycles during start-ups, and shutdowns, etc. Fatigue testing is complex and it is important the end user of the equipment defines the appropriate test parameters (minimum and maximum stress, R, frequency etc.) and test methodology that will reflect the cyclic loading conditions in service. The end user should also specify the acceptance criteria based upon the minimum cycles to failure over the design life of the equipment.

6.1.6.10.2 The fatigue properties of a metal may vary with environment. Metals with a fatigue limit in air mostly likely will not have a similar fatigue limit in a corrosive environment. Fatigue life will vary with temperature, alloy, strength level, heat treat condition, and microstructure. Extreme caution should be used when utilizing published fatigue data for an alloy to ensure that the data is representative of the material under consideration and in a similar environment.

6.1.6.10.3 There are two basic methodologies for fatigue analysis. Conventional fatigue analysis done with S-N-based methodologies utilizes a fatigue curve generated with stress or strain vs the number of cycles to failure. The fracture mechanics design approach utilizes a da/dN vs ΔK curve. This requires that a starting flaw size be agreed upon and this should correlate with the minimum flaw size detectable in the part by the specified nondestructive testing procedures. Additionally threshold stress intensity should be defined for the da/dN vs ΔK material data which can be used in the design.

6.1.6.11 Typical Protocols for Mechanical Property Determination

A summary of test procedures is provided in Table 6.

A list of specifications for metal products like bars or flanges are as follows:

— ASTM A182/A182M,

— ASTM A276,

— ASTM A351/A351M,

— ASTM A743/A743M,

— ASTM A744/A744M,

— BS HR 3.

Table 6—Typical Protocols for Property Determination

Material Property	Standard
Elastic properties—Modulus and Poisson's ratio with temperature	ASTM A370, ASTM E111
Mechanical strength—yield and ultimate strength with temperature	ASTM E21
Fracture toughness, K_{IC} from Charpy data	K_{IC} calculation from Charpy V-notch data via the conversion equation specified in ASME *BPVC*, *Section VIII*, *Division 3,* Appendix D, Section D-600. (The same conversion equation is specified in API 579-1/ASME FFS-1, F.4.5.2.)
Fracture toughness— Charpy V-notch impact strength, K_{IC}/J_{IC} with temperature and environment	ASTM E1820 and BS 7448
Plane strain fracture toughness—linear elastic	ASTM E399
K_{ISSC}/K_{IEAC}	NACE TM0177
Fatigue life—fracture mechanics	ISO 12108
Fatigue—S/N and crack growth rate	ASTM E647
True stress–true strain curve	Generated using the information provided in ASME *BPVC*, *Section VIII*, *Division 2*, Annex 3.D (Strength Parameters)
Charpy	ASTM E23
Creep	ASTM E139

6.1.7 Nonmetallics vs Metallics—General Guidance on Selection

6.1.7.1 General Description of Seals

6.1.7.1.1 Nonmetallic seals for completion equipment are typically made of elastomers and plastics. These materials may be used separately or together and are used for sealing systems or sealing elements and for other components.

6.1.7.1.2 There can be metal-to-metal seals or nonmetallic (or resilient) seals. Therefore, the design choice is which type is the more desired or necessary. In general, the metal-to-metal static seal will contain higher pressures and higher temperatures in more severe environments for longer time. However, the nonmetallic seals have greater tolerance to seal and housing irregularities and static seals may be broken and resealed more reliably. Nonmetallic seals may also be used as redundant seals to metal-to-metal seals.

6.1.7.1.3 There are some sealing applications that favor nonmetallics over metal-to-metal seals, such as rotating and linear motion seals. However, friction can affect the life of the nonmetallic. If a seal rotates or reciprocates, the friction factor can determine not only how long the seal will last but whether or not the mechanism will function. Generally, elastomers exhibit higher friction than plastics. The dominant factor in friction is the differential pressure across the seal.

6.1.7.2 Elastomers and Plastics Used for Seals

6.1.7.2.1 Elastomers are polymeric materials that are elastic with significant ductility at ambient temperature and above. This elasticity is formulated with polymers with cross-linked connections. The thermoplastics are rigid and associated with polymers that are not cross-linked. Thermoplastics may not be resilient but they are stiffer and stronger providing complementary properties for seal performance.

6.1.7.2.2 ASTM D2000 describes a basic elastomer classification system. Commonly used elastomers for seals in completion and production equipment include

— nitrile rubber,

— hydrogenated nitrile rubber,

— fluoroelastomers (e.g. Viton® [1] and Fluorel®),

— terafluoroethylene/propylene copolymers (e.g. AFLAS®), and

— perfluorelastomers (e.g. Kalrez® and Chemraz®).

6.1.7.2.3 Compounding of elastomers allows tailoring of both mechanical properties and chemical resistance during the curing and postcuring processes. Fillers may be reinforcing or nonreinforcing in function and include carbon black. Some of the other filler compounds may be metal oxides, extending oils, plasticizers, stabilizers, curatives, and pigments. Specific elastomer response will vary based upon the compounding process use by the seal manufacturer.

6.1.7.2.4 The most common thermoplastics are reinforced/filled polytetrafluoroethylene (e.g. TEFLON®), polyetheretherketone, and polypheylene sulfide (e.g. RYTON®). The thermoplastics are commonly used as backup seals for elastomers in seal assemblies and as primary seals themselves in applications such as valve stem packing. Because of their relative rigidity or stiffness compared to polymers, the thermoplastics in primary seals are usually spring energized with corrosion resistant metal alloy springs. Thermoplastics are typically filled with inert substances such as glass, aromatic polyamide (e.g. Kevlar®), or carbon fiber. Fillers can increase the rigidity and the abrasion resistance of the thermoplastics. Rigidity helps to prevent seal extrusion and is important in the design of packing elements.

6.1.7.3 Mechanical Properties

Mechanical properties are usually measured on test pieces, not finished seals. Hardness is measured using the Shore hardness A or D scale. Higher mechanical stiffness is one factor in resistance to extrusion for elastomers or plastics; note that temperature is also a critical factor reducing most mechanical properties as temperature increases. Elastomers will expand more than metal. This may affect the expansion and sealing capability of elastomers. Softer materials are more compliant and seal better. Carbon black is added to elastomers to reinforce the resulting compound and increase mechanical performance.

Other additives such as graphite, glass fibers, or polytetrafluoroethylene compounds, can stiffen or lubricate plastics or elastomers, but the matrix will still behave similarly to the base polymer.

6.1.7.4 Temperature Resistance Properties

Elastomers and amorphous plastics have a glass transition temperature below which they no longer behave elastically but react as brittle plastics. For elastomers, the glass transition temperature is increased while under high pressure. At low temperatures the glass transition temperature has a greater impact on sealing than the hardness.

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[1] The use of registered trademark names does not constitute an endorsement of these products by API.

Amorphous plastics have a glass transition temperature above room temperature. Plastics and elastomers degrade and out-gas at temperatures above the high temperature limit of the material.

6.1.7.5 Chemical Compatibilities

Knowing the chemical environment and the effects on nonmetallics for a seal's life is necessary. Generally, thermoplastics will have somewhat greater chemical resistance than most elastomers. Each chemical with which a nonmetallic comes into contact may have an effect on seal performance. The production environment may contain CO_2, H_2S, amines, and flow assurance chemicals and periodically may contain acids and clear brines for workover operations. All of these may, to some extent, degrade seals.

Aging is the long-term cumulative effect of an environment on a plastic or elastomer. Chemical reactions such as cross-linking cause elastomers and some plastics to stiffen and become brittle. Other reactions cause molecular bond scission that in a worst case can result in dissolution or actual evaporation of the material. Whatever the reaction, the change in material properties should be considered as part of the design verification and validation processes.

6.1.7.6 Effects of Gas on Elastomers

Gas will permeate into elastomers. Any gas can cause explosive decompression damage to susceptible materials if pressure is bled too rapidly, but carbon dioxide is one of the worst for fluorinated elastomers. When pressure is relieved too rapidly, the expanding gas within the elastomer causes blisters or splits. To resist explosive decompression, amorphous elastomers should have a very high modulus. Plastic materials formulated for oilfield applications are stiffer and more crystalline and much more resistant to explosive decompression than elastomers.

Two laboratory test protocols for evaluating elastomer seals to resist damage due to gas decompression are NACE TM0192 and NORSOK M-710. Tests should duplicate as closely as possible the service environment, housing geometry, seal geometry, and cyclic conditions if the results will conservatively predict field service life.

6.1.7.7 Liquid Exposure

Chemical compatibility data for chemicals the seal may be exposed to (on both sides of the seal) is essential. Using redundant seals is an approach that might be effective in dealing with nonmetallic seal degradation in an aggressive or long-term environment. However, redundant seals still see the same heat history and designs may have a negative impact on the pressure loads on seals in series because of trapped pressure.

Multiple phase exposure may result in performance different than data generated for single-phase (gas or liquid) service.

6.1.7.8 Qualification of Seals and Manufacturers

NORSOK M-710 lists test methods and conditions for qualifying elastomeric and thermoplastic seals. Quality assurance during seal manufacture is also covered. These are some of the recognized standards for evaluating properties.

ISO 23936-1 addresses the resistance of thermoplastics to the deterioration in properties that can be caused by physical or chemical interaction with produced and injected oil and gas-field media, and with production and chemical treatment. Interaction with sunlight is included; however, ionizing radiation is excluded from the scope of ISO 23936-1. ISO 23936-2 addresses elastomer materials in contact with media related to oil and gas production with emphasis on qualification, rapid gas decompression, and aging. Table 7 provides a summary of recognized standards for evaluating properties.

Table 7—Summary of Test Protocols for Nonmetallic Materials in M-710

NORSOK M-710 Recognized Test Standards	Description	Thermoplastics	Elastomers
ASTM D638	*Test Method for Tensile Properties of Plastics*	X	
ASTM D695	*Test Method for Compressive Properties of Rigid Plastics*	X	
ASTM D746	*Test Method for Brittleness Temperature of Plastic and Elastomers by Impact*	X	X
ASTM D792	*Test Methods for Specific Gravity and Density of Plastics by Displacement*	X	X
ASTM D2240	*Test Method for Rubber Property—Durometer Hardness*		X
ASTM D2990	*Test Methods, for Tensile, Compressive and Flexural Creep and Creep Rupture Test of Plastics*	X	
ISO 34-1	*Rubber, vulcanized or thermoplastic—Determination of tear strength—Part 1: Trouser, angle and crescent test pieces*		X
ISO 868	*Plastics and ebonite—Determination of indentation hardness by means of a durometer (Shore hardness)*	X	X
ASTM D3032	*Arrhenius method for life prediction*	X	X

6.1.7.9 Comparison of ASTM Qualification Tests with International Standards

Table 8 provides cross references to ASTM elastomer qualification tests with similar DIN and ISO standards.

Table 8—Cross References of Industry Standards

Test	ASTM	DIN Standard	ISO Standard
Abrasion resistance	D2228	53516	4649
Air aging	D573	53508	188
Compression set	D395	53517	815
Density	D792	53479	2781
Elongation at break	D412	53504	37
Fluid compatibility	D471	53521	1817
Hardness	D2240	53505	48
Modulus	D412	53504	37
Stress relaxation	D1646	53537	3384
Tear strength	D624	53507/53515	34-1/34-2
Tensile strength	D412	53504	37

6.1.7.10 Fixture Testing to Predict Expected Service Life

Seal performance should be documented for their expected service life. The design life of the seal can vary from having to remain for the life of the component to a seal that can easily be replaced on a schedule or when a leak is detected. The life expectation should be communicated between manufacturer and user. The ease and consequence of change-out should also be communicated.

Seal performance and life are sensitive to seal design as well as materials selection. Considerations include: surface area exposed to pressure, backup materials, seal groove and containment configuration, and other factors. Seal degradation may take the forms of swelling, fissuring, softening, and embrittlement. However, some extent of degradation may be acceptable based upon design and function, for example some swelling of static seals may be acceptable if pressure containment is acceptable. Therefore, manufacturers will rely upon fixture or full-scale component testing of seals in the simulated production environment to best predict service life. API 6A, Annex F provides guidance for wellhead and Christmas trees.

6.1.7.11 Bond Strength Evaluation

Elastomers may be bonded to metallic substrates for additional reinforcement or to perform other functions. If the bond of the elastomer to the substrate is critical to performance, the integrity of the bond should be evaluated in the same manner as the performance of the seal itself.

6.1.8 Field Failures

A survey of metallurgical-related failures of completion and production equipment was undertaken and is summarized in Annex B. Only failures that are available in the open literature are listed in Table B.1.

6.2 Design Verification

6.2.1 General

6.2.1.1 The purpose of the design verification is to verify the equipment adequately meets the specified requirements. This may include confirming the accuracy of design results through the performance of alternative calculations; review of design output documents independent of design and development review; or comparing new designs to similar proven designs.

6.2.1.2 The following topics are outside the applicability of the design verification calculations and may be addressed by other industry standards or practices or included in some sections of this document:

a) nonmetallic pressure-retaining components;

b) metallic equipment intended to operate in a post-yield stress state (e.g. threaded connections, vacuum insulated tubing, steam well casing, ring gaskets, and other metal-to-metal seal mechanisms, etc.);

c) the choice of design margins and the utilization limits of the equipment; hence this report makes no recommendation of design margins and no recommendation regarding usage of equipment based on the calculated performance limits;

d) calculation of the pressure or fatigue performance limits of equipment operating in sulfide or stress cracking or other corrosive environments. Additional guidance on evaluation of fatigue performance in sulfide or stress cracking environments may be contained in the documents listed in Table 2

6.2.1.3 This technical report is intended to aid (not replace) existing industry practices. The primary analytical design verification method used by existing API equipment specifications (API 6A, API 16A, API 16C, and API 17D, etc.) is based upon ASME *BPVC*, *Section VIII*, *Division 2* (2004), Section 5.2.2. This report provides additional means of calculating the performance limits of pressure-containing equipment beyond the scope of the methods contained in these API specifications. These optional methods reference several industry standard practices for making the relevant calculations; that is, calculation methods provided by

— API 579-1/ASME FFS-1,

— BS 7910,

— API 2RD,

— API 1111,

— API 17N,

— ASME *BPVC*, *Section VIII*, *Division 3*, or

— additional methods in ASME *BPVC*, *Section VIII*, *Division 2*, etc.

