Design of Risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs)

RECOMMENDED PRACTICE 2RD
FIRST EDITION, JUNE 1998

REAFFIRMED, MAY 2006

ERRATA, JUNE 2009

energy API

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FOREWORD

API Subcommittee 2 (Floating Systems) formed a task group in 1992 to draft a production system riser RP. The RP was divided into eight sections. Volunteers were distributed among seven groups, with each group responsible for one or two sections of the RP. A leader was appointed for each of the section groups. The first draft of the RP was written at a three day workshop November 16 through 18, 1992. The workshop was attended by 25 specialists and included three attendees from Europe. This first draft was published in January, 1993. A second draft was published in January 1994, and a third draft was published in November 1994. Between 55 and 60 specialists contributed to these drafts. Further refinements of the RP continued in 1995, including a major revision of the section on materials. To speed up the work, in November 1995 the DeepStar JIP was asked to fund a contractor to complete the RP. A contractor was hired for this work in April 1996.

The RP Task Group is now under API Committee 2 (Offshore and Arctic Structures), Subcommittee 2 (Offshore Structures), Resource Group 10 (Risers).

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INTRODUCTION

The design of risers for Floating Production Systems (FPSs) and Tension-Leg Platforms (TLPs) requires recognition that risers form a subsystem that is an integral part of the total system. The presence of riser systems within an FPS has a direct and often significant effect on the design of all other major subsystems. Their presence and influence generates load case conditions that must form part of the basis of design and load case matrix of the FPS, just as the characteristics and behavior of the other FPS subsystems influence the basis of design and load case matrix for the riser systems. The relationship between riser design and FPS global design is particularly close. Therefore, the designer should recognize the need to interact with engineers for the other major subsystems, such that mutual needs and conflicts can be accommodated to ensure the design of a safe, practical FPS.

The reader should note that for the purposes of this document TLPs are considered a type of Floating Production System that is characterized by a heave-and-pitch restraining mooring system. Therefore, unless a specific reference is required to clarify a feature unique to TLPs, the term FPS should be read as covering TLPs.

Section 1 presents introductory material on the contents of this RP. Section 2 provides an overview of risers functions, configurations and components. Section 3 presents general design considerations. Design loads and conditions arising from environmental and functional causes are defined in Section 4. Design criteria, in terms of allowable stresses and deflections, are described in Section 5. A detailed description of design analysis methods and procedures is given in Section 6. Finally, Section 7 presents an overview of materials considerations in riser design.

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1 General

1.1 SCOPE AND METHOD

1.1.1 This document addresses structural analysis procedures, design guidelines, component selection criteria, and typical designs for all new riser systems used on FPSs. Guidance is also given for developing load information for the equipment attached to the ends of the risers. The recommended practice for structural design of risers, as reflected in this document, is generally based on the principles of limiting stresses in the risers and related components under normal, extreme, and accidental conditions. This approach is often referred to as "working stress" design.

1.1.2 This document assumes that the risers will be made of steel or titanium pipe or unbonded flexible pipe. However, other materials, such as aluminum, are not excluded if risers built using these materials can be shown to be fit for purpose. Design considerations for unbonded flexible pipe are included primarily by reference to API RP 17B and API Spec 17J. Steel and titanium pipe will be called "metal" pipe and unbonded flexible pipe will be called "flexible" pipe.

1.1.3 Future development of these guidelines for riser system design will need to take account of the international focus on statistical methods to address uncertainties in creating and operating safe, functional, riser systems. Therefore, future release as an international standard should eventually incorporate statistical load and resistance factor design methodologies. Reliability-based limit state design principles may be applied provided that all relevant ultimate and serviceability limit states are considered. All relevant uncertainty in loads and load resistance should be considered and sufficient statistical data should be available for adequate characterization of those uncertainties.[1,2]

1.1.4 A list of referenced publications may be found in Annex E. Annex A presents a glossary of terms used in this RP.

1.2 GENERAL FUNCTIONS OF RISERS

1.2.1 FPS risers are fluid conduits between subsea equipment and the surface platform. Figures 1 and 2 introduce the essential functional elements (or features) of risers and riser systems. An FPS responds dynamically to environmental forces. The riser system is the interface between a static structure on the ocean floor and the dynamic FPS structure at the ocean's surface. Riser system integrity includes not only fluid and pressure containment, but structural and global stability as well.

1.2.2 Figure 3 introduces some aspects of the complexity that may evolve when implementing a specific riser design. The simple conduit may be complicated by intermediate connections, changes in material or form of cross-section construction, couplings, attachments (e.g., buoyancy modules), and multiple flowpaths.

1.2.3 Risers may perform the following specific functions:

a. Convey fluids between the wells and the FPS (i.e., production, injection, or circulated fluids).

b. Import, export, or circulate fluids between the FPS and remote equipment or pipeline systems.

c. Guide drilling or workover tools and tubulars to and into the wells.

d. Support auxiliary lines.

e. Serve as, or be incorporated in a mooring element.

f. Other specialized functions such as well bore annulus access for monitoring or fluids injection.

1.2.4 This document is intended to provide guidance for design of risers that may be categorized according to these functions.

1.3 CONFIGURATIONS OF RISERS

1.3.1 Risers, regardless of function, have a wide range of possible configurations. It is possible to differentiate between various riser configurations on the basis of:

a. Cross-section complexity (a single vs. multiple tubes).

b. Global geometry or behavior (small vs. large deflection).

c. Structural integration (integral vs. non-integral risers).

d. Means of support (top tensioned with tensioners or hard mountings vs. concentrated or distributed buoyancy).

e. Structural rigidity (metal vs. flexible risers).

f. Continuity (sectionally jointed vs. continuous tube).

g. Materials.

1.3.2 The designer may refer to Section 2 for a catalog of riser and riser system configurations that are (or have been) in service, as well as some concepts (proposed for imminent use) that serve as examples of the range of possible configurations. The designer should find guidance within this document for establishing the viability of specific systems and components indicated by those figures.

1.4 WHAT IS NOT (FULLY) COVERED

There are many topics, materials and concepts for riser applications that are of interest and evolving toward potentially advantageous applications. This RP is intended to cover only such issues that are considered established through practice or operator commitment. This section tries to identify topics that are not intended to be fully covered in this first release of the RP. The following headings, of course, cannot be a completely comprehensive listing of the possible riser system topics that are not covered by this document. One reason for noting these issues or options here is to highlight that there may be need for future efforts to provide necessary guidance for future releases of the RP as new concepts gain acceptance.

This document covers new risers not reuse of existing risers.

1.4.1 Risers as Mooring Elements

This document does not provide comprehensive coverage for applications of risers for service as (or part of) the FPS mooring system. For example, when a riser or riser system is intended to function as a tendon to provide direct mooring restraint of an FPS, structural design must also consider the recommendations outlined for tendons in API RP 2T. Further, piping that is integral to anchor leg structure of, for example a Single Anchor Leg Mooring, is not addressed in this RP. In such cases, the designer should find suitable guidance in API RP 2SK (for FPS mooring systems) and API RP 1111 (for risers on fixed structures).

1.4.2 Control Lines or Umbilicals

Control lines or umbilicals fit some of the functional definition of a riser in that they may provide a conduit for fluids between the FPS and subsea equipment. This RP does not address their design specifically, although they may be attached to risers and thereby influence the riser's design and analysis. The designer may refer to API RP 17A for guidance on umbilicals.

1.4.3 Low Pressure Fluid Transfer Hoses

This RP is not intended to provide guidance for the design of low pressure hoses for such service as cargo transfer. Appropriate guidance is available through documentation prepared by the Oil Companies International Marine Forum (OCIMF).

1.4.4 Bonded Flexible Pipe

Bonded flexible pipe is not specifically considered in this RP. Where such is intended to be used, a level of safety comparable to other riser systems should be documented.

1.4.5 Composite (Fiber-reinforced) Materials

This document does not provide comprehensive coverage for the design of risers of composite (fiber-resin matrix) construction. Introductory information is provided in Annex D.

1.5 STATUS OF TECHNOLOGY

The reader should be aware that riser systems technology (i.e., concepts, design and analysis methodologies and criteria, components manufacturing and testing, operational roles and demands, maintenance and inspection, etc.) is in a state of rapid and continuing evolution. This evolutionary status means that the technology relating to any given riser system or component is not likely to be well-proven by years of practical, successful application. Therefore, designers are advised to take appropriate measures to ensure that their practice incorporates suitable quality control to avoid errors of unquestioning, unfounded confidence in the results of any phase of the complex design process. This advice is particularly applicable when evaluating the vast quantities of numerical results that can be facilitated by modern high speed computational methods and tools.

1.6 QUALITY ASSURANCE

1.6.1 The integrity of a riser system should be improved by the application of quality systems. These systems should be applied to the design, procurement, construction, testing, operating, and maintenance activities in the applications of this RP.

1.6.2 When these systems are applied, reference shall be made to the relevant quality systems standard (ISO 9000 series).

1.7 REFERENCES

1. ISO 2394, "General Principles on Reliability for Structures," 1986.

2. ISO 2393, A1, "Addendum 1 to General Principles on Reliability for Structures," 1988.

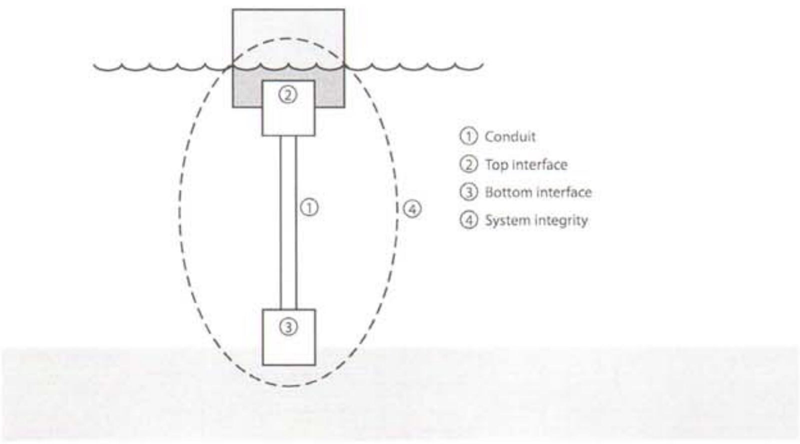

Figure 1—Essential Functional Elements of a Riser System

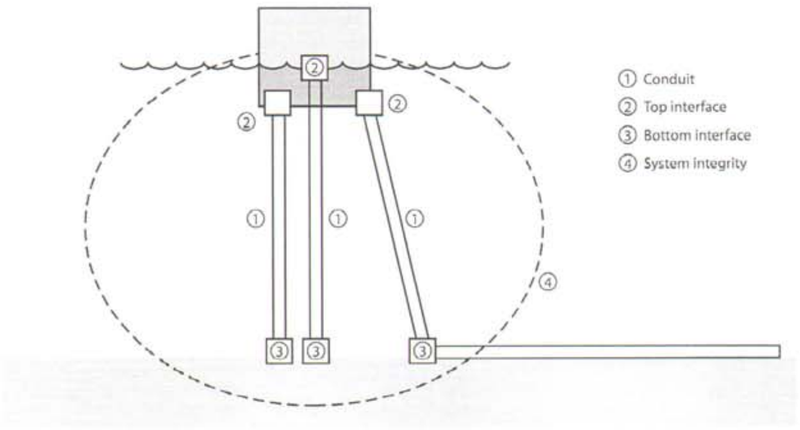

Figure 2—Essential Functional Elements of an FPS Riser System

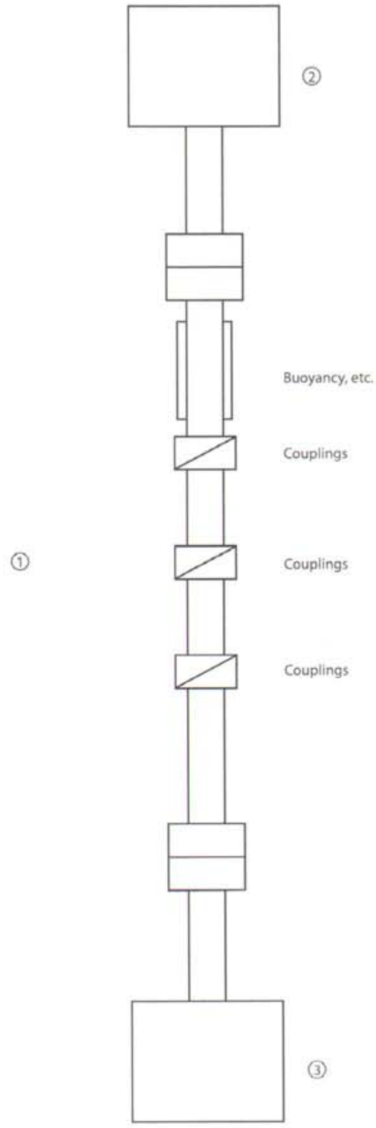

Figure 3—Elements of Complexity Enter the Basic Riser Design

2 Description of System and Components

2.1 GENERAL

2.1.1 This section, containing supplementary elements, further defines the essential features and functions of riser systems for FPS applications and describes riser components and their primary functions.

2.1.2 Risers on FPSs cover the full range of production, injection, drilling, completion, workover and exporting operations. Mobile offshore drilling units (MODU) normally use risers in single-well situations. Risers for FPS systems, on the other hand, have additional requirements associated with operating multiple risers of potentially different types in relatively close proximity. Section 3 discusses the unique requirements of riser design and operations that can be imposed by concurrent drilling and production operations. Riser components associated with these requirements are the focus of this section.

2.2 ESSENTIAL SYSTEM FEATURES

2.2.1 Riser Body

The primary function of FPS risers is to convey fluids to and from the vessel. Depending on site-specific considerations, these risers are either metal or flexible pipe.

2.2.1.1 Metal Pipe

2.2.1.1.1 Segmented

Limitations on the maximum continuous length of metal pipe that can be reasonably manufactured, transported, handled, installed, retrieved and replaced offshore often require that metal pipe conduits be segmented. These segments can be joined onsite by mechanical connectors or welding.

2.2.1.1.2 Continuous

Risers can be towed, dragged, or floated out in one piece and upended on location, or they can be transported on a reel to the site. The reel method consists of assembling a length of pipe on shore. This pipe is then coiled onto a reel or a drum. The coiled pipe is then transported to the site and unreeled. The coiling and uncoiling of the pipe involves plastic deformation that reduces its impact resistance. Welding at the site is only required for joining reels, hence installation proceeds much more quickly than segmented pipe.

2.2.1.2 Flexible Pipe

Flexible pipe is usually stored and transported on reels, baskets or carrousels. The reel size limits the maximum length of flexible pipe of a given pipe diameter that can be fabricated without connectors. Several sections may be required to achieve the riser length required. End fittings are required at both ends of each pipe segment. Flexible pipe can be segmented, for example, to accommodate a change over from a dynamic section to a less expensive static section. The pipe can be segmented when there is a reel capacity problem or when it is more economic to do so.

2.2.2 System Interfaces

2.2.2.1 In addition to the design of the riser body, the designer must consider interface requirements at the top and bottom of the riser. At the top, equipment on the vessel must be designed to accommodate the range of riser loads, motion, and ancillary equipment needed to maintain riser integrity (e.g. tensioners) and to enable necessary operations to be conducted (e.g. drilling, completion, workover, support equipment). At the bottom, interface components must also be designed to accommodate riser loads and maintain fluid conduit and pressure integrity.

2.2.2.2 Conduits for fluid transport, control or monitoring system umbilicals and load paths for structural support must be provided and their continuous operation maintained. Components necessary for connection, installation, maintenance, and disconnection may have to be provided at the top and bottom interfaces for each of these essential riser features.

2.3 FPS RISER SYSTEM DESCRIPTIONS

2.3.1 Production/Injection Risers

2.3.1.1 Production risers transport fluids produced from the reservoir. Injection risers transport fluids to the producing reservoir or a convenient disposal or storage formation. The systems can be designed to operate interchangeably. They consist of an apparatus to hang the riser at the surface and attach it to surface valves and piping. The sea bed portion contains an apparatus that connects the riser to a wellhead or receptacle. Included are also methods/equipment to space out the riser and to account for bending loads at the bottom and/or top of the system. The riser may also have bumpers, vortex-suppression devices and other attachments such as buoyancy modules.

2.3.1.2 The cross sections of production/injection risers are often complex, as they can contain multiple parallel or concentric tubing strings. They also may contain special equipment like slip joints, packers, and control lines. Required pressure rating is tied to the reservoir characteristics and anticipated well performance.

2.3.1.3 Top-tensioned TLP risers (see Figure 4) have been developed to provide surface access to wells in a manner analogous to fixed platforms. This can be accomplished because of the minimal heave and pitch/roll motions of these platform types. Such risers comprise metal pipe cross sections which may be thought of as a continuation of the well bore to the ocean's surface. Similar risers, using buoyancy to create top tension have been used as SPAR production risers

2.3.1.4 Flexible-pipe production risers are associated with subsea trees. A large number of flexible-riser configurations are possible, two of which are shown in Figure 5. In all cases, flexible risers hang from the FPS under their own weight, but external buoyancy modules may be attached to achieve the required riser shape or curvature.

2.3.2 Export Risers

2.3.2.1 Export riser systems will usually include equipment similar to production/injection risers. The riser diameters may be larger so as to accommodate total production through the FPS. Pressure ratings are determined by export pipeline and flow conditions. Typically, a pig launcher will be required. Because bending loads in larger diameter risers are higher, the designer must pay particular attention to stress joints or flex joints. The system's cross section is usually a single pipe forming the flow path compared to production risers which may have multiple pipes and multiple paths.

2.3.2.2 Figure 6 shows one pipeline riser option, a steel export pipeline laid in a simple catenary and connected at pontoon level to the surface platform. Moment relief at the top end may be provided by a stress joint or an elastomeric flex joint.

2.3.2.3 TLPs have used top-tensioned export risers that are analogous to the top-tensioned production risers described earlier, but with a single flow path compared to production risers' multiple paths.

2.3.3 Drilling Risers

2.3.3.1 The major functions of drilling riser systems for mobile offshore drilling units (MODU) are to provide fluid transportation to and from the well; support auxiliary lines, guide tools, and drilling strings; serve as a running and retrieving string for the BOP. Low pressure drilling riser systems used on FPSs perform the same functions as riser systems on drilling vessels.

2.3.3.2 Most TLP systems have been designed with the drilling BOP at the top of the riser (see Figure 7). In such cases, the drilling riser must be designed for the added requirement of containing maximum formation pressure.

2.3.3.3 When used from a MODU, the drilling riser is almost always deployed alone. When used from FPSs the drilling riser may be deployed amongst production risers. Consequently it must be treated as just one element of a system of risers, with appropriate safety and potential interference considerations for each riser.

2.3.4 Completion/Workover Risers

2.3.4.1 Completion/workover risers (see Figure 8) are used to provide full bore, unrestricted access to a well for the purposes of completing or working over the well. Typically, these are custom-designed, but some standardization may be implemented to reduce costs.

2.3.4.2 A form of compliant riser that has been proposed for providing well bore access for workover is shown in Figure 9.

2.3.5 Multibore Hybrid Risers

Hybrid risers such as the one shown in Figure 10 provide multiple flowpaths from the seabed to an FPS by a combination of vertical metal piping over most of its water column and flexible piping between its top and the FPS. There are many possible variations. The key components of the hybrid riser in Figure 10 are as follows:

a. Structural member—steel tubular providing structural backbone to the vertical metal piping and buoyancy modules, support for the top assembly and providing reaction path to the riser base. The structural member may also provide buoyancy and contain fluid conduits for import or export.

b. Buoyancy modules—syntactic foam buoyancy formed in two or more segments around the riser circumference providing guide tubes for the peripheral lines and attached to the structural member by strapping.

c. Peripheral lines—vertical steel pipe flowlines running full length of metal riser section.

d. Flexible jumper hoses—flexible pipes connected from the goosenecks at the top assembly of the metal riser to the support points on the FPS providing compliancy needed to allow relative motion between vessel and riser top assembly.

e. Top assembly or upper riser connector package (URCP)—upper termination point for metal peripheral lines having isolation valves and emergency disconnect package (EDP). A tether may be attached from this point to the FPS to maintain compatibility of lateral displacements in extreme conditions. Goosenecks and their support structure are provided to attach flexible jumpers.

f. Air tanks—near surface buoyancy tanks attached to the top of the riser providing fixed and variable components of tension to the metal riser section.

g. Riser base—foundation to which the riser is attached by a stress joint and hydraulic connector. The base provides resistance to riser tensioning forces, overturning moments, and lateral loading. It may consist of an independent piled steel structure. Flowline connection porches located on the periphery are hard piped to a central location for connection to peripheral lines. Alternatively, the riser may be connected directly to a well template.

2.3.6 Multibore Top-Tensioned Metal Risers

2.3.6.1 A multibore top-tensioned metal riser (see Figure 11) pierces the water surface and extends its rigid geometry all the way up to a deck of the vessel. At the top, standard tensioning equipment provides support for the riser. Multibore top-tensioned risers have been used for applications such as import and/or export of fluids coming from subsea manifolds or templates.

2.3.6.2 A top-tensioned metal riser can also support metal freestanding flowlines. The flowlines vary in functionality, number, size, dry weight, submerged weight, fluid content, and pressure characteristics, as dictated by different field requirements such as:

a. Satellite trees.
b. Subsea manifolds.
c. Flowlines coming from other platforms.

2.3.6.3 The metal riser joints, stress joint, lower riser connector package (LRCP), and riser base follow the same pattern as described for the hybrid riser.

2.4 RISER COMPONENT DESCRIPTIONS

2.4.1 Components for Fluid Transfer

2.4.1.1 Riser Segments

2.4.1.1.1 Metal-Pipe Riser Segments

The main function of the metal-pipe riser segment is to provide a fluid conduit between the adjoining riser sections or end terminations. The complete riser extends from the seabed equipment to the supporting surface vessel. Structural requirements of the riser segments are based on ensuring that the riser continues to meet the requirements of the fluid conduit for the service life of the FPS or its planned replacement cycle.

Metal-pipe riser segments are joined together to make up a complete riser. A metal-pipe riser segment is typically constructed using a steel tube.

Individual riser segments may differ. The lowermost segment may contain a tapered stress joint section or a flex joint. It may also have a different end connection designed to transfer structural loads into the riser end termination rather than have the same connection used to connect the intermediate segments. The uppermost joint normally contains an attachment for the surface completion and for a load ring for the riser devices that tension or restrain the riser. Some intermediate joints may contain buoyancy or have buoyancy components attached to reduce the weight of the riser string in water. Some intermediate joints may also be designed to accommodate interaction with the vessel, e.g., keel joints in SPAR risers.

Riser joints may incorporate several tubulars, rigidly connected. This is often referred to as an integral riser joint. An example is a conventional marine drilling riser joint used in floating drilling.

2.4.1.1.2 Flexible Pipe Segments

Non-bonded flexible pipes consist of several individual and separate layers having no adhesion between them (see Figure 12). Each succeeding layer is wrapped or extruded over the previous layer in a continuous process along the entire length. Transported fluids and gases are contained by a layer made of polymeric material. Flexible pipes rely on one or more layers of metallic and/or synthetic strand to provide axial and radial strength. They may incorporate a spiral or helical structure to provide for collapse resistance. An outer sheath made of polymeric material protects the steel layers from the environment. The choice and thickness of layers, the number and angle of the reinforcement materials, and the order of layers and reinforcement in the pipe construction are governed by service and installation requirements.

Because of environmental conditions and installation or space limitation around the FPS, it may be advantageous to bundle several lines together. As shown in Figure 13, an Integrated Service Umbilical (ISU) consists of wrapping the control hydraulic hoses and electrical cables around the service line, instead of having a separate umbilical. It is also possible to bundle several flexible pipes or ISUs together, as in a multi-bore flexible riser consisting of one production line and an ISU that services more than one subsea well (see Figure 14).

2.4.1.2 Fluid Conduit Interfaces

A fluid conduit interface is any mechanical connection between segments of the complete riser string from the seabed to the surface at the support vessel. Connections between riser sections will be referred to as riser couplings. Connections at interfaces of metal pipe risers to either seabed or surface equipment are referred to as end connectors. Interfaces for flexible pipe risers are referred to as end terminations.

Flexible risers are connected at the upper end to the FPS and at the bottom end to either a flexible or metal pipeline or flowline, a subsea production tree, or some other subsea hardware [e.g. pipe line end manifold (PLEM)].

2.4.1.2.1 Couplings

Coupling designs have taken many forms, including threaded types, dog types, and bolted flanges, depending on the type of riser. Couplings must provide a seal between the mating segments that is compatible with any of the fluids that will be passed through the riser. The seal must maintain its integrity under all external and internal loading conditions. Seal designs are either integral or non-integral. Integral seals are built into the connector and are non-replaceable. Non-integral seals use separate seal elements that can be removed and replaced.

Couplings may provide attachment points for separate fluid lines. These lines must also contain seals at their connection interfaces. The design of these seals depends on the type of riser to which they are attached. There may be a requirement to connect to the mating member at the same time the riser segments are made up. If fluid lines are run independently, they can be attached separately. Additionally, the coupling type may vary along the length of the riser to accommodate variations in the riser segments themselves, such as in a tapered bottom segment.

The break-away flowline coupling (see Figure 15) protects templates, satellite trees, and flowlines from stress caused by external forces. It is preset to a desired breaking force. If a drift-off, drive-off, or other emergency situation occurs, the break-away flowline coupling separates without damage to other riser components.

2.4.1.2.2 End-Connectors

End-connectors for a metal pipe must provide an attachment to equipment that interfaces with the top and bottom ends of the riser. This attachment must provide a means of containing the riser fluid at this interface under all loading conditions.

The top end-connector of a metal pipe riser provides fluid containment in the connection to the surface production equipment. The top riser segment serves as part of the connection and contains the fluid seal. This segment also provides the attachment point for the tensioner system or hard tie-off depending on the configuration of the riser system.

The top end-connector seal, like those of the couplings, may either be integral or non-integral. The integral seal forms part of the top riser segment. The connection mates to it and is non-replaceable. The non-integral seal configuration involves a replaceable seal housed in the top end connector, and is the type most commonly used.

The configuration of the top connector is dependent on the overall configuration of the riser system. This includes the tensioner or tie-off type, surface completion configuration, additional fluid line configuration, and handling equipment, as well as the overall configuration of the FPS.

The bottom connector must provide the fluid containment seal between the riser and sea-floor equipment. The bottom connector differs from the other connectors (coupling and top connector) in that it usually must provide for remote makeup at the sea-floor. For this reason, the bottom connector uses a replaceable seal assembly and a latching mechanism that is capable of being operated remotely via a control system or ROV.

The bottom connector of a metal-pipe riser in an FPS is subject to tension and bending loads induced in the riser from the motions of the structure and other environmental loads. The connector must have adequate strength and rigidity to resist these loads while maintaining seal integrity.

2.4.1.2.3 End Fittings for Flexible Pipe Conduits

End fittings are composed of:

a. An end-connector that connects the flexible pipe conduit at a top, bottom or intermediate interface or a coupling that couples segments of flexible pipe.
b. An end-termination that provides the connection between the flexible pipe and the metal end-connector or coupling.

The end-termination connects all of the strength members in the pipe to the connector or coupling so that axial loads, torques and bending moments can be transmitted to or from the connector or coupling while maintaining the fluid containment functions of the pipe. Bend restrictors can be used to limit the bending radius (see 2.4.2.3).

End fittings should be designed to withstand the loads resulting from the flexible riser installation and operation. These loads include tension, pressure, shear, thermal loads, and bending moments. The end-termination should be designed in such a way that the flexible line, in no case, will be divorced from the coupling or end-connector. Couplings and end-connectors may be an integral part of, or attached to, the end-termination to complete the end fitting.

End fittings may be installed on the pipe at the completion of pipe manufacture or installed in the field.

The flexible pipe manufacturer should be responsible for the method and design of the end-termination so that it meets or exceeds the performance requirements.

The type of coupling or end-connector should be specified by the operator. A variety of couplings exist, such as bolted flanges, clamp hubs, threaded connections, and welded joints. A discussion of pertinent types of couplings and end-connectors can be found in API RP 17A and API Spec 17D.

2.4.1.3 Fluid Control and Fluid Isolation

2.4.1.3.1 A quick disconnect can be used at the surface termination of metal or flexible risers. This has been done in the case where it was possible for extreme weather to force the vessel off location. The risers are evacuated of hydrocarbons and filled with sea water before the onset of extreme weather. If a drift-off occurs, the risers can be disconnected. The risers can be reconnected when suitable conditions have been restored.

2.4.1.3.2 Sales risers that connect the FPS to the subsea pipelines have isolation valves in the surface equipment and may have them in the sea bed equipment. The surface isolation is usually a ball or gate valve just upstream of the riser or a number of valves that isolate a manifold that co-mingles the flow going into the riser. The subsea equipment can be a ball or gate valve or a check valve. Large check valves with pigging capability have been introduced as isolation equipment in subsea pipelines.

2.4.1.3.3 Deepwater drilling risers sometimes have riser fill-up valves. These valves are set to automatically allow sea water to enter the drilling riser in the event the exterior water pressure is above the internal fluid pressure and might collapse the riser. These valves usually consist of a spring loaded sliding sleeve on one of the riser joints. The sleeve has internal and external pressure areas that cause it to open when required. It closes automatically when the pressure imbalance is corrected.

2.4.2 Components for Stability and External Load Control

2.4.2.1 Tensioning and Heave Motion Compensating Systems

2.4.2.1.1 The upper support connection of a metal riser provides adequate axial tension support of the riser while at the same time allowing motions of the riser with respect to the FPS. The tensioner connection to the riser can be adjustable to conform to uncertainty in required riser length. The tensioner's centralizer system restricts lateral motion to provide safe spacing between equipment during operation. The tensioner system should be designed so that it is dimensionally compatible with installation, operating, maintenance, and inspection procedures of the FPS design.

2.4.2.1.2 During drilling or workover operations, tubulars may be hung off at the top of the riser. However, the added weight of the tubulars below the mudline does not contribute to global buckling of the riser. Therefore, it is not necessary to increase the capacity of the tensioner for the below-mudline weight. Nevertheless, local stresses in the riser should be checked for this load case.

2.4.2.1.3 The tensioner system provides the full range of tension required during inspection and maintenance program activities. The tensioner system design must meet minimum tension requirement in the event of individual component failure during normal operations and during inspection and maintenance activities.

2.4.2.1.4 Structural design of the tensioner follows the latest edition of API RP 16F. Electrical design conforms to class and division requirements of the operating area on the FPS. The tensioner design load considers the normal operating load and any normal additional loads during operation that are incurred in standard operations. (An example of a normal additional operating load is additional load during drilling or workover operations.)

2.4.2.2 Supplemental Buoyancy

FPS production risers may require external methods for tension and/or configuration support. In many cases this is provided by buoyancy added to the production riser system. Buoyancy force may be provided at discrete points or continuously along a length of the production riser. The following describes some methods and types of buoyancy that have been used with production risers.

2.4.2.2.1 Distributed Buoyancy

A commonly-used type of buoyancy material is syntactic foam. Syntactic foam is a composite material of small spheres of air trapped in a matrix or binder that surrounds and protects the spheres. The most common forms of syntactic foam consist of tiny glass microspheres in a matrix of thermo-setting resin. This material is usually used for deep water applications due to its ability to withstand high external hydrostatic pressure. See Section 7.7. Distributed syntactic foam is discrete modules of syntactic foam (attached along the length of the production riser). See Figure 16.

Closed cell foam is a type of buoyancy material that is usually produced by mixing two or more liquids that when mixed expand and fill the area into which they are poured. While expanding, the mixture creates vapor bubbles that gives it buoyancy. This foam usually cannot withstand external hydrostatic pressures as high as syntactic foams.

