

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

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

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	API 17P
	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:

- 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.

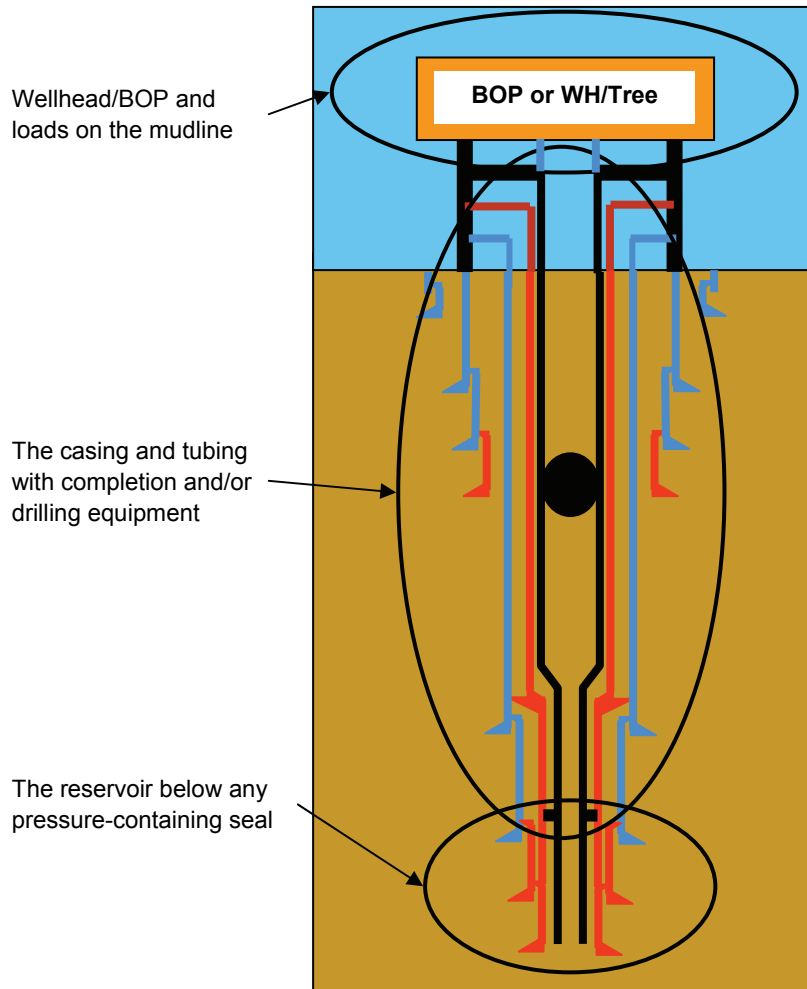


Figure 1—System Analysis Specification Breaks (Completion)

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.