6.2.2 Design Verification Analysis

6.2.2.1 General

6.2.2.1.1 Where API product standards exist with specific design margins for HPHT equipment, these margins should be met as a minimum. Where the design analysis is performed in accordance with a recognized code or standard such as those referenced in Table 9 and Table 10, design margins from the code or standard should be used. Any additional requirements (such as quality or material) from the same reference should be considered. Alternatively, a complete system analysis with risk assessment may be done to establish the design margins to be used.

6.2.2.1.2 The following are types of analyses for calculating the performance limits of HPHT equipment at the rated working pressure and external loading requirements. However, other factors, such as performance of parts due to deflection, may be the limiting factor and reduce the working pressure over that determined by the structural analysis. Extremes of service loadings, including stresses resulting from thermal gradients, and stresses introduced by the fabrication and testing processes (e.g. autofrettage, residual stresses) should be considered and the assessment should be documented in the design documentation report.

6.2.2.1.3 Design verification should be performed using one or more of the applicable methods listed in Table 9. Not every method of analysis applies in every case. For example, assessment of fatigue is not needed when loads or cycles are not sufficient to cause fatigue damage or a linear elastic fracture mechanics assessment may not be needed if leak-before-burst can be demonstrated. In some cases the methodology is advanced analytical calculation and in other cases the methodology is elastic or elastic-plastic finite element analysis. Either method is acceptable on a case-by-case basis. The reference standards containing the subject matter are also listed in Table 1. The acceptance criteria for the applicable methods should be established. The analysis method chosen should be representative of the anticipated failure mode.

6.2.2.2 Elastic Analysis

Elastic analysis is the determination of stresses using linear material properties. Stress results are compared against allowable values to ensure adequate design margins against relevant failure modes under the stated conditions.

For HPHT equipment, the following are considerations in performing elastic analyses:

a) temperature effects on the material properties,

b) stress classification and effects of structural discontinuities,

c) heavy wall ($R/t \leq 4$) pressure-containing components.

Table 9—Reference Industry Standards for Design Verification

Reference Standard [a]	Verification Analysis Methods						
	Elastic Analysis	Elastic-plastic Analysis (Elastic-perfectly Plastic Analysis)	Strain-based Design	Elastic-Plastic Analysis (with Work Hardening/ Softening)	Fracture Mechanics Elastic-plastic Failure Assessment	Fatigue Assessment (S-N Analysis)	Fracture Mechanics Life Assessment
API 6A	X						
API 17D	X						
API 16A	X						
API 16C	X						
API 2RD	X					X	X
API 1111	X	X [b]					
API 5C3/ISO 10400	X	X		X	X		
ASME *BPVC*, *Section VIII*, *Div 2*	X	X	X	X		X	
ASME *BPVC* *Section VIII*, *Div 3*	X	X	X	X		X	X
BS 7608						X	X
API 579-1/ASME FFS-1					X	X	X
BS 7910					X	X	X
ISO 12108							X
RMA MO-1 Handbook, ASTM D-2000, SAE J200, ASTM D1056, SAE J18	X [c]						

[a] Other methods for performing verification analysis are possible but should be fully detailed in the analysis.

[b] Elastic-plastic analysis based on testing.

[c] Hyper-elastic analysis.

When all of the above conditions are present, more advanced analysis methods such as elastic-plastic or limit-load analysis should be considered.

Temperature gradients across wall sections will cause thermal stresses that will act in both tension and compression, generating nonlinear stress distributions through a section. As wall thicknesses increase, the linear representation of stresses across a section may become less accurate.

6.2.2.3 Elastic-plastic Analysis

6.2.2.3.1 Elastic-perfectly Plastic Method

The elastic-perfectly plastic method utilizes elastic-perfectly plastic material properties in a structural evaluation of a component or system. This type of analysis is used to determine the lower bound for the load(s) at which unbounded deformation occurs. Applicable loads should be applied, including differential temperature and temperature effects on material properties. Once a “limit-load” design case has been established, a suitable design margin should be implemented against this value to establish the maximum allowable rated working load (pressure, tension, bending, torsion, temperature, etc.).

The limit-load solutions to elastic-perfectly plastic analysis methods can be used to identify the lower bound primary stress at which failure will occur, given that primary stresses will not redistribute and the perfectly plastic condition offers no support from strain-hardening. Conversely, features with reactions that could be classed as a secondary stress or features in which local plastic deformation will result in a load being redistributed, can be tested in a perfectly-plastic situation.

NOTE 1 The deformations and strains of a structure using perfectly-plastic yielding have no physical meaning since the predicted post-yield plastic strain levels will exceed the actual strains of the material. If dimensional or deformation boundary conditions exist for a design that require precision with regard to the plastic strain level, then the methods described in 6.2.2.3.2 should be used.

NOTE 2 See ASME *BPVC, Section VIII*, *Division 2*, Paragraph 5.2.4 or *Section VIII*, *Division 3*, Paragraph KD-231.

6.2.2.3.2 Elastic-plastic Method

The elastic-plastic methods incorporate the work hardening/softening of a material during a structural evaluation of a component or system. The von Mises yield function and associated flow rule should be utilized if plasticity is anticipated. This type of method is used for determining the plastic collapse load of the component. The maximum allowable load on the component is established by applying a design margin to the calculated plastic collapse load. Applicable loads should be applied, including differential temperature and temperature effects on material properties.

The elastic-plastic analysis is generally considered to provide a more accurate assessment of the structural behavior of the component than the elastic-perfectly plastic analysis because the actual structural behavior is more closely approximated. The elastic-plastic analysis method should consider the plastic collapse load, local strain limits, the limits on deformation, and the potential for unsatisfactory performance of the equipment. It is recommended that the stress–strain curves of the material used be inputted using true-stress vs true-plastic strain format and that the material be represented as perfectly-plastic beyond the ultimate tensile stress or the actual material test data is used. There are analytical methods which have been developed to determine plastic strength by limit analysis that should be reviewed when applying the elastic perfectly plastic and elastic-plastic criteria. See WRC Bulletin 254.

6.2.2.4 Fatigue Assessment

6.2.2.4.1 General

It should be determined whether or not a fatigue analysis is needed. There are several means of evaluating whether a fatigue analysis should be performed on an equipment component. These include experience with comparable equipment operating under similar conditions, and screening calculations using simplified fatigue assessment procedures. An example of fatigue screening guidelines can be found in ASME *BPVC*, *Section VIII*, *Division 2*, Section 5.5.2. Other recognized industry standards may provide additional guidelines for fatigue screening assessments.

If successful experience over a sufficient time frame is obtained with comparable equipment subject to a similar loading histogram as addressed in the functional design specification, then a fatigue analysis may not be required. When evaluating experience with comparable equipment, the effects of design changes relative to prior equipment experience should be considered such as nonintegral construction, abrupt thickness changes, and stress concentrations.

Fatigue life may be established analytically using either analytical tools or finite element analyses or based on documented experience with similar product designs, sizes, material properties, and operating conditions. The calculation of fatigue life may be based on either S/N or fracture mechanics methods. An example of fracture mechanics analysis can be found in ASME *BPVC*, *Section VIII*, *Division 3* or API 579-1/ASME FFS-1. Residual stresses resulting from welding should be considered along with primary and secondary stresses in fracture mechanics calculations.

6.2.2.4.2 Assumed Initial Crack Size

The initial crack size to be used for the calculation of the crack propagation design cycles should be based on the measurement threshold of the NDE method used and the ability of that method to reliably detect indications of this size.

HPHT equipment may have different NDE acceptance criteria for various zones of the component based on anticipated stresses. The design and manufacturing documentation should specify the NDE acceptance criteria for each zone when required.

6.2.2.4.3 Critical Crack Depth

The critical crack depth should be calculated for specified design load and environment combinations stated in the technical specification and based on applicable material properties at those conditions.

6.2.2.4.4 Fracture Mechanics Life Assessment

The calculated fatigue life is based on the number, magnitude, and order of operating cycles which are necessary to grow a crack from the assumed initial crack depth to the critical crack depth. An appropriate design margin should be applied to this value to determine a useful operating life or inspection interval. The fracture mechanics analysis is based on the following assumptions:

— the crack initiation stage is complete;

— cracks exist at highly stressed points in the high pressure equipment;

— the assumed preexisting and deleteriously located cracks are of a size equal to the maximum allowable limits defined by the NDE inspection criteria;

— cracks exist in the worst-case orientation relative to the principle stresses.

The fracture mechanics analysis can be used to determine the maximum allowable imperfection size at the intended service and/or test conditions and to verify that the maximum allowable indications in the NDE procedures are acceptable.

NOTE In some HPHT equipment, loads can decrease with time due to reservoir depletion as the well is produced. The number of loading cycles for well-based equipment is low compared to other products (i.e. hundreds of cycles vs millions of cycles).

An IMP (see 5.7.3) should cover the estimated service life of the equipment. If the calculated design life is less than the required service life, then an in-service inspection plan for this equipment should be developed. This inspection plan should outline the monitoring and recording of the load history of the equipment in service; the type of NDE inspection requirements; and allow for the recalculation of the remaining life of the equipment in service to ensure adequate life span for the equipment.

6.2.2.5 Other Verification Analyses

6.2.2.5.1 Stress Relaxation

The phenomenon known as stress relaxation can reduce the clamping force in bolted connections. The manufacturer should demonstrate through analysis or testing that stress relaxation will not affect the pressure integrity of bolted connections in HPHT equipment.

6.2.2.5.2 Creep

Creep is the time-dependent deformation of materials that occurs at temperatures greater than about 40 % to 50 % of the lowest melting point or lowest end of the melting range. Many of the engineering alloys that are likely to be used to manufacture HPHT equipment, including low-alloy steels and CRAs melt in the range from 2400 °F to 2700 °F. Thus, sustained metal temperatures above approximately 950 °F are required for significant amounts of creep deformation to occur. Although temperatures this high are encountered in some refining operations, they are rarely, if ever, experienced in upstream producing environments, where most HPHT equipment will be utilized. Therefore, creep, in the classical sense, may not need to be considered in the design of HPHT equipment unless the maximum design temperature exceeds 40 % of the melting point or lowest part of the melting range of the alloy used.

6.2.2.5.3 Embrittlement

Embrittlement may be defined as the loss of ductility or toughness resulting from exposure of materials to various environments. The manufacturer should demonstrate that the alloys from which they propose to manufacture HPHT equipment will not experience embrittlement in the HPHT service environment specified by the user. The allowable level of embrittlement, if any, as well as the test method(s) selected to demonstrate this characteristic should be agreed upon between the user and the manufacturer.

6.2.2.5.4 Other Loadings

Loadings (structural and thermal) beyond those outlined in 4.3 may result from fluid flow, especially at high production rates. These loadings may affect the resulting stresses in the equipment and/or impede equipment function. Loading due to fluid flow should be considered. This may be done with methods such as computational fluid dynamics analysis or finite difference calculations.

6.2.2.5.5 Vortex Induced Vibrations

Vortex induced vibrations of structures, such as vertical risers, flexible risers, steel catenary risers, tendons, mooring lines, and pipelines, involve complicated interactions between the structure modes of vibrations and the fluid forces, which might cause structural failure or fatigue damage under certain conditions. As a result of the structure being subjected to currents at high Reynolds numbers, vortex shedding is produced which results in the oscillation of the hydrodynamic loads, which in turn force the structure to vibrate at its natural frequencies. A proper design of a structure based on a prediction of vortex-induced vibration will reduce risk of structural failure or fatigue damage.

6.2.2.5.6 Flow Induced Vibrations

Flow induced vibrations of systems is generally regarded as being caused by broad band turbulent energy sources associated with discontinuities in the flow such as those occurring at partially-closed valves, target elbows and tees. If there is sufficient energy generated close to natural frequencies of the piping, the vibration levels can be high. Excessive vibration has the potential to cause fatigue cracking of the girth welds in the piping which could ultimately lead to fatigue failure. A proper design of a system based on a realistic prediction of flow-induced vibration will reduce risk of structural failure or fatigue damage [85].

6.2.2.6 System Analysis

The life cycle of the system should be defined and the life cycle or durability of individual components of the system should be compatible with the life cycle of the system. The life cycle of the system is the minimum life cycle of the components. The system should consider the most vulnerable components.

6.2.2.7 Design Simulations

6.2.2.7.1 Simulations represent a technique for testing, analysis, or training in which real-world systems are used, or where real-world and conceptual systems are reproduced by a model. A model is defined as a physical, mathematical, or otherwise logical representation of a system, entity, phenomenon, or process [81].

6.2.2.7.2 Simulations can reflect system functions or the detailed structure of the system. They are composed of representations of system elements, connected in the same manner as in actual systems. Usually the simulation is run through the operational parameters to simulate the behavior of the real system [82].

6.2.2.7.3 As an example, modeling and simulations can be applied to a system comprised of end connections with an internal bore gasket. The system can include a variety of end connections such as hubs with clamps, flanged connections or hydraulic connectors. Upon verification and then validation of the model and the simulation, system design parameters can be established for a variety of sizes, pressure ratings, and temperature ratings.

6.2.2.7.4 A simulation can be used to examine a range of sizes, system configurations and design parameters. This ensures that the optimum fit-for-service solution is obtained. In addition to examining nominal conditions, tolerance studies and extreme load evaluations may be made to determine system reactions or breakage.