Air cans are structures that provide a net buoyant force by displacing water with a gas in a confined reservoir space attached to or surrounding the riser. Air cans can be either configured with open bottoms such that the gas pressure equals the surrounding ambient pressure or be completely enclosed with an internal pressure significantly different than the surrounding ambient pressure.

Other buoyant materials can be used. The amount of buoyancy provided, the length of time the buoyancy must be present, the water depth and the cost usually determine the adequacy of the material chosen.

2.4.2.2.2 Concentrated Buoyancy

Concentrated buoyancy supports all or part of the riser at a single point with a buoy. A surface buoy is a structure located at the air water interface. Such a buoy can be constructed as an air chamber or of syntactic foam or both. A submerged buoy is a structure located below the air-water interface. A surface buoy provides a varying tension force to the riser because of the change in the submerged volume of the buoy. A submerged buoy provides a constant tension force to the riser system.

When concentrated buoyancy is used as a tensioner for spars, stops to limit vertical motion of the buoyancy cans may be provided. The lower stops limit buckling of the riser caused by excessive loss of buoyancy and the upper stops protect the deck area from upward motion of the buoyancy cans caused by a parted riser.

2.4.2.3 Flexure Controlling Devices

Various devices are used to reduce riser bending moments or control curvature.

2.4.2.3.1 Metal pipe

2.4.2.3.1.1 Flex Joint

Metal-elastomer bearings, also referred to as flex bearings or flex elements, are constructed of alternating layers of metal and elastomeric materials. These layers are typically contained between two metal interfacing rings or are integrally molded to a component member of the assembly that provides flexibility. Metal-elastomer bearings can support high loads in compression, yet transfer relatively small bending moments.

One or more metal-elastomer bearings are used in flex joints such that tension and pressure loads through the joint produce compression in the bearing. Angular offsets of the tubular ends of the joint, such as those induced by offset and pitch and roll of the FPS vessel, produce minimal bending moments. Therefore, flex joints are used to allow large angular deflections in risers without producing large moments near the end connector. Because of the lack of parts that move relative to one another by sliding, flex elements have an inherent advantage of extended service life and require minimal maintenance when compared to ball joints.

2.4.2.3.1.2 Ball Joints

Ball joints consist of a ball and matching socket housing that join two pipe segments. Where required, fluid flow can be maintained through the ball joint by a sliding seal between the ball and socket. Shear and tension loads can be transferred across the joint with a minimal bending moment. Ball joints have the disadvantage of sliding friction and wear between internal parts and generally do not have a long service life compared to the metal-elastomer type flexure elements. The are usually not used for high pressure and high tension applications.

2.4.2.3.1.3 Tapered Stress Joint

Within production riser installations there is a need to provide a transition member (tapered wall thickness) between rigidly fixed or stiffer sections of the production riser and less stiff sections of the production riser. One approach is through the use of a transition member where the bending stiffness at one end is close to the stiffness characteristics of the more rigid section of the riser while the opposite end has a stiffness that is lower than that of the less stiff or moveable member of the riser. This can be achieved by varying the wall thickness of the transition member to form a tapered stress joint (see Figure 17).

2.4.2.3.1.4 Keel Joint

Where metal risers protrude through the keel of spar hulls, a strongback type of joint can be used to stiffen the riser in bending. Additional wear material can also be provided on the keel joint and on its guide to prevent wear on the net section.

2.4.2.3.2 Flexible Pipe

To control or limit the bending radius in flexible pipe, flexure controlling devices may be required. Either bend stiffeners or bend restrictors are used, depending on the application. These are usually fitted on the end fittings of the flexible riser.

2.4.2.3.2.1 Bend Stiffeners

Bend stiffeners are used to increase and distribute the pipe bending stiffness in localized areas (see Figure 18). When subjected to anticipated bending moments that would otherwise be unacceptable, the increased stiffness reduces curvature and hence strain in the pipe layers. A typical application of bend stiffeners is at the top of dynamic risers, where they provide a continuous transition between the flexible pipe, with its inherent low bending stiffness, and the metal end fitting, which is very stiff. Bend stiffeners are often made of a polymeric molded material surrounding the pipe and attached to the end fitting.

2.4.2.3.2.2 Bend Restrictors

Bend restrictors do not change the pipe bending stiffness. They mechanically prevent the pipe from being bent below a given radius of curvature. One type of bending restrictor consists of a series of interlocking steel or rigid polymeric vertebrae that limit the bending radius of the flexible pipe passing through the vertebrae. This is not used in dynamic applications (see Figure 19).

Another type of bend restrictor consists of a device with a tapered conical inner surface through which the flexible pipe passes. The bending radius of the pipe is restricted by contact with the surface.

2.4.2.4 Stabilizing Structures

Structural Support Members—Some risers have plates or upsets along their length that act as supports for the riser during running and retrieving. Some have plates or upsets that act as attachment points or supports for other equipment attached to the riser. These attachments are not part of the structural portion of the riser that carries the primary working loads. These support members are referred to as load shoulders and reaction plates.

2.4.2.5 Centralizing Devices

Centralizing devices are used at the support frame elevation on production risers or multibore risers with the purpose of maintaining proper riser spacing during vessel offset. The rollers of the centralizer frame restrict the lateral displacement of the riser only, thus imposing no constraint on the axial displacements at the top of the riser.

2.4.2.6 Devices for Reduction of Hydrodynamic Loading Effects

2.4.2.6.1 Waves and currents induce drag loads on risers. Equipment such as hydrofoil elements, fairing vanes and other rotating equipment that can orient itself to the current direction, reduces the drag effect.

2.4.2.6.2 Currents may induce the periodic shedding of vortices in the wake of the riser, which may induce a vibrational response known as vortex induced vibration (VIV). Normally a fatigue assessment is made to determine if a vortex suppression device is required. Various types of vortex suppression equipment have been used. Attaching fairings in the shape of a hydrofoil have been used on some risers. The foils must rotate to align with the current. The foils are made of metal or composite structural material.

2.4.2.6.3 Attached streamers have been used on some small diameter risers. The width and length of the streamers determine their effectiveness. The streamers are made of fibers that can withstand the sea water environment.

2.4.2.6.4 Flow disrupters have been used on all sizes of risers. The shape of the disrupter determines its effectiveness. Locating smaller cylinders around the cylinder to be protected, wrapping the riser with helical strakes, varying the outside diameter of the riser by adding material and changing the surface shape, i.e., dimples or bumps, have all been used as flow disrupters. The specific application usually determines which flow disrupter is used.

2.4.2.6.5 Equipment that disrupts the coherence of the flow, such as helical strakes, reduces the VIV effects. Figure 20 shows a typical strake pattern. Parameters governing the effectiveness of the strakes to reduce VIV are strake height, usually specified as a fraction of the riser diameter, strake pitch, and number of strakes (typically three).

2.4.2.6.6 Both hybrid production risers and SCRs have used strakes as VIV suppression devices. Strakes can be manufactured using a variety of materials and shapes. The first hybrid riser installed in the Gulf of Mexico used fiberglass composite material reinforced with plastic and molded in a "T" cross section shape with a wide base and a raised center leg. Fixation of the strakes is either to the outer surface of the riser joint or to foam buoyancy material surrounding the riser.

2.4.3 Monitoring and Control Systems

2.4.3.1 Riser monitoring and control systems are used to determine the operational state of the riser system and to make appropriate adjustments. Monitored parameters could include angles, tensions, strains, vibrations, positions, and actuator positions at various locations along the riser. The control system could vary some of these parameters by changing the tension applied to the riser top or by changing the position of the riser top. It could also control wellhead connector actuators and subsea valve actuators.

2.4.3.2 Sensors and actuators mounted on the FPS or on the riser may use hydraulic, electrical, or optical signals carried via appropriate umbilicals or may use acoustic signals carried through the water. Subsea control systems available at this time utilize direct hydraulic control, piloted hydraulic control, electro-hydraulic/multiplex control, and acoustic-hydraulic/multiplex control. Umbilicals may need to be attached to the riser for support and protection.

2.4.4 Fluid Purge and Containment

2.4.4.1 Planned Disconnect

The planned disconnect makes use of the surface mounted and seabed mounted equipment in a manner that enables purging the risers of hydrocarbons prior to disconnect. This uses the standard surface and seabed trees and manifolds to circulate out hydrocarbons and replace them with sea water.

2.4.4.2 Unplanned Disconnect

The unplanned disconnect makes use of the same surface mounted and seabed mounted equipment discussed above in a manner that minimizes loss of hydrocarbons during disconnect. This uses the standard surface and seabed trees and manifolds to isolate the hydrocarbons in the risers and eliminates the further flow of hydrocarbons into the risers. The following is a short description (for an unplanned disconnect) of the components that might be used.

2.4.4.2.1 Quick Disconnect Connectors

These are connectors located in a position in a riser that allow for a quick or emergency disconnect of the riser from the surface vessel. These connectors must be activated by personnel on the vessel. They are hydraulically or pneumatically operated and are similar in design to standard BOP-to-subsea wellhead connectors. Ideally there would be valves on both sides of the connector.

2.4.4.2.2 Break-away Flowline Couplings

These connectors release automatically when a designed-in load limit is reached. The fail-safe closed valves on either side of the coupling close without permitting any further hydrocarbons flow.

2.4.4.2.3 Lower Riser Packages

These are assemblies of valves and/or BOPs that permit closing in well fluids at the seabed and containment of fluids in the riser string for disconnecting from the subsea wellhead or tree. With the proper valve arrangement, there is little loss of riser fluid to the environment. The riser can be reconnected at a later time.

2.4.4.3 Quick Dsisconnect for Flexible Risers

2.4.4.3.1 Quick disconnect systems for flexible risers may be required at the top of the riser on an FPS, depending on regulations or other technical requirements (risk of loss of position of the platform due to a mooring failure). The function of the system is to disconnect the riser and isolate the fluid path in case of an emergency and to minimize the risk and extent of pollution.

2.4.4.3.2 Individual hydraulic controlled conduit and multiport systems are currently available. They consist of: a remote connector, an alignment frame and usually (depending on the application and the transported fluid) one or two valves, one on the flexible riser side, the other on the platform piping side. The control sequence allows for automatically closing the two valves prior to releasing the connector.

2.4.4.3.3 When released, the riser is dropped into the water in a controlled or uncontrolled fashion, depending on the project requirements and the type of emergency.

2.4.4.3.4 Alternative designs, known as quick connect/disconnect connectors (QCDC) provide a quicker way to perform the initial connection, or reconnection after abandonment of the flexible pipe to the platform.

2.4.5 Guidance (Re-entry) Equipment

2.4.5.1 Risers can have guidance equipment attached at one or more locations along their length. For risers that are not run in close proximity to other risers, it may suffice to have guidance at the bottom only. This bottom only guidance is usually sufficient to get the riser mated to the sea bed equipment. Risers that are run in close proximity to other risers or a hull may require guidance equipment at various locations along their length. Sometimes this guidance is attached to running tools and retrieved with the tools.

2.4.5.2 The BOP system is generally not deployed until the surface casing string is set. Consequently the marine drilling riser is not available as a means of guiding tools and equipment from the drilling vessel to the ocean floor while the conductor and surface casing string are set. Two means of guiding equipment from the vessel to the ocean floor are typically used:

a. Guideline systems employ wire ropes (guidelines) and funnels or other guides to control the motion and position of equipment as it is run from the vessel to the sea floor.

b. Guidelineless systems employ television, acoustics, or other remote sensing systems to monitor the position of equipment as it is deployed. Controlling vessel position and/or ROVs align the equipment as necessary.

2.4.5.3 Guideline systems have traditionally been used for moored operations and guidelineless systems for operations conducted from dynamically positioned vessels. However, guidelineless systems have been used by moored vessels.

2.4.6 Anti-fouling Equipment

2.4.6.1 Risers have been designed with provisions added to enable anti-fouling equipment to travel up and down the riser to remove marine growth. This equipment may need guidance or locomotive means attached to the riser. The riser outside surface must be able to withstand the loads imposed by the anti-fouling equipment.

2.4.6.2 Coatings have been used to reduce or eliminate certain types of marine growth. Many coatings are being investigated to determine their overall effect on the marine environment. Coatings are expected to remain a viable means of reducing marine growth on risers if their interaction with the environment is minimal. See Section 7.8.

2.4.7 Damage Limitation Measures

2.4.7.1 Fire Protection

2.4.7.1.1 Fire protection of the riser and its structural support components should be reviewed in conjunction with the overall operational safety plan designed to provide for the protection of personnel and equipment. To prevent small scale fire hazards from spreading or contributing to personnel harm and equipment failure, consideration should be given to fire protection for the riser, the structure and the tensioning equipment.

2.4.7.1.2 Protection can be provided by active or passive means. Active fire protection involves the extinguishing of fires by dispensing proper fluids in sufficient quantity. Passive protection utilizes enclosures to impede the heat flow of the fire to the equipment to slow the temperature rise. Fire protection requirements for equipment depend on individual requirements for maximum heat influx and temperature rise for a given time period. The safe structural and mechanical operating temperatures should be considered in selection and design of the proper system.

2.4.7.2 Mechanical Damage Protection

The objective of these devices is to limit progressive damage to risers. Any technique that will address the problem can be considered. Some that have been use are: riser protection nets, bumpers, frames, and coverings including buoyancy tanks/foams.

2.4.8 Insulation

There may be a need to reduce heat loss from production risers by creating a dead water or gas filled annular space, using thick protective coatings that double as insulation, using coatings added for insulation reasons only, and reducing the number of heat radiating components attached to the riser.

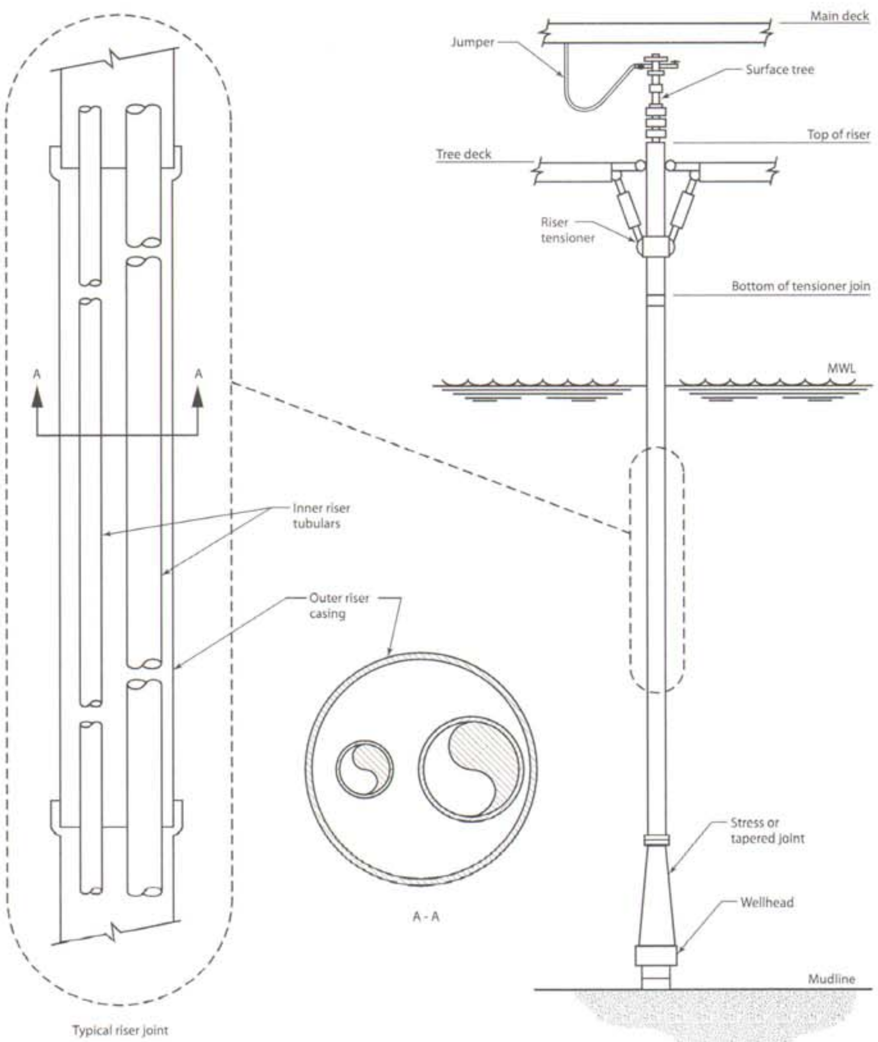

Figure 4—Top-Tensioned Production Riser

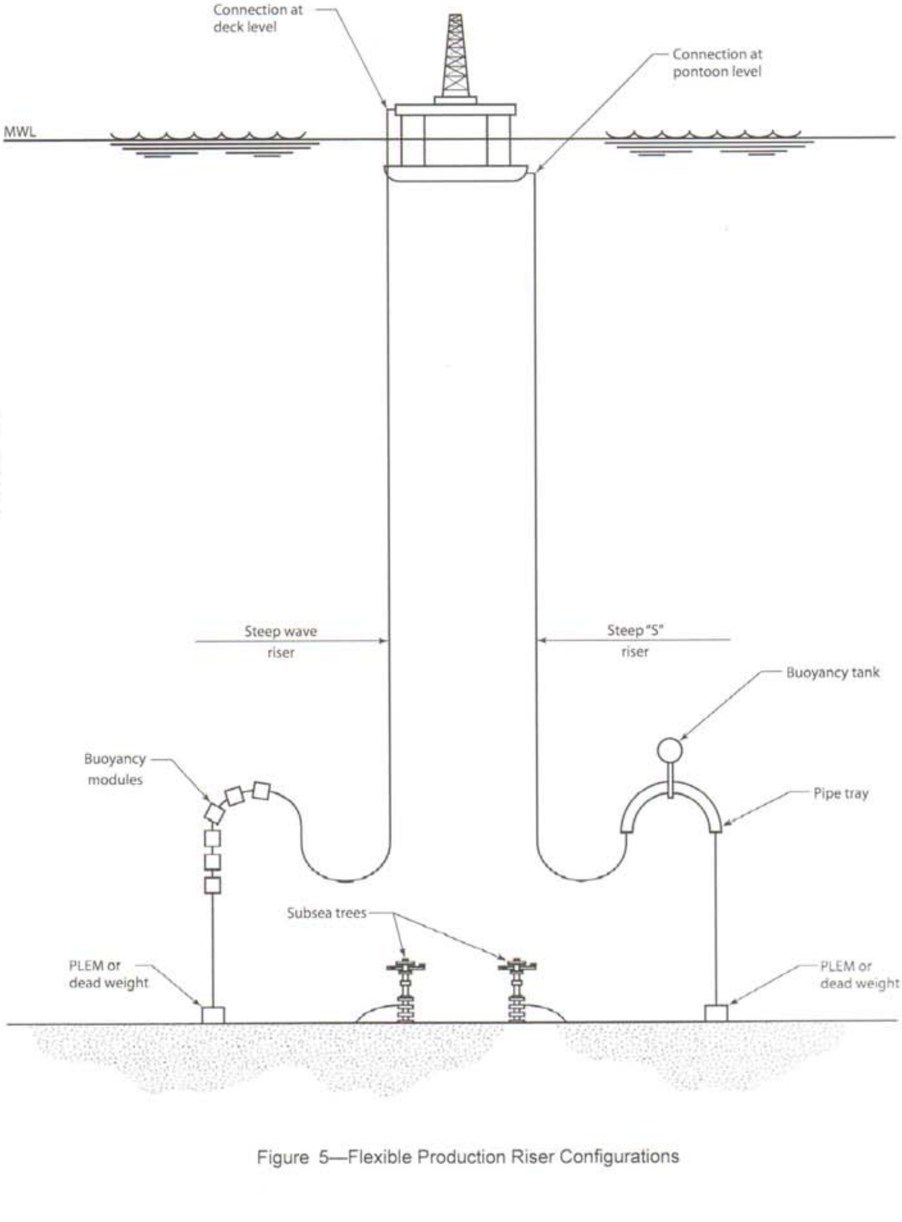

Figure 5—Flexible Production Riser Configurations

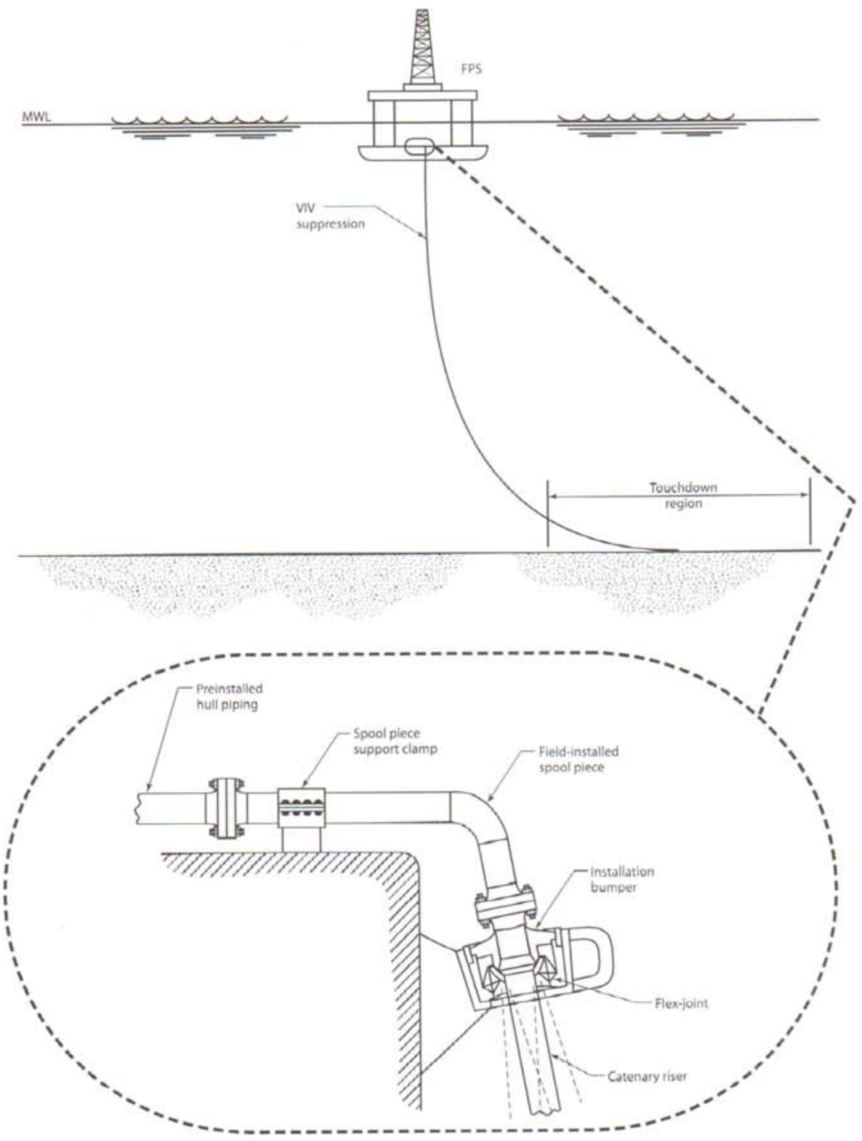

Figure 6—Steel Catenary Riser

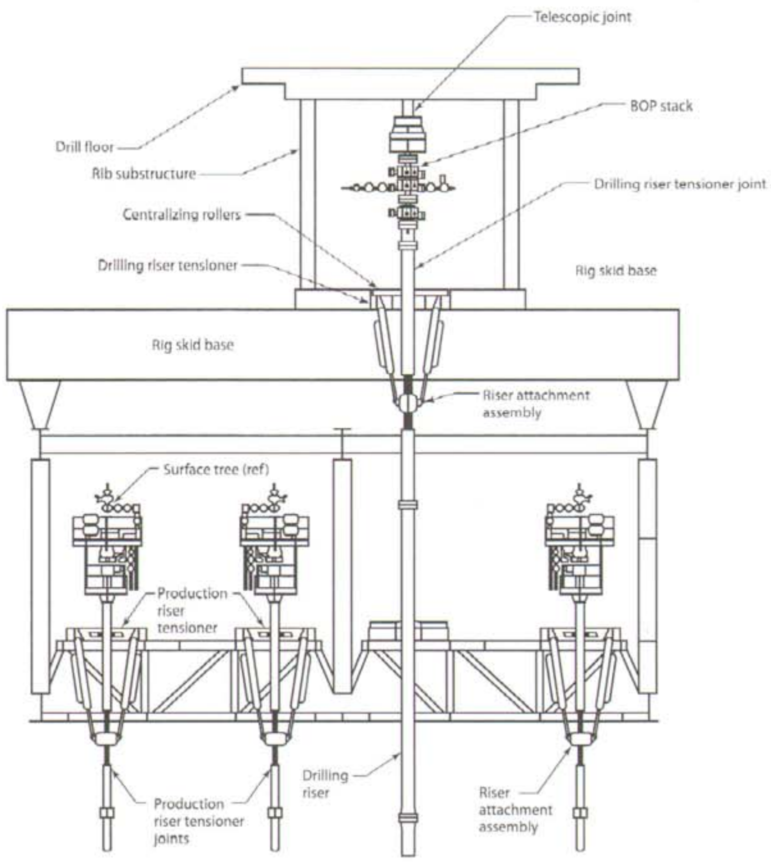

Figure 7—Drilling Riser, BOP at Surface

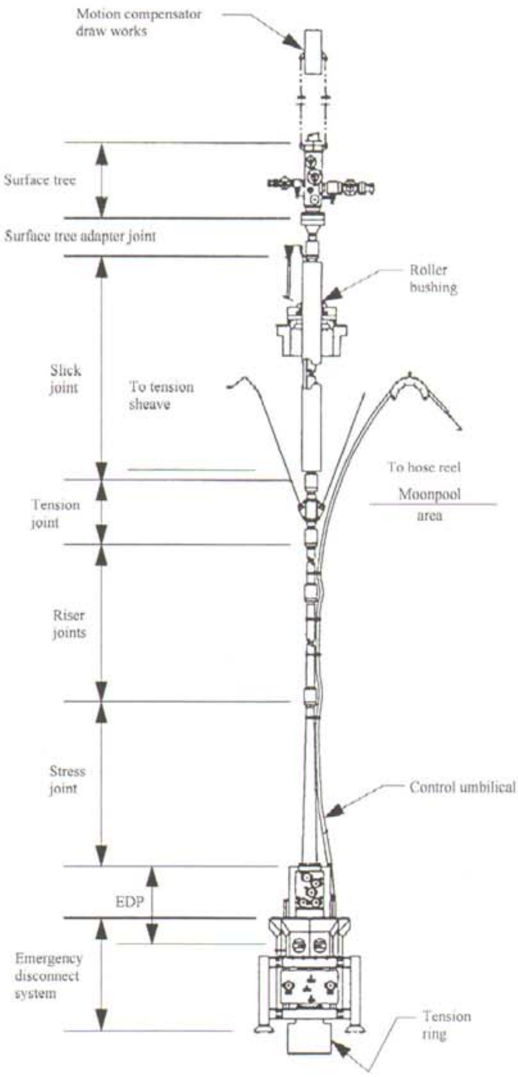

Figure 8—Completion Riser System

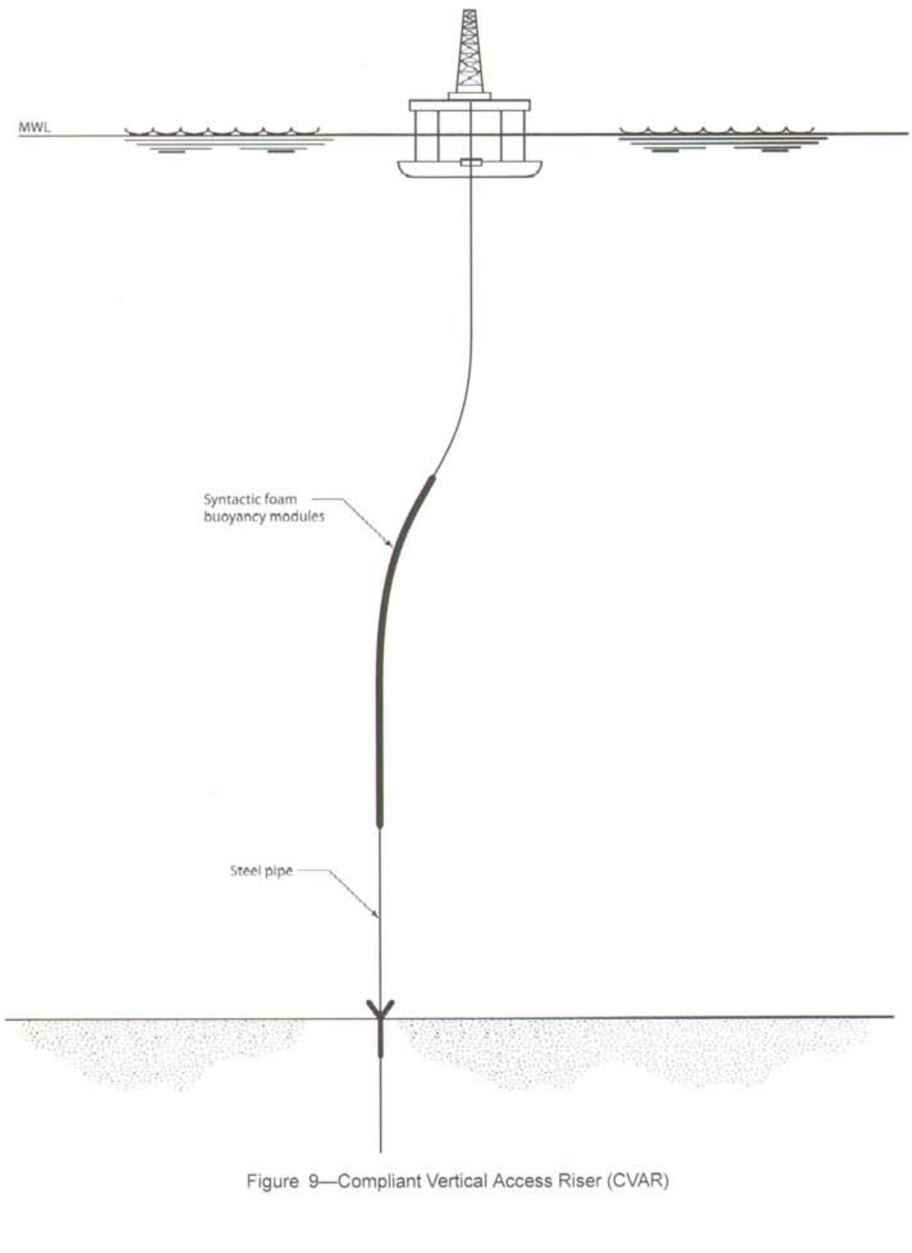

Figure 9—Compliant Vertical Access Riser (CVAR)