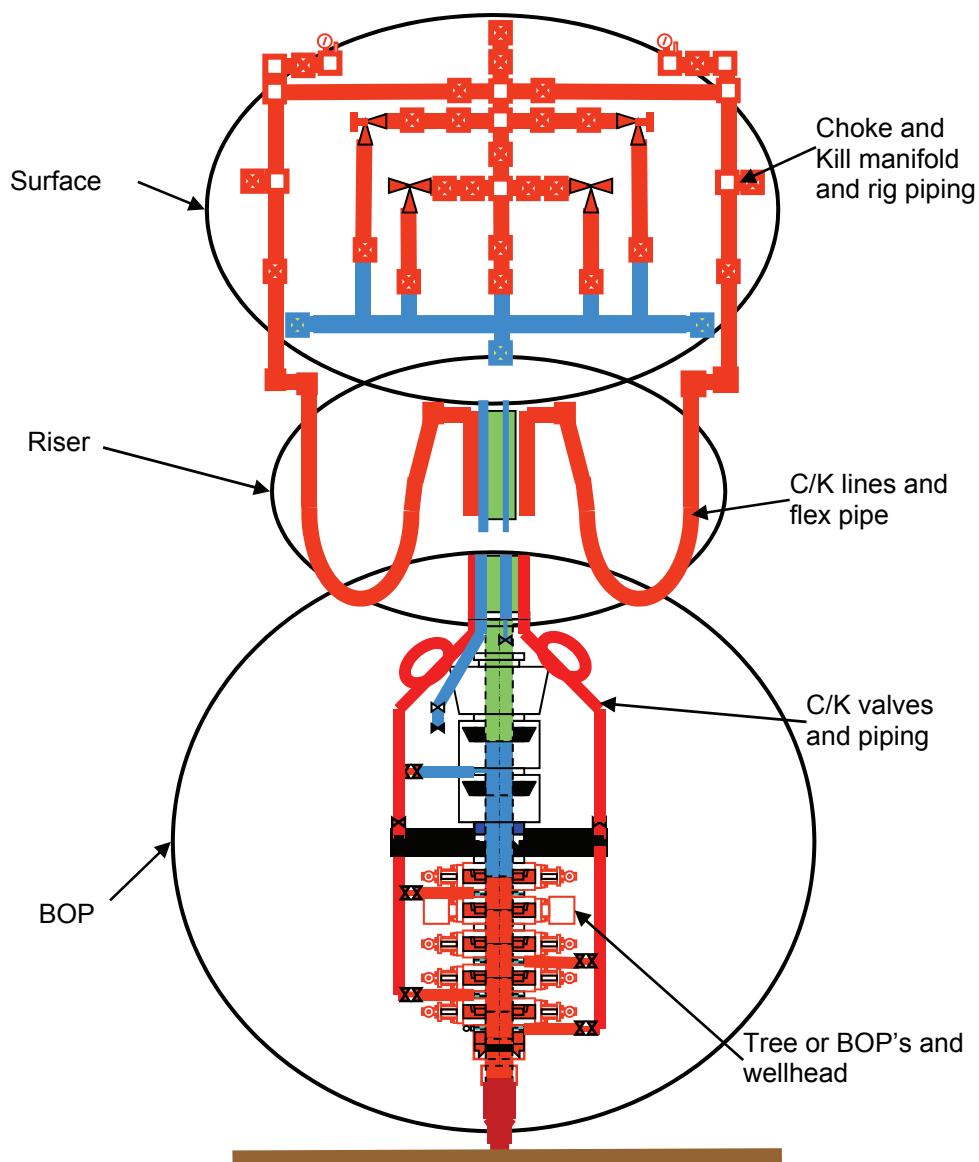


Figure 2—System Analysis Specification Breaks (Drilling)

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:

- interfaces and/or geometry changes that may result in an irregular distribution of loads and stresses;
- avoidance of damage or wall losses, which may result in a progressive failure;
- the loads for the component/subcomponent during its life cycle;
- interface reconciliation of load transfers;
- 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

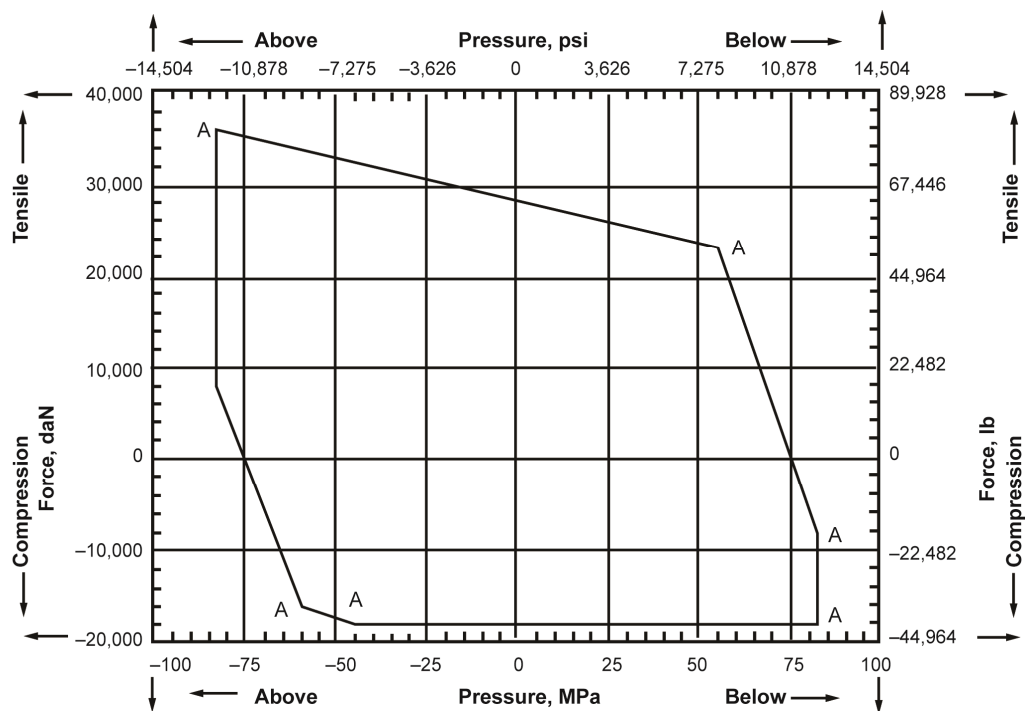
The user and the manufacturer should collectively define the service load cycle and data retention requirements prior to procurement of the equipment. Loading relevant to the performance of the product should be considered, including pressure stresses, thermal stresses, discontinuity stresses, residual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