6.2.2.7.5 To determine whether a model or simulation should be used in a given situation, its credibility should be established by evaluating fitness for the intended use. In simplest terms, verification and validation are distinct processes that gather and evaluate evidence to determine the simulation’s capabilities, limitations, and performance relative to the equipment.

6.2.3 Functional Testing

The intent of functional testing is to prove the ability of the design to perform the intended function. The environmental conditions may or may not be imposed on the system during testing. The functional tests should be designed to check the system, subsystem or component functionality and feasibility. These tests should be performed at the component or subsystem level. The functional tests are not normally considered validation tests.

6.3 Design Validation Testing

6.3.1 General

6.3.1.1 The objective of the validation process for HPHT equipment is to verify the compliance of the system and its components to the technical specifications, their performance as systems, and to provide a confirmation of the verification process.

6.3.1.2 A suitable design validation program should be developed to validate the performance of the equipment against the functional and technical specifications and adequately address the identifiable, potential failure modes. The main purpose of the testing program is to validate the equipment suitability to perform the function for the duration of the mission in the defined environment.

6.3.1.3 The validation program should have the following major components.

a) Validation of the verification method—new or not proven verification methodologies should be validated. Historical verification processes can remain valid if they can be documented, shown to be technically sound, and meet the equipment design requirements and service conditions.

a) Validation of materials used for the design—new materials that are not covered by the verification method should be validated.

b) Validation of the system under development.

6.3.1.4 The validation program should cover the environmental and operating loads on the equipment at the limits and all defined design operating conditions. The tests should validate the in-service condition by simulating the operational environment as close as physically possible. Current API product specifications and the validation methods employed are given in Table 10.

Table 10—Reference Industry Standards for Validation

Reference Standard	Validation Methods						
	Functional Test	Performance Validation	Combined Load Test	Cycle Testing	Elevated Temperature Testing	Fire Testing	Hyperbaric Testing
API 5CT	X						
API 5D	X						
API 5C5	X	X	X	X	X		X
API 5CRA	X						
API 6A	X	X		X	X		
API 6AV1		X		X			
API 6D	X						
API 6FA						X	
API 6FB						X	
API 6FC						X	
API 11D1	X	X	X	X	X		
API 14A	X	X		X	X		
API 14L	X	X			X		
API 16A	X	X	X				
API 16C	X	X		X	X		
API 16F	X	X	X	X			
API 16R	X	X	X	X			
API 17D	X	X		X	X		X
API 17E	X	X	X	X			
API 17K	X		X			X	
API 17C	X						
API 17J	X	X	X				

6.3.2 Validation Process

6.3.2.1 General

6.3.2.1.1 The validation process is the methodology to incorporate the basis of design in system testing and validate the results of the verification process.

6.3.2.1.2 The validation process should use standardized and recognized procedures and methodologies. Applicable industry standard validation processes may be used. Proprietary validation processes can also be used as long as they are proven.

6.3.2.1.3 FMEA, a proven method for constructing a validation matrix, is described in Annex C.

6.3.2.1.4 Proven design verification methodologies and various analytical methods may be sufficient to show the equipment is fit-for-service. Therefore, certain physical tests may not be necessary to demonstrate the fit-for-service equipment. The verification and validation processes should be used to determine the required physical testing of the equipment. Engineering judgment and agreement between user and manufacturer may be used to add additional testing requirements.

6.3.2.1.5 A well-constructed validation program should include the following:

a) recommend testing to be performed on equipment rated design limits;

b) simulate in-service conditions as close as practical and should be correlated back to the design verification analyses, material selection, and QA/QC plans;

c) include components of the system under investigation and the interactions between the components where applicable;

d) tests that are repeatable and reproducible;

e) demonstrate supplier design and manufacturing capabilities;

f) demonstrate the ability of the product to perform its intended function as part of the system in the environment specified in the basis of design for the design life;

g) incorporate experience and history of the equipment in service in testing;

h) incorporate testing identified during the verification process.

6.3.2.1.6 During the validation process of the product the following system information should be known, validated and agreed by the user and manufacturer:

— basis of design,

— functional design specification,

— technical specifications have been derived from the functional design specifications,

— system and components interactions.

6.3.2.1.7 The methodology should define failure modes, design the tests, perform the tests, validate the test results, and determine the critical attributes that should be controlled during the manufacturing process. Figure 6 shows the flow chart of the validation process.

6.3.2.2 Define

Define the subsystems, components, environmental conditions, and operational parameters of the system. This task should be completed prior to entering the validation phase of the project. Some tests may have been identified during the verification process or defined by current industry standards.

A subsequent part of the definition deals with the identification of the specific environment and interactions created within or between the components or subsystems. For example, the pressures required to operate the system.

System requirements should define the test facilities and test equipment needed and highlight the feasibility of actual physical testing.

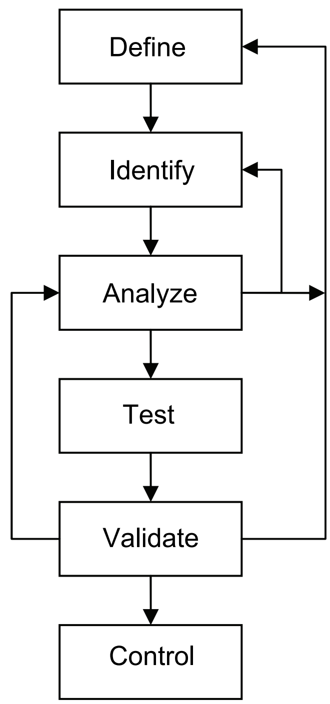

Figure 6—Validation Process

6.3.2.3 Identify

The validation process should identify the following:

a) the verification methods that require validation;

b) the materials that require validation;

c) the system validation requirements;

d) how the requirements (external and internal) affect the system;

e) how these effects can compromise the functionality and design life of the system;

f) known failure modes, such as but not limited to functional failure, structural failure, leakage, and fatigue;

g) identify the critical attributes of the components to be controlled during manufacturing.

Once these steps have been completed, identify the tests required to prove the system under design is fit-for-service.

6.3.2.4 Analyze

The effect of the loads and environmental conditions on the system should be analyzed. The tests that will replicate these effects under simulated loads and environmental conditions should be identified. The number of parts required to be tested to give confidence in the effectiveness of the solution to eliminate the failure mode should be defined. Types of required tests should be selected. The analysis should be performed at the system, subsystem, and component level.

Design of experiments, failure replication, and the Arrhenius method are a few of the methods that can be used to design the tests. Criticality or risk of each failure mode should be identified. An appropriate test for validation should be determined.

6.3.2.5 Test

6.3.2.5.1 General

A complete system test should be performed whenever feasible. If a system test is not practical due to logistical challenges, multiple tests on the minimum number of subsystems (system divided into largest possible subsystems) should be performed. The tests should prove the components and system functionality including interfaces.

Component and subsystem identified tests in accordance with identified failure modes should be performed. Each test should have a goal, a procedure, and acceptance criteria.

There are many test types that can be used to prove that the system/subsystem/component is fit-for-service. One or more types of tests can be performed to qualify a component. The following are examples of test methods that may be used:

a) analytical testing,

b) scale/model testing,

c) full-scale/prototype testing,

d) component/subsystem testing,

e) in-service testing,

f) accelerated life testing,

g) installation/system integration testing.

Other test methods may also be applicable.

6.3.2.5.2 Accelerated Life Testing

Accelerated life testing may be appropriate in some cases. Acceleration factors should be determined prior to defining the length of the test in order to keep the same failure modes. Accelerated life testing should not introduce new failure modes.

6.3.2.5.3 Testing Conditions

Worst conditions may not occur at the extremes of the specified environmental loads. It could be during transition from one state to another. These conditions should be identified during the verification phase. Loads can be grouped into the following categories (see API 1111 and API 2RD):

a) factory loads (loads during manufacturing, assembly, and FAT);

b) installation loads;

c) normal or operational loads;

d) extreme loads (loads that the system are unlikely to exceed during their life as defined in API 1111);

e) survival loads (worst case level)/ultimate load (conditions that exceed the extreme design events API 2RD).

Other loads that should be considered may include system integration loads. Design margins applicable to various loading conditions may be different.

6.3.2.5.4 Test Procedures

The test should follow the following basic guidelines:

a) designed specifically for the system/subsystem/component under test;

b) target previously identified failure modes;

c) validation tests should have acceptance criteria;

d) tests should be performed by competent personnel;

e) proper verification of the test procedure and results is recommended;

f) test procedure and results should be verified by a competent person who did not perform the test;

g) test and measurement equipment calibration should be current;

h) an appropriate number of tests and specimens should be used to ensure the test is valid and reproducible;

i) test failures should be analyzed, reported, and documented;

j) investigation of tests not meeting the acceptance criteria should be conducted to identify the root cause, take corrective action, and then retest.

6.3.2.6 Validate

Test results should be assessed against the objectives. Confirm that the tests validate the verification process and prove the system, subsystems, and components meet the design requirements.

Any new failure modes identified by testing should be added to the list of identified failure modes. A new test should be designed and performed following the same validation process to prove the system/subsystems/components are fit-for-service and the mitigation of the failure modes.

The test should be repeatable and verifiable and should meet the acceptance criteria established in the procedure.

6.3.2.7 Control

Develop a set of procedures to ensure the validated system accurately represents the system defined in the basis of design and subsequently manufactured.

6.3.3 Other Validation Process Considerations

6.3.3.1 General

The critical or governing stresses in parts for which theoretical stress analysis does not meet the established acceptance criteria, or for which design values are not established, should be substantiated by experimental stress analysis testing or design simulations.

Where testing to the limits of the operating loads or environment is not practical, testing and analysis may be combined. The testing and design analysis should simulate in-service conditions.

6.3.3.2 Previously Validated Field-proven Designs

Where verification and sufficient industry experience exists, design validation documentation may be completed and approved by a qualified person to meet the functional and technical specifications and acceptance criteria. This should include a detailed field history of successful performance of the same size, type, model and method operations in an environment similar to that of the functional specifications.

6.3.4 System Considerations

The results of the validation process may indicate a need to update the IMP for the life of the product. This may include potential failure modes and their effects, system interactions, and component life cycles.

6.4 Manufacturing Process Specification (MPS)

6.4.1 Supply of Castings and Forgings for HPHT Service

It is recommended that adherence to a specific quality specification such as API 20A and API 20C be considered. This family of specifications will encompass castings, closed die forgings, and open die forgings. These specifications will address levels of quality numbered in increasing levels of severity in order to reflect increasing technical, quality and qualification criteria. Materials used for HPHT service should meet the materials selection guidelines in 6.1. API 6HT should be considered for heat treatment and testing guidelines of carbon and low-alloy steel large cross-section components.

See Annex D for a discussion on the technical considerations involved in selecting castings or forgings.

6.4.2 Quality Assurance

6.4.2.1 General

The attributes identified in the verification and validation processes should be part of the quality assurance plan for the equipment and should be agreed between the manufacturer and the user. Important steps in any quality assurance program for HPHT equipment are

— the detailed development of the product requirements to clear and measurable attributes for material, dimensions, and manufacturing processes and

— the selection of approved suppliers who maintain a high level of quality assurance in their manufacturing processes.

See Annex E for information on quality management systems.

6.4.2.2 Product Requirements

These requirements should be clearly defined by measurable factors documented in the basis of design and functional specifications. These requirements should include relevant inspection and test methods and acceptance criteria.

6.4.2.3 Supplier Quality Assurance

When providing critical products or services, a supplier should have and maintain a quality management system that is certified in accordance with API Q1 or other internationally accepted quality standard. For products or services that are not of a critical nature, certification to a quality standard is not required; however, the supplier should have and maintain a quality management system that meets the intent of API Q1 or other internationally accepted quality standard.

6.4.3 HPHT Equipment Manufacturing Process Quality Control

6.4.3.1 General

Quality Control should be applied to ensure the manufactured product falls within the design requirements previously defined by the verification and validation processes. It may include 100 % product testing or sample lot testing, depending upon quality requirements of the product standard.

6.4.3.2 Inspections

6.4.3.2.1 Records

Inspection records should be addressed in the specifications of the components. Consideration should be given to future in-service life cycle inspection requirements and fit-for-service evaluations when determining records and their retention requirements.

6.4.3.2.2 Nondestructive Examination (NDE)

NDE plays a unique role in HPHT equipment. Existing standards all contain requirements for NDE. Critical imperfection size as determined during the verification analysis should be compared against the inspection methodology to ensure imperfections can be found and assessed for criticality.

6.4.3.3 Factory Acceptance Tests

Factory acceptance tests should be determined in the design verification and validation process. Factory acceptance for product components or final product/system should be conducted to verify that the product conforms to the design requirements including any systems integration considerations and to ensure conformance to established technical, manufacturing, and quality acceptance criteria relative to fit, form, and function.

6.4.4 Documentation Retention

Document retention should be addressed in the specifications of the components. Consideration should be given to retaining documentation that will support future assessments of residual service life verification or service life extension.

6.5 Aftermarket Activities

In-service inspection may be used to qualify equipment for additional life beyond the initial determined service life or service loads. These inspections (type, frequency, and acceptance criteria) should be detailed in the IMP (see 5.7 for the equipment).

Annex A
(informative)

Material Properties

A.1 General

This annex contains the temperature-affected properties available for carbon or low-alloy steels, stainless steels, and CRAs.

NOTE All of the material properties are for reference only and are only a subset of available information for the industry. The information presented is only for example and subject to change.

A.2 Carbon and Low-alloy Steels—High-temperature Strength Data

A.2.1 General

The AISI or SAE alloy steels contain, in addition to carbon, several percent additions of various alloying elements to improve their strength, depth of hardening, toughness, or other properties of interest. Some alloy steels are identified by the AISI four-digit system of numbers. The first two digits indicate the alloy group and the last two the approximate carbon content in hundredths of a percent. The alloying elements used in these steels include manganese, silicon, nickel, chromium, molybdenum, vanadium, and boron.