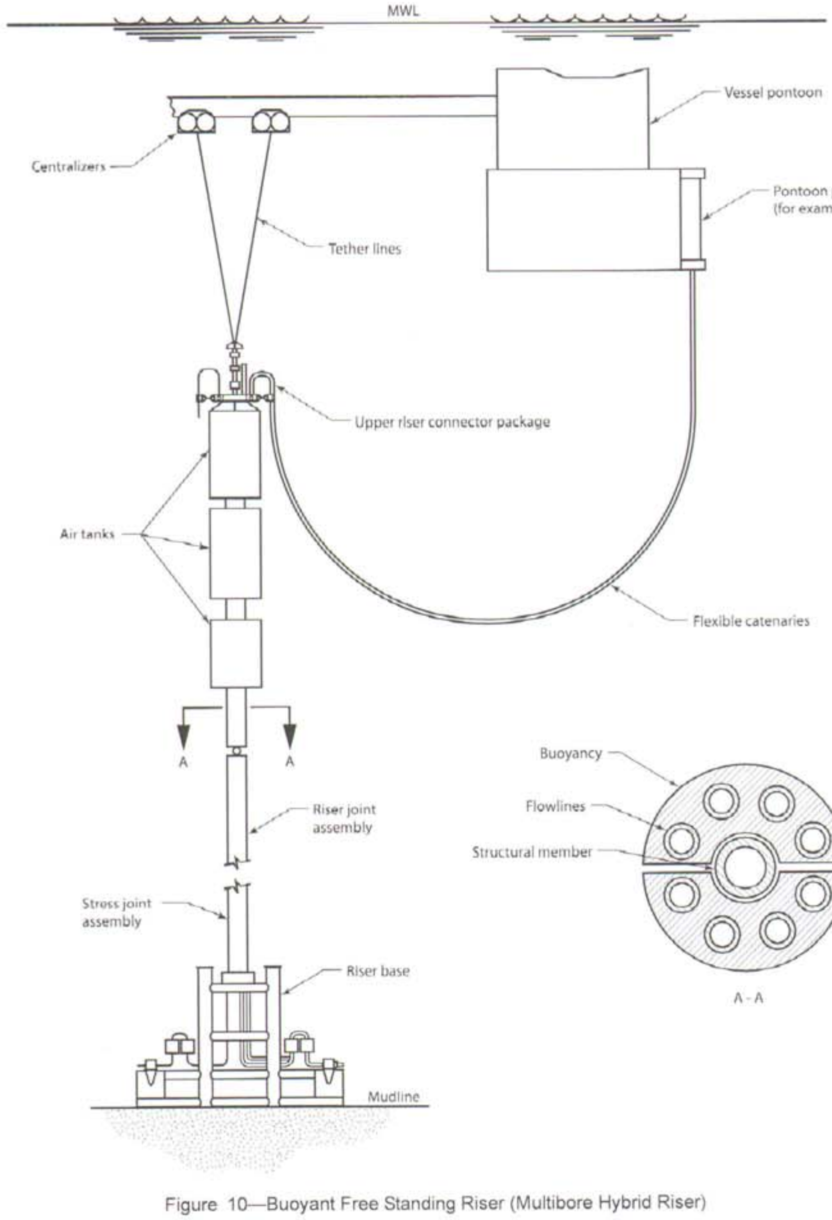

Figure 10—Buoyant Free Standing Riser (Multibore Hybrid Riser)

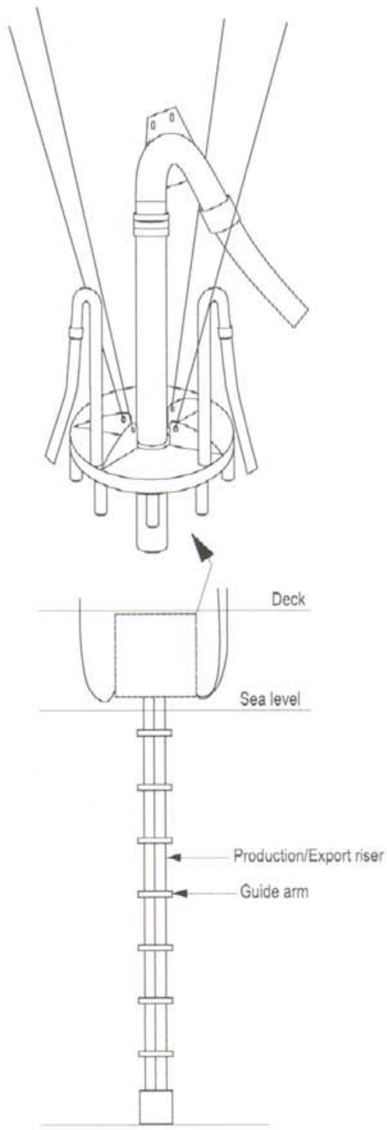

Figure 11—Multibore Top-Tensioned Rigid Riser

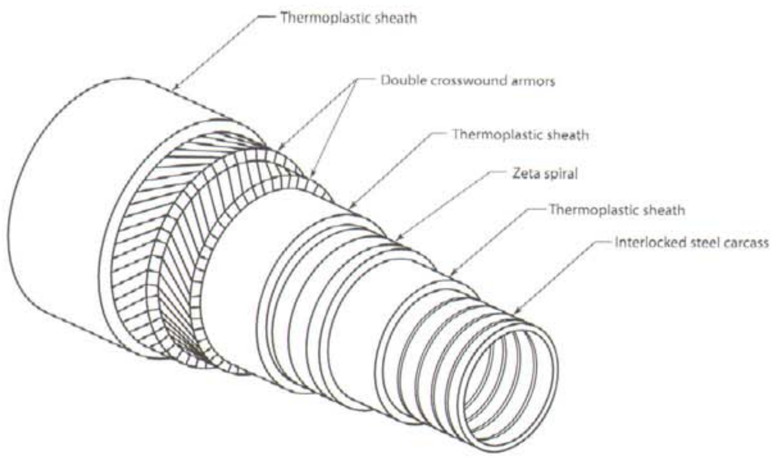

Figure 12—Typical Flexible Pipe Structure

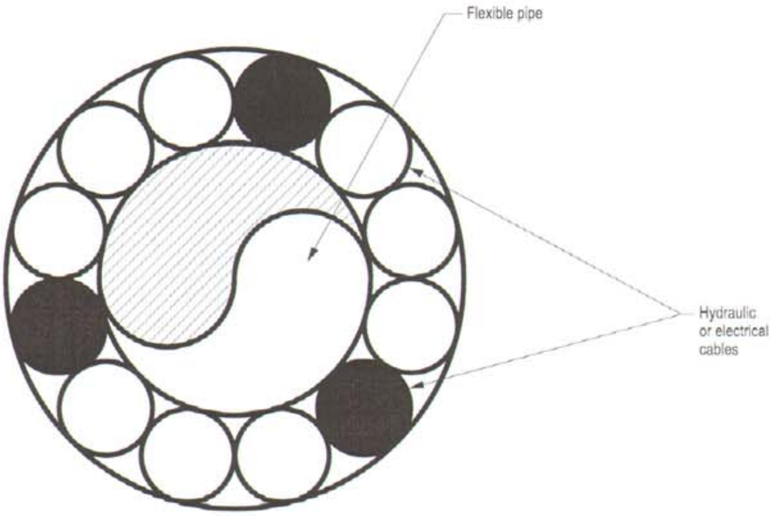

Figure 13—Integrated Service Umbilical or Single Well Multibore

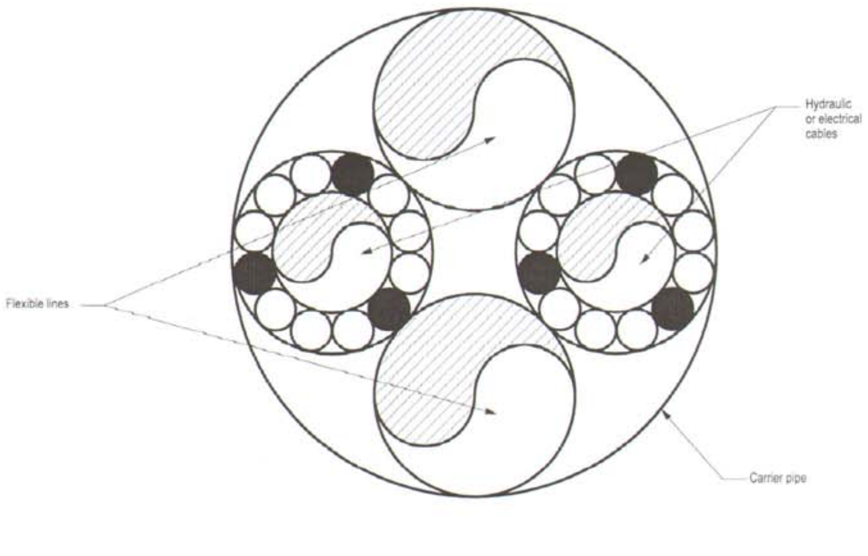

Figure 14—Multibore Flexible Pipe

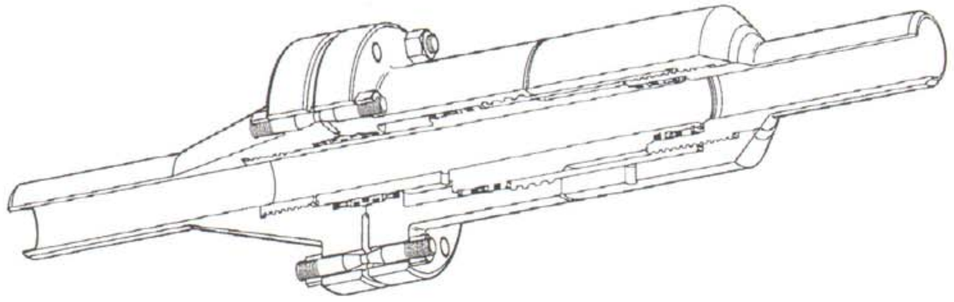

Figure 15—Break-away Flowline Coupling

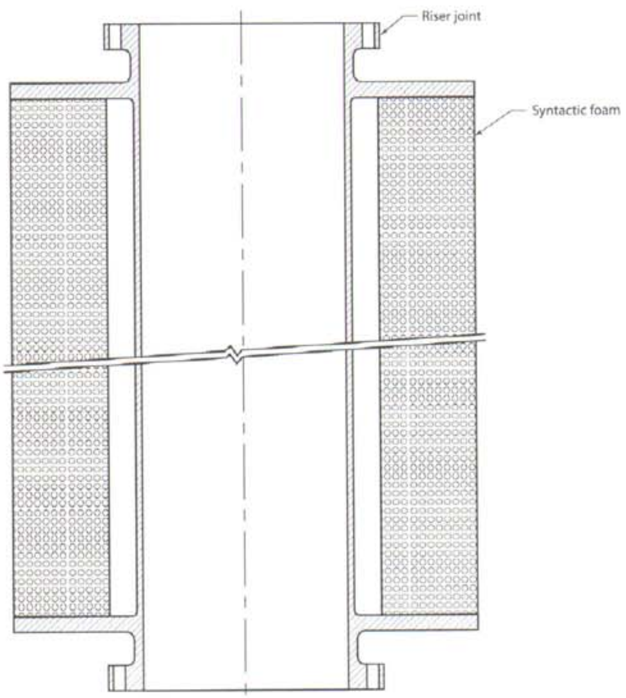

Figure 16—Syntactic Foam Buoyancy

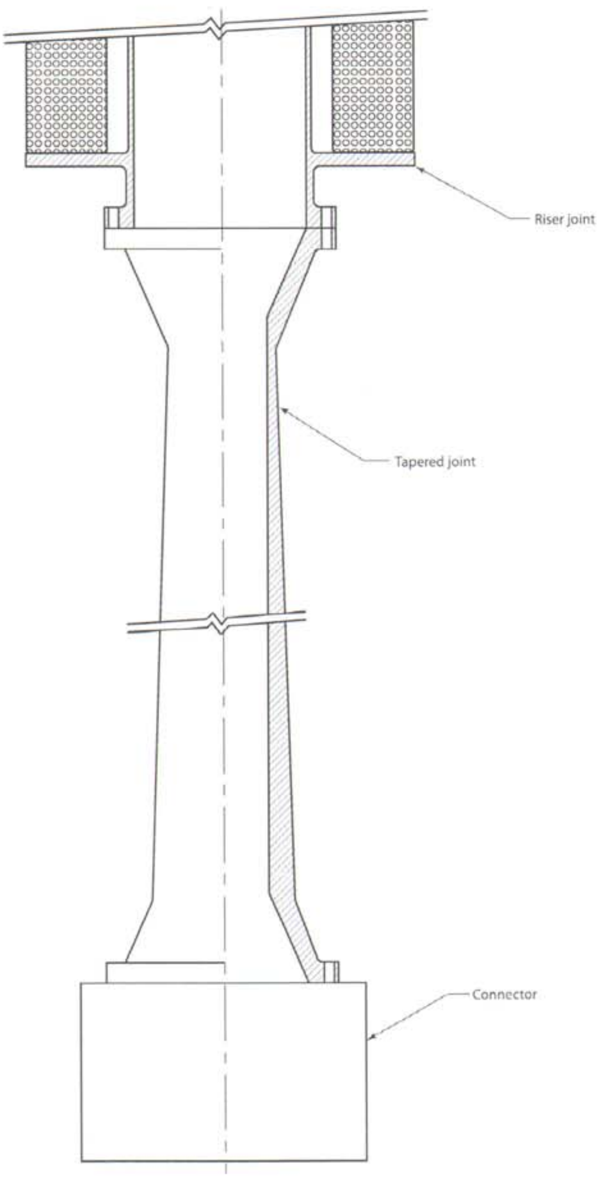

Figure 17—Tapered Stress Joint

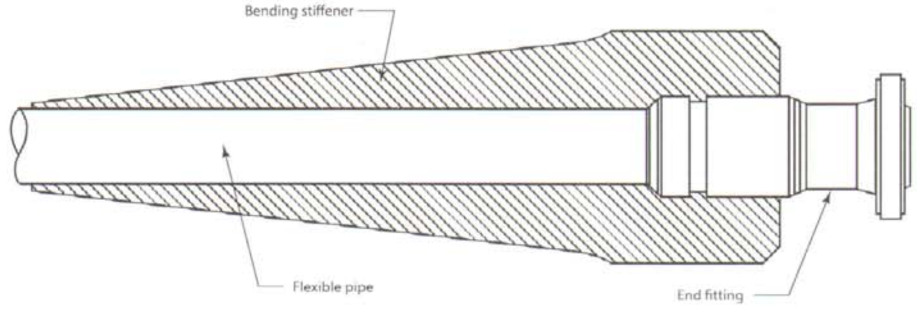

Figure 18—Bending Stiffner

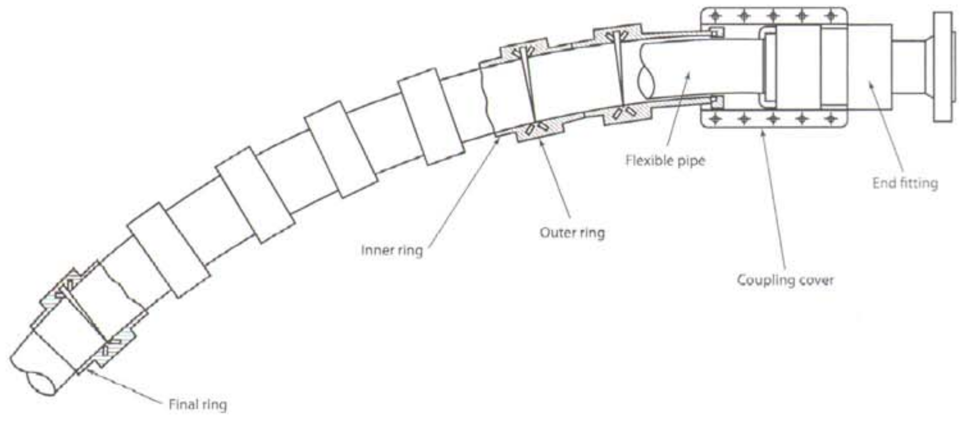

Figure 19—Bend Restricter

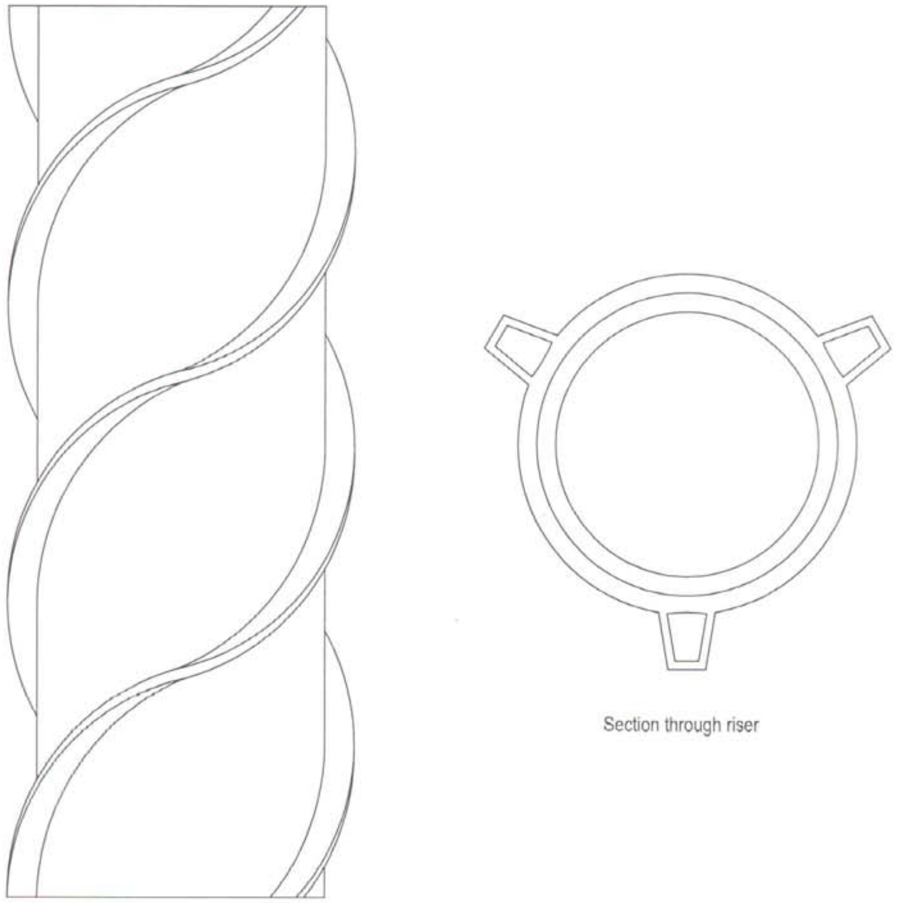

Figure 20—Cross Section and Span Views of Helical Strakes

3 General Design Considerations

3.1 GENERAL

3.1.1 Designing a riser system for a FPS is a multi-disciplinary task. Since the riser is a part of a larger system, its design is influenced by the environment and performance requirements as well as by interaction with both the FPS and the sea floor equipment.

3.1.2 This section further develops material in Section 1 by describing general design parameters that should be considered by the riser designer. This section begins with safety, risk, and reliability and continues with functional, operational and structural considerations and materials standards. It also identifies some applicable design codes and standards. The intent is to provide an introduction to the considerations that govern an FPS riser design. This section also gives designers of other major FPS systems an appreciation of the interfaces their systems may have with the riser system.

3.2 SAFETY, RISK, AND RELIABILITY

3.2.1 Designers of riser systems need to consider personnel safety and protection of the environment and equipment within a framework of efficient, cost-effective design. Designers carefully assess the risks associated with operating a riser system and strive to minimize the probability and consequences of an uncontrolled release of riser system contents. Such a release could be caused by either internal or external events. In addition, riser systems are often non-redundant structures conveying pressurized hydrocarbons between seabed terminations and surface vessel. Therefore, risk assessment plays an essential role in riser design. Riser systems should be designed recognizing that they are an integral element of the overall offshore production system.

3.2.2 Although risk assessment is essential in the design process, the designer will have some latitude in selecting among the various qualitative and quantitative risk assessment techniques, depending on a project's specific regulatory environment. Whether qualitative or quantitative, risk assessment fits well within the framework of developing an efficient, cost-effective design through the early identification of hazards, assessment of failure consequences and frequencies of occurrence and identification of mitigation and prevention measures. Risk assessment is also particularly useful in comparing relative risks among riser design options.

3.2.3 The consequences of failure are often assessed in terms of the possible hazards to personnel, effects on the environment and potential financial loss. Although the integrity of the riser system is the primary concern, a riser risk assessment should encompass a larger scope, including well system operations, marine operations (including escape and evacuation procedures), and system interfaces at the top and bottom of the riser. System deployment and retrieval procedures are also considered when assessing risk.

3.2.4 The types of events to be considered in a risk assessment should include leaks (especially hydrocarbon releases), riser structural failure, component functional failure, and major surface events:

a. Riser system leaks can occur in any number of components, from the riser (joints/couplings), downhole (casing/tubing, packers, seals, safety valves, etc.) or external (leak in neighboring riser, process area, etc.). Leaks can affect riser operability, riser structural integrity, and well control.

b. Structural failure can result from excessive load, accidental impact, corrosion, or fatigue.

c. Failure and/or inadvertent actuation of mechanical components can lead to undesirable events such as dropping the BOP stack and/or riser or disconnect of the subsea wellhead connector.

d. Major surface events include accidents such as fires, explosions, blowouts, or vessel collisions that could be a serious detriment to riser system integrity.

3.2.5 All FPS subsystems and interfaces should be considered in assessing the risks of these events to the riser system.

3.2.6 The term "reliability" may have different connotations with reference to offshore structures. In its simplest form, reliability is synonymous with dependability (e.g., component reliability), and there are several databases that catalog the reliability (e.g., number of expected failures per year) of common components on offshore facilities. In formal risk assessment, reliability analysis focuses on estimating the probability of an event (e.g., release of hydrocarbons, component failure, etc.). In structural engineering, structural reliability analysis assesses a structure's ability to accommodate loads in excess of its design loads and estimates the likelihood of structural failure given anticipated loading conditions (e.g., determining a platform's reserve strength). Reliability is also the key word in the reliability-based structural design method, which differs from the working stress design approach followed in this RP by explicitly accounting for uncertainties in loading and in a structure's resistance to loads. One application of reliability-based design methods is the load and resistance factor design (LRFD) method that has been implemented for fixed platforms in API RP 2A-LRFD.

3.2.7 Reliability, as used here, relates to estimating the likelihood that the riser system will fail because of component failure, operator error, an external event, or structural loading. Therefore, reliability assessment is an integral part of evaluating risk, which by definition combines both the frequency of occurrence and the consequences of an undesirable event. The validity of riser reliability assessments is a function of accumulated field experience. As more field data is compiled, the accuracy of these assessments will improve.

3.3 FUNCTIONAL CONSIDERATIONS

Functional requirements for risers associated with FPS systems can vary significantly, depending on the application. Functional requirements are also determined by the primary duty or service of the riser. A riser for a single subsea well, for example, will typically have fewer functional requirements than a riser handling produced fluids for multiple wells. The number of functional requirements generally correlates with system complexity.

3.4 STRUCTURAL CONSIDERATIONS

Once functional and operational considerations are established, the structural components are designed to perform their function and satisfy allowable stress limits and design life requirements. In this RP, structural design is based on an allowable stress approach that defines acceptability on the basis that calculated stresses in the riser are below allowables established herein for all applicable loading conditions. With such an approach, the designer should be aware of the range of external and internal loads to which a riser will be subjected (see Section 4). These loads are combined to establish extreme conditions used to verify that the riser design satisfies specific design acceptance criteria. The designer should use the types of riser analyses that provide sufficient riser response information to compare predicted riser stresses and deflections with allowables.

This subsection introduces the primary issues that the structural designer and analyst should consider in designing a riser system. A more thorough and detailed description of structural design loads and criteria for FPS risers are contained in Sections 4 and 5 of this RP. Section 6 gives additional guidance on how to analyze risers.

3.4.1 Load Combinations For Design Cases

3.4.1.1 A design case is a combination of loads calculated for a specific operational phase and particular system and environmental conditions. The design cases to be evaluated are outlined in Section 4. For each design case, appropriate load combinations of the applicable external and internal forces should be developed. An example of the general components of a typical load combination is shown in Figure 21.

3.4.1.2 For extreme event analysis, the riser should be designed for the loading condition combinations (of reasonable probability of occurrence) that produce the most severe effects on the riser. A sufficient number of load combinations should be developed to represent all installation conditions, in situ conditions and unusual event conditions according to the guidance given in Section 4.

3.4.2 Design Criteria

3.4.2.1 Allowables

3.4.2.1.1 The following design limits should be considered where applicable:

a. Allowable stress (include burst, tensile, and combined).
b. Allowable deflection.
c. Collapse.
d. Fatigue/service life.
e. Inspection/replacement interval.
f. Temperature limits.
g. Minimum bending radius.
h. Permeability of flexible pipe.
i. Abrasion and wear.
j. Interference.

3.4.2.1.2 The determination of appropriate allowable stresses is addressed in Sections 4 and 5.

3.4.2.2 Interference

3.4.2.2.1 The riser system design should include evaluation or analysis of potential riser interference (including hydrodynamic interaction) with other risers, mooring legs, tendons, hull, the seabed, and with any other obstruction. Interference should be considered during all phases of the riser design life including installation, in-place, disconnected, and unusual events.

3.4.2.2.2 If contact is to be permitted, resulting collision loads should be determined to demonstrate that structural integrity is maintained.

3.4.2.2.3 The estimated accuracy and suitability of the selected analytical technique should be assessed when determining the probability and severity of contact.

3.4.2.3 Fatigue and Service Life

3.4.2.3.1 Fatigue analysis of risers involves calculation of the fatigue damage caused by waves, vortex induced vibration, vessel motions, and thermal and pressure cycles. The goal is to ensure that a component's calculated fatigue life exceeds its service life multiplied by a safety factor (see 5.6).

3.4.2.3.2 Service life analysis requires the calculation of the long term effects of chemical, biological or ultraviolet exposure on non-metallic riser components.

3.4.2.3.3 The following items should be included in a riser fatigue analysis:

a. All causes of cyclic stress variations should be identified including wave actions, VIV and vessel motions (low and wave frequency), and thermal and pressure cycling.
b. The applicable set of hydrodynamic coefficients should be developed for each flow condition.

c. The fatigue analysis procedure may use a fracture mechanics or cumulative damage analysis (S-N) approach, as appropriate. Normally, the S-N approach is used for design, while fracture mechanics is used to establish inspection criteria during both fabrication and in-service operation of components in riser systems.

d. If the cumulative damage approach is followed, an appropriate S-N curve should be selected or generated for each component subject to cyclic stress variations. The component corrosive environment, fabrication method, and surface finish should be considered.

e. The designer should include a sufficient number of seastates and approach directions to accurately predict the long term distribution of stress ranges. For spectral techniques, an appropriate seastate spectrum type should be identified.

f. An appropriate Stress Concentration Factor (SCF) for each component in the load path should be applied to the calculated cyclic stress variations.

g. The fatigue design load cases for each seastate should account for the appropriate functional loads based on their statistical probability of occurrence during the given seastate;

h. An appropriate method for calculating fatigue damage should be established.

i. If wear is a factor on any component in the load path, its effects should be included in the analysis.

j. Determination of riser fatigue life should take into account any effects of internal and external corrosion, biofouling, chemical deterioration and ultraviolet rays.

k. Safety factors should reflect component maintenance, inspection and replacement program.

3.4.2.4 Degradation of Syntactic Foam Buoyancy

3.4.2.4.1 The designer should select the type and quantity of materials to provide the required buoyant lift over the intended service life while accounting for the predicted degradation of buoyancy. Factors which may affect syntactic foam buoyancy performance relative to specific applications include:

a. Hydrostatic pressure.

b. Duration of service.

c. Cycling of hydrostatic pressure.

d. Mechanical loads and load cycles; (buoyancy modules are usually designed and installed for service in a manner that avoids or limits the imposition of bending or tensile loads).

e. Temperature.

f. Chemical or UV exposure.

3.4.2.4.2 Syntactic foam exhibits a progressive buoyancy loss resulting from water absorption over time. The rate of buoyancy loss (due to water absorption) is inversely proportional to the strength (and density) of the syntactic foam. Typically, heavier or stronger syntactic foam materials will be required for service at greater depths and/or over longer periods of time in service.

3.4.2.4.3 Syntactic foam manufacturers maintain extensive data on the performance of specific materials in various densities at various depths, as well as extrapolation methods which permit the prediction of degradation of lift over extended time in service. Selection of a particular syntactic foam should be based on test data.

3.5 MATERIAL CONSIDERATIONS

3.5.1 Factors to be considered when selecting materials that are fit-for-purpose in a riser system include:

a. Yield and ultimate strength.

b. Material toughness and fracture characteristics.

c. Young's modulus.

d. Shear modulus.

e. Poisson's ratio; S-N fatigue curve.

f. Internal erosion or wear requirements based on the fluid properties and flow rate.

g. H_2S/CO_2 produced water salinity/acidity.

h. Internal corrosive effects.

i. External corrosive effects.

j. Biofouling.

k. Operating temperature.

l. Welding; weldability and HAZ properties.

m. Machining.

n. Manufacturing processes.

o. Galvanic corrosion.

3.5.2 See Section 7 for a more in-depth discussion on materials.

3.6 OPERATIONAL CONSIDERATIONS

3.6.1 General

3.6.1.1 This section describes considerations that a riser designer should be aware of to produce a design that is safe and efficient to install, operate, and maintain. Safe operation of a riser requires:

a. The designer to take into account all realistic conditions under which the riser will be operated.

b. Operations personnel to be aware of the riser's safe operating limits. This information needs to be communicated to operations personnel in a understandable manner.

3.6.1.2 FPS risers generally fit into two operational types:

a. Risers installed and left for (many) years until subsequent retrieval.

b. Risers run and retrieved many times during their service life, which may also accommodate drilling and/or workover operations.

3.6.1.3 Some general considerations apply for both types of riser. Specific considerations may apply to only one of these two riser types.

3.6.1.4 A riser's operational requirements should be distinguished from its functional requirements. Functional requirements define how the riser must function to achieve its intended purpose. Operational requirements define how the riser should be operated to assure a safe operation.

3.6.1.5 Operational requirements are typically documented in a Riser Installation and Operation Manual. The manual, which should be prepared jointly by the designer and the operator, defines how to safely install, operate and maintain the riser and its component systems.

3.6.2 Operating Philosophy

An operating philosophy should be developed early in the design process to ensure that riser operations are conducted in a safe and efficient manner. Detailed procedures should be developed and verified for all aspects of riser operations. They should consider:

a. Vessel motions and environmental limits.
b. Manning.
c. Control centers and ancillary support.
d. Riser deployment and retrieval.
e. In-service operations.
f. Inspection and maintenance philosophy.

3.6.3 Vessel Motions and Environmental Limits

Vessel motion and stationkeeping performance can have a significant effect on the riser design and operation. For instance, the riser can be designed to stay connected when subjected to the extreme environment or designed to be disconnected. Certain operations such as riser running or pulling, drilling, workover and through-bore operations may be restricted or require shutdown, depending upon vessel motions and environmental limits.

3.6.4 Manning

The manning requirements for all operational phases of the riser should be considered. Risers that are pulled frequently or require pulling during severe storm conditions may require additional trained personnel onboard.

3.6.5 Vessel Interfaces

3.6.5.1 The vessel interfaces for riser operations, which include the control centers, laydown areas, craneage, riser deployment equipment, weight and space restrictions, utility systems and ancillary support, should be considered early in the design.

3.6.5.2 Utility support such as electrical power, hydraulic power, air and water may be required to operate a riser and should be interfaced with the vessel systems.

3.6.5.3 Ancillary support equipment such as diving, ROVs, video monitoring, and subsea positioning systems should be considered early and interfaced with the riser and vessel systems.

3.6.6 Riser Deployment and Retrieval

Step-by-step installation and retrieval sequences should be developed. These sequences should identify the personnel and equipment that is required and all critical considerations for the operation. Shutdown sequences for both planned and emergency disconnects should be accounted for.

3.6.7 In-Service Operations

The riser may be used for more than one purpose, in which case the riser operating procedures should consider the riser's other functions. For instance, the production riser may be used for minor and major well workovers, injection, completion, and other purposes. Drilling risers may be used for well completion and testing.

3.6.8 Inspection and Maintenance Philosophy

The type and frequency of in-service maintenance of a riser needs to be balanced throughout the design process, since increases in robustness of design, or material quality, may lessen inspection and maintenance requirements.