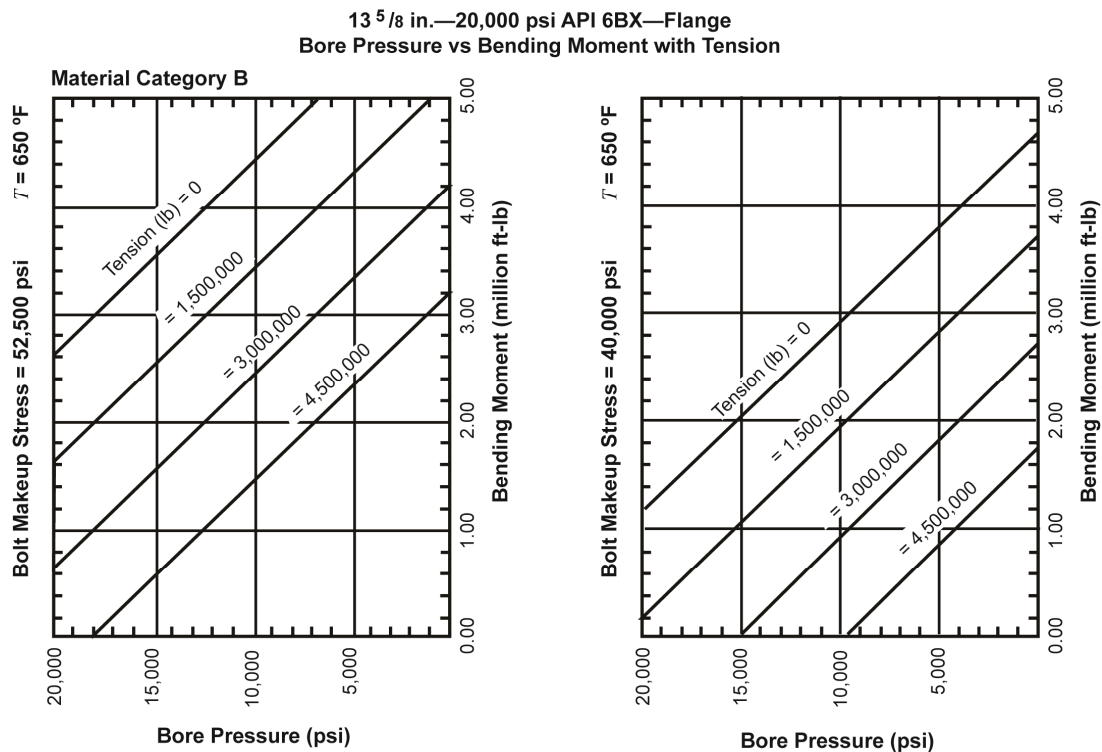


Figure 4—Combined Loading Capacity Chart from API 6AF1

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
($T > 350\text{ }^{\circ}\text{F}$ or $P > 15,000\text{ psi}$)

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
($T > 350^{\circ}\text{F}$ or $P > 15,000\text{ psi}$)

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		X
	S31260	25Cr		X	X	X	X	X	X	X	X		X
	S32760	25CrW		X	X	X	X	X	X	X	X		X
	S39274												
Super duplex	S39277												
	S32750	26-6-3			X	X	X	X	X				X
	S31600	316		X	X	X	X	X	X	X	X		X
	N08028	28Cr			X	X	X	X	X				X
Austenitic Fe-based	N08535	25Cr			X	X	X	X	X				X
	N08135	2035			X	X	X	X	X				X
	N08020	20Cb3®			X	X	X	X	X				X
	N08825	Alloy 825			X	X	X	X	X				X
Austenitic Ni-based	N04400	Alloy 400							X				X
	N06007	Hastelloy® G			X	X	X	X	X				X
	N06985	G-3			X	X	X	X	X				X
	N06950	INCONEL® Alloy 050			X	X	X	X	X				X
	N06255	G-2			X	X	X	X	X				X
	N06975												
	N10276	Hastelloy® C-276			X	X	X	X	X				X