A.2.2 Low-alloy Steel—4130/4140

A.2.2.1 Tensile Derating for Casing

Table A.1 presents an example of thermal decay for API 5CT casing.

Table A.1—Example of Thermal Decay of API 5CT Casing

API Grade	Temperature °F				
	122	212	302	347	392
L80	99.6	95.9	91.3	89.5	88.7
P110	97.2	93.6	90.7	90.1	89.5
Q125	98.6	95.6	93.8	92.6	91.3

NOTE 1 Example data courtesy of Sumitomo.

NOTE 2 This table denotes the percentage of room temperature strength levels.

A.2.2.2 Mechanical Properties of 4130 and 4140 (from MMPDS)

The mechanical properties of AISI 4130 and AISI 4140 as a function of temperature are shown in Figure A.1 and Figure A.2.

A.2.3 Mechanical Properties Available from AWHEM for Low-alloy Steel Forgings

API 6A, Annex G provides derating factors for low-alloy and stainless/CRA steels used in high-temperature service. Table A.2 gives the data from a series of tests conducted by AWHEM for API [30].

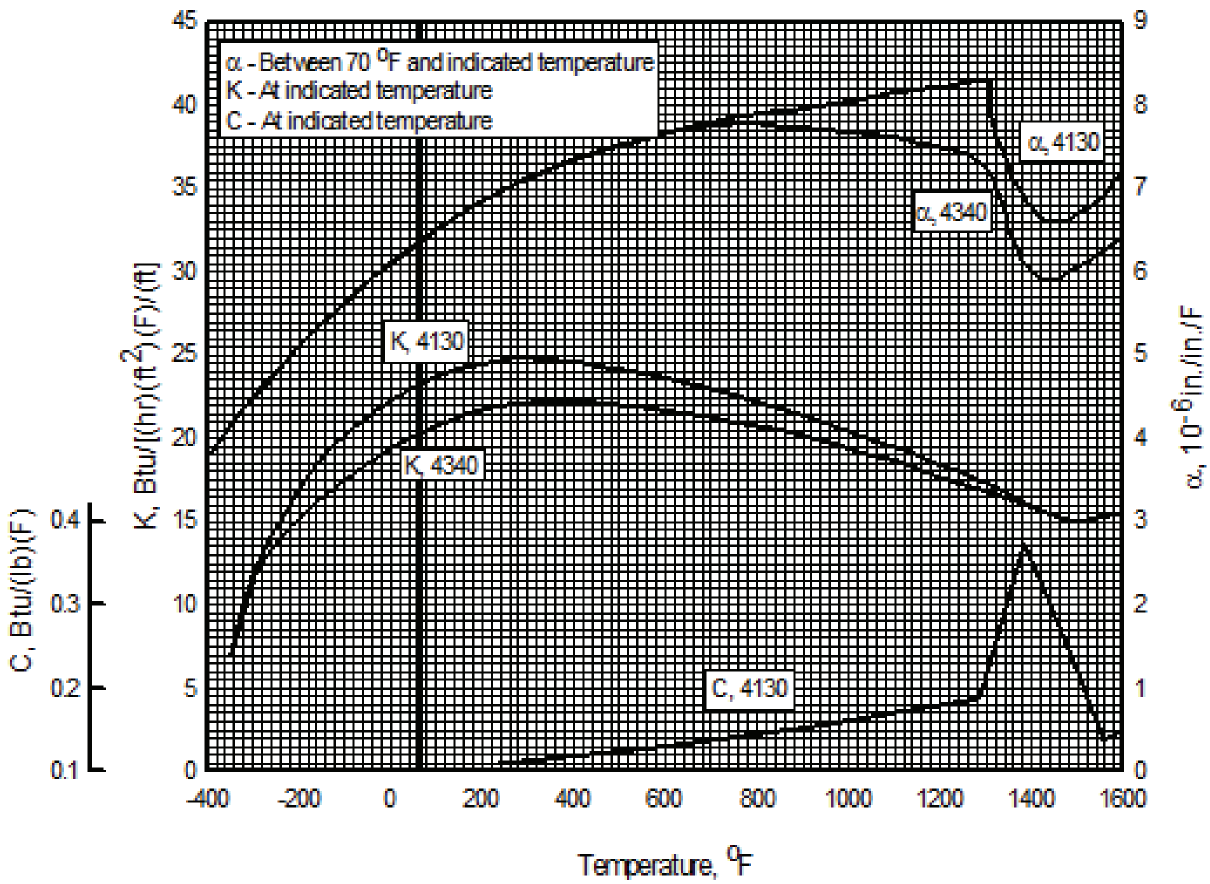

Figure A.1—Example of Effect of Temperature on Thermophysical Properties of 4130 and 4340 (MMPDS)

Table A.2—Recommended Yield Strength Reduction Ratios in Percent by Temperature for Low-alloy Steels

Material	**Temperature °F**			
	300	**350**	**400**	**450**
AISI 4130 low-alloy steel	91	90	89	88
AISI 8630 low-alloy steel	92	90	89	87
2 1/4Cr-1Mo low-alloy steel	92	91	90	89
AISI 4140 low-alloy steel	92	90	89	88
NOTE This table denotes the percentage of room temperature strength levels.				

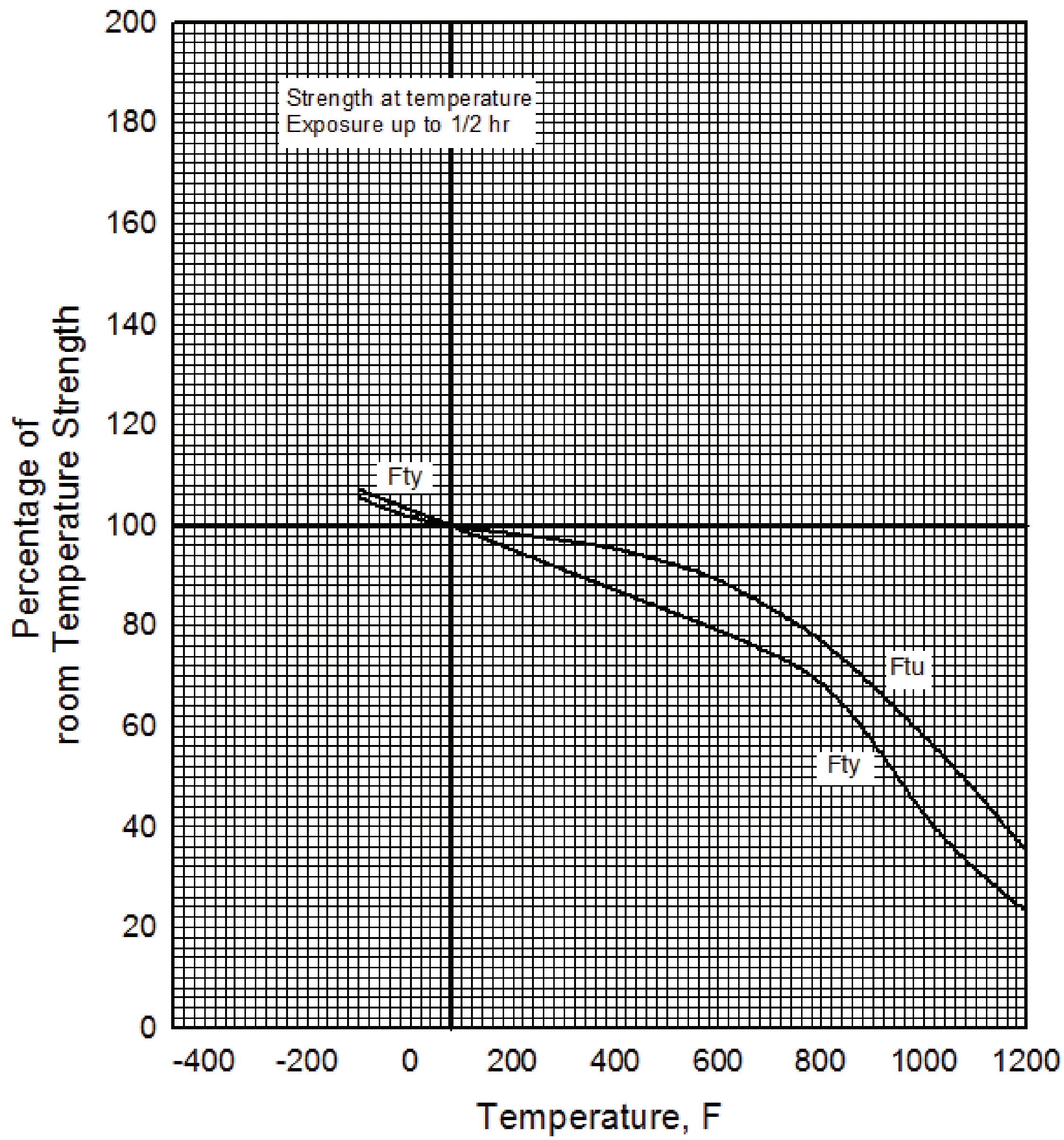

Figure A.2—Example of Effect of Temperature on the Tensile Ultimate Strength (F_{tu}) and Tensile Yield Strength (F_{ty}) of AISI Low-alloy Steels (All Products) (MMPDS)

A.2.4 Strength Properties for 4130M7

Reference data for tubing with the chemistry as provided in Table A.3 and Table A.4.

Table A.3—Example of Composition of 4130M7 Tubing

C	Mn	P	S	Si	Cr	Ni	Mo	Cu	Al	V	Cb
0.31	0.80	0.01	0.01	0.26	1.44	0.13	0.67	0.22	0.02	0.01	0.03

Table A.4—Example of Hot Tensile Testing of 4130M7 Tubing

Material	Tensile Diameter in.	Test Temp. °F	0.2 % Yield ksi	UTS ksi	%EL	%RA
5.160 in. OD × 1.438 in. wall CTTF [a] Q/T [b] line	0.505	75	118.5	132.4	21	68
	0.357	100	120.8	132.6	22	69
	0.357	200	115.8	127.9	20	70
	0.357	300	109.5	125.0	21	70
	0.357	400	104.6	124.5	20	67
	0.357	500	101.0	125.4	22	66

a Continuous thermal treating facilities.
b Quench and temper.

A.2.5 Cyclic Test Data for Low-alloy Steels

Fatigue properties are based upon a material characterization program sponsored by the BSEE in 2007.

The crack growth relationship between the stress intensity factor range, ΔK, and the crack growth per cycle, da/dN, is shown in Figure A.3 for 2 1/4Cr-1Mo steel. In addition, curves from API 579-1/ASME FFS-1, ASM *Atlas of Fatigue Curves*, BS 7910, and ASME *BPVC*, *Section VIII*, *Division 3*, environmental growth curves from Suresh and Ritchie have been added.

Additional fatigue data for the 2 1/4Cr-1Mo alloy can be found in Reference [126].

A.3 Corrosion Resistant Alloys (CRAs)

A.3.1 Derating Factors for Stainless Steels and CRAs from AWHEM

API 6A, Annex G provides derating factors for low-alloy and stainless steels and CRA steels used in high-temperature service. Table A.5 gives the data from a series of tests conducted by AWHEM for API [30].

A.3.2 Martensitic Stainless Steels

The martensitic stainless steels were developed as the first step in CRAs. They have good CO_2 corrosion resistance up to 400 °F. For oilfield applications, the forgeable 12Cr alloy (AISI 410) has been in use as wellheads since the 1970s. Nickel was added to the basic 12Cr alloy (F6NM) to provide good low temperature toughness in a wellhead forging. A tubing version of the 12Cr alloy is available (called 13Cr). In the 1990s additional tubing alloys were developed with the addition of nickel and molybdenum to improve strength greater than 110 ksi. These alloys are hardenable by a heat treatment of quench and tempering. Ni and Mo also improved impact toughness as compared to Grade L80 13Cr that has lower impact toughness and no minimum Ni and Mo levels.

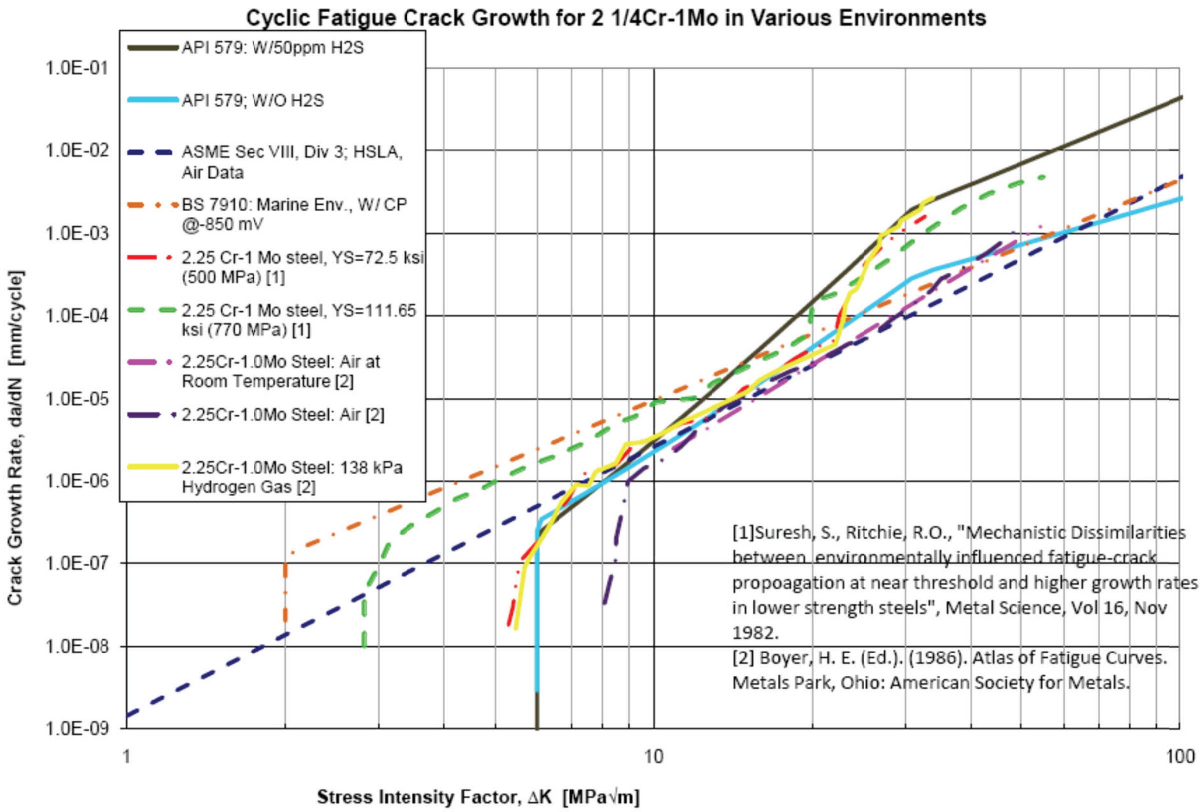

Figure A.3—Example of Compendium of Cyclic Curves for Carbon Steel and 2 1/4Cr-1Mo

Table A.5—Recommended Yield Strength Reduction Ratios in Percent by Temperature for Stainless Steels and CRA Steels

Material	Temperature °F			
	300	350	400	450
AISI 410 martensitic stainless steel	91	90	89	88
F6NM martensitic stainless steel	92	91	89	88
25Cr super duplex	81	78	76	73
ASTM A453 Grade 660 precipitation hardened austenitic stainless steel	99	95	96	97
718 (in accordance with API 6A718) nickel alloy	94	93	92	91
725/Custom Age 625PLUS® nickel alloy	93	92	90	89
INCOLOY® Alloy 925™ nickel alloy	92	92	91	90

NOTE 1 This table denotes the percentage of room temperature strength levels.