3.7 INSTALLATION, RETRIEVAL, AND REINSTALLATION OF METAL RISERS

It is common to think of metal risers as being held in taut, vertical configurations. However, it is important to recognize that normally metal riser pipe sections may be configured in such a manner where inherent compliance is achieved. In such cases, many of the following considerations would still apply, but special features may lead to treatment as other riser types (see 3.9).

The following sections refer to operations involved with the establishment of metal riser systems for floating production developments. Metal risers include all riser types where the riser sections are normally considered to be solid metal. This includes risers for drilling, completion/workover, production, injection, and export/import service. The special features and service demands for metal risers involved in drilling and completion/workover functions make it prudent for the designer to refer to guidance provided in API RP 16Q and API RP 17G.

3.7.1 Preparations, Testing, and Required Support Equipment

3.7.1.1 Trial runs of all installation steps should be performed, to the extent practical, prior to mobilization of a riser offshore.

3.7.1.2 Tank testing of ROV, diving, and subsea interfaces should be considered. All ROV functions, including installation and other operation and maintenance functions, should be tested by actual equipment operation or by mockups of the ROV interfaces.

3.7.1.3 All utilities and installation support equipment should be checked and tested. Critical installation equipment should be load tested, if possible.

3.7.1.4 Step-by-step installation procedures, from transporting equipment from the manufacturing facility to completing installation of all risers, should be prepared. All risers should be considered, as well as plausible combinations of connected risers.

3.7.1.5 The following should be considered in the installation and operational planning:

a. Space out requirements, where special segments may be used in the riser string to achieve a specific overall length between desired connection points.

b. Accessories that must be attached to the riser during running.

c. The method(s) used to guide the riser to the sea floor. In the case of multiple risers, there may be different guidance means required during the different stages of the installation.

d. Interference with other risers, mooring lines and other obstructions during installation.

e. Motion compensation requirements for installation of each riser system, during the running, landing, and disconnect phases.

f. Support vessels, if any, used during riser deployment.

g. Contingency plans concerning actions required for suspending operations if there is riser damage or equipment malfunction.

h. Whether the riser is installed empty or full of water.

3.7.1.6 Installation procedures should be designed to provide reversibility as far as possible. It should be possible to stop operations at any time and retrieve the riser or abandon it for later retrieval.

3.7.1.7 Installation procedures (and scheduled durations) should allow for pigging, if appropriate, and hydrostatic testing of the riser after installation.

3.7.2 Transportation and Handling

3.7.2.1 Structural design of lifting and handling equipment and rigging should follow guidance in API RP 2A.

3.7.2.2 Requirements for protecting the riser system during shipment and handling on the rig should be considered. Protective shrouds, end caps, and other protective devices should be used if necessary.

3.7.2.3 The means for transporting riser and associated equipment to and from the site should be evaluated. Motions of the transportation vessels (barges or supply boats) should be considered in the design of seafastenings and tiedowns.

3.7.2.4 Depending upon the installation method, equipment on the FPS or support vessel should be capable of handling the riser. Crane capacities and reaches at load, derrick capacities, and clearances must be considered.

3.7.2.5 Deck load and deck space requirements during and after installation, including installation tools, should be considered in the installation procedures. Adequate laydown areas should be provided.

3.7.2.6 Moonpool areas and clearances for moving equipment into and out of restricted areas on the vessel should be considered.

3.7.3 Installation Considerations

Metal risers may be installed by the FPS or from either a floating drilling rig, a construction vessel (derrick barge), or by a tow and upend procedure.

In this phase of the operation, safe riser deployment operating envelopes are needed.

Special running tools may be required to deploy the riser. These tools facilitate connecting, lifting, lowering, and riser support. Other tools, such as those used for pressure testing and inspection, may be used as well.

The installation method must allow for a weather window that is large enough to accomplish the work. Contingency procedures must be considered to include suspension and reversal of the installation.

3.7.3.1 FPS Deployed

3.7.3.1.1 Metal risers are normally deployed from the FPS, utilizing a derrick and pipe handling system, if available. The riser is normally handled in joints between 40 to 75 ft. in length. Joint dimensions and weight limitations need to be considered in handling the riser through the V-door and in deployment through the drill floor.

3.7.3.1.2 Special tools may be required to assemble the riser component and to lift and lower the riser string. Also, special tools are normally needed to handle the riser joints.

3.7.3.1.3 Special appurtenances, such as large buoyancy modules or drag fairings, may be attached to the riser and deployed through the rig's moonpool area.

3.7.3.1.4 During running, the riser may be guided either by guidelines, or by the vessel stationkeeping system if it can be used to position the rig and the suspended riser during riser deployment.

3.7.3.1.5 Single bore risers and multibore risers that have integral joints are normally deployed similar to a drilling riser on a drilling rig (i.e., joint by joint).

3.7.3.1.6 Multibore risers that have non-integral joints are deployed first by running and landing the central structural core and then running each bore separately.

3.7.3.2 Other Riser Deployment Methods

3.7.3.2.1 Other methods to deploy a metal riser, rather than directly from handling equipment on the FPS, can be used. Some of these methods are described below.

3.7.3.2.2 Installation methods developed for pipelines can be used to install the riser. These include the J-lay method, the reel method and the S-lay method. In these methods, the flowline or pipeline is usually laid first, followed by directly attaching and running the riser.

3.7.3.2.3 In the J-lay method, riser joints are assembled vertically on a drilling rig or a derrick barge with a suitable frame. The riser can be assembled while the installation vessel is moving toward or away from the FPS with the top of the assembled riser passed over to the FPS at the appropriate time.

3.7.3.2.4 In the Reel method, the riser is assembled in a continuous length and is coiled onto a large diameter reel. A special vessel then deploys the riser by paying the riser out of the reel and passing the top end to the FPS.

3.7.3.2.5 For riser installation by the S-lay method, a pipe-lay vessel is used to assemble the riser joints and to lay them off the stern of the vessel.

3.7.3.2.6 Another method has the riser transported to the site and installed by a tow and upend procedure. In this case the riser is assembled on land (or in protected waters), then towed out horizontally with one or more tugs to the site. At the site, the riser is upended by removing buoyancy tanks or controlled flooding and is then attached to the seabed and the FPS. This technique has been successfully used with TLP tendons, although much care is required in the design of temporary buoyancy and its attachment.

3.7.3.2.7 Some of these deployment and installation operations may involve "keelhauling." Such an operation has the riser or riser system components passed from the installation vessel to the FPS with handling lines attached in a manner that allows the FPS to pull the top end of the riser underwater, beneath part of the submerged FPS hull, toward the connection point.

3.7.4 Disconnect and Retrieval

3.7.4.1 There are two levels of riser disconnection: normal or planned disconnection and rapid or emergency disconnection.

3.7.4.2 Rapid or emergency disconnection of the riser system may be necessary if vessel or well system emergencies occur, the FPS stationkeeping system fails or the weather suddenly and unpredictably deteriorates beyond the riser's operating threshold.

3.7.4.3 If riser recovery is required following an emergency disconnect response, all wellhead valves should be closed, the production fluids in the riser system flushed and the riser vented before the riser system is recovered. Sufficient storage capacity needs to be available to stack the riser, otherwise it will need to be off-loaded.

3.7.4.4 Some difficulties can arise if workover/drilling activities are being performed at the time of an emergency. In such cases all equipment should be designed to be fail safe to prevent the escape of fluids from the wellbore to the environment.

3.7.4.5 The following items should be considered for riser retrieval:

a. Reverse installation procedures should be altered to suit riser retrieval.
b. Related vessel ballast control operations should be anticipated and clarified in procedures.
c. If mass has been added or removed from the riser by adjusting ballast or any other means, the riser mass may need to be altered before removal of the riser.
d. Recoil after disconnect needs to be considered and tension adjusted so that no riser or vessel damage is sustained.
e. If the riser requires guidelines (or other guidance systems) for removal and these are not present, then replacements or alternatives should be used.
f. Rig offset control should be performed, if required (see 3.12.2).

3.7.4.6 In some situations, it may not be desirable or safe to attempt to recover a riser to the surface as a temporary response to an emergency situation. In such cases, alternative riser protection measures should be taken. The designer should consider the need for laying down the riser or parking it vertically in an acceptable configuration. If the parking option is planned, the designer should provide a secure connection point for docking the lower riser connector and adequate buoyancy to ensure that the riser does not damage nearby equipment or itself during the temporary emergency situation.

3.7.5 Reinstallation Considerations

Riser reinstallation should follow the original installation method to the extent practical to make use of procedure and personnel learning curves. In addition to the original installation considerations, the proximity of other risers and their interaction with the riser to be reinstalled must be considered as these risers may not have been present during the original installation.

3.7.6 Hydrostatic Testing

Pre-service or in-service pressure testing of the riser should be done with inert or non-environmentally damaging fluids in the riser. The methods, equipment and personnel required for purging and displacing the riser and performing the hydrotest need to be considered.

3.8 INSTALLATION, RETRIEVAL, AND REINSTALLATION OF FLEXIBLE RISERS

3.8.1 Preparations and Required Support Equipment

3.8.1.1 In addition to the considerations in 3.7.1, the considerations discussed below apply to flexible risers.

3.8.1.2 Compatibility of the riser with installation equipment, including winches, pipe tensioners and overboarding chutes, should be checked to ensure that the riser under installation tension is not damaged by crushing, bending or kinking.

3.8.1.3 If the flexible pipe is installed dry, the installation equipment should be able to hold the riser should it be accidentally flooded.

3.8.1.4 Installation procedures and equipment should account for the installation of riser appurtenances such as anodes at intermediate couplings, bending stiffeners, bending restricters, buoyancy modules, and end connectors.

3.8.1.5 The installation procedures and equipment that is used should be able to install the risers and then check that the risers are within the installation tolerances.

3.8.1.6 The equipment arrangements on the installation vessel should consider weight, function, and the presence of all ancillary support equipment. Additional reloadings of the installation vessel may be required due to space or stability limitations.

3.8.1.7 Installation procedures should allow for pigging and hydrostatic testing of the riser after installation.

3.8.2 Transportation and Handling

3.8.2.1 Flexible pipe can be stored in either reels or carrousels.

3.8.2.2 Reels with a horizontal axis are commonly used for storage of long lengths of flexible pipes. Reels, used in conjunction with a winch, can be used to maintain the riser tension during installation and recovery.

3.8.2.3 The following should be considered when handling flexible pipe with reels:

a. The drum radius should meet or exceed the minimum bending radius for storage of the flexible pipe.

b. If used for installation, the reel dimensions, structural design, construction and seafastening should account for installation and transportation loads, and the reel should be compatible with the winch system.

c. The reel design should ensure that all surfaces in contact with the flexible pipe be compatible with the outer jacket of the flexible pipe. The reel should protect the end fittings and other pipe accessories that may damage the outer layer of the adjacent layer of pipe.

d. The flexible risers should be prerigged with any slings, hold back wire rope, and "Chinese fingers" that will be required to install the riser.

3.8.2.4 Because of the inherent torque-balanced characteristics of flexible pipes, a fixed basket should not be used for storing or deploying flexible risers. However, rotating baskets or carrousels can be used. Since carrousels are not normally capable of supporting significant pipe tension during installation, a pipe tensioning system is normally used in conjunction with a carrousel. The design requirements for carrousels are similar to those for reels.

3.8.2.5 The flexible riser should be stored under conditions that are not detrimental to its performance:

a. Maximum and minimum storage temperature should be within allowable pipe operating temperature.

b. Connections should be protected against damage of the seal area, threads and other areas susceptible to damage.

c. Pipe should be covered to prevent degradation by ultraviolet radiation.

d. Any fluids left inside the riser, e.g. pressure test fluid, should be compatible with pipe materials.

3.8.2.6 Precautions should be taken during handling and transportation of flexible pipe to prevent damage. Dragging on the floor or against equipment, or unacceptable torsional or bending loading resulting from transfer of the riser should be avoided.

3.8.3 Installation Considerations

3.8.3.1 In certain applications, such as deep water, the flexible riser configuration could be selected based on ease of installation.

3.8.3.2 Flexible pipe installation methods and equipment vary greatly, depending on the application and the environmental conditions. The three most common methods are:

a. Winch/chute lay: The flexible pipe is paid out from its storage reel powered by a winch system and launched over

the edge of the vessel by an overboarding steel chute having a radius greater than the minimum bending radius of the pipe.
b. Horizontal tensioner/sheave lay: The flexible pipe is on a reel or carrousel, and a tensioner is used to provide the laying tension. A sheave is used to overboard the flexible pipe from the laying vessel to minimize the contact pressure and friction forces.
c. Vertical tensioner lay: The tensioner is installed vertically, and the flexible pipe is overboarded directly over one side of the installation vessel or through a moonpool.

3.8.3.3 Some of these applications are shown in Figure 22.

3.8.3.4 Flexible pipe is normally laid in a catenary shape, with a small initial deflection from the vertical axis. The pay out rate of the flexible pipe should be coordinated with the movements of the installation support vessel to prevent either overtension or formation of loops or kinks. This is especially important when laying multiple lines.

3.8.3.5 Particular attention should be given to the passage of intermediate connections over a sheave, chute, roller, or drum to prevent excessive bending behind the end fitting.

3.8.3.6 The loads imposed during installation can be an important parameter for the design of the flexible riser structure and the selection of the installation equipment and accessories. The two primary installation loads are the pipe tension and the crushing force on the pipe from the tensioning system and the overboarding chute.

3.8.3.7 The installation equipment should be designed or selected considering:

a. Crushing loads exerted on the pipe by the overboarding chute, the installation reel, and/or the tensioner.
b. The variation of pipe outer diameter along its length due to manufacturing tolerances.

3.8.3.8 Typical installation procedures for Steep S, Lazy S, and Lazy Wave riser configurations are shown in Figures 23, 24, and 25.

3.8.3.9 After installation, the riser configuration should be checked by divers or an ROV.

3.8.4 Disconnection and Retrieval

3.8.4.1 The selected riser configuration, riser accessories and appurtenances should allow retrieving a riser line, whether single or part of a multiple riser system.

3.8.4.2 Tension in the flexible pipe is usually significantly higher during retrieval than during installation due to friction on overboarding chutes. Depending on the tension and the riser configuration, it may be necessary to void the riser before retrieval.

3.8.5 Reinstallation

Prior to reinstallation, the riser should be visually inspected for external damage and repairs carried out where required. The riser should also be drifted and hydrostatically tested at its rated operating pressure.

3.8.6 Hydrostatic Testing

On-site testing during and after installation should be carried out according to recommendations given in API RP 17B. Riser components should be tested similarly.

3.9 INSTALLATION, RETRIEVAL, AND REINSTALLATION OF OTHER RISERS

3.9.1 In general, the riser classifications addressed in the preceding sections should cover the range of riser system types in current practice. There may be special features of a given riser system that may lead the designer to consider it unique in terms of configuration and/or service. For example, the riser system may be a hybrid riser that combines both metal and flexible pipe elements, or the riser may be considered as primary mooring element in addition to the role of conduit. In very deep waters, what may normally be considered rigid metal riser pipe sections may be configured such that the riser system has the inherent compliance more commonly associated with flexible risers. Examples are catenary risers, twisted pipe bundles or pre-buckled vertical S risers.

3.9.2 In such cases, the designers may have to allow for special features or demands associated with unique installation or retrieval operations. Reference to other guidance documentation may be required. For example, risers providing both production and mooring service as riser/tendons would need to meet all the requirements of performing as a production riser and the additional requirements of acting as a mooring element (API RP 2T).

3.10 IN-SERVICE OPERATIONS

3.10.1 Simultaneous Drilling and Production

3.10.1.1 Safety Considerations

3.10.1.1.1 This section is intended to define the basic philosophy and minimum operational requirements for the safe conduct of simultaneous drilling and production operations as they relate to production risers. The success of each simultaneous operation depends on developing an operating plan and following the practices outlined in that plan to limit the operational risk.

3.10.1.1.2 A Simultaneous Operation consists of any combination of two or more of the following activities executed independently and concurrently which may interact to increase operational complexity and risk:

a. Producing.
b. Drilling.
c. Workovers and completions.
d. Wireline work.
e. Testing.
f. Pigging.
g. Construction and major maintenance.
h. Supply operations.
i. Off-loading.

3.10.1.1.3 Factors which contribute to increased operational complexity and risk during simultaneous operations include:

a. Incompatible activities if work groups have different goals, skills and/or supervision.
b. Hydrocarbon release potential, both controlled and uncontrolled, may increase.
c. More ignition sources may exist.
d. Facilities design and safeguards may not be ideal for conditions experienced during simultaneous operations, e.g. structural integrity, available work space, protection for processing equipment, etc.

3.10.1.1.4 Simultaneous operations require identification of the specific hazards and taking steps to limit the risk. They should only be conducted after thorough evaluation and risk mitigation.

3.10.1.2 Limitations and Restrictions

3.10.1.2.1 These items should be given careful consideration to assess their possible application to each specific operation. If any of these items contribute to increased risk, mitigating measures should be more fully described in the plan.

3.10.1.2.2 Limitations and restrictions on operating conditions and activities should consider:

a. The type of production equipment on the platform.
b. Means for shutting-in wells.
c. The type of wells (oil or gas), shut-in and flowing tubing pressures, and annular pressures.
d. Maximum and expected oil, water and gas production rates for individual wells and for the total facility.
e. The presence of H_2S in the gas.
f. Gas lift and whether used for sustained production or only to kick-off wells.
g. Controlled well kill operations used prior to starting a workover or for reversing out a backsurge.
h. Drilling or workovers in close proximity to live wells.
i. Repair and maintenance on safety systems, including well control system, ESD, fire or gas detection systems, fire fighting system and ventilation systems, or drain systems that affect area integrity.
j. Whether well testing is performed.
k. Whether heavy jarring is performed.
l. Any flaring or gas venting to atmosphere.
m. Well unloading and swabbing.
n. Running or pulling other risers.
o. Repairs to process facilities which may impair normal operations.

3.10.1.3 Interference Considerations

3.10.1.3.1 If a guideline system is employed, the risk of interfering with an adjacent riser during the deployment of a drilling or a production riser should be manageable as long as the guideline system remains intact. Maintaining acceptable risks for interference (and the consequences of contact) must also depend on field personnel carefully monitoring the changing environmental conditions when starting and during running operations. Consideration needs to be given to the hazards associated with the possibility of dropping the riser during the running operation. In general, operators should consider shutting-in adjacent wells during running and retrieval operations, based on the proximity of those wells to these hazardous operations.

3.10.1.3.2 If a guidelineless system is employed, additional wells may need to be shut in to further ensure that a failure of the positioning system during reentry operations is not likely to damage a flowing well.

3.10.1.3.3 Consideration may be given to using ROVs or tugger lines to steady or guide risers as the connector approaches the wellhead, whether guidelines are used or not.

3.10.1.3.4 In the presence of deeply penetrating currents that can cause significant horizontal riser deflections, particularly during deployment, riser running operations may have to be curtailed to avoid potential damage to adjacent risers or wellheads. In some cases, even with a lateral mooring system or dynamic positioning system, it may be difficult or impossible to safely guide the riser.

3.10.1.3.5 Disconnects must be carefully made, with or without current, to avoid damaging adjacent wellheads or risers. As a general practice, the riser angle at the lower connector should be away from neighboring wells such that the riser will swing free immediately after the disconnect.

3.10.1.3.6 Interference can occur in the water column with a connected riser as well as with a disconnected one. Careful analyses of all anticipated conditions should be made by the design team prior to conducting operations. Interference in the presence of deeply penetrating currents is very sensitive to the tension distribution, contents and buoyancy in adjacent risers. A drilling riser adjacent to production risers poses an especially difficult situation due to major differences in the risers' hydrodynamic drag as well as tension and weight. Risers with significantly different dynamic characteristics will respond at different frequencies and phases during severe current or storm conditions.

3.10.1.3.7 In some cases, it is difficult to detect the possibility of riser interference or collision in the water column without TV cameras or an ROV. When close approaches of hardware are expected in the water column, some monitoring means is desirable.

3.10.2 Well Completions and Workovers

API RP 17G provides design and operational guidelines of riser systems during well completions and workovers when using a wireline BOP, riser and associated surface control equipment and systems.

3.10.3 Through-Riser Operations

3.10.3.1 Through-riser operations performed from an FPS may include some or all of the following:

a. Wireline operations.
b. Coiled tubing operations.
c. Major workover.
d. Drilling and sidetracking considerations.
e. Through flowline (TFL) operations.
f. Flushing.
g. Pigging and riser bore maintenance (scraping).

3.10.3.2 These operations may be performed through more than one riser. For instance, a drilling riser may be used for drilling and the production riser used for wireline and workovers. Pigging is normally performed through a sales riser.

3.10.3.3 Well control functions must be designed to perform properly with the various risers and in the various modes of operation.

3.10.3.4 The riser bore should be adequately designed for these through-bore operations. The size, tolerances, material, curvatures, and presence of dog-legs are primary considerations.

3.10.3.5 Using the production riser for workover operations will require proper interface at the top. Workover BOPs, and other equipment not normally used in production operations may be attached.

3.10.3.6 Wireline or rotary drilling operations may produce severe tracking or keyseating when "dog-legs" (bends) are present in the riser bore. In this case, consideration should be given to using a replaceable wear bushing and limiting vessel offsets during these operations to mitigate this problem. Pipe rubbers and downhole motors can also be used to minimize wear caused by rotation. Calipers should be run in the riser following any operation requiring rotation in the riser. Analysis tools are available to assess the significance of this situation to planned operations.

3.10.4 Monitoring

3.10.4.1 A riser monitoring system is not mandatory, but it is useful for setting and maintaining precise tension, for monitoring riser dynamics, and for design verification. The riser monitoring system can also be used to estimate riser fatigue damage.

3.10.4.2 In some cases, such as closely-spaced risers in high current situations, careful riser monitoring of tension, stroke, and pressure may be used to minimizing the possibilities of riser-to-riser collisions. Each of these measurements can be set up with alarms for high or low limits.

3.10.4.3 Riser tension can be monitored by measuring the pressure in the tensioner cylinders and applying correction factors for riser angle, tensioner wire, and friction. Strain gages can be used in load pins, on the riser body, on the tensioner structure or in special load cells connecting the tensioner system to the riser.

3.10.4.4 Riser angles can be measured with inclinometer devices. Some units may be sensitive to the surge and sway of the FPS and require motion corrections.

3.10.4.5 Tensioner or riser stroke measurement can be made with something as simple as a string potentiometer. The inclination of the tensioner arm can be used to infer riser stroke.

3.10.4.6 Standard pressure transducers can be used to monitor riser pressure if they are suitable for the hazardous area classification of the area where they are used.

3.10.5 Operational Support

Once the riser system has been deployed and function tested, a series of pre-start checks should be performed before operations begin. The type of checks will depend on the riser design but may include the following:

a. Ensure that all utilities required for riser operation are available.

b. Ensure that all required tensioner maintenance or repair work has been performed.

c. Check the condition of the tensioner wire ropes and ensure that they set in their respective pulley grooves around the wireline tensioners and turndown sheaves.

d. Function check all alarm systems and indicator lamps.

e. Test any emergency disconnect systems.

f. Test any riser monitoring system.

3.10.6 Control

3.10.6.1 Depending upon the type of riser and the operation performed, temporary control stations may be needed during certain phases of riser operations. It may be advantageous or necessary to designate a number of control centers, each with its own area of control and monitoring which is subordinate to the primary or main control station.

3.10.6.2 The various control stations may need to be manned and communication lines established before these operations take place. Some of these control stations may include the following:

a. The bridge of a ship.
b. Ballast control room.
c. Operations control room.
d. Production control room.
e. Moonpool control room.
f. ROV and diving control center.

3.10.6.3 The number, location, and manning requirements for the control centers will depend on the type of riser and the surface support facility.

3.10.7 Manning

The number of operations staff that will be required together with their responsibilities should be defined. This manning list should reflect the duties of the operating staff and the organization and reporting relationships under all modes of the riser operations.

3.10.8 Riser Limitations

The riser operating limits are determined by the designer and may be presented as graphs of riser maximum offset against sea state (or other important Metocean parameters). A typical diagram for a latched steel tensioned drilling riser is shown in Figure 26, which shows the range of acceptable riser excursions for a set of operating conditions. Factors which may influence the allowable offset are:

a. Moonpool clearance range before impact.
b. Lower flex joint limitations.
c. Upper flex joint limitations.
d. Riser tension.
e. Internal conditions (pressure, weight of internal strings or fluids, etc.).
f. Vessel heading.
g. Current profile.
h. Water depth.
i. Flexible flowline (jumper) length.

3.11 MAINTENANCE AND INSPECTIONS

3.11.1 General Considerations

3.11.1.1 Regular monitoring of the riser system helps to provide a safe and trouble-free operation. Depending upon the water depth of the installation, subsea equipment inspection and monitoring can be carried out on a routine basis or when trouble is detected using either divers, ROV system, or guidewire run camera systems. Surface equipment should also be regularly inspected and monitored and a routine inspection/monitoring program be established.

3.11.1.2 Planned or scheduled system maintenance and early detection of problems may save a great deal of time, especially in water depths beyond diver capability.

3.11.2 Tensioner System Maintenance

3.11.2.1 Designers should ensure that inspection and renovation of tensioner components is facilitated by the system design. For example, all tensioner wires should be routinely visually checked for broken strands. A regular slip and cut program should be planned.

3.11.2.2 Riser tensions should be monitored on a regular basis. Critical valve functions should be checked and locked off, if possible, to prevent inadvertent operation.

3.11.2.3 Accumulator, cylinder, and system inspection and maintenance should be performed routinely.

3.11.3 Riser Inspections

3.11.3.1 Routine riser inspections should be performed for signs of leakage, corrosion or damage to the riser system and control equipment. The type and frequency of inspections should be established by the designer in consideration of system and component criticality.

3.11.3.2 The riser can be inspected visually by a diver or ROV-deployed video or still camera system. NDE ultrasonic inspections can be performed on critical areas of the riser pipe. The use of this equipment and its interfacing to the riser system components and the ROV or diver should be established during the riser design.

3.11.3.3 The riser cathodic protection (CP) system can be inspected by means of in-situ probes that measure the potential voltages of the surfaces to protect.

3.11.4 Miscellaneous Inspections

3.11.4.1 The condition of the riser jumper hoses should be visually inspected for any signs of wear and damage from contact with the moonpool or other hoses or umbilicals. A method of replacement may need to be considered during production operations.

3.11.4.2 Riser control umbilicals should be inspected regularly, as they can become entangled with the riser system.

3.11.5 Marine Growth

3.11.5.1 Routine inspections to ascertain the thickness and type of marine organisms on marine risers should be performed to identify if and when removal of the fouling is needed. Visual or ROV camera inspection is adequate to identify dimensions and trends. Length of time between inspections will be determined by environment and the tolerance in the riser design for increased loading due to the marine growth (see 6.3.5.3).

3.11.5.2 Maintenance will consist of removing part or all of the marine growth when design tolerance is exceeded. Before selecting a marine growth removal procedure, its compatibility with the riser corrosion protection system should be determined. Candidate removal procedures include water jetting, mechanical brushing or scraping.

3.12 RIG MOVEMENTS AND STATIONKEEPING

3.12.1 Stationkeeping Considerations

3.12.1.1 Active, adjustable stationkeeping is necessary for making guidelineless reentries or for the initial positioning of wells on the seafloor when a template is not used. It may also assist in making reentries with guideline systems in the presence of ocean currents. It can be useful for maintaining low riser angles during drilling or workover operations to minimize wear. With some types of structures, adjustable stationkeeping may be necessary to limit riser angles or tensioner strokeout during storms or when exposed to high currents.

3.12.1.2 A lateral mooring system is the most common type of adjustable stationkeeping system. However, a dynamic positioning system may be a viable alternative.

3.12.2 Strategy For Vessel Offset Control

3.12.2.1 For guidelineless systems, the vessel's mooring system can be used for subsea BOP or riser/wellhead connector and riser running operations when safe distances must be maintained between the subsea packages and any adjacent well or riser. It is desirable to keep the connector package away from any wellheads until the final approach for the reentry is made.

3.12.2.2 The movements should be carefully calculated in advance of each adjustment of the vessel's positioning system (e.g., moorings). Avoiding overshooting the target is important in minimizing the possibility of impacting adjacent wellheads.

3.12.2.3 A safe disconnect from a well will require that the disconnected package, when released, swings a minimal distance away from the well and away from adjacent wells, if possible. The lower riser angle must therefore be biased in the desired direction of motion by a precalculated amount.

3.13 STORM AND CONTINGENCY OPERATIONS

3.13.1 Riser Operating Limitations

When there are riser operating limitations due to weather conditions, production should be restricted to the normal operating envelope of the riser system.

Riser operations can be divided into four main classifications as follows:

a. Latched operations where the riser system is latched to the seabed equipment.
b. Hang-off, with riser detached from the seabed.
c. Parking the riser by attaching the lower marine package to a parking stump located a suitable distance away from critical equipment and leaving the riser free-standing with appropriate top-end buoyancy.
d. Retrieval/re-deployment of the riser.

Operating limitations should be established for each of the selected riser operating modes.

3.13.1.1 Latched Operations

3.13.1.1.1 Latched operations of the riser system cover all operations with the riser system at operating tension as set by the riser design requirements. This is discussed in 3.10.8, along with a sample latched operating envelope.

3.13.1.1.2 The operating envelopes should be developed based on realistic combinations of various conditions of current, wellbore fluids and Metocean conditions.

3.13.1.1.3 Riser operating limits may also be determined by use of a riser management program, where an operator can input actual condition, and the program will determine whether the conditions are acceptable.

3.13.1.2 Riser Hang-off Mode

3.13.1.2.1 For the hang-off mode, the riser is filled with sea water, disconnected and picked up clear of the seabed. Riser hang-off curves should be generated for the range of anticipated conditions. Figure 27 shows how guidelines for riser hangoff limits as a function of wave height might be constructed for an FPS riser system. Depending on the shape of the hull, the limits might be sensitive to the weather and current heading as well.

3.13.1.2.2 When the riser is disconnected and hanging-off, vessel offset is generally not a governing criteria. Riser impact with the vessel hull is. The onset of impact is dependent on vessel heading and motions such as roll, pitch, surge and sway together with current profile. The length of riser suspended beneath the hull is also an important factor.

3.13.1.2.3 Operating conditions for the hang-off mode should be developed based on realistic combinations of conditions that affect riser performance.

3.13.1.2.4 The hang-off condition may cause increased fatigue damage to the riser and should be assessed. A detailed log should be kept on the length of time, sea state and configuration in which the riser is hung-off. This log can be reviewed regularly to assess the need for riser joint inspection requirements. Durations of and levels of exposure in any/all modes should be logged for keeping track of fatigue status.

3.13.1.3 Riser Deployment and Retrieval

3.13.1.3.1 During unlatching of the riser, the applied tension is reduced before disconnection. This reduction in tension reduces the stability of the riser. A minimum tension requirement should be determined during the riser design.

3.13.1.3.2 The following should be considered regarding storm disconnection operations:

a. The lower riser angle should be monitored to ensure that it does not exceed maximum angle criteria.
b. The riser tension should be above minimum allowable tension determined during the design.
c. With high currents or severe storm conditions, extreme care should be taken, and the riser tension should be carefully maintained.

3.13.1.3.3 During deployment and retrieval, the riser will be held alternately in the derrick and in the slips and the top tension will increase as the deployed length goes up. This causes changes in the top riser angle and bending moment as the deployment progresses. This could result in the generation of limits as suggested in Figure 28, which shows the sensitivity of safe operating limits to the length of the riser. Risers on vessels with motion response that is very sensitive to heading will also require studies at a variety of headings.