NOTE 2 The use of registered trademark names does not constitute an endorsement of these products by API. These alloys are listed for information only; API does not require the use of proprietary or patented products.

A.3.3 Fe-based Austenitic Stainless Steels

A.3.3.1 General

The austenitic (18-8) stainless steels were developed as corrosion-resistant alloys. They possess excellent corrosion resistance and good creep strength at elevated temperatures, along with good cold formability and other properties in tubing. These steels are also used extensively at cryogenic temperatures. The primary alloying elements in the austenitic stainless steels are chromium and nickel. Chromium adds corrosion and oxidation resistance and high-temperature strength, and nickel gives an austenitic structure, with its associated toughness and ductility. The AISI 300 series stainless steels constitute a wide variety of compositions designed for different applications. The basic grade, Type 304, contains 18 % chromium and 8 % nickel. Varying one or both of these elements creates special characteristics. UNS N08535 (25 % chromium, 35 % nickel, 3 % molybdenum is considered a Fe-based alloy by API 5CRA, but is considered Ni-based in NACE MR0175/ISO 15156) work hardens to high strengths, has higher elevated temperature strength, and greater corrosion resistance than Type 316. Sulfur and selenium additions promote free machining but can have adverse effects on mechanical properties. Low carbon and/or columbium or titanium additions minimize intergranular corrosion for elevated temperature applications and welded construction. The addition of molybdenum improves corrosion resistance in reducing environments, e.g. 316. These alloys are not hardenable by heat treatment but achieve high-strength through cold working. Without cold working, their yield strength is approximately 35 ksi. The strength imparted by cold working is decreased by exposure to elevated temperatures.

Heat-treating should be adequate to permit thorough heating of the billet but should be controlled carefully to limit grain growth when small reductions are involved during forging. At forging temperatures, the stainless steels are stronger than alloy steels, and forging should be conducted at higher temperatures. Heavier forging equipment and more frequent reheating are required. The stainless steel billets forge much better when the surface is free of defects, and machine turning of the billets is advisable.

A.3.3.2 UNS N08535

Figure A.4 illustrates the effects of temperature on yield strength and ultimate tensile strength of UNS N08535.

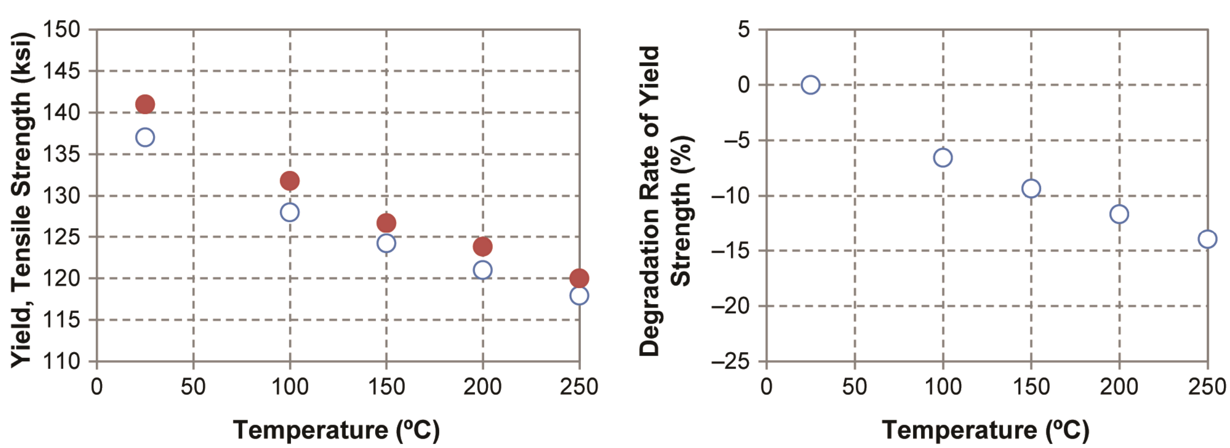

Figure A.4—Example of Effect of Temperature on Tensile Properties of Alloy N08535 in 125 ksi Minimum Yield Strength Grade

A.3.4 Duplex Stainless Steels

A.3.4.1 General

Duplex stainless steels have a mixed microstructure of austenite and ferrite aiming for a 50-50 mix. They have improved strength over austenitic stainless steels and corrosion resistance. The chromium content is 19 % to 28 %, molybdenum is up to 5 % with lower nickel contents than austenitic stainless steels. The most common duplex is 22 % chromium, 2205. Super duplex refers to 25 % chromium grades such as UNS S32760 (Zeron® [2] 100), S32750 (2507), and S32550 (FERRALIUM® Alloy 255) (trade names are provided for identification purposes but can also be found in the UNS listings.) Duplex stainless steels find their use in oilfield applications in valves, piping, heat exchanger tubing, and production tubing. The properties of duplex stainless steels are achieved with an overall lower alloy content than similar austenitic steels, making their use cost-effective for many applications. The duplex stainless steels find use in low H_2S environments. They have good strength and ductility for oil country tubular goods. Care in use is needed at temperatures greater than 150 °F because of the reduction of yield strength at elevated temperature.

Duplex SS are used often in subsea applications because of their good seawater resistance. Care with the cathodic protection potentials and stresses is needed, since this alloy can suffer from hydrogen embrittlement if the protection potentials are too negative (see DNV RP-F112).

In manufacturing (e.g. forging, extrusion, stress relieving, and welding), the most common problem is the formation of sigma phase that can lead to brittle failure. Good quality control and attention to time at temperature is the key to preventing the formation of this deleterious second phase.

The time–temperature relationship that leads to the precipitation of sigma phase in duplex and super duplex stainless steels effectively limits the size and wall thickness of components that can be manufactured. Therefore, for HPHT applications where wall thicknesses increase, designers are cautioned in using these alloys.

A.3.4.2 UNS S39274 Strength Properties

Decrease in strength properties as a function of temperature are shown in Figure A.5.

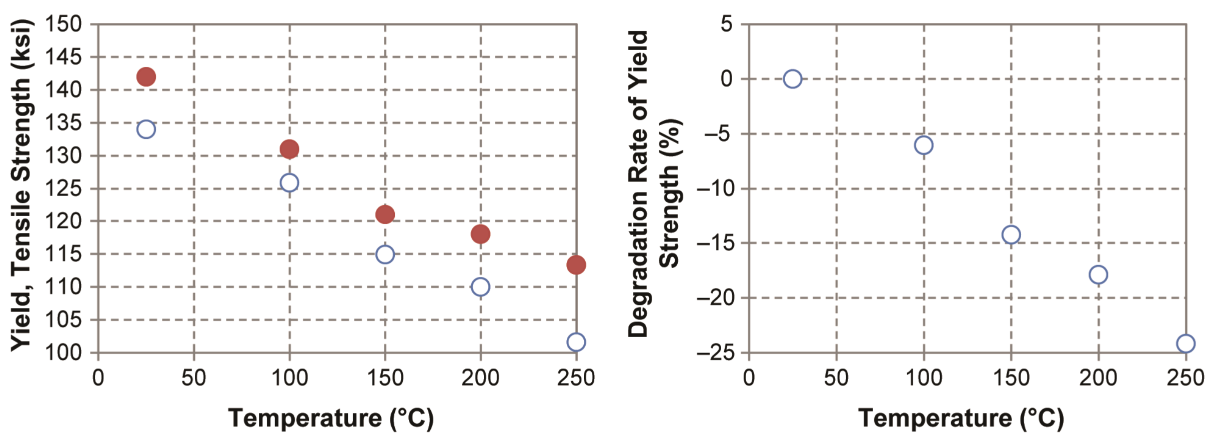

Figure A.5—Example of Effect of Temperature on Strength of Alloy 25CrW (UNS S39274)

2 The use of registered trademark names does not constitute an endorsement of these products by API.

A.3.5 Austenitic Ni-based Alloys

A.3.5.1 General

The common alloying elements for nickel-based alloys are cobalt, iron, chromium, molybdenum, titanium, and aluminum. Cobalt, when substituted for a portion of the nickel in the matrix, improves high temperature strength; additions of iron tend to strengthen the nickel matrix and reduce the cost; chromium is added to increase strength and oxidation resistance at very high temperatures; molybdenum contributes to solid solution strengthening. Depending on the alloy, strength can be achieved by cold work for use as production tubing (e.g. UNS N08825) or by heat treatment for use as a tubing head or packer (e.g. UNS N09925). The cold worked tubing alloys have good high temperature corrosion resistance to H_2S and CO_2 with high strength (up to 180 ksi maximum yield strength). The heat treatable alloys also provide good corrosion resistance and high strength.

A.3.5.2 Alloy 825 Strength Properties (UNS N08825)

Mechanical properties for Alloy 825 as a function of temperature are shown in Table A.6.

Table A.6—Example of Mechanical Properties of Alloy 825 (Cold Worked) from 4 in. Diameter Tube

Temp °F	**Yield Strength** ksi	**Tensile Strength** ksi	**Reduction in Area** %	**Elongation** %	**Hardness** HRC @ RT
Data Set 1					
RT	115.6	125.4		21.9	25
300	103.9	109.5	66.8	18.7	
400	101.7	105.8	63.9	15.9	
	103.2	109.5	68.4	16.0	
425	104.5	108.6	66.9	15.6	
	102.2	107.1	62.8	16.1	
450	103.7	109.5	68.9	17.5	
	103.9	108.5	66.8	16.4	
Data Set 2					
RT	116.1	127	—	22.4	25
300	105.6	110.3	74.4	19.1	
Data Set 3					
RT	117.1	125.0	—	22.8	26.0
300	105.0	110.0	74.1	18.3	
400	105.0	109.0	67.8	17.0	
	105.0	109.3	67.0	17.6	
425	109.6	114.1	64.6	15.6	
	104.1	108.9	64.7	17.1	
450	103.9	108.3	70.0	17.3	
	102.8	108.0	62.8	17.5	

A.3.6 Age-hardened Ni-based Alloys

A.3.6.1 General

The requirements for UNS N07718 are controlled in API 6A718. No similar control is available for the other heat treatable alloys like INCONEL® [3] Alloy 725™, Custom Age 625PLUS®, or INCOLOY® Alloy 925™; thus attention to the material requirements are advised. The background on the control needed for 718 is based on the contradictory requirements of aerospace alloys vs oil field requirements. If the alloy is manufactured for an aerospace application it is virtually impossible to heat treat it for use in the oil field.

A.3.6.2 UNS N07718 Strength Properties

Figure A.6, from MMPDS, is provided for general background on the effect of temperature on the properties of alloy UNS N07718. This is for an aerospace version of the alloy and the details of strength loss may differ from the oilfield version of UNS N07718 (API 6A718).

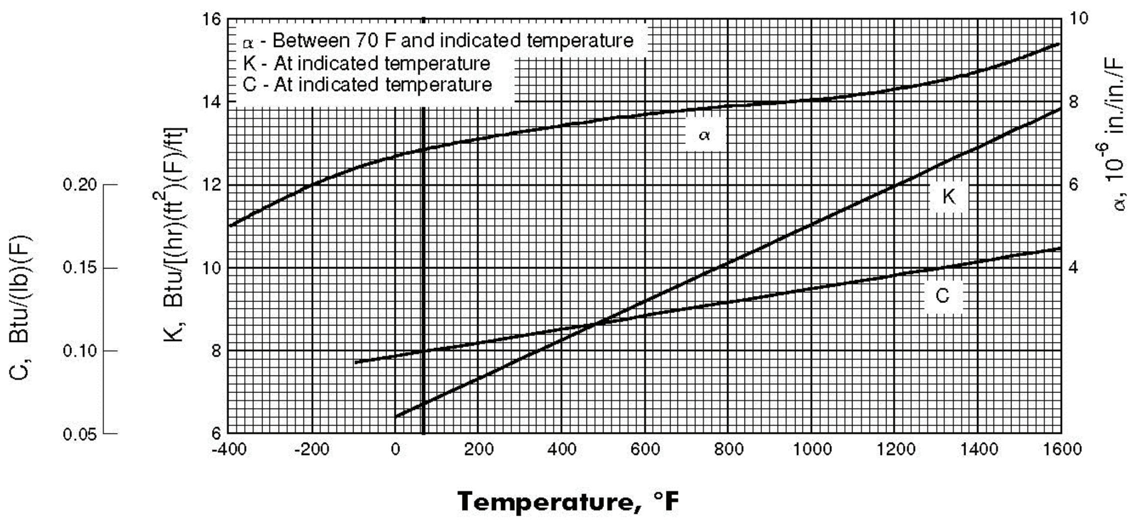

Figure A.6—Example of Effect of Temperature on the Thermophysical Properties on UNS N07718 (MMPDS)

A.3.6.3 Alloy 725 (UNS N07725) Strength Properties

The tensile properties of material from three heats of INCONEL® Alloy 725™ were determined at temperatures from ambient to 1000 °F to support development of allowable design stresses for INCONEL® Alloy 725™ products for ASME *BPVC*, *Section VIII*, *Division 1* construction. The material for these tests was solution annealed and precipitation hardened. The chemical compositions of the heats tested are presented in Table A.7. The tensile data reported by test temperature are found in Table A.8. These data are the basis for ASME Code Case 2217.