3.13.2 Disconnect Considerations

3.13.2.1 A rapid or emergency disconnect, if required, should consider the following:

a. A complete production shutdown of all process equipment.
b. Closure of all subsea and riser valves.
c. An emergency riser unlatch which will unlock the riser. If warranted, when the riser is disconnected safety systems can be designed which will cause all of the subsea valves to close and render the production system to a safe condition fully shut-in.

3.13.2.2 If possible, riser recovery after a rapid or emergency disconnection can be carried out in the normal manner, according to developed operating procedures. Otherwise, the riser will have to remain hung-off until such time as it can be recovered.

3.13.2.3 See 3.7.4 and 3.8.4 for considerations regarding riser disconnection.

3.14 SAFETY

3.14.1 Personnel and Platform Safety

Marine riser safety issues should be integrated with the platform and/or vessel safety manual and procedures. Of particular concern are the handling of the large riser components and operating conditions that could lead to emergency disconnects or component failures. All personnel should be made aware (by training and guidance provided in the safety manual) of contingency measures and the consequences of riser system failures. The riser system designer should help ensure that these issues are included in the operational safety documentation.

3.14.2 Pollution Safety

A two-independent barrier design should be considered for any riser when it is operating with environmentally damaging fluids inside. This could be two tubulars, one inside the other, such that the inner tubular carries the working fluid, and the annulus catches any leaks. This could also be a BOP or shear valve type mechanism installed on the seabed to stop the flow of working fluid should a riser leak develop. Other features such as SCSSV or completion kill fluid in the riser may also be considered as a barrier. Contingency plans would have to be made to purge, retrieve and repair the riser.

3.15 TRAINING

3.15.1 Training Program

3.15.1.1 In the case where the riser system needs to be run and retrieved frequently, a fully trained crew may be needed to safely and efficiently carry out the various riser operations that are required.

3.15.1.2 Required personnel should be identified during the project construction phase. Qualifications should be developed and placed in the job descriptions of those who will work the riser systems. Specialists with marine operations or subsea and/or drilling backgrounds can be used or trained to carry out these duties.

3.15.1.3 A strong effort should be made to involve operating personnel in the design, construction, and commissioning phases.

3.15.2 Training Manuals

The designer should develop a training manual for classroom instruction. This document should provide a quick reference to the equipment and describe procedures that need to be followed and why they are important.

3.15.3 Operational and Safety Procedures

A full set of operational and safety procedures should be developed for all of the riser operations anticipated. These procedures should be updated as required and be tested if possible.

3.15.4 Offshore Commissioning Phase

The training program should ensure a trouble free and safe operation. During the pre-commissioning and commissioning phases, consideration should be given to making available experienced design engineers who can assist with onsite training of personnel.

3.15.5 Training Maintenance

Riser operations personnel may have to be replaced or supplemented during the on-going production operation. New personnel should be given the necessary training on the riser operational and safety requirements.

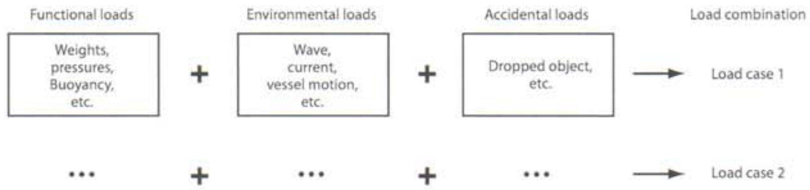

Figure 21—Example Load Combination Development

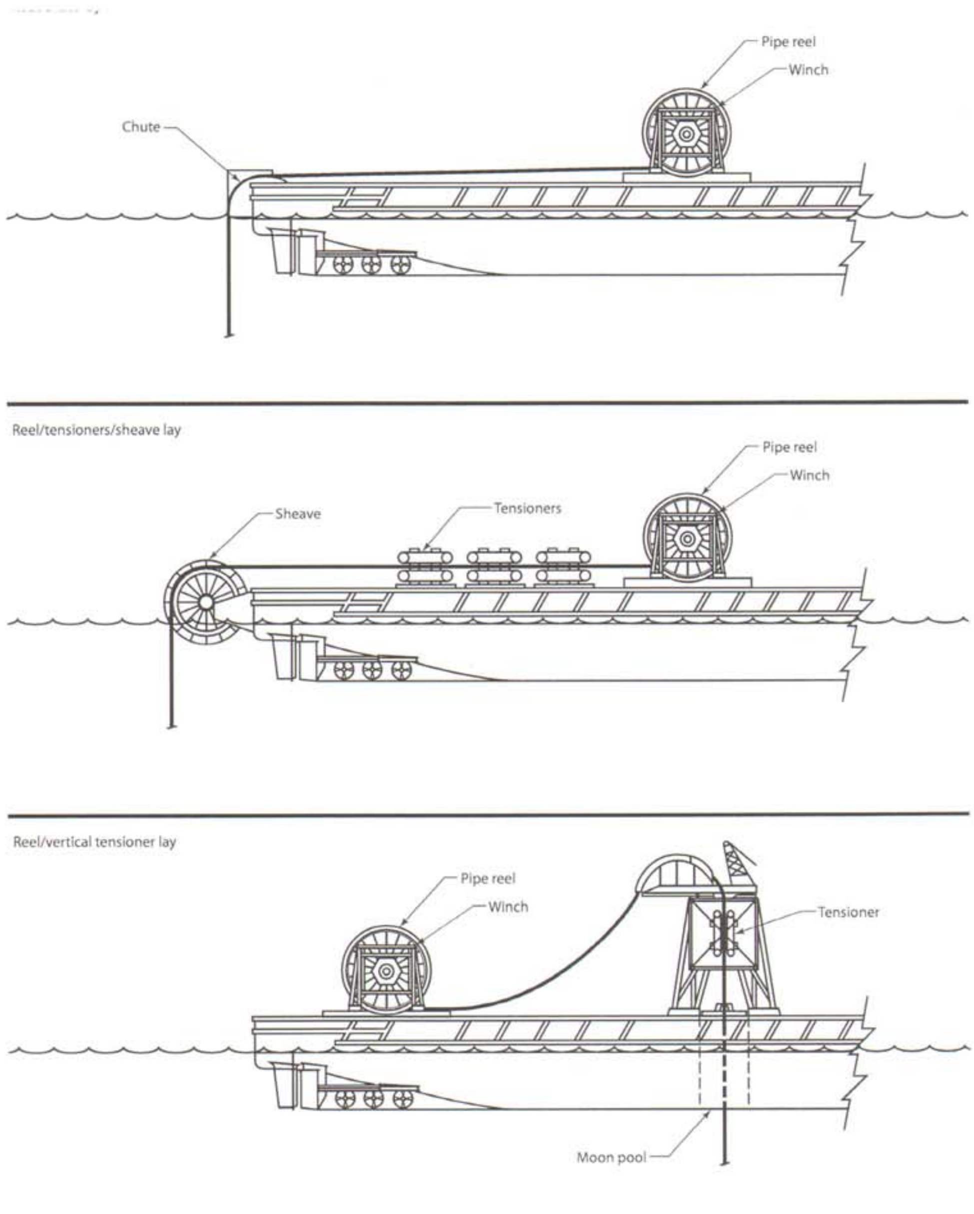

Figure 22—Laying Methods and Associated Equipment

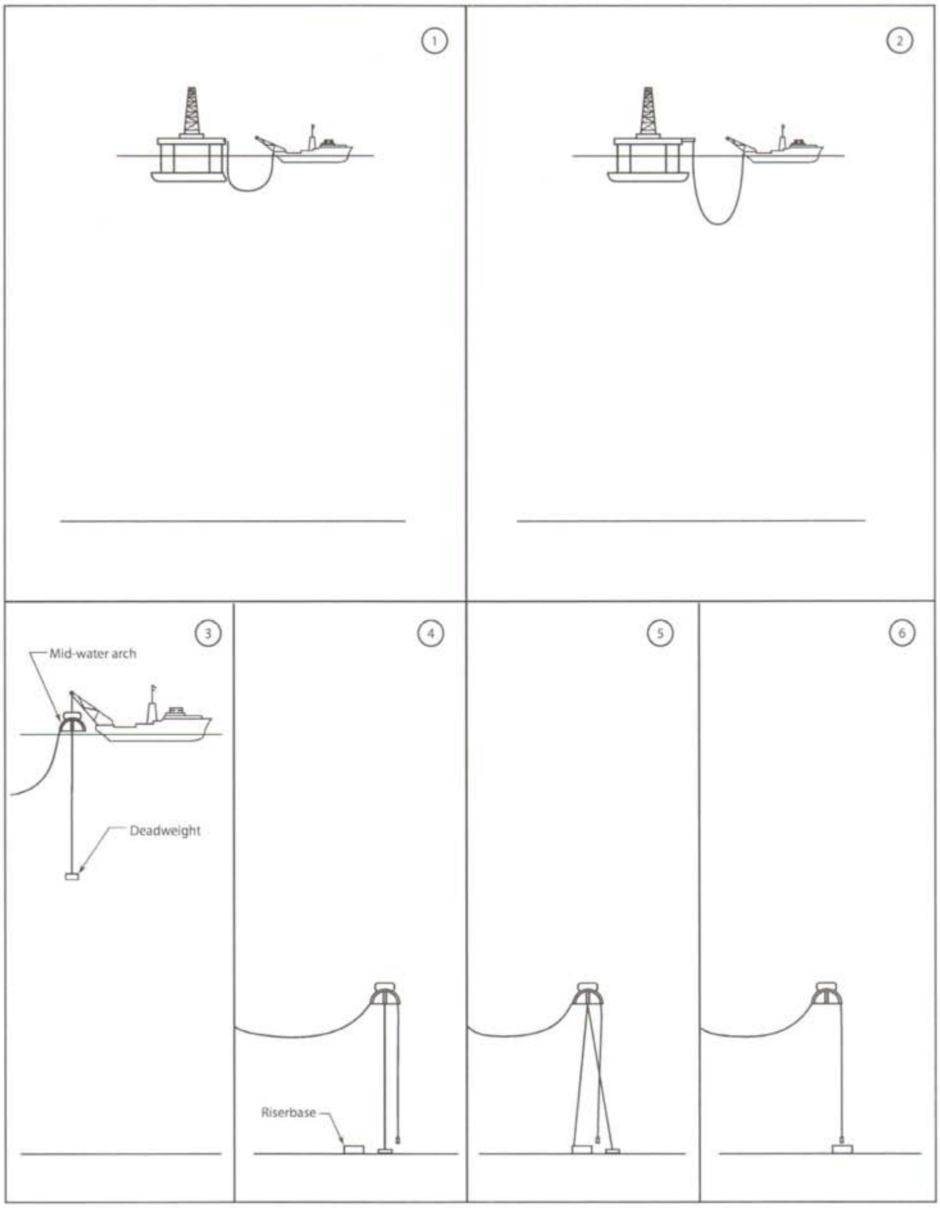

Figure 23—"Steep S" Installation

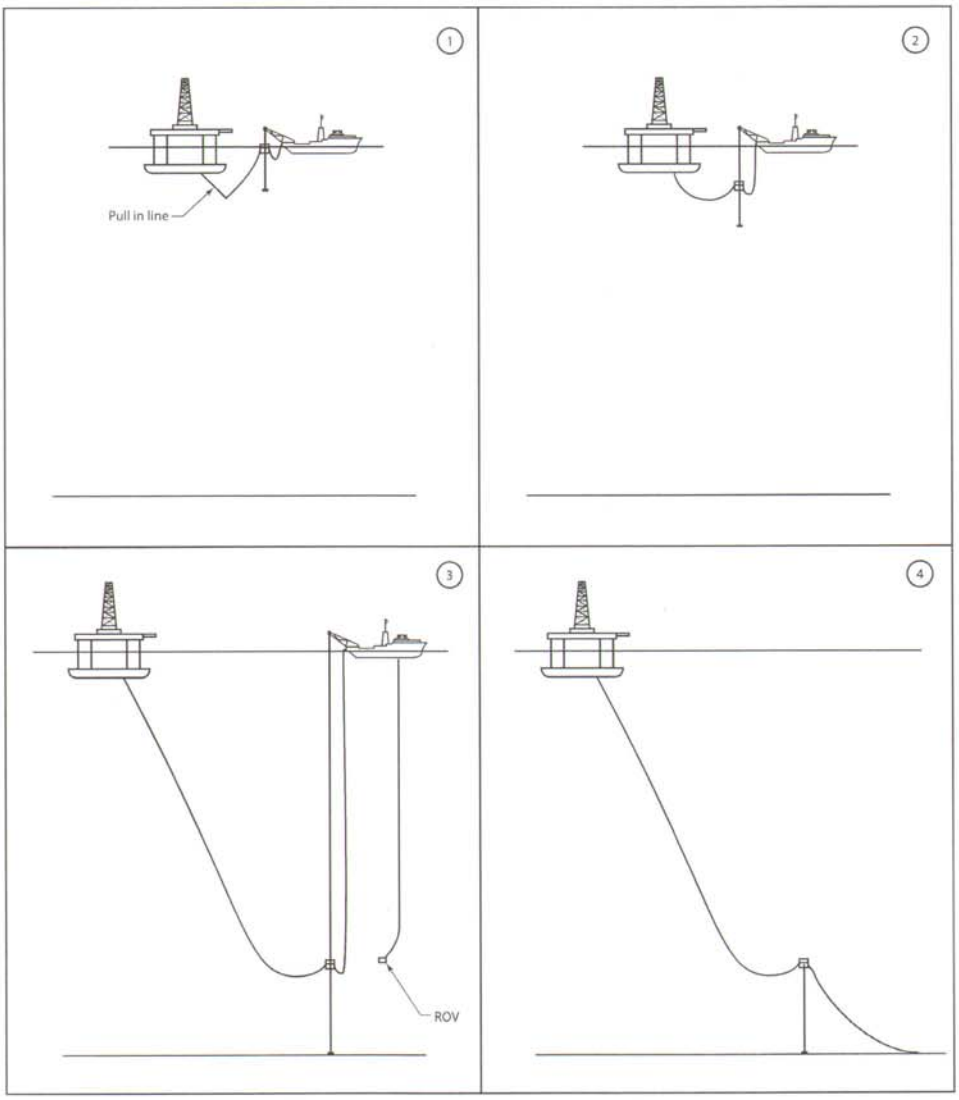

Figure 24—"Lazy S" Installation

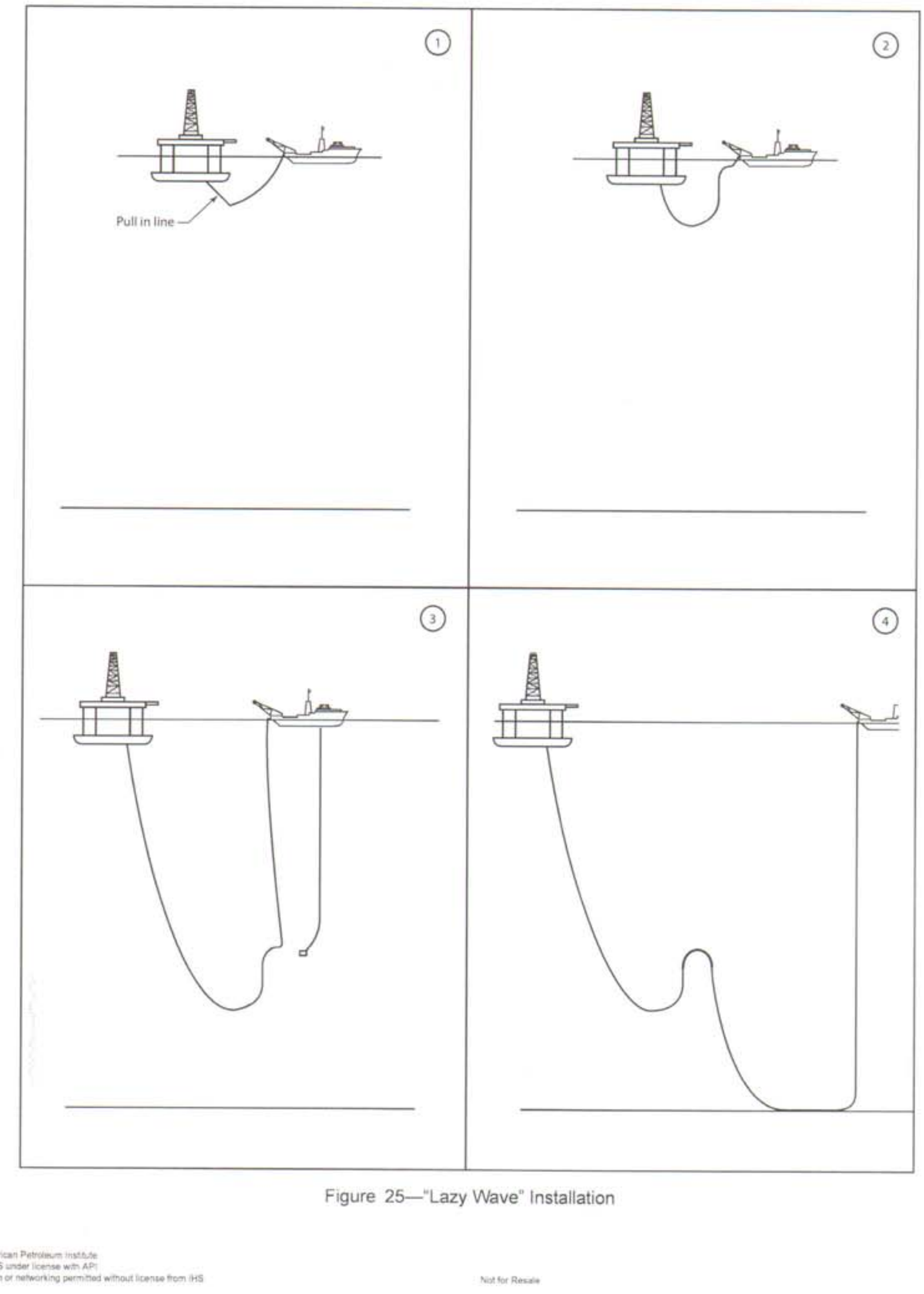

Figure 25—"Lazy Wave" Installation

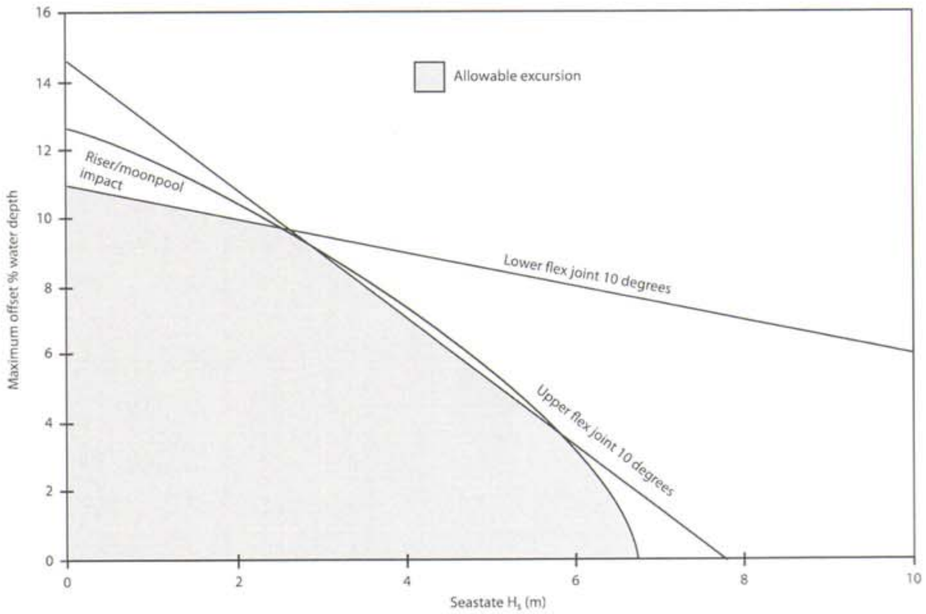

Figure 26—Latched Riser Operating Limits

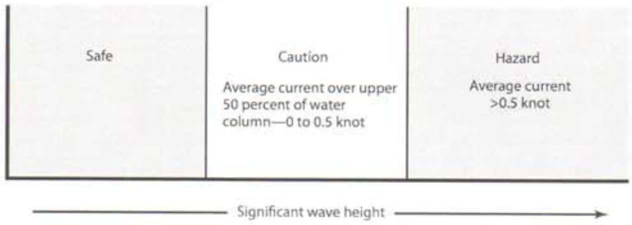

Figure 27—Riser Hang-off Limits

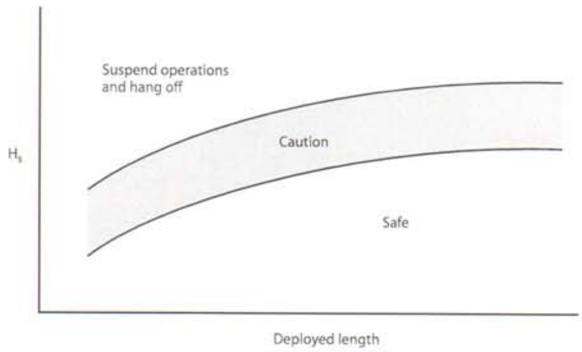

Figure 28—Riser Deployment Limits

4 Design Loads and Conditions

4.1 GENERAL

This section describes the load combinations used to design an FPS riser. It first describes the different loads or actions. Then, it gives the loading conditions that the designer should consider. Finally, it tells how to combine various loads to create design cases for metal risers and gives the design case factor to use in the allowable stress formula.

4.2 LOADS AND LOAD EFFECTS

The following categorizes riser loads. Functional loads are loads that are a consequence of the system's existence and use without consideration of environmental or accidental effects. Environmental loads are those imposed directly or indirectly by the ocean environment. Accidental loads are those resulting from unplanned occurrences.

Functional	Environmental	Accidental
Weight of riser	Waves	Small dropped objects
Weight of coatings, attachments, and tubing	Current	Normal handling impacts
Weight of tubing contents and annulus fluid	Vessel motions	Tensioner failure
Internal pressure	Seismic	Partial loss of stationkeeping capability
External hydrostatic pressure	Ice	Flow-induced impact between risers
Nominal top tension		
Loads caused by internal fluid flow, surges, slugs, or pigs		
Buoyancy		
Soil interaction (catenary risers)		
Inertia		
Internally run tools		
Thermal		
Installation		
Vessel constraints		

The effect of marine growth and tide on fluid and gravity loads should be included. While not a load, consideration of internal fluid composition and temperature are important for the design of risers, especially flexible pipe.

4.2.1 Pressure Loads

The riser should be designed for the pressures exerted by both internal and external fluids. Various combinations of internal and external pressures should be considered to determine the appropriate design cases. The table on the following page, Design for Internal Pressure, gives guidance for determining internal pressures for different riser types. Two pressures are defined, design pressure and extreme pressure. Design pressure is the maximum pressure that will be seen for an extended time during normal operations. Extreme pressure is the pressure that is unlikely to be exceeded during the life of the riser.

4.2.2 Environmental

4.2.2.1 Surface Waves

4.2.2.1.1 Wind driven surface waves exert significant oscillating forces directly on the risers. Such waves are irregular in shape, can vary in length and height and can approach the riser from one or more directions simultaneously. Because of the random nature of the sea surface, the seastate is usually described in terms of a few statistical wave parameters such as significant wave height, spectral peak period, spectral shape, and directionality. Other parameters of interest can be derived from these. Waves also induce steady and oscillatory forces on the FPS vessel to which risers are attached.

4.2.2.1.2 Wave data should generally be developed in accordance with the requirements of Section 6.

4.2.2.2 Current

Currents exert lateral forces on the risers and offset the FPS vessel. Currents can be caused by winds, tides, ocean circulating currents, eddies that spin off from a circulating current and by internal waves. The designer should combine various current profiles (current velocity vs. water depth) with waves to get design loads.

4.2.2.3 Vessel Motions

4.2.2.3.1 The FPS vessel transmits its response to the environmental loading directly to the top end of the riser. Vessel offset and motions constitute a source of both static and dynamic loading on the riser. Vessel motions needed for riser design are:

a. Static offset (horizontal).

b. Wave frequency motions (horizontal and vertical).

c. Low frequency motions.

d. Setdown.

4.2.2.3.2 This information can be obtained by analysis or by the use of model testing. See Section 6.

Design for Internal Pressure

Riser Type	Design surface pressure[1,3]	Extreme surface pressure[2,3]
1. Drilling riser above subsea BOP stack	Zero	Maximum diverter line back pressure.
2. Drilling riser with surface stack	Zero (or if drilling underbalanced, maximum underbalance pressure)	Design as an extension of the last casing string that will be drilled through. Use company approved burst design criteria. This applies to both outer riser and inner riser, if used.
3. Drilling riser with both surface and subsea BOP stacks	Zero (or if drilling underbalanced, maximum underbalance pressure)	Surface pressure that will handle most well control situations. Assume subsea BOP will be closed before pressure rises higher.
4. Production or injection riser used as extension of production casing	Maximum sustained pressure allowed by regulation or company policy	Pressure caused by near-surface leak of shut-in tubing (maximum)
5. Outer riser of dual casing production or injection riser with surface tree	No requirement	Pressure caused by near-surface or near-bottom leak of inner riser maximum operating pressure
6. Tubing (single pipe) riser or flowline from subsea satellite well	Surface shut-in pressure with subsea valves open	Maximum surge pressure or maximum well kill pressure
7. Import riser from subsea manifold	Surface shut-in pressure with subsea valves open unless pressure can be reliably limited to a lower value	Maximum surface shut-in pressure with subsea valves open unless pressure can be reliably limited to a lower value
8. Export riser	Maximum export pressure	Maximum surge pressure
9. Other riser type	Highest pressure that will be seen for an extended time	Pressure that is unlikely to be exceeded during life of riser

Notes:
[1]Design surface pressure is the maximum pressure that will be seen for an extended time during normal operations.
[2]Extreme surface pressure is the pressure that is unlikely to be exceeded during the life of the riser.
[3]Local design pressure or local extreme pressure is the surface design or extreme pressure plus the static head of the riser fluid.

Comment: It is the operator's responsibility to determine design and extreme pressures based on the guidelines given in notes 1 and 2. The descriptions of these pressures in Table 1 are intended to be examples of how to accomplish this task.

4.3 LOADING CONDITIONS

Riser structural analysis should consider, as a minimum, design cases comprising combinations of conditions for checking:

a. Maximum stress.
b. Maximum deflection or curvature.
c. Lifetime fatigue or service life.
d. Hydrostatic collapse.
e. Maximum loading on specific components.

The objective is to find the appropriate structural response for comparison to the limits and allowables given in Section 5.

4.3.1 Maximum Operating Conditions

The operator's plan of operation affects many of the design and operating limits for the risers. Environmental limits should be set for each mode of operation, including normal operation, in-place pressure testing, connected operation, inspection, maintenance and repair. Riser functions, stress levels, angles, clearances and equipment handling methods should be evaluated when setting design and operating limits.

4.3.2 Extreme Conditions

Extreme events are those events that produce riser responses having a low probability of being exceeded in the lifetime of the riser, e.g. an event with a return period of 100 years. There may be different events that give the worst response for different parts of the structure. To find the maximum or minimum responses, different combinations of wave heights and periods, current profiles, internal pressure, minimum and maximum vessel offset, etc., should be considered. When waves and vessel motions in waves contribute to the loads, the expected maximum response in a suitable duration should be estimated.[1,2] See Section 6.

4.3.3 Temporary Conditions

4.3.3.1 Transportation

Each riser component should be designed for the loads it will see during transportation. This may involve a trade off between design details of the component and design of the transportation system.

4.3.3.2 Installation/Retrieval

The risers should be analyzed for installation and retrieval conditions with varying amounts of riser deployed. The guidance system should be modeled and clearances checked. Vertical dynamics may need to be analyzed.[3]

4.3.3.3 Testing

Riser components should be designed for loads imposed during testing.

4.3.4 Fatigue Conditions

Lifetime installation and deployment and operating conditions should be developed to evaluate fatigue life. All loads and load combinations that can contribute significantly to fatigue should be accounted for when establishing the long term distribution of stress or strain ranges. The effects of cyclic response to primary wave frequencies and to low frequency wave drift and low frequency wind force variations should be combined. Fatigue damage caused by VIV should also be evaluated and combined.[4] See Section 6 for a description of fatigue analysis methods.

4.3.5 Accidental

4.3.5.1 Design cases associated with partial loss of riser tension (or buoyancy) should be checked.

4.3.5.2 Design cases associated with partial loss of station-keeping ability should be checked:

a. Loss of one mooring line or tendon.
b. Dynamic positioning (dp) failure (drive-off or drift-off).

4.3.5.3 Production risers that serve as production casing should be designed for pressures caused by a tubing leak near the surface in combination with associated environmental conditions. The probability and consequences of fire, explosion, and collision should be evaluated and mitigating strategies appropriate to the level of risk considered.

4.3.6 Survival

To test the robustness of the design, the designer should evaluate response to survival conditions that exceed the extreme design events. For example, the response to events with a longer return period could be checked to determine that the component does not fail. Some regulations require this kind of check.[5]

4.4 DESIGN CASES

Design loading cases are created by combining functional, environmental, and accidental loads as shown in Figure 21.

4.4.1 Environmental Conditions

4.4.1.1 The environmental conditions presented in Table 1 should be used in analyzing the design cases outlined in Table 2 for the various loading conditions described in 4.3.

4.4.1.2 Environmental conditions should be developed from site-specific data and should include information on occurrence and persistence of conditions. In addition to the information listed in Table 1, data on wind, air and water temperature and density, and on marine growth will also be needed.

4.4.1.3 Wave conditions will generally be described by spectrum type and by spectrum parameters such as significant wave height and peak period. Extreme wave height and period should be varied to explore riser responses up to the boundary of the extreme event conditions. To find the maximum response for some dynamically-sensitive riser configurations, the designer may need to check various wave and period combinations in the wave scatter diagram.[6] Current conditions should be described by a set of current profiles and their associated probability of occurrence, with profiles specified by current speed and direction vs. elevation in the water column. Wind speeds used for computing static and low-frequency (LF) offsets should be consistent with the wave and current conditions with which they are associated.

4.4.1.4 Maximum operating conditions, when less than extreme conditions, should be established by the operator at a level consistent with the probability of occurrence of the riser operating state or event being analyzed and should cover all expected operating conditions. For example, if the riser system is designed to be disconnected before reaching the extreme condition, then the maximum connected case would be analyzed for some lesser environmental condition.[3]

4.4.1.5 Several tensioner failure conditions should generally be examined, including one where there is reduced capacity and one where there is total collapse of the tensioning system. In addition, the riser system should be analyzed for the situation where one mooring line is broken, potentially resulting in a larger offset of the vessel.

4.4.1.6 Installation and transportation environmental conditions should be established by the operator but should generally ensure that the required operations can be conducted without undue interruptions or delays. A 1-year seasonal storm level can be considered as a starting point. Different conditions may be selected for various stages in the opera-

Table 1—Environmental Conditions[a]

Environmental conditions	Description	Wave	Wind	Current profile
Extreme	Extreme wave	100 yr.[b] Hs/Tp varied	Associated[c]	Associated[c]
	Extreme wind	Associated[c]	100 yr.[b]	Associated[c]
	Extreme current	Associated[c]	Associated[c]	100 yr.[b]
Maximum Operating	Restricted conditions	See 4.3.1	See 4.3.1	See 4.3.1
Temporary	Installation/Retrieval Transportation	Seasonal[d]	Associated	Associated
Fatigue	Fatigue conditions Wave VIV	WSD[e]	Associated	Associated Annual Distribution
Survival	Survival condition	See 4.3.6	Associated[c]	Associated[c]

Notes:
[a]The static vessel offset plus or minus the low frequency offset caused by wind and wave-drift forces should be included in the riser analysis.
[b]May use less than 100-year event if risk consistent criteria are maintained.
[c]Associated wind, current profile or wave to be determined by considering joint wind, wave and current probabilities.
[d]Wave and current conditions should be based on the season during which the operation will take place, the duration of the operation, and weather forecasting accuracy.
[e]WSD = wave scatter diagram.

tion, depending on the duration of the operations and the consequences of exceeding the selected conditions.