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[3] The use of registered trademark names does not constitute an endorsement of these products by API.

Table A.7—Example of Chemical Composition of Heats Tested

	C	Mn	Fe	P	S	Si	Cr	Ni	Mo	Cu	Al	Ti	V	Nb
HT4593LY	0.009	0.10	9.22	0.002	0.002	0.04	20.92	56.33	8.02	—	0.019	1.62	—	3.54
HT4732LY	0.004	0.08	9.18	0.005	0.001	0.05	21.01	56.22	8.13	—	0.200	1.50	—	3.60
HT4757LY	0.004	0.07	9.66	0.004	0.002	0.04	20.88	55.90	8.06	—	0.200	1.59	—	3.57

Table A.8—Example of Tensile Properties as a Function of Temperature for INCONEL® Alloy 725™

Diameter in.	**Heat Number**	**Temperature** °F	**UTS** ksi	**0.2 % Yield Strength** ksi	**Elongation** %	**Reduction in Area** %	**Hardness** Rc
0.625	HT4732LY-1B	Room	178.9	127.0	32.6	51.4	36
	HT4732LY-1B	Room	180.1	121.4	32.1	51.7	
	HT4732LY-1B	Room	181.5	123.3	32.9	51.3	
1.000	HT4732LY-18	Room	177.6	120.5	35.0	51.0	37
	HT4732LY-18	Room	175.9	124.4	35.7	52.1	
4.500	HT4593LY-1211	Room	186.9	135.6	28.3	42.8	38
	HT4593LY-1211	Room	195.5	140.4	29.3	45.4	
	HT4593LY-1211	Room	181.8	133.9	31.4	45.7	
6.500	HT4757LY-211	Room	179.9	134.3	31.4	47.8	37
	HT4757LY-211	Room	184.3	135.6	30.7	45.8	
	HT4757LY-211	Room	178.9	126.7	32.9	46.9	
0.625	HT4732LY-1B	100	181.9	127.0	34.0	51.7	
1.000	HT4732LY-18	100	177.0	123.7	38.0	52.3	
4.500	HT4593LY-1211	100	185.9	140.5	29.0	42.3	
6.500	HT4757LY-211	100	184.0	135.7	29.5	49.5	
0.625	HT4732LY-1B	200	173.5	118.0	32.0	51.2	
	HT4732LY-1B	200	176.9	118.0	32.0	52.8	
1.000	HT4732LY-18	200	172.4	114.4	33.0	50.2	
4.500	HT4593LY-1211	200	186.8	137.3	25.5	39.1	
	HT4593LY-1211	200	183.5	129.8	27.0	44.6	
6.500	HT4757LY-211	200	180.2	134.3	28.0	46.4	
	HT4757LY-211	200	175.9	129.7	30.0	45.1	
0.625	HT4732LY-1B	300	168.6	115.9	33.0	55.3	
	HT4732LY-1B	300	172.2	117.6	30.0	51.4	
	HT4732LY-1B	300	171.7	115.5	33.0	53.8	
1.000	HT4732LY-18	300	168.0	111.0	34.0	49.1	
	HT4732LY-18	300	167.9	107.9	34.0	53.6	
4.500	HT4593LY-1211	300	177.8	134.5	27.0	41.8	
6.500	HT4757LY-211	300	176.6	129.1	28.0	49.4	
	HT4757LY-211	300	176.8	126.9	28.0	47.3	

Table A.8—Example of Tensile Properties as a Function of Temperature for INCONEL® Alloy 725™ (Continued)

Diameter in.	**Heat Number**	**Temperature** °F	**UTS** ksi	**0.2 % Yield Strength** ksi	**Elongation** %	**Reduction in Area** %	**Hardness** Rc
0.625	HT4732LY-1B	400	166.1	116.0	33.0	57.1	
	HT4732LY-1B	400	168.1	115.8	31.0	53.5	
	HT4732LY-1B	400	168.9	115.6	31.0	53.9	
1.000	HT4732LY-18	400	165.4	110.4	34.0	55.4	
	HT4732LY-18	400	164.9	108.5	35.0	55.3	
4.500	HT4593LY-1211	400	174.2	133.7	27.0	46.0	
	HT4593LY-1211	400	175.4	124.8	27.0	48.4	
6.500	HT4757LY-211	400	172.2	127.0	29.0	50.7	
	HT4757LY-211	400	171.7	123.9	29.0	51.5	
0.625	HT4732LY-1B	500	161.6	112.8	35.0	56.7	
1.000	HT4732LY-18	500	163.2	109.1	32.0	51.5	
4.500	HT4593LY-1211	500	172.5	125.6	27.0	48.9	
6.500	HT4757LY-211	500	164.8	123.0	30.0	53.7	
0.625	HT4732LY-1B	600	158.2	110.2	35.0	58.9	
1.000	HT4732LY-18	600	156.9	106.6	33.0	52.6	
	HT4732LY-18	600	156.7	105.6	36.0	55.4	
4.500	HT4593LY-1211	600	165.4	124.8	27.0	48.5	
6.500	HT4757LY-211	600	160.5	119.7	31.0	55.6	
0.625	HT4732LY-1B	650	157.2	110.8	33.5	56.8	
1.000	HT4732LY-18	650	158.4	110.1	31.0	54.9	
	HT4732LY-18	650	154.6	104.2	36.0	55.1	
4.500	HT4593LY-1211	650	167.6	127.1	28.0	50.4	
	HT4593LY-1211	650	161.9	121.9	29.0	51.4	
6.500	HT4757LY-211	650	158.9	124.4	30.0	54.0	
	HT4757LY-211	650	160.1	123.4	30.0	51.8	
0.625	HT4732LY-1B	700	154.6	110.2	34.0	57.7	
1.000	HT4732LY-18	700	155.1	105.8	33.0	53.2	
4.500	HT4593LY-1211	700	165.5	123.0	27.0	50.7	
6.500	HT4757LY-211	700	160.0	119.7	30.0	54.9	
	HT4757LY-211	700	159.5	119.8	30.0	50.6	

Table A.8—Example of Tensile Properties as a Function of Temperature for INCONEL® Alloy 725™ (Continued)

Diameter in.	**Heat Number**	**Temperature** °F	**UTS** ksi	**0.2 % Yield Strength** ksi	**Elongation** %	**Reduction in Area** %	**Hardness** Rc
0.625	HT4732LY-1B	750	154.2	110.4	33.0	57.4	
1.000	HT4732LY-18	750	154.9	106.9	32.0	54.6	
4.500	HT4593LY-1211	750	165.8	123.4	28.0	48.7	
6.500	HT4757LY-211	750	156.1	122.8	30.0	54.7	
0.625	HT4732LY-1B	800	153.6	111.0	33.0	54.8	
1.000	HT4732LY-18	800	154.9	105.6	33.0	51.1	
4.500	HT4593LY-1211	800	161.5	121.6	28.0	47.9	
6.500	HT4757LY-211	800	155.0	117.7	30.0	54.9	
0.625	HT4732LY-1B	850	151.2	109.5	33.0	55.4	
1.000	HT4732LY-18	850	153.2	106.7	32.0	53.7	
4.500	HT4593LY-1211	850	162.0	123.9	30.0	45.9	
6.500	HT4757LY-211	850	154.6	118.1	31.0	51.4	
0.625	HT4732LY-1B	900	151.2	109.9	32.0	51.7	
1.000	HT4732LY-18	900	152.1	104.1	33.0	50.0	
4.500	HT4593LY-1211	900	162.0	122.7	30.0	47.9	
6.500	HT4757LY-211	900	160.5	124.4	30.0	49.7	
	HT4757LY-211	900	154.1	120.8	28.0	50.6	
	HT4757LY-211	900	155.5	120.6	31.0	48.4	
0.625	HT4732LY-1B	950	151.3	107.8	31.0	52.9	
1.000	HT4732LY-18	950	155.5	102.6	33.0	52.8	
	HT4732LY-18	950	147.1	103.0	36.0	53.8	
4.500	HT4593LY-1211	950	156.9	120.2	30.0	46.5	
	HT4593LY-1211	950	162.4	118.8	29.0	45.5	
6.500	HT4757LY-211	950	153.0	117.4	31.0	49.0	
0.625	HT4732LY-1B	1000	150.6	110.0	33.0	46.3	
	HT4732LY-1B	1000	150.7	109.7	32.0	51.9	
1.000	HT4732LY-18	1000	147.4	104.1	33.0	53.0	
	HT4732LY-18	1000	147.6	103.1	34.0	49.5	
4.500	HT4593LY-1211	1000	165.4	124.0	26.0	39.7	
	HT4593LY-1211	1000	156.6	121.5	29.0	45.8	
6.500	HT4757LY-211	1000	155.9	117.8	30.0	47.4	

NOTE 1 The use of registered trademark names does not constitute an endorsement of these products by API.

NOTE 2 These alloys are listed for information purposes only; API does not require the use of proprietary or patented products.

A.3.7 Titanium Based Alloys

A.3.7.1 General

Titanium is a relatively lightweight, corrosion-resistant structural material that can be strengthened through alloying and, in some of its alloys, by heat treatment. Among its advantages for specific applications are: good strength-to-weight ratio, low density, low coefficient of thermal expansion, good corrosion resistance, good oxidation resistance at intermediate temperatures, good toughness, and low heat treating temperature during hardening, and others. It finds its greatest applications in aerospace, but is used in offshore oilfield applications as stress joints in tension leg platforms. Some production applications have been installed, but its use is limited due primarily to availability and cost. Some high temperature data is provided in A.3.7.2.

A.3.7.2 Titanium 6246 (UNS R56260)

Data for oilfield applications from bar stock is provided in Table A.9 and Table A.10.

Table A.9—Example of Composition of Alloy Tested in the Accompanying Tensile Data

Diameter in.	**Heat Number**	**C**	**Mo**	**N**	**Fe**	**Ti**	**Al**	**O**	**Sn**	**Zr**	**H**
1.625	8-35-3203	0.007	5.500	0.007	0.046	Bal	5.720	0.124	1.95	3.690	0.004
3.250	8-41-4226	0.006	6.270	0.006	0.038	Bal	5.920	0.116	2.070	3.920	0.0031
4.000	8-41-4140	0.006	6.080	0.008	0.050	Bal	5.740	0.108	2.040	3.680	0.0072
4.250	9521748	0.007	6.140	0.002	0.040	Bal	6.040	0.110	1.980	3.980	0.0034
5.188	8-841-4465	0.005	6.060	0.004	0.008	Bal	5.870	0.120	2.08	3.890	0.0042

Table A.10—Example of Tensile Properties of Titanium 6-2-4-6 (UNS R56260)

Diameter in.	**Heat Number**	**Temperature** °F	**UTS** ksi	**0.2 % Yield Strength** ksi	**Elongation** %	**Reduction in Area** %	**Hardness** HRc
1.625	8-35-3203	Room	168.2	158.1	18	46.0	40
1.625	8-35-3203	450	143.9	127.6	19	52.0	
3.250	8-41-4226	Room	177.7	167.1	15	46.0	40
3.250	8-41-4226	350	149.0	132.7	20	50.0	
4.000	8-41-4140	Room	171.5	164.4	14	41.0	39
4.000	8-41-4140	400	150.5	136.3	16	45.0	
4.250	9521748	Room	192.5	175.2	12	39.0	43
4.250	9521748	400	156.8	133.4	17	52.5	
5.188	8-41-4465	Room	146.6	139.0	21	49.0	36
5.188	8-41-4465	400	130.7	111.6	21	53.0	

Annex B
(informative)

Metallurgical-related Failures

The information summarized here includes the alloy, component, geographic location, and the reference for the failure that contains details of the failure analysis.