4.4.1.7 Fatigue wave conditions should be specified by wave-scatter diagrams. For top-tensioned risers, vessel offset and current are often taken as zero for the purposes of fatigue-condition wave dynamic riser analysis. The effect of this assumption should be checked. Any low-frequency vessel offset contribution to fatigue is often checked in an analysis separate from the wave-frequency riser dynamic analysis. VIV-induced fatigue calculations should be based on the site current profiles.

4.4.1.8 Guidance on choosing vessel quasi-static offsets for riser dynamic analysis may be found in API RP 2FP1. When risers and vessel are analyzed separately, offsets should be selected to model the expected extreme positions of the top of the riser. These will be developed by vessel-motion analyses for each Design Environmental Case being studied. When a coupled vessel-mooring-riser analysis is performed, offset should be computed from input environmental conditions, rather than being specified. Care should be taken to ensure that the simulation achieves representative maximum offset levels.

4.4.2 Metal Risers

4.4.2.1 This section addresses the design of metal risers.

4.4.2.2 The design cases listed in Table 2 should be used for metal riser design with allowance for the requirements of a particular riser configuration. Table 2 includes cases that investigate strength of the risers as well as cases that produce loads for riser system design. System design loads include, for example, loads on the well and riser top attachment structures.

4.4.2.3 Riser Design Cases should be structured to explore system sensitivities to such parameters as:

a. Density, temperature, and pressure of riser contents.
b. Top tension.
c. Corrosion.
d. Variations in hydrodynamic force coefficients and marine growth.
e. Vessel offsets.
f. Wellhead location and inclination tolerances.

4.4.2.4 The user and manufacturer should agree on the plant tests to be performed on a riser component. The purpose of these tests is to confirm the component's integrity. Since risk is limited in a plant test, Table 2 allows a higher design case factor, C_f, for plant testing than for maximum operating load cases.

4.4.3 Flexible Pipe Risers

The reader is referred to API RP 17B and API Spec 17J for design case information on flexible risers.

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Table 2—Design Matrix for Rigid Risers

Design Case	Load Category	Environmental Condition (from Table 1)	Pressure	Reduced Tensioner Capacity or One Mooring Line Broken	C_f[a,b]
1	Operating	Maximum operating	Design	No	1.0
2	Extreme	Extreme	Design	No	1.2
3	Extreme	Maximum operating	Extreme	No	1.2
4	Extreme	Maximum operating	Design	Yes	1.2
5	Temporary	Temporary	Associated	No	1.2
6	Test[d]	Maximum operating	Test[d]	No	1.35
7	Survival	Survival	Associated	No	1.5
8	Survival	Extreme	Associated	Yes	1.5
9	Fatigue	Fatigue	Operating	No	Note[c]

Notes:
Anisotropic materials may require special consideration.
[a]Use of C_f is described in Section 5: strength issues are discussed in 5.2, deflections in 5.3, collapse issues in 5.4 and 5.5, fatigue in 5.6.
[b]Pipeline codes may require lower C_f for risers that are part of a pipeline.
[c]Not applicable.
[d]Plant testing for rigid risers should be agreed between user and manufacturer.

2. Ochi, M. K., "On Prediction of Extreme Values," *Journal of Ship Research*, March 1973.

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5 Design Criteria

5.1 GENERAL

5.1.1 The purpose of this section is to provide safe, practical design criteria consistent with the other recommendations in this document. These criteria are applicable to the design cases developed in Section 4.

5.1.2 The definition of stresses, method of stress combination and allowables used by this RP are explained. In addition, criteria are discussed for other failure mechanisms including for example excessive deflection, hydrostatic collapse, buckling, fatigue, wear, and deleterious effects of temperature extremes. Inspection criteria as they relate to the design are also covered in this section.

5.2 ALLOWABLE STRESSES

This section applies to metal risers made of steel or titanium. For flexible risers, refer to API Spec 17J.

5.2.1 Stresses To Consider

5.2.1.1 The three principal stresses should be calculated at all critical locations in the riser. At locations with axisymmetric geometry such as plain pipe, the principal stresses will usually be in the axial, hoop and radial directions. For non-axisymmetric geometry, the directions may be different. The principal stress components should be classified as one of the following:

Primary	Any normal or shear stress that is necessary to have static equilibrium of the imposed forces and moments. A primary stress is not self-limiting. Thus, if a primary stress substantially exceeds the yield strength, either failure or gross structural yielding will occur.	
	Membrane	σ_p is the average value across the thickness of a solid section excluding the effects of discontinuities and stress concentrations. For example, the general primary membrane stress in a pipe loaded in pure tension is the tension divided by the cross-sectional area. σ_p may include global bending as in the case of a simple pipe loaded by a bending moment.
	Bending	σ_b is the portion of primary stress proportional to the distance from the centroid of a cross section, excluding the effects of discontinuities and stress concentrations.
Secondary	σ_q is any normal or shear stress that develops as a result of material restraint. This type of stress is self limiting which means that local yielding can relieve the conditions that cause the stress, and a single application of load will not cause failure.	

5.2.1.2 Notice that a principal stress component can be separated into more than one stress category. For example, consider a simple pipe in tension and bending. At the extreme fiber perpendicular to the neutral axis, the axial stress is generally the sum of a general primary membrane stress and a primary bending stress.[1] However, the bending stresses in the sagbend of a steel (or titanium) catenary riser are displacement controlled and thus may be considered as secondary stresses. Bending stresses that exceed yield in this case do not in general cause gross structural yielding and failure.

5.2.2 Combined Stresses

5.2.2.1 Principal stress components at each critical section should be combined using the von Mises yield criterion defined by the following equation:

$$\sigma_e = \frac{1}{\sqrt{2}}\sqrt{(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2} \quad (1)$$

where

σ_e = von Mises equivalent stress.

$\sigma_1, \sigma_2, \sigma_3$ = principal stresses.

5.2.2.2 There will be an equivalent combined stress for each category of stress that occurs at a section. For example, if the primary membrane stress is the only stress at a section, then only the primary membrane equivalent stress will be calculated. However, if all three stress categories occur, there will be three combined stress values (see Equations 2, 3, and 4 below).

5.2.3 Allowable Stresses

5.2.3.1 The von Mises equivalent stresses should be less than the allowable stresses defined by the right hand side of the following inequalities.

$$(\sigma_p)_e < C_f\sigma_a \quad (2)$$

$$(\sigma_p+\sigma_b)_e < 1.5C_f\sigma_a \quad (3)$$

$$(\sigma_p+\sigma_b+\sigma_q)_e < 3.0\,\sigma_a \text{ (see ref. 1 and Annex C)} \quad (4)$$

where

σ_a = $C_a\sigma_y$ = basic allowable combined stress.

C_a = allowable stress factor, $C_a = 2/3$

σ_y = material minimum yield strength, defined for steel or titanium as the tensile stress required to produce a total elongation of 0.5 percent of the test specimen gage length.

C_f = design case factor (see 4.4, Table 2).

5.2.3.2 Annex C demonstrates how to use the above criteria for a simple cylindrical pipe with a step change in outside diameter.

5.2.4 Allowable Stress in Plain Pipe

5.2.4.1 For plain round pipe, where transverse shear and torsion are negligible, the three principal stress components of primary membrane stress (average stress across pipe wall) are σ_{pr}, $\sigma_{p\theta}$, and σ_{pz}, where r, θ, and z refer to radial, hoop, and axial stresses. Thus,

$$\frac{1}{\sqrt{2}}\sqrt{(\sigma_{pr}-\sigma_{p\theta})^2+(\sigma_{p\theta}-\sigma_{pz})^2+(\sigma_{pz}-\sigma_{pr})^2} \le C_f\sigma_a \quad (5)$$

5.2.4.2 Moreover, for a thick walled pipe,

$$\sigma_{pr} = -\frac{(P_oD_o+P_iD_i)}{D_o+D_i} \quad (6)$$

$$\sigma_{p\theta} = (P_i-P_o)\frac{D_o}{2t}-P_i \quad (7)$$

$$\sigma_{pz} = \frac{T}{A} \pm \frac{M}{2I}(D_o-t) \quad (8)$$

where

P_i = internal pressure.

P_o = external pressure.

D_o, D_i = outside, inside diameters.

t = pipe wall thickness.

A = $\frac{\pi}{4}(D_o^2-D_i^2)$.

T = true wall tension in pipe at section being analyzed.

M = global bending moment in pipe.

I = moment of inertia = $\frac{\pi}{64}(D_o^4-D_i^4)$.

Note that the criteria for $(\sigma_p+\sigma_b)_e$ and $(\sigma_p+\sigma_b+\sigma_q)_e$ are never controlling for this case.

5.2.4.3 Substituting Equations 6, 7, and 8 into Equation 5 gives, following a little algebra,

$$\sigma_e^2 = \left[\frac{\sqrt{3}(P_i-P_o)D_oD_i}{2(D_o+D_i)t}\right]^2+\left[\frac{T_{eff}}{A} \pm \frac{M(D_o-t)}{2I}\right]^2 \le (C_fS_a)^2 \quad (9)$$

where

$$T_{eff} = T-P_iA_i+P_oA_o$$

and

$$A_i = \pi D_i^2/4$$

$$A_o = \pi D_o^2/4.$$

5.2.4.4 Minimum wall thickness, after taking into account manufacturing tolerances and wear and corrosion allowances, should be used for t in Equation 7 and in the first bracket in Equation 9. Otherwise, nominal dimensions may be used.

5.2.5 Minimum Material Toughness

The riser pipe and other components in the primary load path should meet minimum fracture toughness requirements described in 7.1.2.2.

5.2.6 Differences From Other Codes

See Annex G for a commentary on differences between the methods of design by analysis utilized in this document and those specified in ASME *Pressure Vessel Code*, Section VIII, Division 2 and in API RP 16Q.

5.3 ALLOWABLE DEFLECTIONS

5.3.1 Riser deflections may need to be limited to prevent unacceptably high bending stresses (see 5.2) or in the case of flexible risers, a bend radius less than the manufacturer's recommended value. Even when riser stress and bend radius are within allowables, large riser curvatures may overstress tubing or other items constrained to move with the riser body.

5.3.2 Riser deflections may also need to be controlled to prevent multiple risers from interfering with each other or with other parts of the production system.

5.3.3 The riser system may include tensioners, flex joints, telescopic joints, or attached items such as jumper hoses. Stroke and rotation requirements of these components should be the maximum of the values found by riser analysis in extreme and accidental design cases multiplied by an appropriate safety factor.

5.4 HYDROSTATIC COLLAPSE

This section applies to metal risers. For flexible risers, refer to API Spec 17J.

5.4.1 Collapse Pressure

5.4.1.1 Unless more accurate methods are used, the criteria provided in this section should be applied to demonstrate that metal tubulars used in FPS risers will not collapse under external hydrostatic pressure.

5.4.1.2 The tubulars should be adequate to withstand external pressures experienced at any period during installation or operation. The effect of co-existing loads such as tension and bending should be accounted for in the analysis, as should the effects of variation in pipe properties such as ovality, eccentricity, anisotropy, and residual stress.

5.4.1.3 The net allowable external design pressure, P_a, should be less than the predicted collapse pressure, P_c, times the design factor, D_f, where P_c is calculated by the method given in 6.6.2.1.

$$P_a \leq D_f P_c \tag{9}$$

where

D_f = 0.75 for seamless or Electric Resistance Welded (ERW) API pipe.

D_f = 0.60 for (DSAW) internally cold expanded API pipe.

5.4.2 Collapse Propagation

5.4.2.1 For a pipe designed to meet the external collapse criteria outlined above, collapse may still be initiated at a lower pressure by accidental means. Examples of such means would be impact or excessive bending due to tensioner failure. Once initiated, such a collapse may form a propagating buckle that will travel along the pipe until the external pressure drops below the propagation pressure or until some change in properties arrests the buckle.

5.4.2.2 The consequences of such a failure should be examined, considering the amount of pipe that can potentially fail and the means available for repair or replacement. Features such as buckle arrestors may be incorporated into the design to limit the extent of a propagating failure. If buckle arrestors are used in sections of pipe subject to fatigue, stress concentrations due to the presence of the arrestors should be addressed by the analysis.

5.4.2.3 This may be done using the formula in 6.6.2.2. In this case, the design pressure differential P_d should be less than the predicted propagation pressure differential P_p times the design factor D_p:

$$P_d < D_p P_p \tag{10}$$

where

D_p = 0.72.

5.4.2.4 Where the pipe design is sufficient to meet the above propagation criterion, the collapse criterion is also met.

5.5 OVERALL COLUMN BUCKLING

Prevention of overall column buckling, caused by excessive negative effective tension, is not in itself a design criterion for risers since the displacement of the top is controlled. It is essential that an appropriate tensioned-beam model (see 6.4.3.6) be used for the analysis of this case. The consequence of a too-small effective tension is excessive curvature and bending moment near the location of minimum effective tension. If curvature and bending stress meet recommendations in this document, then the magnitude of effective tension is usually irrelevant. The exception is when a small decrease in top tension of a top-tensioned metal riser could cause excessive stress. In that case, the designer should establish a minimum tension that gives a margin above the tension that is predicted to cause excessive stress.[2]

5.6 FATIGUE/SERVICE LIFE

5.6.1 Service life is defined as the length of time that a component will be in service. Design fatigue life is the life predicted by cumulative fatigue damage ratio calculations. See Section 6.

5.6.2 At locations that can and will be inspected or where safety and pollution risk are low, the design fatigue life should be at least 3 times the service life (SF = 3).

5.6.3 At locations that cannot be inspected or where safety and pollution risk are significant, the design fatigue life should be at least 10 times the service life (SF = 10).

5.6.4 Cumulative fatigue damage from transportation and installation and in-place operation should be accounted for. The following equation should be satisfied:

$$\sum_i SF_i D_i < 1.0$$

where D_i is the fatigue damage ratio for each phase of loading and SF_i is the associated safety factor (see API RP 2A).

5.7 INSPECTION AND REPLACEMENT

5.7.1 General

5.7.1.1 This section deals with post-installation inspection of the riser. Risers should be inspected as necessary to comply with statutory requirements and to confirm riser integrity. They should also be inspected after potentially damaging incidents and to confirm that any repairs have been properly performed.

5.7.1.2 Inspections relating to areas such as the following may be necessary for risers and riser components:

a. Cracking.
b. Leaks.
c. Damage.
d. Internal and external wear.
e. Internal and external pipe corrosion.
f. Anti-corrosion/abrasion coatings.
g. Cathodic protection.
h. Marine growth.

5.7.1.3 The riser's internal and external operating condition should be monitored to reveal whether design conditions have been exceeded. This monitoring should include the recording of severe storms and accidental loads as well as the composition, pressure and temperature of the riser contents.

5.7.1.4 Risers should be visually examined for factors such as external damage, pipe distortion, excessive marine growth, external corrosion, general pipe configuration, sliding of buoyancy modules, change in the location of subsea buoys, and condition of flexible pipe bend restricters or stiffeners. Defects should be documented with respect to type, size, and location. The influence of defects on structural or pressure integrity should be assessed.

5.7.1.5 Corrosion of metallic components or aging of non-metallic components can be checked by installing short test pipes or coupons in the flow path. The test material can be retrieved after a specified interval and non-destructively and destructively tested to measure the amount of degradation. This information can then be used to predict remaining life.

5.7.1.6 Inspection philosophy should be an integral part of the design. Criticality of components and ease of inspection should be considered early to ensure that provisions are made for adequate inspection. Inspection methods are described in Section 3.

5.7.1.7 The designer should ensure that necessary inspection methods or replacement procedures are available and are scheduled and described in adequate detail as part of the operating and maintenance documentation for the facility.

5.7.1.8 The maximum interval between inspections should be based on the component's predicted time to failure divided by a safety factor. For example, the recommended safety factor for fatigue inspections is 10. The safety factor should account for uncertainties in time-to-failure predictions, risks of failure and ease of inspection. The designer should also consider the time required for repairs or replacement when determining maximum inspection intervals. Inspection intervals should be developed for each mode of failure such as fatigue, abrasion, wear, aging, and corrosion.

5.7.1.9 Equipment consumables such as seals, lubrication, periodically disconnected components and paint should generally be inspected or replaced on a scheduled basis. Moreover, the equipment should be designed to facilitate these maintenance operations. Manufacturer supplied data should include recommended maintenance operations and intervals. Refer to API RP 16Q.

5.7.1.10 If the maximum inspection interval is longer than the intended service life, inspection is not expected to be necessary and need not be included in the operation and maintenance documents. However, if during operation the intended service life is extended beyond the original maximum inspection interval of a component, then the component should be inspected and refurbished if necessary or replaced.

5.7.2 Fatigue Inspections

5.7.2.1 Unless the design fatigue life is at least ten times the intended service life, risers should be inspected periodically for fatigue cracks. The maximum inspection interval should be established by a fatigue analysis based on a cumulative damage theory or appropriate crack growth analysis as addressed in 6.5.1. The inspection interval should not be more than one-fifth of the time necessary for a reliably detectable crack to grow to failure or one-tenth the design fatigue life (see 7.9).

5.7.2.2 A through-wall crack of an operating riser constitutes failure. In-place NDT or removal of the riser for dry inspection are acceptable means of inspection.

5.7.3 Guidelines For Inspection Intervals

5.7.3.1 The following factors should be taken into account when determining inspection intervals:

a. Consequences of failure to human life, property or the environment.
b. Well parameters, e.g., naturally flowing, sour gas or high pressure.
c. Specific intervals based on criteria discussed elsewhere in this section.
d. Present condition and service history, e.g., age, results of previous inspections, changes in design operating or loading conditions, or prior damage and repairs.
e. Redundancy.
f. Operational criticality of the riser and component.
g. Riser type and location, e.g., deep water or new design with few long term operating examples.

5.7.3.2 The intervals given in the Table 3 should not be exceeded unless experience or engineering analysis justifies longer intervals. In such cases, justification for changing guideline inspection intervals, based on the factors listed in this section, should be documented and retained by the operator.

Table 3—Guidelines for Inspection Intervals

Component	Inspection type	Interval
Above water components	Visual	1 year
Below water components	Visual	3 to 5 years
All components	NDT	As needed
Flexible pipe	Visual	1 year or after connect or reconnect
Cathodic protection	Visual or potential survey	3 to 5 years
Areas of known or suspected damage	As appropriate	After exposure to design event
Components retrieved to surface	As recommended by manufacturer	After disconnect

5.8 TEMPERATURE LIMITS

5.8.1 The operator should specify both the maximum and minimum temperatures of the fluid transported by the riser system during service and during installation. Any unusual extreme temperatures such as those caused by emergency blowdown should also be defined.

5.8.2 Temperature criteria should be used to determine riser material properties such as the following:

a. Temperature derating factors.
b. Toughness and other metallurgical properties.
c. Mechanical characteristics of thermoplastics, resins, and composite materials.

5.8.3 Temperature criteria should be used in analyses like:

a. Metal pipe stress and expansion analyses.
b. Fatigue/cracking analyses.
c. Corrosion and cathodic protection analyses.
d. Chemical aging analyses for nonmetallic materials.

5.8.4 The designer should ensure and demonstrate that the riser is suitable for operation at the specified temperatures in conjunction with the associated chemical composition and pressure of the transported fluid. For steel, the yield strength should be reduced by a factor above a certain temperature. For example, NS3472E[3] gives this factor as $kt = 1.14 - T°C/850$ for temperatures above 120°C.

5.9 ABRASION AND WEAR

5.9.1 Abrasion, wear and erosion may be internal, external or between components of the riser, (e.g., between layers of a flexible pipe). For any part of a riser which is expected to experience abrasion, the designer should show that expected material loss is within design allowables or that adequate measures have been taken to protect the riser from excessive abrasion and wear.

5.9.2 In cases where material loss is predicted, for example between drill string and drilling riser, the material loss should be included in the stress analysis to obtain conservative results.

5.9.3 For catenary risers, design should address the abrasion caused by movement of the pipe touchdown point at the seabed. If the anti-corrosion coating or weight coating on the pipeline is to withstand abrasion, it should be designed with suitable thickness and abrasion resistant characteristics. The catenary riser analysis should consider the geotechnical description, topography and any local debris likely to be found in the vicinity of the riser touchdown point.

5.10 INTERFERENCE

5.10.1 Riser interference is defined as a riser outer wall coming in contact with an object which the riser normally would not touch.

5.10.2 Interference may occur between a riser and any object sufficiently close to it. This may be the FPS hull, mooring line, or another riser. The latter may be of a different size or differ in such properties as contents, extent of marine growth, top tension, tension distribution, or other boundary conditions. It may also be a riser in a different flow field as caused by wake effects.

5.10.3 Riser systems should be designed to limit interference because of potential damage to the risers or other parts of the FPS if interference occurs. Hydrodynamic interaction of multiple risers (see 6.3.3.4.2) and partial loss of riser tension should be considered.

5.10.4 Either of two design approaches may be taken to limit the effects of riser interference. One approach requires that the probability of "negative" clearance between a riser and another object be less than a specified value during any operation or environmental condition. The other approach permits contact between the riser and another object but requires that the effects of contact be analyzed and designed for.

5.10.5 These two approaches may be combined so that no contact is permitted in the extreme storm with all riser tensioner elements intact, and contact is permitted but without progressive collapse of the riser in the survival storm with all tensioner elements intact or in the extreme storm with the loss of one of the tensioner elements.[4]

5.11 BOLTING

Bolting design criteria may be found in ISO WD 13819 Part 2—*P&NGI—Offshore structures—Part 2: Fixed Steel Structures*.

5.12 BIBLIOGRAPHY

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6 Analytical Considerations

6.1 GENERAL

This section describes structural analysis procedures for FPS risers, including:

a. Overview of analyses required for different types of risers (see 6.2).
b. Hydrodynamic considerations for riser analyses (see 6.3).
c. Procedures for global riser analysis, riser component analyses, service life (fatigue) analyses, and other special purpose analyses (see 6.4).

6.2 ANALYTICAL CONSIDERATIONS BY RISER TYPE

6.2.1 Top-Tensioned Risers

This section describes analytical considerations and procedures for top-tensioned risers such as:

a. Drilling risers.
b. Production risers.
c. Completion/workover risers.
d. Import/export risers.

The Figure 29 flowchart outlines a typical procedure for top tensioned risers. It provides a structure for the following overview tasks that are considered to be established practice. It can also provide a basis for the design and analysis procedures which may be developed for a specific riser/FPS combination.

The following information is required for modeling top-tensioned FPS risers:

a. Estimated riser length (water depth).
b. Number of tubulars required (e.g., main drilling riser tube, choke and kill lines and booster line).
c. Minimum allowable inside diameters of the riser tubulars and wall thickness.
d. For the drilling riser, whether a surface BOP or subsea BOP is to be used, and estimated weight and height of the BOP or lower riser package (LRP).
e. Estimated height above the mudline of the lower attachment point.
f. Whether stress joints, flex/ball joints or some combination of these special joints are to be used.
g. Estimated densities, temperatures, and pressures of the contents of the riser tubulars.
h. Size and weight of equipment attached to the top of the riser for the different operating scenarios to be evaluated.
i. Telescoping joint stroke requirements, if a telescoping joint is used.
j. Estimation of the riser tensioner limits (i.e., capacity and stroke).
k. Type of external buoyancy to be used, if required.
l. Description of the environmental conditions to be evaluated.
m. Definition of the FPS motions (i.e., static offset, slow drift offset and wave-frequency motion RAOs).
n. *Cd* and *Cm* values for use in analysis.

Design/analysis of top tensioned risers can be divided into three phases:

6.2.1.1 Start-up Phase

This phase includes all of the tasks which must be performed before the preliminary design and analysis of the riser can be performed:

a. Define service—The goal of this task is to define the riser mission. It depends on the type of riser and FPS being considered. This task includes the evaluation of the riser design and operational considerations as defined in Section 3 and the definition of the design loads and design criteria to be used as defined in Sections 4 and 5.
b. Define basic configuration—The goal of this task is to define the riser's basic configuration. This includes definition of the number of tubulars, definition of the riser cross-section (i.e., arrangement of tubulars, etc.), definition of the length of the riser, definition of the location of the riser within the well pattern, and with respect to other equipment.
c. Gather data and build the design matrix—The goal of this task is to gather all data required to perform the design and analysis of the riser (i.e., description of the environmental loads, definition of the FPS motions, definition of the pressure, and temperature requirements, etc.). This task also includes the generation of the design matrix to be used for the riser as defined in Section 4.

6.2.1.2 Preliminary Design and Analysis Phase

The goal of the preliminary design and analysis phase is to generate preliminary sizes and designs for the riser tubulars and components. The tasks include analyses performed to generate loads used in sizing riser tubulars and designing riser components. The preliminary tubular sizes and component designs generated in this phase should be refined enough to require only minor modifications in the detailed design/analysis phase. Several iterations may be required for some of the tasks or group of tasks to generate the preliminary tubing sizes and component designs.

6.2.1.2.1 Preliminary Riser Sizing

The goal of this task is to obtain the preliminary sizes of the riser tubulars. In some cases, estimates of the sizes for some of the riser components (i.e., stress joints, tensioner joint, etc.) may also be generated in this task. The analyses included in this task would generally employ hand calculation methods.

6.2.1.2.2 Preliminary Global Riser Analysis

The goal of this task is to generate the riser response information required to evaluate the preliminary sizes of the riser tubulars and to generate the preliminary design of the riser components. The riser is idealized using an equivalent pipe model of the riser. The methods used to generate the equivalent pipe model are defined in 6.4.4.1. The load cases used in this task are obtained from the design matrix.

Several iterations through this task in conjunction with the tasks defined below will be required to refine the riser design. The analyses performed during some of the initial iterations through this task may be started using quasi-static or regular wave analyses. As the refinement of the riser design proceeds, the refinement of the analysis increases.

The preliminary global riser analyses are generally performed using planar frequency domain solutions. If non-linearities (i.e., tension variation, wave kinematics, etc.) are deemed to be important for the preliminary sizing of the riser components, then they should be incorporated into the analysis. Inclusion of these non-linearities may require the use of time-domain solutions in this early phase. See 6.4.3.8 and 6.4.3.9.

6.2.1.2.3 Preliminary Global Riser Response Assessment

This task includes the evaluation of the global riser response for all of the design cases defined in the design matrix. Some of the activities included in this task are:

a. Optimize applied tension to achieve acceptable extreme and dynamic stresses. Evaluate the need for buoyancy.

b. Evaluate riser clearances.

c. Evaluate tensioner stroke requirements.

d. Evaluate need for VIV suppression devices. If suppression devices are required, the effect of the devices should be evaluated.

6.2.1.2.4 Tensioner Design

The information generated in preliminary analysis should be used to design the riser tensioner. The tensioner capabilities and spring rates (load variation vs. stroke) should also be obtained in this task.

6.2.1.2.5 Preliminary Analysis of the Individual Tubes

This task includes the evaluation of each of the riser tubulars. Each of the riser tubulars should be analyzed using the loads and displacements obtained from the preliminary global riser analysis. The effects of temperature, pressure, end boundary conditions, riser installation sequence, relative axial stiffnesses, and global riser displacements should be included in determining the tensions in the tubulars. The following activities should be included in this task:

a. Compare the maximum stresses in each tubular with the appropriate stress criteria.

b. Compare the estimated service lives obtained for each tubular with the appropriate service life criteria.

c. Determine the allowable stress amplification factors for the riser components. The allowable stress amplification factors are the maximum stress amplification factors the riser components may have and still satisfy the service life criteria.

d. Determine the required centralizer spacing if centralizers are needed.

The methods used to analyze the riser tubulars for risers with more than one tubular are described in 6.5.1.

6.2.1.2.6 Riser Component Design/Analyses

The analyses of the individual riser components should be performed using the loads and displacements obtained from the preliminary global riser analysis and the preliminary analysis of the individual tubes. The riser components should be evaluated for the design event and service life criteria. The riser components to be evaluated include special riser joints (e.g., flex joint, lower stress joint, special tensioner joint, wave zone joint), riser connectors, and riser attachments (e.g., anodes and buoyancy).

6.2.1.2.7 Assess Data and Mission

This task includes an evaluation of the results from the preliminary design and analysis of the riser. The suitability of the riser design should be assessed for the defined service. The necessary design changes should be made before beginning the detailed design and analysis of the riser.

6.2.1.3 Detailed Design and Analysis Phase

The goal of this phase is to obtain a final riser design. The tasks include generating the loads used for the final sizing, checking the riser tubular designs, checking the riser component designs, and modifying the designs if required. Several iterations may be required to generate the final riser design.

6.2.1.3.1 Global Riser Analysis

The goal of this task is to generate the riser response information required to evaluate the riser design. As in the preliminary global riser analysis, the riser is idealized using an equivalent pipe model of the riser. The load cases used in this task are obtained from the design matrix.

Several iterations through this task in conjunction with some of the tasks defined below may be required to obtain the final riser design. All of the design modifications made since the last preliminary global analysis was performed should be incorporated into these analyses.

The non-linearities (e.g., tension variation and wave kinematics) that are considered to be important to the riser design should be evaluated and if found to be significant, incorporated into these analyses. Time-domain solutions should be performed to determine the effect that these non-linearities have on the riser response. If significant, these non-linearities may be incorporated into the analyses through the use of time-domain solutions or through the use of a combination of time-domain and frequency-domain solutions. When using a combination of time-domain and frequency-domain solutions, the time-domain solutions are used to generate factors which are applied to the frequency-domain solutions to correct for these effects.

This task includes generating the design event loads and fatigue loads to be used for the design/analysis of the riser tubulars, the riser components, and the riser foundation.

6.2.1.3.2 Global Riser Response Assessment

This task includes the evaluation of the global riser response for all of the design cases defined in the design matrix. Some of the activities included in this task are listed below:

a. Finalize tension requirements. Determine the tensioner strokes and tension variations.

b. Evaluate the riser clearances.

c. Finalize any VIV suppression devices.

6.2.1.3.3 Verification of the Tensioner Design

The goal of this task is to verify that the tensioner design satisfies all of the tensioner design criteria. The information generated in the global riser analysis should be used for this task.

6.2.1.3.4 Analysis of the Individual Riser Tubulars

This task repeats the activities from the corresponding task in the preliminary design phase.

6.2.1.3.5 Riser Component Design Check

The goal of this task is to verify that the riser component designs satisfy the design criteria using the loads and displacements obtained from the global riser analysis and the analysis of the individual tubes. The riser components should be evaluated for the design event and service life criteria.

6.2.1.3.6 Design Iteration

As stated above, the goal of the detailed design and analysis phase is to obtain a final riser design. If any results do not satisfy the appropriate design criteria, then the necessary design modifications should be made. If these significantly alter riser response, then re-evaluation of the modified design should begin with global riser analysis.

Other results from the analysis of a top tensioned riser, in addition to the final riser design, are required to determine operating limits, to set the spacing between adjacent risers, to set spacing between the risers and adjacent equipment, and to design other equipment. Some of the other results required from the analysis are given below:

a. Maximum stresses obtained for the various design load cases.

b. Expected service life.

c. Optimum and minimum allowable top tensions.

d. Expected tensioner strokes.

e. Loads at the top and bottom of the riser.

f. Displacements and rotations along the length of the riser.

6.2.1.4 Special Analytical Considerations

6.2.1.4.1 External Drilling Riser Lines

If external lines (e.g., choke and kill, mud boost) are attached to the drilling riser, then it may be necessary to include them in the global analysis of the drilling riser. In the regions of the drilling riser which do not have external buoyancy covering the external lines, the lines should be considered when calculating the riser's drag and inertial diameters. If the combined bending stiffness of the external lines is significant when compared to the main riser tube (greater than 10 percent of the main tube's bending stiffness), then the external lines should be considered when calculating the global stiffness. The masses of the external lines and their contents should always be included in the global analysis model.

Analyses of each of the external lines should be included in the riser component analysis task. These analyses are needed to evaluate the structural integrity of the lines and to determine the required distance between the supports tying the external lines to the main riser tube.

6.2.1.4.2 Multiple Tubes for Production, Workover/ Completion, and Import/Export Risers

All of the production riser tubulars are generally included in the model used for the global analysis. The tubulars are included in the global analysis through the use of an equivalent pipe model of the riser. The methods used to generate the equivalent pipe model are defined in 6.4.4.1.

Analyses of each of the riser tubulars should be included in the riser component analysis task. These analyses should be performed to evaluate the structural integrity and service life of the tubulars and to determine the required distance between the centralizers attached to the tubulars if centralizers are required.

6.2.1.4.3 Special Riser Joints

The special riser joints that may be used in a top tensioned FPS riser include telescoping joints, flex/ball joints, stress joints, tensioner joints, keel joints, centralizer joints, and wave zone joints. One or most of the special joints may be included in a particular riser configuration. These special joints should be appropriately modeled in the global riser analysis and specifically evaluated in the riser component analysis.

6.2.1.4.4 Riser Clearance

See 5.10.

6.2.1.4.5 Fatigue

Fatigue analyses performed on top-tensioned FPS risers should include the effects of wave cycles, slow drift cycles, and VIV.

6.2.1.4.6 BOP Installation

If a subsea BOP is to be installed within riser arrays, the clearances between the disconnected drilling riser and the adjacent risers should be evaluated.

6.2.1.4.7 Production Riser Installation

The clearances between the disconnected production riser and adjacent risers should be evaluated. The tubular pretensions generated during the riser installation operation should also be determined and optimized. The tubular pretensions significantly affect the loads and stresses generated in the individual tubes.

6.2.1.4.8 Completion/Workover Riser Installation

The completion/workover riser may be used to run the subsea tree and other subsea equipment. Because these operations are performed in the open water, there is potential for contact between the completion/workover riser and adjacent risers, particularly if the riser is being used in an array of risers. The clearances between the disconnected completion/workover riser and adjacent risers should be evaluated for these operations.

6.2.1.4.9 Well Completions

Some FPS production risers are used for well completion operations. The analytical considerations to be included in the evaluation of these operations are the effects of the tubulars and equipment being run inside the riser and the equipment attached to the top of the riser. Attention should also be given to the changes in internal pressure and density associated with the various operations.

6.2.1.4.10 Tubing Hanger Installation Operations

The completion/workover riser may be used to run the tubing hanger. This operation is usually performed through the drilling riser. The completion/workover riser should be evaluated for displacements applied to it by the drilling riser.

6.2.2 Flexible Pipe Risers

For analytical considerations of flexible pipe risers, see API RP 17B. The most common configurations for a flexible riser are:

a. Steep-S or buoy-tensioned catenary configuration.

b. Lazy-S or double catenary configuration.

c. Steep-wave configuration with distributed buoyancy.

d. Lazy-wave configuration with distributed buoyancy.

e. Single free-hanging catenary.

f. Double free-hanging catenary.

g. Pliant wave.

h. "Chinese Lantern" configuration is also sometimes used, especially with single point mooring systems.

Examples of these common configurations are shown in Figure 30. The selection of the configuration depends on the water depth, vessel excursion and motion, clearance requirement and other design factors.

6.2.3 Hybrid Risers

The purpose of this section is to describe design and analysis of hybrid risers. Annex F details design considerations for hybrid risers.

6.2.3.1 Analysis Approach

6.2.3.1.1 Before modeling a hybrid riser, it is necessary to obtain first the field requirements and carry out a preliminary sizing of the riser system to obtain as a minimum the following information:

a. Number, size, dry weight, submerged weight, fluid content, pressure, and function of the freestanding flowlines.

b. Distance below the water surface where the flexible jumpers attach to the FPS.

c. Distance below the water surface of the upper riser connector package (URCP). For any storm condition, the FPS and the top elevation of the URCP should not interfere.

d. Dry weight and submerged weight for the URCP and goosenecks.

e. Number, size, dry weight, and net lift for the upper tanks located below the URCP.

f. Dry weight, submerged weight, outside diameter, and characteristics of the typical riser joint with foam modules and of the riser joints that use VIV suppression devices, internal air chambers, or pressurized bore characteristics if any.

g. Dry weight, submerged weight, outside diameter for the lower stress joint, and for the bottom riser connector.

h. Type of material for lower stress joint.

i. Elevation above the seabed where the riser bottom connector latches to the subsea template, manifold, or monopile foundation.

6.2.3.1.2 Most riser analysis packages are geared towards the modeling of single string risers. While all strings of the hybrid riser may be modeled individually this could result in an exceedingly complex model, with associated potential for errors and analytical difficulties. It is more convenient to simulate the rigid metal section of the hybrid riser using an equivalent single string model. Key properties for an equivalent single string model are typically obtained as follows:

a. Mass—sum of all line weights, weight of foam buoyancy, weight of contained fluids, including air at pressure in central member or air can buoyancy, entrained water between buoyancy modules, and structural member and in peripheral line guide tubes.

b. Bending stiffness—sum of the stiffnesses of all members.

c. Axial stiffness—stiffness of the structural member.

d. Buoyancy diameter—outside diameter of the buoyancy modules or projected diameter of all pipe sections on exposed pipe sections.

e. Effective tension—superimpose the effective tension of the flowlines onto the effective tension of the riser.

6.2.3.1.3 Such an approach may be used for extreme load, fatigue, and VIV analysis.

6.2.3.1.4 Modeling the top assembly may also be conveniently achieved using single string riser model proper-ties. Goosenecks, valves and tethering hardware may be modeled using pipe elements to simulate the relevant hydrodynamic properties and weights. A spring element that simulates the appropriate level of load variation with stroke may be used to model a tether. Modeling of flexible jumper hoses is somewhat more complex. At the most simplistic level, all jumper hoses may be modeled individually, though this may result in an unnecessarily complex model. The jumper hoses can be more conveniently modeled by use of just two or four jumper hoses which simulate the mass, stiffness and hydrodynamic loading contribution of all jumpers. Such an approach is far more conducive to the iterative nature of hybrid riser design development and further jumpers can be added in the later stages of analysis to verify the simplified approach and produce flexible jumper hose termination loading for detailed design purposes. When modeling the top assembly for VIV analysis, free movement of the top assembly is damped by the presence of the jumper hoses. The top of the riser may therefore be constrained laterally with a rotational spring stiffness applied equivalent to the rotational resistance to movement provided by the jumpers.

6.2.3.1.5 Due to their significant change in curvature during a storm, the structural behavior of flexible jumpers cannot be properly modeled in frequency domain analyses; therefore, the frequency-domain analysis of a hybrid riser can consider only the equivalent effect of the flexible jumpers' properties, such as: spring stiffness, mass, drag, and inertial properties.

6.2.3.1.6 Irvine presents expressions that can be used to compute the flexibility and stiffness matrices of extensible cables based on the relative displacement between the two jumper ends. These matrices, which can have linear or nonlinear behavior, have been used successfully to represent the stiffness properties of flexible jumper systems.

6.2.3.1.7 Hybrid risers are likely to exhibit much greater levels of structural damping than typically found in single string risers due to the movement of the peripheral lines in the guide tubes. This can either increase or decrease loading in the riser, depending on loading conditions. Parametric analyses are needed to quantify the effects of structural damping and determine the sensitivity of response to changes in modeling assumptions. Depending on the significance of such results, tank testing may be needed in order to define damping levels and verify predicted response.

6.2.3.1.8 Having equivalenced all lines into a single string model for global analysis, it becomes necessary to de-equivalence the model for the purpose of post-processing analysis results. Bending moments in individual lines can be obtained according to the ratio of line bending stiffness to the sum of stiffnesses for all metal lines. Calculation of effective tension in the peripheral lines can be readily achieved based on distance from points of vertical support and weight of the line, as the inertia effect of the line is small. Effective tension in the structural can then be calculated as the difference between the effective tension in the riser model at a given elevation and sum of that in all peripheral lines. While such calculations are straightforward, they add to the complexity of the analysis process and the interpretation of analysis output.

6.2.3.1.9 Where peripheral lines are top supported, such de-equivalencing may show regions where the structural member is in compression. Unlike single string riser systems where compression is likely to be considered unacceptable, compression in one or more lines need not be a problem provided this is considered in the design. At peripheral line support points, local buckling resistance of the structural member must be checked and lateral restraint of the peripheral lines must be carefully detailed to ensure that Euler buckling effects are adequately restrained.

6.2.3.1.10 The top section of the riser inclines during the lateral motion and bending of the riser; therefore, the base of the goosenecks must clear any interference with the top riser section. Freestanding flowlines must have an extra length at the top to accommodate the relative displacement between the flowlines and the structural riser.

6.2.3.2 Design Approach

The principles of hybrid riser design development are similar to those for any other riser system. The stages involved and objectives of each are as follows:

a. Sizing—determine line sizes, develop a design that can resist functional loading such as self weight and pressure effects.
b. Preliminary analysis—determine minimum requirements for tension, tethering and VIV suppression.
c. Extreme load analysis—conduct storm analysis, determine optimum global arrangement, define loading on and refine key components to resist extreme loading conditions.
d. Fatigue and fracture analysis—modify global design, define design details needed to meet service life requirement, define manufacturing inspection requirements and verify fatigue analysis with fracture analysis.
e. Installation analysis—define installation equipment requirements, ensure satisfactory weather windows can be achieved, and modify design as required.

The main difference between analytical development of a hybrid riser and that of single string risers is that a greater degree of iteration is required over all stages and at each stage of development to optimize the design.

6.2.3.2.1 Sizing

The steps involved in riser sizing are as follows:

a. Size peripheral lines.
b. Select can diameter and determine contribution to buoyancy.
c. Determine distributed buoyancy needed.
d. Determine distribution between air-can and foam buoyancy needed for installation.
e. Lay out flowlines within the buoyancy modules.
f. Determine weight of top assembly including emergency disconnect package and make an estimate of jumper hose lengths and weights.
g. Assess weight tolerances and buoyancy absorption to determine minimum overpull required.

The diameters of the peripheral lines are determined by flowline sizes, and wall thicknesses are sized to provide adequate resistance to internal and external pressure loading. Where high levels of bending may be experienced, such as along the length of the base stress joint, or axial compression is experienced, peripheral flowlines may need to be designed to resist collapse and buckle propagation. Elongation of peripheral lines due to temperature and end cap pressure should be calculated and suitable support points for the lines defined. The circumferential layout of the peripheral lines must account for grouping and directional requirements at the base, ballasting operations conducted during trimming prior to tow-out and symmetry of loading on the structural member.

The quantity of distributed buoyancy required depends on many factors. One approach is to design the riser section such that it is neutrally buoyant in production mode, with the overpull at the riser base needed to provide resistance to current loading provided by air cans at the top of the riser. Such cans provide an element of variable buoyancy to account for weight tolerances, absorption of seawater into the buoyancy with time, and variation in production fluid densities or line functions. This approach is convenient for tow-out installation, enabling a surface tow to be achieved by keeping the peripheral lines empty, or submerged tow by flooding the lines with seawater or addition of drag chains. For installation from a drilling rig a similar approach could be adopted if peripheral lines are installed with each joint. If the lines are run after installation of the main riser structure, the foam buoyancy must be sized to simply provide support to the structural member, which could be flooded during running. As the peripheral lines are installed, the structural member or air tanks can be evacuated to provide some or all of buoyancy needed to support these lines.

Preliminary design of the riser top terminations must next be made. This may incorporate the valves forming part of the emergency disconnect package, goosenecks for connection of peripheral lines, the associated support structure and flexible jumper hose lengths and weights. The jumper hose lengths can be based initially on the relative vertical movement between the vessel and the riser at maximum drift-off position, assuming the riser moves with the vessel and considering the maximum expected heave amplitude.

6.2.3.2.2 Preliminary Analysis

Preliminary extreme load analysis is used to provide an indication of minimum required buoyancy and tension distribution through the riser. As a starting point, the tethering tension, if needed, may be based on readily available tethering equipment, distributed buoyancy equivalent to that needed for neutral buoyancy in production mode and upper air cans sufficient to provide a nominal overpull at the riser base and with sufficient reserve capacity to accommodate weight tolerances and buoyancy loss over the riser life. Preliminary analysis using such a model provides a quick means of assessing which way the starting point parameters should be varied to improve response. For example, excessive rotation of the riser about the base or excessive lateral movements may indicate that the riser has insufficient buoyancy, upper air cans are too large or the top elevation should be lowered. Too little movement relative to vessel may indicate too much buoyancy. Hence, the preliminary results provide the basis for determining the direction in which parameters should be adjusted to provide the optimum riser configuration.

Following preliminary extreme load analysis, preliminary VIV analysis should be conducted to determine whether VIV suppression devices are needed. If so, the preliminary extreme load riser model should be modified accordingly and re-analyzed. The resulting riser arrangement forms a suitable basis for more detailed design optimization.

6.2.3.2.3 Extreme Load Response

Extreme storm analysis is used to optimize distributed buoyancy requirements, top tension, tethering tension (if needed) and foundation loading based on riser performance, jumper hose, riser and vessel interaction, stress joint performance, and cost. Parametric analysis of the riser configuration resulting from preliminary analysis is carried out with varying tether tension, air can buoyancy, distributed buoyancy and riser top elevation. The dependency of response of different parts of the riser on different loading conditions requires that the full range of possible conditions including extreme wave and extreme current conditions should be applied to each arrangement forming part of the parametric study. Associated extremes of vessel drift motions and the possibility of high winds and currents from different or opposite directions should also be addressed. For the most suitable arrangements, stress joint profiles should be developed from which extreme loading on the riser base connector and foundation can be obtained.

Many of the configurations analyzed as part of the parametric study may meet extreme load design requirements. Selection of the optimum arrangement will be based on an assessment of hardware availability and cost and ease of installation. Ease of operation should also be considered if simultaneous drilling or workover are to be carried out and preliminary design of the foundation may be warranted to assist in the selection process.

Following global extreme load analysis of the riser, the arrangement of design details should be developed. These may include heat loss analysis of peripheral lines to determine temperature variation along the riser, analysis of riser base piping and transition to peripheral lines, design of the upper goosenecks and support structure to resist extreme dynamic loading from the jumper hoses and the structural arrangement of supports for the peripheral lines. Any adjustments to preliminary estimation of loading from these components can be updated in the global analysis model and the riser reanalyzed.

6.2.3.2.4 Fatigue and Fracture Analysis

Fatigue analysis of the in-place riser must consider the effects of first order wave action, VIV due to steady current flow, and vessel drift motions. The installation process may also produce a significant contribution to fatigue damage from VIV or wave action during tow-out.

First order fatigue damage results from direct hydrodynamic loading on the upper regions of the riser, loading from the jumper hoses, and fluctuating load and direction of load application from a tether. Fatigue damage from direct hydrodynamic loading and the effect of jumper hoses can be reduced by lowering the elevation of the top of the riser and increasing the length of flexible jumper hoses, but both modifications will add to cost. Tethering effects, if present, can be lessened by reducing tether stiffness though this will also add to cost. Nonetheless, such means of reducing fatigue damage may be more suitable than alternatives such as improvement of fabrication details.

Drift motions may cause significant levels of fatigue damage in the goosenecks where the flexible jumper hoses are attached to the riser and in the base stress joint. Response can be calculated by global analysis of the riser in selective sea-states and a statistical distribution such as Weibull used to determine long term stress cycling. Mean drift offsets must be carefully selected when conducting such analyses as a tether attached to the FPS may have a substantial nonlinear effect on response.

The low in-water weight and tension which are characteristic of the hybrid riser makes the riser susceptible to high levels of fatigue damage from VIV. The objective of VIV analysis is to determine the extent to which suppression devices are required.

As for other riser systems, VIV analysis of hybrid risers may consider current profiles of varying exceedence level, up to and including 100-year return currents. The total VIV induced fatigue damage may then be calculated using the damage from each profile and the associated percentage occurrence. Preliminary analysis may be conducted assuming no suppression devices are fitted. The regions in which excitation occurs and the magnitude of unsuppressed fatigue damage can then be determined. Suitable devices must then be selected which provide the necessary level of suppression. Helical strakes form a convenient solution as these may be readily attached to the surface of the syntactic foam buoyancy modules.

When determining the extent of such devices it is often sufficient to base suppression requirements on the more severe current profiles which, though of short duration, may produce the greatest levels of fatigue damage. Over specification of suppression devices should be avoided, as the higher drag loading such devices can produce may have adverse effects on buoyancy requirements and riser base loading.

The fatigue damage distribution along the riser length is given by the sum of the damage from first and second order effects, from VIV in service, and from damage accumulated during installation. The fatigue lives of critical components should be verified using fracture analysis. Fracture analysis, un-like fatigue analysis based on an S-N curve analysis approach, enables consideration of extreme loading in addition to long-term fluctuating loads. Extreme load levels used to assess unstable fracture should be based on extreme design loads. Fluctuating loading used to compute crack growth must be derived for each component of loading. The damage incurred from each effect should be used to derive loading histograms, which must be developed in a sequence representative of riser installation and long term behavior.

Fracture analysis should be conducted on the structural member, particularly adjacent to the top assembly and stress joint and welded connections between peripheral lines and base connectors. This work will determine the level of inspection required following fabrication and may lead to the specification of improved post-weld heat treatment procedures to alleviate residual stresses and improve fracture resistance.

6.2.3.3 Installation

6.2.3.3.1 Tow-out Option

The controls and procedures to be adopted for tow-out installation (see Figure 32) are determined by riser analysis. The four main operations which must be addressed are as follows:

a. Launch—lifting off the beach site or launch from a bundle fabrication facility.

b. Trimming—inshore ballasting of the riser.

c. Tow-out—transfer from fabrication facility to operational site.

d. Up-ending—ballasting or lowering to the vertical.

Transfer of the riser from a fabrication site into the water may be achieved by launch from a bundle fabrication facility by tug or tow vessel, or from a beach fabrication site by skidding on bogeys or lifting using cranes. Using either approach, the terminations must be attached at each end of the riser and strakes may need to be fitted as the riser enters the water. For launch from a beach site, limiting out-of-straightness must be determined based on lateral bending response and methods of monitoring riser curvature should be defined. If the riser is to be lifted, spreader beams must be designed and the level of load alarms to control differential lift rates must be calculated. As the riser enters the water and the end terminations are attached, tolerable motions are likely to be small. Analysis should be conducted to determine interaction between the wet and dry sections of the riser, environmental limitations for the operation and the possible need for environmental protection from direct wave or current action.

The riser should enter the water in a positively buoyant state. Once fully launched, trimming is carried out. Lines may need to be flooded or chains attached, depending on tow method, to ensure the riser takes up its correct position in the water. Where lines are to be flooded, a sequence should be developed to account for manufacturing weight tolerances, which starts from the bottom of the riser working upwards to avoid rolling of the riser during tow.

The tow-out operation must be analyzed to determining limiting currents and wave heights in which the tow operation can be conducted and the amount of back tension, if required, to be applied to the riser. When modeling the riser, care must be taken to ensure that axial loading on the surface and ends of the riser are properly accounted for. This may include analytical development of nose and tail tow fairings which improve response. If surface tow is used, free-surface effects must be accounted for which will require the use of time-domain analysis.

Long, neutrally buoyant bodies such as the hybrid riser may experience severe oscillations during tow at one or more of the risers' natural frequencies.[97] An exhaustive set of wave height, period, and direction combinations must therefore be applied to the riser to ensure that environmental conditions which preclude overstressing are properly identified. The effect of tow speed on apparent current velocity and wave period must be accounted for and varying current directions must be considered to determine the relative position of lead and tail vessels and associated back tension. Fatigue analysis must also be conducted due to the potentially high levels of damage which may be incurred, which in some designs, may be a significant part of the total riser fatigue damage. In view of the importance of the tow-out operation, model testing will normally be required to verify analytical predictions of riser response.

Upending of the riser may be achieved by removal of buoys or flooding of some of the flowlines together with lowering or releasing the base of the riser. Analysis is required to determine suitable means of harnessing the base to avoid local overstressing and the sequence of operations needed to ensure that ballast lines flood as intended without creating airlocks. For example, this may consist of supporting the base, removing base buoyancy, then lowering the base a short distance prior to flooding some of the peripheral lines. Suitable contingency actions must be determined to account for riser and buoyancy weight variations which may involve the sequential flooding of small diameter lines. Analysis may also be carried out to determine the controls to be applied during lowering, such as correlation of riser base elevation with upper end inclination. Once the riser becomes near vertical, similar analyses as those used to determine response of a riser during running are required.

6.2.3.3.2 Running Option

If the riser is installed by running, the operation should be analyzed to determine limiting weather windows which preclude overstressing of the riser, overloading of handling equipment and interference with the vessel. The riser should be analyzed with the base at a number of depths throughout the water column. One important difference between modeling of the riser during installation and in-place is the greater care required to ensure that axial dynamics are properly modeled. For the in-place riser such effects are small, but during installation, response may be dominated by surface drag and inertia and loading on the riser base.

Ballasting may be required during running to control the weight supported from the vessel. Rates of flooding and evacuation must be calculated and acceptable variations in ballast at different depths determined. Ballasting equipment may then be specified and the speed of installation calculated. This may then be compared with the joint make-up procedure to determine which process controls installation speed and design adjustments made as necessary.

6.2.4 Multibore Top Tensioned Metal Risers

There are some differences in the analytical modeling techniques used for hybrid and top tensioned multibore risers, since the hybrid riser does not pierce the water surface, thus avoiding the direct impact of the surface environment that is significant for surface piercing risers.

Before modeling a top tensioned metal riser, it is necessary first to obtain the specifications for the field requirements, such as: satellite trees, subsea manifolds, flowlines, etc. and carry out a preliminary sizing of the riser system to obtain as a minimum the following information:

a. Number, size, dry weight, submerged weight, fluid content, pressure, and function of the freestanding flowlines.

b. Estimated required top tension. Size, weight, and main characteristics of the top tension equipment. Stiffness characteristics of the tensioning system as a function of tension and stroke.

c. Elevation above water level and vessel coordinates for the tensioning ring and centralizer frame.

d. Elevation of goosenecks. This elevation is often the point of connection between metal and flexible lines.

e. Dry weight, submerged weight, outside diameter, and general characteristics:

1. For the typical bare riser joint.
2. Of the tensioning joint.
3. Of the riser joints that use VIV suppression devices.
4. For the typical riser joint with buoyancy modules.
5. For the lower stress joint.
6. For the bottom riser connector.

f. Material for lower stress joint.

g. Elevation above the seabed where the freestanding flowlines are supported and stabbed into the flowline receptacles.

h. Elevation above the seabed where the bottom connector latches to the subsea template, manifold or monopile foundation.

The analytical discretization for top tensioned riser models should follow the general recommendations provided in 6.3.3.1. Special considerations for top tensioned metal risers are:

a. The rigid riser part of the top tensioned riser should be modeled using finite elements or finite difference methods that consider the coupled effects of tension and bending, thus representing the beam column behavior of the riser. The standard beam column finite element that uses the third degree polynomial for the bending and geometric stiffness matrix usually yields satisfactory results.

b. The top tensioning system must be included in the global riser analysis, thus including the effect of tension and stiffness variation during the riser motion. One way to accomplish this objective is to use a spring element that joins the riser elevation at the tensioning ring location with the elevation of the centralizers' frame. The mass of the tensioning system must also be superimposed onto the mass of the riser.

6.2.5 Steel Catenary Risers (SCRs)

SCR design and analysis is concerned with both the in-place performance and installation of the riser. It has many features in common with flexible riser static and dynamic analysis.

Design information as described in 4.2 should first be developed. When this is available, work can start on static design, which largely sizes the SCR. This is followed by dynamic and fatigue analyses.

6.2.5.1 Initial Sizing and Static Design

6.2.5.1.1 After collecting data and specifying coatings, use spreadsheet or hand calculation methods to select SCR wall thickness 1) to satisfy requirements for burst and collapse, and 2) the desired submerged weight.

6.2.5.1.2 A simple catenary solution can then be efficiently used to estimate top angles and sagbend bending and direct stresses. Although the unstiffened catenary solution can give quite good results, a static finite element model can obviously be used as well.

6.2.5.1.3 Once a candidate geometry has been selected, combined pressure and bending stresses should be used to again check for burst and collapse resistance.

6.2.5.2 VIV Analysis and VIV Suppression Requirements

6.2.5.2.1 Using current profiles appropriate for the site, conduct VIV analysis to determine fatigue life and whether VIV suppression will be needed. If so, select the suppression device and specify its dimensions.

6.2.5.2.2 The VIV modeling program should account for the effects of sheared as well as uniform current profiles and should preferably be calibrated with model test and full-scale data.

6.2.5.2.3 It is important to take into consideration the directionality between a current and the SCR. Since VIV occurs mainly in the cross-flow direction, corresponding structural and current information should be used in the analysis. The SCR's in-plane and out-of-plane motions should both be investigated.

6.2.5.2.4 Careful consideration should be given to the modal information, if a method based on mode superposition is to be used in the VIV analysis. The modal information is typically obtained from either finite-element or other modeling methods:

a. Mode shapes from finite-element programs are usually expressed in the global system. When SCR's out-of-plane motion is studied, these results can be directly used. An SCR's in-plane motion is two-dimensional. The upper portion of the riser vibrates primarily in the horizontal plane. In-plane sagbend motions are primarily vertical. Therefore, an equivalent mode shape sufficiently representing the SCR's in-plane motion should be used since neither the global horizontal nor the global vertical mode shape alone can represent the SCR's overall in-plane motion.

b. If vibration modes excited by VIV are high, SCR's in-plane modal information may also be developed from an equivalent straight beam model. Consideration should be given to the boundary condition at the lower end of the beam (touchdown region) since this should accurately model the effect of the pipeline lying on the seabed.

6.2.5.2.5 Fatigue damage rate due to VIV should be computed for each of the current states specified for the site. Total damage can be obtained by adding the damage caused by each current. When evaluating the critical location along the SCR, careful considerations should be given to the touchdown region, where the pipe tension is low and to the other portions of the riser, where the vortex-shedding is strong. The appropriate factor of safety (see 5.6) should be applied.

6.2.5.2.6 In addition to the study on normal current states (those currents occurring year after year), an extreme current event (such as a 100-year eddy current) should also be evaluated. It is desirable that in such a case the SCR's fatigue life be several times longer than the expected duration of the extreme current event.

6.2.5.2.7 When VIV suppression is required, select the suppression device and specify its dimensions. Possible suppression devices include the helical strakes, fairing, and perforated shrouds.

6.2.5.3 Extreme Response and Strength Analysis

Extreme responses should be computed for comparison with design allowables in Section 5. The primary responses of interest are:

a. Tensions.
b. Stresses.
c. Upper-end rotations.

6.2.5.3.1 SCR Model

Once the question of VIV suppression has been answered, a detailed riser model can be developed for computing static and dynamic responses of the SCR. An SCR finite element model can be created-which includes any VIV suppression devices, upper-end boundary condition definition (for example, flexible joint rotation stiffness) and a pipe/seafloor interaction model. The model must be sufficiently detailed in the critical areas to reasonable stress recovery. A fine-enough mesh must be provided over the expected range of motion of the touchdown point over the static and dynamic excursions of the FPS. Several trials may be necessary to obtain the right mesh.

6.2.5.3.2 Analysis Considerations

To model the seafloor interaction, many programs utilize some form of non-linear or gapping elastic-foundation model for the vertical support: the foundation only provides stiffness and reaction in one direction. Frictional models have been used for axial and lateral element local directions. Such non-linear foundation models can only be run in the time-domain. One approach that can be used in the frequency domain is to compute the static solution for the specified position of the FPS and use the resulting stiffness matrix in a frequency domain solution. Such analyses are likely to be conservative, since further changes in the touchdown point are not permitted. Consideration should be given to exploring the effects of a range of seabed stiffnesses bracketing the expected conditions at the site. Both fatigue damage and maximum stresses in the touchdown region increase with increasing soil stiffness.

It may be necessary to account for velocity modifications caused by the nearby hull structure. This can be accomplished by appropriately increasing drag coefficients in the upper riser model.

Once the riser model has been established, it remains to compute the dynamic responses and extreme values for the specified storm durations (generally 3 hours). This can be done by several methods:

a. Frequency-domain solution for response *rms* and T_z with an extreme factor computed from the Rayleigh distribution.

b. Frequency-domain with extreme factor computed from another distribution based on time-domain results.

c. Time-domain solution using regular waves followed by spectral analysis with Rayleigh-based extreme factor.

d. Time-domain solution using random waves with extreme values computed from a distribution fitted to the time series peaks.

The time-domain approach is generally preferred for extreme conditions while the frequency-domain approach may be adequate for fatigue analysis. Because of the various nonlinearities, assuming that the peaks are Rayleigh distributed is probably not adequate for the touchdown region and is, in any case, an assumption that should be checked.

To find the total responses, the dynamic values are then added to mean values obtained for the FPSs quasi static position.

As indicated in Section 4, it is necessary to calculate responses for a range of conditions. For each extreme wave condition for three headings—near, far, and cross—and in the extreme current for at least one heading (probably the cross). Damaged condition cases, for example partial loss of station-keeping ability, should be formulated if applicable.

After comparing the extremes to allowables, it may be necessary to adjust installed top angle and/or wall thickness and pipe grade to get satisfactory utilizations. Check whether the upper end design is satisfactory, for example, whether the flexible joint rotational stiffness needs to be reduced and/or a tapered section of pipe is needed to control upper portion stresses. This is usually much more challenging for semisubmersibles than for TLPs where the latter's low rotational motions are distinctly beneficial.

6.2.5.4 Fatigue Analysis

SCR fatigue-damage comprises contributions from FPS motion, direct wave loading, and VIV excitation. FPS motion damage can be further split into that due to wave-frequency and slowly-varying motions. The latter translate into potentially large, but less frequent, stress cycles in the sagbend region. The balance between these damage contributions is clearly site dependent. VIV fatigue damage should have already been completed prior to this stage, but it may be necessary to revisit it if substantial changes in the SCR have resulted from the extreme analysis.

6.2.5.4.1 Stress Responses for Fatigue Analysis

a. Wave frequency—In addressing wave-induced fatigue damage, it is first necessary to compute SCR dynamic responses to "mild" or "moderate" conditions. These can be developed in the form of either: a) stress transfer functions or b) stress *rms* and T_z (for each seastate in the wave-scatter diagram) for each fatigue critical location. FPS motions will generally lead to the most critical locations being near the upper end of the SCR or in the touchdown region. Such analyses can be carried out in the time or frequency domains, but the latter may be sufficient if mild conditions govern fatigue.

b. Slowly-varying—FPS surge/sway natural periods range from 50 to 300 seconds or longer, depending on structure type and size. If it can be shown that the SCR does not have significant modes in this range, the stresses can be computed quasi-statically. One procedure involves computing sagbend stress range as a function of FPS offset. A separate analysis computes the *rms* FPS offset due to wave-drift and wind-gust effects for each seastate to be considered. These offsets can then be converted to SCR stress *rms*'s from the relation between stress and offset. Alternatively, if dynamic excitation is involved, then it will be necessary to compute the *rms* stress or transfer function by dynamic analysis.