Table B.1—Field Failures of Completion and Production Equipment from 1975 to Present

Alloy	Year	Component	Location	Causes of Failure		Reference
				Primary	Secondary	
X750	1975	TBG hanger and valve stem		SSC/HE	Acids present at failure	J. Kochera and J. Tralmer, Corrosion 1976, Paper 50
13Cr	1988	SSSV	Gulf of Mexico	SCC	Out-of-spec alloy	J. D. Alkire and S. W. Ciaraldi, “Failures of Martensitic SSs in Sweet and Sour Service,” Corrosion/88, Paper 210
Duplex alloys 22Cr and 25Cr	1989	Production tubing	Marathon, North Sea	HE	Alloy out of spec	P. Sentence, “Hydrogen embrittlement of CW Duplex SS Oilfield Tubulars, Duplex Stainless Steels,” 1991, Vol. 2, Proceedings of Conference held in Beaune, France, October 1991, J. Charles and S. Berhardsson, eds. p. 895
25Cr	1991	Production tubing	Texaco, Erskine, North Sea	SCC	Oxygen ingress	D. E. Mowat, M. C. Edgerton, and E. H. R. Wade, “Erskine Field HPHT Workover and Tubing Corrosion Failure Investigation,” SPE 6779, SPE/IADC Drilling Conference, Amsterdam, Netherlands, 27th February to 1st March 2001
Duplex—Zeron 100	1997	Production manifold forging subsea	Foinaven	HE via CP	Fit-in stress	T.S. Taylor, T. Pendlington, R. Bird, BP Amoco plc, Foinaven Super Duplex Materials Cracking Investigation, OTC-10965-MS, 1999
4140	1998	Outer housing of upper tree connector	Mensa, Gulf of Mexico	Low Cv	Heat treatment	“Brittle Fracture in Upper Tree Connector System at Mensa: An Analysis,” by R. Mack and S. Norton, Corrosion 2001, Paper 01015
17-4PH	1999	Tubing hanger	Total/Elf North Sea	Low Cv	Heat treatment	“Limitations of 17-4 PH Metallurgical, Mechanical, and Corrosion Aspects,” Corrosion 2003, Paper 3102
718	2000	Production hanger	Shearwater, North Sea	Delta phase	Forging/heat treatment	Offshore Ni-alloy Tubing Hanger and Duplex SS Piping Failure Investigations,” by S. Huizinga, B. McLoughlin, W. E. Liek and J. G. de Jong, Corrosion 03129, Corrosion 2003
13CrS	2000	Production tubing and coupling pup joint	Resak Malaysia	SCC	Oxygen contaminated $CaCl_2$ + CO_2 and H_2S	Corrosion 03097, M. Z. Ibrahim, N. Hudson, K. Selamat, P.S. Chen, K. Nakamura, and M. Ueda, 2003, “The Environment that Caused the Cracking Problem was $CaCl_2$ Brine with the Presence of Oxygen, CO_2 and H_2S in the Brine.”

Table B.1—Field Failures of Completion and Production Equipment from 1975 to Present (Continued)

Alloy	Year	Component	Location	Causes of Failure		Reference
				Primary	Secondary	
22Cr	2001	Production tubing	Alex Well, Gulf of Mexico	SCC	Completion brine additive NaSCN	R. Mack, C. Williams, S. Lester, and J. Casassa, "Stress Corrosion Cracking of a Cold Worked 22Cr Duplex Stainless Steel Production Tubing in a High Density Clear Brine $CaC1_2$ Packer Fluid—Results of the Failure Analysis at Deep Alex and Associated Laboratory Experiments," Corrosion/2002, Paper No. 02067, Houston TX: NACE, 2002
SM25CrW	2003	Production tubing	Shearwater, North Sea	SCC	High hardness zone	"Offshore Ni-alloy Tubing Hanger and Duplex SS Piping Failure Investigations" by S. Huizinga, B. McLoughlin, W. E. Like, and J. G. de Jong, Corrosion 03129, Corrosion 2003 and "A New Method of Material Categorization for Super Duplex SS Tubulars," by N. Renton, D. Seymour, I. Hannah, and W. Hughes, SPE 00097, 2005 SPE HPHT Sour Well Design ATW, Woodlands, TX, 17–19 May 2005
13CrS-110	2004	Production tubing	High Is, TX	SCC	Completion brine additive NaSCN	E. Moskowitz-Robinson, "Thiocyanate Corrosion Inhibitors Suspected in Chloride Stress Corrosion Cracking," Offshore, October 2004, p. 64
22Cr	2004	Production tubing	W. Cameron (Gulf of Mexico)	SCC	Completion brine additive NaSCN	E. Moskowitz-Robinson, "Thiocyanate Corrosion Inhibitors Suspected in Chloride Stress Corrosion Cracking," Offshore, October 2004, p. 64
M13Cr-110	2004	Production tubing	Vermillion Parish, LA	SCC	Completion brine additive NaSCN	E. Robinson, "Thiocyanate Corrosion Inhibitors Suspected in Chloride Stress Corrosion Cracking," Offshore, October 2004, p. 64
718	2007	Tubing hanger	Total, North Sea	HE	Cs formate completion brine	T. Cassagne et al., "Understanding Field Failures of Alloy 718 Forging Materials in HP/HT Wells," Eurocorr Conference Paper 1468 (Edinburg, September 2008)
25Cr	2007	Production tubing	Franklin Field, North Sea	SCC	Cs formate completion brine	"Investigation of Production Tubing Coupling Failures from a Suspended HPHT Well," by D. J. Hillis, M. Eddy, T. Cassagne, and J. Ligertwood, 2009 SPE Offshore Europe Oil & Gas Conference & Exhibition, Aberdeen, UK, 8–11 September 2009

Annex C
(informative)

Failure Modes and Effects Analysis (FMEA)

C.1 General

FMEA is a methodology developed during the 1940s by the U.S. armed forces. It was later used in aerospace. It was applied to hazard analysis and critical control point during the race to the Moon. It was introduced to the automotive industry in the 1970s. The oil and gas sector started using FMEA in the late 1990s. The FMEA methodology is currently an accepted practice used by the many oil and gas companies and suppliers as part of their toolkit in various areas of operations and design.

The FMEA is designed to identify failure modes and hazards affecting a focus item (focus items can be a component, a subsystem, or a system). The main goal is to come up with solutions to prevent the failure from happening, hence, improving the reliability of the focus item. It is preferably applied at as many levels as feasible of the system in question to include more specific solutions. The narrower the focus of the FMEA, the more specific the solution to the problem. FMEA has been used extensively in other industries, and it is becoming an integral part of the development process in the upstream oil and gas industry.

There are many standards that address the FMEA methodology. The following is a snapshot of the most cited standards:

— SAE ARP 5580,

— IEC 60812,

— SAE J1739,

— AIAG FMEA-4,

— ISO TS 16949.

C.2 The Validation Process

The FMEA table follows the validation process discussed in the main document and presented in Figure C.1.

C.3 FMEA Process

C.3.1 General

The suggested validation FMEA process should follow some basic rules. In this document, we will develop a validation FMEA matrix using the proven FMEA methodology to come up with test verification protocol for equipment development in HPHT environments. The validation protocols should include:

a) *Validation Plan*—Description of the methodology and list of tests that are designed to prove the fit-for-service status of the system or subsystem;

b) *Test List*—List of the tests performed on the system, subsystem, component that validates the design;

c) *Test Plan*—Plan of how the tests are going to be conducted to achieve the results.

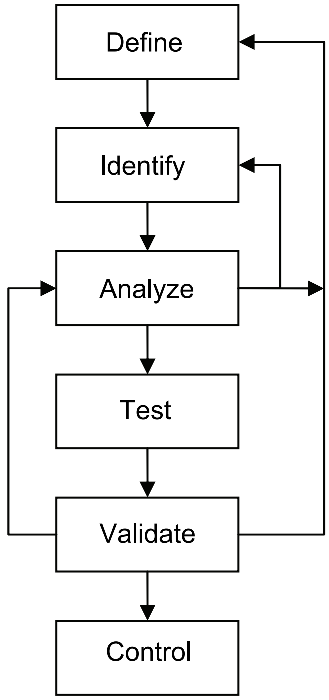

Figure C.1—FMEA Process

C.3.2 FMEA Team

A team should be assembled to assess the technical merits of the design and should be made up of seven to twelve persons. The FMEA team should have at least representatives from

— design,

— manufacturing,

— systems, and

— materials.

The user should be involved in the FMEA process whenever deemed appropriate.

C.4 The Validation FMEA Process

C.4.1 The Matrix

In general, a link will be established between the environmental and functional loads and their resultant failure modes. Then, a test that reproduces these loads and establishes the design conformance to the requirements should be defined. In simpler terms, start with the loads present and finish at the tests required to check the design tolerance to those loads. Figure C.2 presents the FMEA work flow.

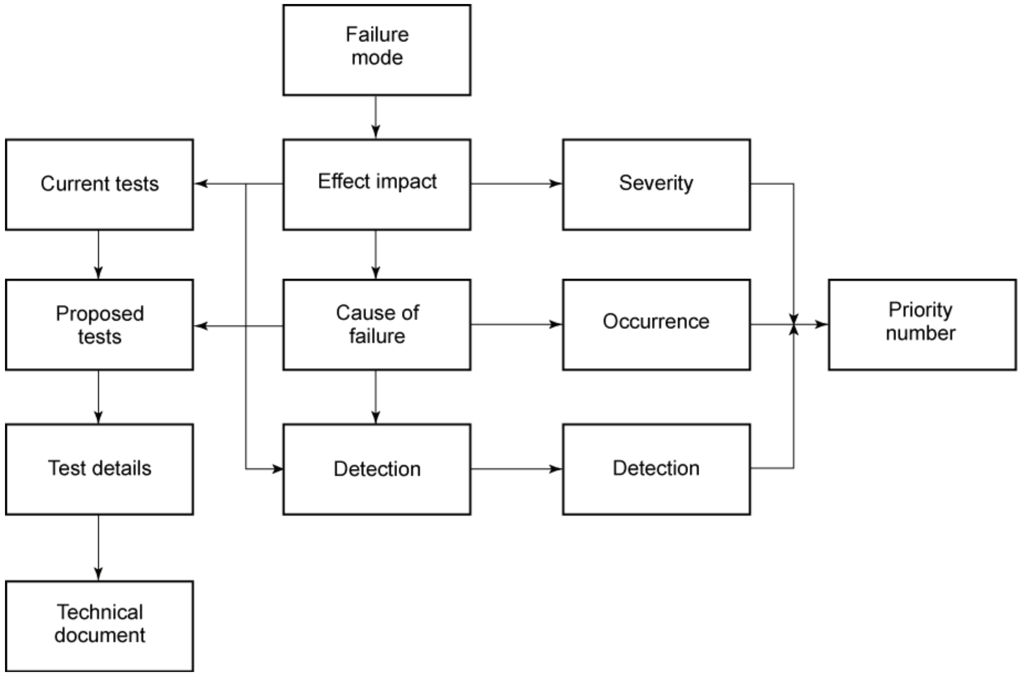

Figure C.2—General Validation FMEA Workflow

Figure C.3 presents a more detailed validation FMEA workflow.

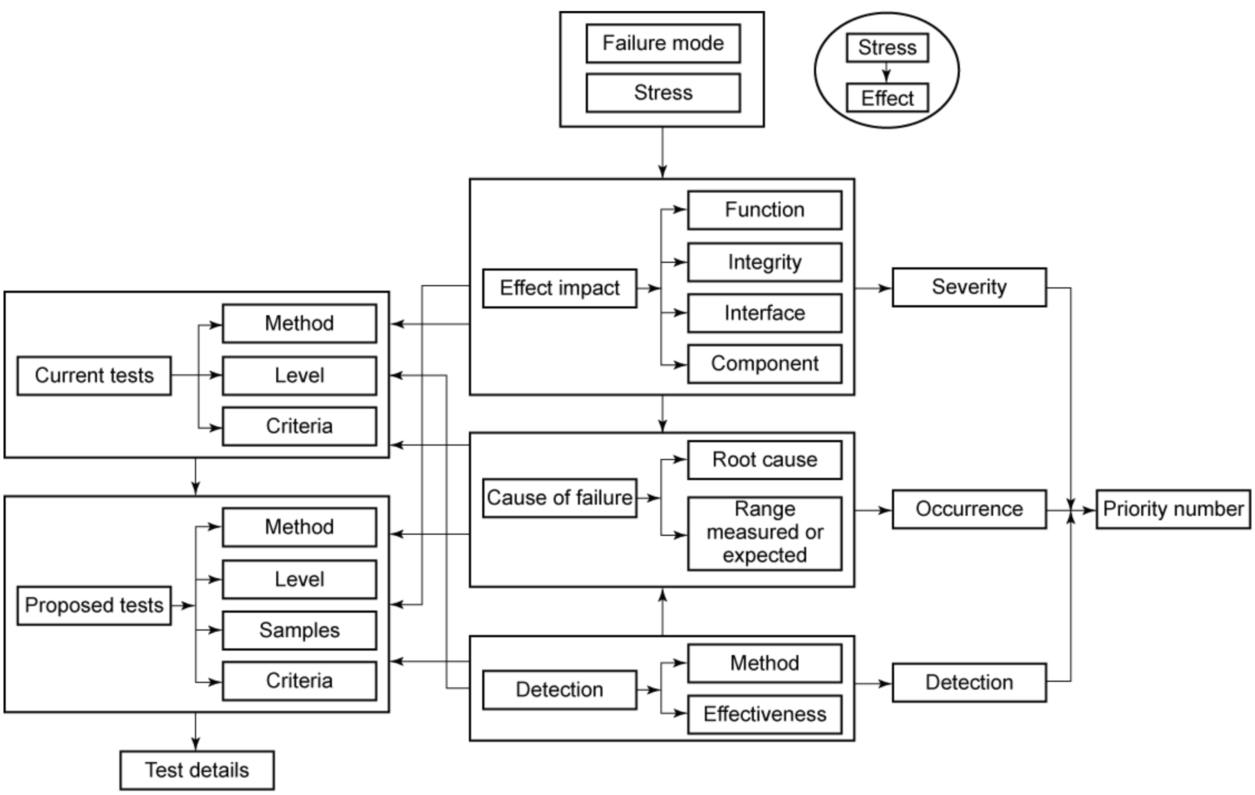

Figure C.3—Detailed Validation FMEA Workflow

The validation FMEA worksheet that follows the workflow presented in Figure C.3 is shown in Table C.1. For each load applied to the item under consideration (i.e. pressure, axial load, etc.), the remainder of the table is filled out to assess how each load affects the item.

Table C.1—Validation FMEA Worksheet Headings

Load	Load effect	Effect Impact				**Severity (see Step 4)**	Cause of failure	Physical cause of failure	Range measured/expected in operations	**Occurrence (see Step 7)**	Detection method	**Detection (see Step 9)**	Test Priority Number	Current testing method	Current testing levels	Proposed Test		
		Function	Integrity	Interface	Component											Test	Range	Proof method

C.4.2 Method

C.4.2.1 General

First set the validation FMEA focus item. Will the FMEA focus on the system, subsystem, or component? By setting the focus, the boundary conditions are better defined and the test can be better designed and implemented.

C.4.2.2 Step 1: Load Determination

Determine the load or stress acting on the focus item whether it is environmental or induced by the design.

C.4.2.3 Step 2: Load Effect

The possible failure caused by the load; usually the observable effect of the load that is not well supported by the design. For example, pressure can cause leak.

C.4.2.4 Step 3: Impact

What is affected by the load?

— *Integrity*—Lost ability to contain or connect physically to the system.

— *Functionality*—Lost or degraded functional performance.

— *Interface*—Lost ability to interact with the system.

— *Component*—Effect is localized in the focus item only.

C.4.2.5 Step 4: Severity

Determine the potential consequence of the failure. The ranking should stay the same through the system analysis (see Table C.2). The effect definition should be adjusted to fit the focus item. The adjustment will provide better test differentiation in the final priority number.

Table C.2—Severity Matrix

Ranking	Effect
1	Minor
2	Low
3	Moderate
4	High
5	Hazardous without warning

C.4.2.6 Step 5: Cause of Failure and Physical Cause of the Failure

The reason for the failure should be determined. The physical cause of failure is basic physical phenomenon that made the condition for failure. Why the reason existed in the first place is the physical cause of the failure. For example, material loss could be the cause the failure but the reason for the metal loss could be erosion or corrosion.

C.4.2.7 Step 6: Cause Ranges Expected in Operations

Based on the service requirements what would be the levels (preferably in ranges) of the cause or physical cause of the failure expected during system life cycle?

C.4.2.8 Step 7: Occurrence

Based on the defined service requirements and the environmental conditions, use existing data, past experiences, or expert opinion to determine the probability of failure during the life of the system. An example of an occurrence matrix is provided in Table C.3.

Table C.3—Occurrence Matrix

Ranking	Probability of Failure
1	Remote: failure is unlikely
2	Low: relatively few failures
3	Moderate: occasional failures
4	High: frequent failures
5	Very high: persistent failures

C.4.2.9 Step 8: Detection Method

The question to answer is: Is there a detection method that can be used to find the condition that lead to the failure mode? In addition, there should be an action in place to rectify the detected condition.

C.4.2.10 Step 9: Detection

How effective is the detection method? An example of a detection matrix is provided in Table C.4.

Table C.4—Detection Matrix

Ranking	Detection Effectiveness
1	Almost certain
2	High
3	Moderate
4	Low
5	Remote

C.4.2.11 Step 10: Test Priority Number (TPN)

Calculate the test priority number as:

$$\text{Test priority number} = \text{severity} \times \text{occurrence} \times \text{detection}$$

C.4.2.12 Step 11: Current Test

Is there an existing test that is currently performed and designed to address this failure mode?

— What is the test? The test can be industry standard test or design team specific test.

— How to test for the failure mode in question?

— Is it a direct or indirect test?

— What are the levels of the test parameter?

Test—What to test for? For example, use “combined load” or “cyclic temperature” to describe the test.

Range—State the desired levels of the test. For example, 100 % working pressure at 100 °F and 350 °F.

Proof method—State how many samples will be used to prove the design is immune from the failure mode in question.

C.4.2.13 Step 13: Test prioritization

The list of proposed tests will be tabulated and ranked based on the test priority number. The higher the test priority numbers the more important the test to the validation process. See Table C.7 for example headings.

C.4.2.14 Step 14: Test implementation

At this time the team should make a decision. A test priority number cutoff can be set. Cut off number is the value below which the test can be eliminated. The team should use engineering judgment, historical data, and previous test experience to assess the importance of the test below the cutoff test priority number and add them when the tests are deemed important.

C.4.3 The Test

C.4.3.1 General

Each test should have:

— purpose,

— procedure,

— agreed upon acceptance criteria except for exploratory tests,

— documented in a report with analysis and results,

— level of testing (acceleration or absolute).

The test should serve the product function, design, and adaptability to the system. This does not mean engineering or scientific tests should not be performed to enhance the team's understanding of the issue at hand; however, they should not be a substitute for validation testing.

C.4.3.2 Test Designs

Verification tests design should be designed to prove the system capability to overcome the specific failure mode they are designed to detect.

The test method of detection (measurement) should be considered to allow enough time for the measurement system to accumulate the information needed to reach the appropriate conclusion.

Accelerated tests should be designed to accelerate failure mode rather than introduce new ones.

Test levels should be given in ranges.

Procedure should be clear and sequential. It should include test specimen and fixture assembly procedures to avoid induced failures during test setup.

Test procedure should include test equipment verification before and after the focus item test.

Specify the data to be acquired and the frequency of the acquisition.

The system test should be designed to replicate the operational environment. Care should be taken to avoid environmental influences from affecting the test

C.4.3.3 Testing

Capabilities of the test facility should be adequate to perform the prescribed test. If any parameter that cannot be tested, the test should be reviewed and redesigned to meet the product functional and environmental requirements.

C.5 Example

Following is an example of a validation FMEA of a hypothetical choke kill valve illustrated in Figure C.4. Table C.5 depicts the verification results and load conditions for this example.

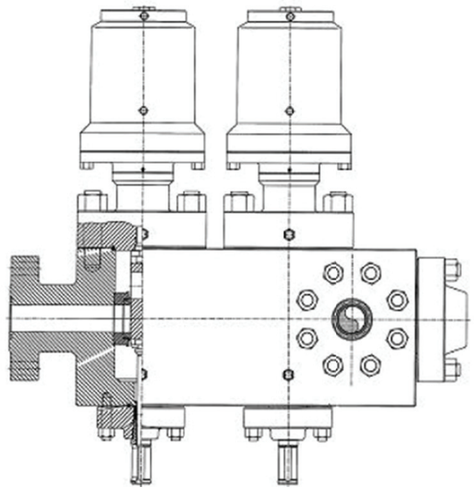

Figure C.4—Modified Choke

Table C.5—Verification Results and Load Conditions

Scenario	Analysis	Load Case	Internal Pressure psi	External Pressure psi	External Tension lb	External Bending Moment ft-lb	Material	Comments
Subsea 20 ksi differential pressure	Plastic collapse analysis and strain limits	1	58,680	10,680	0	0	Elastic-plastic S_y = 72.8 ksi S_u = 86.45 ksi E = 29.1 Mpsi	Plastic collapse Global criteria
		2	51,345	9,345	273,000	26,000		
		3	58,680	10,680	178,500	17,000		
		4	41,565	7,565	0	0		Local criteria
		5	56,235	10,235	0	0	Elastic-plastic S_y = 80.00 ksi S_u = 95.00 ksi E = 30.6 Mpsi	Hydrostatic test criteria
	Ratcheting analysis	1					Elastic perfectly plastic S_y = 72.80 ksi E = 29.1 Mpsi	Flange bolt preload
		2	27,500	0	0	0		
		3	0	0	0	0		
		4	27,500	0	0	0		
		5	0	0	0	0		
		6	24,450	4,450	105,000	10,000		
		7	0	0	0	0		
		8	24,450	4,450	105,000	10,000		
		9	0	0	0	0		
		10	24,450	4,450	105,000	10,000		
		11	0	0	0	0		
	LEFM analysis	1	0	0	0	0	Linear elastic E = 29.1 Mpsi	Thermal analysis Int = 350 °F Sea = 38 °F
		2	24,450	4,450	105,000	10,000		

The team consisted of 19 participants from 15 companies. The choke was divided into seven subassemblies and components. They are

— body,

— flanges,

— bolts and nuts,

— gaskets,

— gates and seats,

— actuator, and

— valve stem

The test matrix was developed and shown in Table C.6.

Table C.6—Test Matrix

Load		Effect Impact														Proposed Test		
	Load Effect	Function	Integrity	Interface	Components	Severity	Cause of Failure	Physical Cause of Failure	Range Measured/ Expected in Operations	Occurrence	Detection Method	Detection	Test Priority Number	Current Test Method	Current Test Level	New Tests	Range	Proof Method
External loads	Yielding	X	X	X	X	4	Material	Defect		2		5	40	3. Quality manufacturing process for material consistency		8. Dimensional inspection before and after test		Multiple Items
								Temperature	350 °F	3		5	60			9. Absolute temp test	350 °F	Multiple items
								Overpressure	125 %	4		5	80			2. Dimensional inspection after hydro test 1. NDE after hydro test		
								Structure overload	100 yield	4		5	80					
	Short fatigue life	X	X	X	X	4	Material	Fatigue		2		5	40			6. Differential temperature test	Service conditions: internal 350 °F and 38 °F external	One Item
										2		5	40			5. Material sample fatigue test		Multiple items
	Bent	X	X	X	X	4	Bending loads	Geometry of the system		4		2	32					
								thermal expansion		4		2	32			4. Combined load test at temperatures (HIGH and LOW)	100 % pressure with 110 % design loads	One Item
Improper makeup	Leak	X			X	4	Under preload	Friction effects		3		5	60					
							Uneven preloading	Friction effects		3		5	60					
								Bolting method		3		5	60					
	Yielding	X			X	4	Over preload	Friction effects		3		5	60			7. Thread gauging of selective bolts		Multiple Items

The test list is shown in Table C.7.

Table C.7—Test List

New Tests	TPN
1. NDE after hydrotest	80
2. Dimensional check after hydro test	80
3. Qualify manufacturing process for material consistency	40
4. Combined load test at temperatures (HIGH and LOW)	32
5. Material sample fatigue test	40
6. Differential temperature test	40
7. Thread gauging of selective bolts	60
8. Dimensional inspection before and after test	40
9. Absolute temperature test	60

The tests are then ranked by TPN to complete the final test listing shown in Table C.8.

Table C.8—Tests Ranked by TPN

New Tests	TPN
1. NDE after hydro test	80
2. Dimensional check after hydro test	80
7. Thread gauging of selective bolts	60
9. Absolute temperature test	60
3. Qualify manufacturing process for material consistency	40
5. Material sample fatigue test	40
6. Differential temperature test	40
8. Dimensional inspection before and after test	40
4. Combined load test at temperatures (HIGH and LOW)	32

Annex D
(informative)

Technical Considerations on the Selection of Castings and Forgings

The primary motivation for specifying a casting vs a forging is to achieve cost reduction for raw material and finish machining of components. In some cases, due to size and geometry, some components are not practical to manufacture from forgings, making castings an obvious choice. However, for HPHT equipment strong considerations should be given to forgings for several reasons.

a) Castings can have the following advantages:

— complex shapes,

— weight reduction,

— reduced machining.

b) Castings can have the following disadvantages:

— dendritic microstructure that results in lower toughness,

— lack of grain flow lines,

— internal porosity that is sometimes difficult to find even with modern NDE methods,

— castings often require weld repairs which can be problematic in HPHT service,

— limitations in availability of qualified HPHT materials such as nickel-based alloys.

c) Forgings can have the following advantages:

— presence of grain flow lines leading to increased toughness,

— forged microstructure instead of a dendritic microstructure,

— reduced chance of porosity and internal defects,

— predication in as designed performance is improved.

d) Forgings can have the following disadvantages:

— anisotropy of material properties,

— may require more machining.

Increased internal defects in a material will increase susceptibility to initiation and propagation of cracks. This is a primary concern with HPHT equipment. For HPHT equipment extra micro-cleanliness testing following ASTM E45 may be warranted and more sensitive NDE may also be warranted.

When practical, prototype testing of a full-scale casting or forging should be performed.

Annex E
(informative)

Quality Management System Guidelines

E.1 Procurement and Supplier Qualification

Each manufacturer of HPHT equipment should qualify the suppliers by requiring those suppliers to demonstrate their capability to make materials or equipment. The suppliers should be part of the manufacturer's approved vendors list. The process of approving a supplier should be by direct examination of documented objective evidence of proficiency in producing materials of consistent quality.

E.2 Quality Control

E.2.1 General

Inspection and testing should be conducted according to documented procedures established by the manufacturer. Any deviations from these procedures should be noted and approved by the user.

E.2.2 Personnel

Personnel performing inspection and testing operations should be qualified in accordance with the manufacturer's documented training program such as specified in ASNT SNT-TC-1A, ISO 9712, or EN 473.

E.2.3 Calibration

Equipment used to inspect, test, or examine material or other equipment used for acceptance should be identified, controlled, calibrated, and adjusted at specified intervals in accordance with documented manufacturer instructions and consistent with nationally or internationally recognized standards specified by the manufacturer.

E.2.4 Nonconformance Control

The supplier/manufacturer should establish and maintain documented procedures to ensure that an assembly or component that does not conform to specified requirements is prevented from unintended use or installation. This control should provide for identification, documentation, evaluation, segregation (when applicable), and disposition of nonconforming assemblies or components.

The responsibility for review and authority for the disposition of nonconforming assemblies or components should be defined by the supplier/manufacturer. Nonconforming assemblies or components may be

— reworked to meet the specified requirements,

— accepted with or without repair by concession, or

— rejected and scrapped.

Repaired and/or reworked assemblies or components should be inspected in accordance with the requirements of the appropriate API product specification and the documented specifications of the supplier/manufacturer.

E.3 Documentation Control

The supplier/manufacturer should establish and maintain documented procedures to control documents and data that relate to this technical report. These documents and data should be maintained to demonstrate conformance to specified requirements. All documents and data should be legible and stored and retained in such a way that they are readily retrievable in facilities that provide a suitable environment to prevent damage, deterioration, and loss. Documents and data may be in any form or type of media, such as hard copy or electronic media. All documents and data should be available to, and auditable by, the user.

Documentation and data associated with design verification, design validation, and design change justification should be maintained for a minimum of 10 years after the date of last manufacture.

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