6.2.5.4.2 Damage Computation

Once stress transfer function information is developed, calculate weld fatigue damage rates for a full set of sea states (wave scatter diagram), for at least three headings, and combine those (in correct proportion relative to the directional distributions) to obtain a weld fatigue life estimate. Parent metal fatigue should also be checked at critical locations with appropriate stress concentration factors at locations where there are transitions in wall thickness or arrestor rings.

Damage computation should be carried out for both wave and low-frequency excitation and the damages, in principal, combined with that from VIV. Achieving this combination remains problematical. Simply adding up separately computed damages based on narrow-banded assumptions appears to be unconservative, while that based on the total *rms* stress, computed assuming narrow bandedness, is overly conservative. A bi-modal approach has been used that is less conservative.[100] Other formulations have been proposed in the literature.

6.2.5.5 Installation Analysis

SCRs can make either a first- or second-end connection to the FPS, although the latter seems to be more commonly considered. In any case analysis should be carried out covering extreme stresses in these various operations. These usually comprise a series of static analysis for the SCR in various positions between the seabed and FPS or lay-vessel.

6.3 HYDRODYNAMIC CONSIDERATIONS

6.3.1 Waves

6.3.1.1 Sea State

6.3.1.1.1 Site specific environmental data should be used for the design and analysis of a marine riser. The environmental conditions should be based on a suitable combination of simultaneous wind, waves, and current profile likely to occur at various headings for a specified return period. In general, the maximum values of wind, wave, and current do not occur simultaneously during a storm (see API RP 2A-LRFD). The return periods for waves and current should be specified. The effect of wind on riser stresses and displacement may be accounted for indirectly through the simulation of wind-induced vessel offset and slow drift movement.

6.3.1.1.2 For a fully developed sea, a common practice is to represent the waves by the two-parameter Pierson-Moskowitz spectrum.[2] For fetch-limited areas where the wave energy is concentrated in a more narrow frequency band, the JONSWAP spectrum should be considered.[4]

6.3.1.1.3 In the calculation of moments of the spectrum, a cutoff frequency three times the spectral peak frequency is recommended. This cutoff will substantially reduce the zero-crossing frequency defined as the square root of the ratio of the second-and zeroth-moments of the spectrum. The results using a cutoff frequency are in closer agreement with time-domain, zero-crossing analyses.

6.3.1.1.4 The joint probability of occurrence of the significant wave height H_s and the mean zero crossing period T_Z (or peak period T_p) is typically presented in a wave scatter diagram. Corresponding to a significant wave height in the scatter diagram, one may identify a number of sea states with different T_Z. Accordingly, a family of wave spectra can be prescribed to determine the effect on riser response due to the variation of T_Z. For riser fatigue analysis, the wave scatter diagram also provides the source information for deriving the total number of wave counts.

6.3.1.2 Wave Spreading

6.3.1.2.1 Riser analysis has usually been conducted based on assuming a unidirectional sea. The effect of directional spreading can be considered as a sensitivity check in the design process. The directional spectrum is given by:

$$S(\omega, \theta) = S(\omega)\, G(\theta) = S(\omega)\, C_n \cos^{2n}(\theta - \theta_o) \quad (13)$$

where

$S(\omega)$ = spectral density function.

θ_o = main direction of the waves, $|\theta - \theta_o| = \frac{\pi}{2}$.

θ = wave spreading angle.

Γ = gamma function.

$$C_n = \frac{\Gamma(n+1)}{\sqrt{\pi}\,\Gamma\left(n+\frac{1}{2}\right)}, \ (n = 0, 1, ...)$$

6.3.1.2.2 The value of n should be chosen in such a way that Equation 13 will best fit the areawise wave data (see API RP 2A).

6.3.1.3 Wave Profile and Kinematics

6.3.1.3.1 The wave profile of a random, 2-dimensional sea can be represented by field measurement data or by means of synthesis of a wave spectrum. A common practice of modeling the wave profile is based on a combination of linear (Airy) waves with random phases:

$$\eta(t) = \sum_{n=1}^{n=N} A_n \cos(k_n x - \omega_n t + \varepsilon_n) \quad (14)$$

where

A_n = wave amplitude, obtained from the wave spectrum, $S(\omega_n)$.

ω_n = discretized frequency.

ε_n = random phase distributed between 0 and 2π.

k_n = wave number associated with frequency ω_n.

N = total number of discretized frequency bands.

6.3.1.3.2 In realistic sea conditions, the wave amplitude as a function of frequency is a random and variable quantity. When attempting to match a target spectrum, each discrete wave amplitude A_n should be generated from a Rayleigh distribution with the expected value of $[2S(\omega_n)\Delta\omega]^{1/2}$ and the corresponding random phase ε_n from a uniform distribution between 0 and 2π.[3] However, normal practice is to use the expected value.

6.3.1.3.3 The wave profile in Equation 14 is consistent with the general approach used to simulate the motions of the FPS. The velocity field induced by the incoming waves Equation 14 is determined by the gradient of the associated velocity potential. The presence of the FPS may lead to local disturbances in the wave field. Such disturbances are caused by wave diffraction and radiation from the vessel. The hydrodynamic forces acting on the vessel are usually obtained by integrating the pressure of the combined wave field.[4]

6.3.1.3.4 The calculation of hydrodynamic forces on a riser is in general based on the kinematics of the incoming waves. Wave kinematics can include contributions from the diffraction and radiation wave potentials induced by the vessel, but non-linear waves can only be handled wave-component by wave-component.

6.3.1.3.5 Nonlinear aspects of steep waves should be considered for calculating the impact velocity on the riser. Technology for modeling the higher-order dispersion of irregular waves in the time-domain includes the use of the third order Stokes wave theory and the Green-Naghdi theory of fluid sheets.[5,6,7]

6.3.1.3.6 In practice the use of linear wave theory is sufficiently accurate in determining the kinematics (velocity and acceleration field) of incoming waves. At the free surface level, simple techniques like the linear (Wheeler) stretching of the Airy potential to the actual wave elevation can be applied (API RP 2A-WSD, "Commentary on Wave Forces").

6.3.1.4 Wave Spectrum Discretization

Since the flexural periods of a riser may be located in the wave frequency range, a sufficiently large number N of the discretized wave frequencies should be used to generate sufficient wave energy at and around the resonant frequencies.

6.3.1.5 Wave Directionality

The effect of multi-directional waves should be accounted for during the fatigue analysis of a riser. The operational wave conditions should be specified on an annual basis in which the probability of occurrence of the significant wave height is distributed at various headings. Riser clearance should be determined by the most severe condition for each sector.

6.3.1.6 Regular Waves

A traditional approach for designing a shallow water riser is based on regular waves. The wave height is normally set equal to the maximum height of the design sea state. The types of wave profile to be chosen may range from Airy waves to higher order Stoke's waves. Such an approach is valid if the riser response to the sea state is quasi-static. More sophisticated analytical techniques such as spectral analysis in the frequency-domain or time-domain simulation with irregular waves should be considered if the natural periods of the riser are within the frequency range of the wave spectrum. This is usually the case with deepwater risers.

6.3.2 Current

6.3.2.1 For a specified sea state, the associated current velocity profile should be used in the riser analysis. In some areas, the current may include contributions from areawise phenomena such as loop/eddy current and solitons, tide and circulation of ocean currents.[8,9] In general, wind generated current is found in the top layer of the ocean. It can be represented by a shear or slab profile; whereas the loop/eddy current and solitons penetrate deeply in the water column. The corresponding velocity profile does not change rapidly with time. Because of this, the velocity profile may be treated as time invariant for each seastate in riser analysis. Some current profiles are shown in Figure 33.

6.3.2.2 In time-domain analysis, current profiles should be stretched to the free surface using one of the approaches given in API RP 2A.

6.3.3 Loading Types and Flow Conditions

Hydrodynamic forces on risers can be classified by three basic categories:

a. Inertia forces due to the acceleration of the fluid and/or the riser body.

b. Forces induced by flow separation and vortex formation.

c. Skin friction on the surface of the riser. (Forces in this category are of a higher order. In general, they are combined with the drag force in category b.)

Force vectors in category b can be decomposed into two components, a drag force in line with the incident flow vector and a lift force orthogonal to the incident flow. The drag or lift force may be further expressed by two terms. One represents the component which is a function of the square of incident flow velocity, and the other represents the resultant of pressure fluctuation due to vortex shedding. These two terms represent the loadings in two different frequency ranges.

A brief summary of the flow conditions is given in the following:

6.3.3.1 Oscillatory Flow Due To Waves and Vessel Motions

6.3.3.1.1 Condition 1: Stationary Vertical Riser In Waves

This flow condition is characterized by unsteady flow in the wave field. The fluid particles follow cyclic orbital movements that decay exponentially with depth. The flow surrounding the riser is three dimensional. Since the wake reverses its position relative to the riser in each motion cycle, continuous vortex shedding at a nominal frequency is unlikely but possible. Accordingly, the fluctuating lift and drag forces induced by vortex shedding are often ignored in common practice, unless there is potential for lock-on. Referring to the definition in the nomenclature located at the end of Section 6, the fluid force per unit length is defined by the following two components:

$$\text{Initial Force} \quad F_I = C_M \rho A \frac{\partial u}{\partial} \tag{15}$$

$$\text{Drag Force} \quad \text{FD} = \frac{1}{2} C_D \rho D |u| u \tag{16}$$

Since the flow incident to the riser may be contaminated by the reversal of the wake from the previous motion cycles, the fluid forces may demonstrate a hysteretic phenomenon. Scattered data is anticipated in model test experiments and field measurements if the inertia and drag coefficients are computed on a wave-by-wave basis. In this regard, it is appropriate to determine the inertia and drag coefficients based on the least-squared fit of the whole force measurement record.[10,11]

The coefficients C_d and C_M are governed by the geometry of the riser cross section, the Keulegan-Carpenter number, KC, the Reynolds number, Re.12, and the surface roughness. Typically, the value of C_M is in the range of 1.5 to 2.0 for a smooth circular cylinder. The value of C_d in the post-critical steady-state is about 0.6 to 0.7.

6.3.3.1.2 Condition 2: Riser Oscillating In Calm Water

The oscillatory flexural displacement of the riser can be extended well below the wave zone where the orbital movements of the water particles cease to exist. Under this condition, the flow condition is nearly two dimensional. The inertia force exerted by the fluid is 180 degrees out of phase and linearly proportional to the body acceleration. The corresponding constant has a dimension of mass and is known as the added mass of the fluid. The drag force is due to the dissipation of kinetic energy of the fluid motion in the wake and therefore can be treated as the damping force. The added mass and drag coefficient are defined by the following:

$$\text{Added Mass Force} = C_a \rho A \ddot{x} \tag{17}$$

$$\text{Viscous Damping Forces} = \frac{1}{2} C_d \rho D |\dot{x}| \dot{x} \tag{18}$$

where $\dot{x}$ and $\ddot{x}$ are the velocity and acceleration of the riser.

The values of C_a and C_d are governed by two dimensionless parameters, namely Re and KC, and the surface roughness. The value of C_a for a smooth circular cylinder tends to approach the theoretical value of 1.0 if the motion amplitude is less than one diameter. The magnitude of damping is determined by the loss of fluid momentum due mainly to flow separation and vortex formation. The corresponding flow condition is sensitive to the surface roughness. For large amplitude motion, the hydrodynamic forces may experience hysteretic effects due to the reversal of the wake in each motion cycle.[13]

6.3.3.1.3 Condition 3: Riser Oscillating In Waves

In this case, the riser oscillation may be caused by the excitation of the waves and/or the movement transmitted from the surface vessel through the upper riser termination. The hydrodynamic loading function may be expressed in terms of a pressure force acting on the volume occupied by the riser, an added mass force due to the perturbation of the flow field by the motions of the riser and a drag force proportional to the square of the relative velocity of the riser and the incident flow. The velocity field of the ambient flow is typically expressed in a global coordinate system. Referring to the Eulerian frame of reference, the acceleration of the ambient flow is given by:

$$\frac{DV}{Dt} = \frac{\partial V}{\partial t} + (V \cdot \nabla)V \tag{19}$$

where DV/Dt denotes the material derivatives of the velocity vector $V(x_1, x_2, x_3, t)$ and ∇ denotes the gradient differential operator.

The leading order term $\partial V/\partial t$ represents the acceleration of the unsteady flow evaluated at a fixed point in the flow field. The convective acceleration term $(V \cdot \nabla)V$, which produces the second harmonics of the pressure force, is due to the non-uniformity of the wave particle motions. In order to calculate the hydrodynamic forces in terms of local coordinates, the transformation of the incident flow velocity and its derivatives requires the information of the instantaneous position and direction cosines of the riser's longitudinal axis.

Introducing the velocity components (u, v, w) of the incident flow in the body-fixed local coordinate system (x, y, z) as shown in Figure 34, a higher-order convective term due to the interaction of the riser's rotational motions and the tangential velocity component (w) of the incident flow can be expressed[14] as $(u - \dot{x})\,\partial w/\partial z - w\,\partial \dot{x}/\partial z$. This high order term is often omitted in riser analysis because its magnitude is within the error bound of the leading order term $C_a \rho A \ddot{x}$. Thus, unless a higher degree of accuracy is provided for the added mass coefficient C_a, the overall accuracy of the hydrodynamic forces may not be improved by including this term in the computation.

In general, the diameter of a riser is small in comparison with the displacement of wave particle motions, and it suffices to evaluate the pressure force based on the acceleration of the incident flow at the longitudinal axis of the riser. Care must be taken if the riser diameter is large enough such that Du/Dt can no longer be treated as a constant over the riser cross section. Under this condition, Du/Dt should be taken as an averaged value over the cross section, at each time step.

Within the context of viscous fluid flow, the perturbation pressure force due to the presence of a stationary cylinder in waves is in general not equal to the added mass force of an oscillating cylinder in calm water; even though the respective KC numbers are identical. Except for the following two limiting cases, the principle of flow superposition is not applicable for evaluating the fluid forces.

Case 1: At low KC number (KC < 5 or the relative displacement less than one), the fluid motion can be described by potential flow. The classical solution indicates that the perturbation term of a stationary cylinder is equal to the added mass term of an oscillating cylinder.

Case 2: At high KC number (KC > 90, or the relative displacement greater than 15), the flow condition reaches post-critical steady-state. The fluid forces would be practically the same regardless whether the body or the fluid is moving.

For these two limiting cases, it is valid to set $C_a = C_M - 1$ and the inertia and added mass terms become $\rho A D_u/Dt + (C_M - 1)\rho A(Du/Dt - \ddot{x})$, in which the coefficient C_M can be referred to the value for a stationary cylinder.

For the intermediate KC numbers, it is appropriate to express the inertia and added mass terms in the following form: $C_M \rho A Du/Dt - C_a \rho A \ddot{x}$, where the coefficients C_M and C_a are to be obtained in conjunction with the variation of four independent parameters: 1) the phase angle between $\dot{x}$ and u,

2) the motion amplitude (A_x/D), 3) the KC number based on the maximum wave particle velocity normal to the riser axis (u_{max} T/D), 4) the ratio of Re to KC numbers ($Re/KC \equiv b$). In other words, the fluid forces are determined by the history of the relative motions between the fluid and the riser. Until such a data base for the relative motions of a cylinder in waves is developed, the value of C_M, C_a, and C_d may be determined by linear interpolation of the coefficients as obtained for the two limiting cases. See Table 4. Note that this will result in $C_a = C_M - 1$ for all KCs. The KC number to be used for interpolation should be based on the maximum relative velocity and T_p. Such a crude approximation would not lead to significant error for the total loading of a drag dominant flow regime at high KC number.

The actual added mass and drag coefficients may change from one cycle to another in a random sea because of the rapid change of the flow field. The use of time invariant C_M, C_a, and C_d to close-fit a force measurement record leads to the filtration of the time-varying components in these coefficients. As an engineering approximation, this approach preserves only the leading order quantities of the hydrodynamic loads. In random waves, the vortex induced lift forces are less significant than those measured under two-dimensional sinusoidal flow conditions, and they are not correlated along the riser length. Because of this nature, these forces are neglected in riser analysis.

6.3.3.2 Non-oscillatory Incident Flow

The subject is concerned with the hydrodynamic forces due to flow separation over the cross section of the riser. Since the incident flow is non-oscillatory, the position of the wake is not reversible to the up-stream side of the riser. The characteristics of the flow may be classified by four different regimes corresponding to the subcritical, critical, supercritical and transcritical Re.[15,16] Boundary layer and flow separation theory provide the background regarding the relationship between the flow field and the hydrodynamic forces.[17] Some factors which may affect the hydrodynamic loads are addressed in the following.

6.3.3.2.1 Static Load

Figure 35 shows the drag coefficient of a stationary smooth circular cylinder in four flow regimes as a function of the Re. The occurrence of drag force is a result of pressure deficit at the downstream side of the riser cross section. In subcritical Re flow, the drag coefficient is in the range of 1.0 to 1.2. Scattered data had been found in the supercritical flow regime in which the flow field and pressure fluctuation are sensitive to small external disturbance. Accordingly, a conservative approach should be taken to estimate the drag force by using the upper bound value of C_d. In the critical flow regime, transition of boundary layer may occur on only one side of the riser cross section. The corresponding asymmetric flow pattern is accompanied with a sizable steady lift force.[15] Outside the critical

Table 4—Hydrodynamic Coefficients for a Circular Cylinder at High and Low KC Numbers

	Smooth			Rough (k/D = 0.02)		
	C_M	C_a	C_d	C_M	C_a	C_d
Case (1) KC < 5	2.0	1.0	0.9	2.0	1.0	1.5
Case (2) KC > 90	1.5	0.5	0.7	1.3	0.3	1.1

Note:
Data is derived from [13].

flow regime, the steady lift force is less significant, and therefore it is often neglected in riser analysis.

6.3.3.2.2 Equivalent Static Load

The slow drift movement of the surface vessel can induce a quasi-steady current load on the attached riser. For time-domain simulation, the vessel slow drift movement should be prescribed as the boundary condition at the attachment point of the riser. For frequency-domain simulation, however, the effect of slow drift movement is approximated by an equivalent static current load on the riser. If a background current is also included in the frequency domain simulation, the combined static load should be computed based on the superposition of velocity vectors of the current and slow drift movement at the mean position of the riser.

6.3.3.2.3 Vortex Induced Fluctuating Loads

In the subcritical flow regime, the vortex induced hydrodynamic forces are concentrated in a narrow bandwidth of frequency. The dominant vortex shedding frequency is represented by the Strouhal number (St) which is in the range of 0.18 to 0.2. The phenomenon of alternate shedding of vortices over the cross section of the riser, leads to the coupled dynamic lift and drag forces. One cycle of lift oscillation corresponds to two cycles of drag. The probability density of the lift fluctuation should be approximated by a Gaussian distribution.[19] The coefficients for the mean and fluctuating lift and drag forces are defined by the following relationship:

$$C_d = \frac{F_D}{\frac{1}{2}\rho D U_n^2} \tag{20}$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho D U_n^2} \tag{21}$$

$$C_d' = \frac{\sigma(F_D)}{\frac{1}{2}\rho D U_n^2} \tag{22}$$

$$C_L' = \frac{\sigma(F_L)}{\frac{1}{2}\rho D U_n^2} \quad (23)$$

In some references, the standard deviation σ() is represented by the root-mean-square value.[20] The variations of C_L and C_d for a smooth stationary circular cylinder are reproduced in Figure 36.

In the critical flow regime, vortex shedding is dominant on one side of the riser cross section. The wake is less organized after the occurrence of boundary layer transition. Scattered values for the Strouhal number (see 6.9) were found in the range of 0.2 to 0.45.[21]

In supercritical Re flow, the fluctuation of pressure is stochastic in nature. The characteristics of the near wake is strongly dependent on the turbulent intensity in the boundary layer. For a smooth circular cylinder, the wake is disorganized but not fully mixed with turbulence. The spectra of the lift and drag fluctuation may demonstrate multiple distinct energy bands. Because of this nature, the lift and drag should not be characterized by a single frequency.

In the high end of the supercritical flow regime, the boundary layer would have gone through another stage of transition.[19] It is believed that a hysteresis process may exist in this flow regime. After this flow regime, the phenomenon of regular vortex shedding reappears in the turbulent wake.[15]

6.3.3.2.3.1 Spanwise Correlation

The correlation of vortex formation in the spanwise (i.e., axial) direction is an important factor contributing to the low frequency component of the hydrodynamic forces. For the time being, the subject remains a research topic. Observed data suggests that the spatial-temporal perturbation of the excitation forces would lead to the modulation of amplitude and frequency (i.e., beats) for the lift forces over a finite segment of a cylinder.[19] The coupled drag force consists of both a low frequency component corresponding to the beat frequency of the lift force and a high frequency component corresponding to the vortex excitation.

6.3.3.2.3.2 Effect of Riser Oscillation

The oscillation of the riser has a tendency to change the characteristics of the surrounding flow. The spanwise correlation of vortex formation can be enhanced due to small amplitude transverse oscillation of the riser. The phenomenon of vortex formation in the near wake, as well as the added mass and damping coefficients of the riser cross section, are governed by three dimensionless parameters including the amplitude ratio (A_y/D), the reduced velocity (U_n/fD), and Re.[22] When the vortex shedding period is close to one of the flexural bending periods of the riser, the lock-on condition is likely to occur. Under this condition, the dynamic equilibrium can be described by a closed feedback loop in which the hydrodynamic excitation, added mass and damping are dependent on the response amplitude of the riser. The oscillating amplitude tends to be self-limiting as a consequence of the dynamic interplay of the fluid-structure interaction. The vortex shedding frequency is locked onto the nearest modal frequency of the riser. Corresponding to a non-uniform current profile, the vortex shedding frequency is not a constant along the riser. Accordingly, the lock-on phenomenon may not occur on the whole length of the riser. Outside the lock-on region, the oscillatory drag forces contribute to the viscous damping.

The interaction of the riser oscillation and the near wake is imposed implicitly in the added mass and damping coefficients. It should be pointed out that the value of the added mass and damping coefficients for in-line and transverse oscillations may not be identical due to the asymmetry of the flow pattern. Furthermore, the transverse oscillation of the riser can also change the mean drag forces. For the lock-on condition, the augmentation of the mean in-line drag is in the range of 1.0 to 3.0 times or even higher in some cases in comparison with a stationary cylinder.[23] The mean in-line drag coefficient of an oscillating cylinder should be deduced in conjunction with either measurements or numerical simulation of the hydrodynamic forces.

6.3.3.2.4 Vortex Induced Loads On Flexible Risers

The effects of vortex-induced vibration on flexible risers should be checked in a particular case. See API RP 17B for further explanation.

6.3.3.3 Superposition of Waves and Currents

The design events of a riser may include the presence of waves and current. Under the extreme wave condition, the flow condition should be classified as oscillatory flow (i.e., $u_{max}/U_n > 1$). The effect of the associated current is represented by the mean drag and augmentation of viscous damping. The kinematics of the incident flow should be modeled based on superposition of velocities of waves, current and riser motions. In the event that the direction of the incoming waves is not co-planar with the current or a directional sea state is prescribed, the flow field as well as the global response of the riser are three dimensional.

In some areas such as the Gulf of Mexico, the east coast of continents or the outlet of major rivers (where strong currents may occur without the presence of an extreme storm) or in areas such as the Andaman and South China seas (where internal waves i.e., solitons have been observed during the operating condition) the design events may include a strong current profile superimposed with a moderate sea state. Under this condition, the current is the dominant factor for the riser response. The effect of waves and vessel motions should be regarded as a perturbation of the flow velocity.

6.3.3.4 Hydrodynamic Interaction of Dual or Multiple Risers

6.3.3.4.1 Dual Risers

This subject is concerned with the behavior of a trailing riser in the wake of a leading riser. Measured data suggests that if the spacing of the risers is too close, adverse effects due to a suction force may be developed between the risers, thereby increasing the possibility of physical contact of the two risers. In common practice, the mean clearance between two risers is determined by the interference coefficients C_{d1}, C_{d2}, C_{L1}, C_{L2}, where the subscripts 1 and 2 denote the leading and trailing risers respectively. For two equal size cylinders arranged in tandem, these coefficients are given as a function of the longitudinal and transverse spacings.[24,25] For unequal size cylinders, the diameter ratio of the two cylinders is another important parameter for the interference coefficients.[26,27] In general, the lift and drag coefficients for the trailing cylinder are less sensitive with respect to the change of the Re. The interference boundary is determined by the characteristics of the near wake of the leading riser. If the diameter of the leading riser is equal to or greater than the trailing riser, the surface roughness of the leading riser is the dominant parameter which dictates the characteristics of the near wake.

The fluctuation pressure in the wake of the leading cylinder may lead to hydroelastic instability such as galloping on the trailing riser.[28,29] In order to address this problem properly, a thorough understanding of the wake flow is considered essential. The fluctuation force on the trailing riser is dependent on the variation of the following parameters:

a. Longitudinal and transverse spacings (X/D_1, Y/D_1).

b. Diameter ratio (D_1/D_2).

c. Transverse oscillation amplitude of the leading cylinder (A_y/D_1).

d. Surface roughness of the leading cylinder (k/D_1).

e. Re of the cross flow ($U_n D_1/n$).

6.3.3.4.2 Multiple Risers

Wake synchronization within a riser array can be a design issue.[30,31,32] In this case, the dynamics of the risers are coupled with the wake flow within the boundary of the array. The general practice for riser system design is to avoid the wake-induced instability problem by properly choosing the riser spacing.

6.3.4 Load Model

For the flow conditions addressed in 6.3.3.1, the general practice for modeling the hydrodynamic forces is based on the Morison formula. The formula was originally derived for calculating the hydrodynamic forces on shallow water fixed piles.[33] Since the introduction of this formula, the offshore industry has extended its applicability to moveable structures, including risers. A modified form of the Morison formula is given by:

$$F = C_M \rho A \frac{\partial u}{\partial t} - C_a \rho A + \frac{1}{2} \rho C_d D \left| (u + U_n - \dot{x}) \right| (u + U_n - \dot{x}) \quad (24)$$

The above formula is based on the following implicit assumptions:

a. For the inertia force term, the diameter of the riser is small in comparison with the displacement of the relative motion between the fluid flow and the riser. The acceleration of the fluid flow is evaluated at the centerline of the riser. The higher order convective acceleration terms are neglected.

b. The inertia, added mass, and drag coefficients are time invariant. The time dependency of the hydrodynamic forces is modeled by unsteadiness of the incident flow and the body motion. The fluctuating lift and drag forces due to vortex shedding are neglected.

c. The hydrodynamic forces are determined by the acceleration and velocity components normal to the riser centerline. The three dimensional effect due to the tangential component of the incident flow is ignored.

d. The riser response is inline with the incident flow. The lift force is omitted.

A more precise definition of the inertia force can be made based on a Eulerian frame of reference by re-placing the 'u/'t term in Equation 24 with 'u/'t + u 'u/'x. However, if the hydrodynamic inertia force is evaluated by a coordinate system which moves with the riser, the 'u/'t term should be replaced by 'u/'t + ($u - \dot{x}$) 'u/'x.

Derivation of higher order terms for the loading function is available in the literature.[14,34,35] Since the Morison formula can be expressed in different forms, each form is associated with a set of coefficients for a specific flow condition. To maintain the accuracy of hydrodynamic loads, the Morison formula to be used in computer simulation must be consistent with that used for defining the hydrodynamic coefficients.

6.3.4.1 Equivalent Linearization

In frequency domain simulation, the drag and damping term in Equation 24 can be linearized to facilitate computation.[36,37,38,98] With the presence of waves, currents, and riser motions, the linearized drag and damping forces are expressed at the mean equilibrium position by the following formula:

$$F_D = C_1(C_2 C_3 + 2U_n C_4)(u - \dot{x}) + C_1 G(\sigma, U_n) \quad (25)$$

where

$$C_1 = C_d \rho D$$

$$C_2 = \sqrt{\frac{2}{\pi}}\sigma$$

$$C_3 = \exp[-{}^1/_2(Un/\sigma)^2]$$

$$C_4 = erf(U_n/\sigma)$$

$$G(\sigma, U_n) = [\sqrt{\frac{1}{2\pi}}\sigma\,\sigma U_n C_3 + C_4(\sigma^2 + U_n^2)]$$

$$erf(\xi) = (2\pi)^{-1/2}\oint_0^{\xi} \exp(-{}^1/_2\gamma^2)\,d\gamma$$

Without the presence of the current U_n, Equation 25 is reduced to the following form:

$$F_D = {}^1/_2\, C_d \rho D \sqrt{\frac{8}{\pi}}\,\sigma \bullet (u - \dot{x}) \tag{26}$$

Note that the unknown $\dot{x}$ is imbedded in the standard deviation of the relative velocity σ. In spectral analysis, the transfer functions of the riser response, x, are to be obtained through an iterative procedure.

The linearized drag force in Equation 26 can be expressed in the following form if the excitation is caused by a single sinusoidal wave train:

$$F_D = {}^1/_2\, C_d \rho D \frac{8}{3\pi}\left|u_o - i\omega x_o e^{i\tau}\right|(u - \dot{x}) \tag{27}$$

where τ denotes the phase angle between $\dot{x}$ and $u(t)$, x_o, and u_o being the amplitude of x and u, respectively.

For the flow conditions addressed in 6.3.3.2, there are three basic conditions to be considered:

6.3.4.2 Calculate the Static Deflection of the Riser

In this case, only the steady drag due to the U_n^2 term is left in Equation 24. The drag coefficient should be prescribed as a function of Re. When the riser axis is inclined in space but coplanar with the incident current, the normal and tangential drag forces per unit length can be estimated by the following formulas:

$$F_n = {}^1/_2\rho\, C_{dn}\, D\, U_\infty^2 \tag{28}$$

$$F_t = {}^1/_2\rho\, C_{dt}\, D\, U_\infty^2 \tag{29}$$

where C_{dn} and C_{dt} are the normal and tangential force coefficient, respectively, and U_∞ is the free stream current velocity.

The coefficients C_{dn} and C_{dt} can be expressed as a function of the riser inclination angle α, as follows:[39]

$$C_{dn} = C_d \sin^2\alpha \tag{30}$$

$$C_{dt} = C_d(0.03 + 0.055\sin\alpha)\cos\alpha \tag{31}$$

In case the riser axis is not coplanar with the current, the riser inclination angle a should be determined by the dot product of the unit vectors z and l, where l defines the direction of the current in the global coordinate system [i.e., $\alpha = \cos^{-1}(z \bullet l)$]. The direction of the normal drag force is defined by the resultant velocity on the x-y plane of the local coordinate system.

6.3.4.3 Calculate the Hydrodynamic Forces Outside the Lock-on Region of the Riser

In this case, the wave particle velocity u vanished in Equation 24. The coefficients C_a and C_d associated with the transverse oscillation, however, should be determined based on the guideline as described in 6.3.3.2. There is an ongoing effort in the industry to study the nonlinear interaction of hydrodynamic loads resulting from the mixed mode oscillation of a riser. As long as small amplitude motion is concerned, the nonlinear modal interaction is assumed to be weak, and the associated modal damping can be approximated by means of linearization. Semi-empirical riser codes are available for calculating riser forces and responses.

6.3.4.4 Calculate the Vortex Induced Forces in the Lock-on Region of the Riser

For the time being, there is no universally accepted method for solving this problem. Methods available in the public domain include: 1) simulate the lift force by a wake oscillator and express the lift coefficient as a function of the riser mode shapes,[40,41,42,43,44] and 2) simulate the vortex induced forces based on random excitation.[45] The applicability of these methods to riser design has not been fully established. Emerging technology for calculating the vortex induced lift and drag forces is based on numerical simulation of flow separation and vortex formation. Various methods were published for simulating the flow over two dimensional blunt bodies.[46,47,48,49,50] The in-line and transverse components of the fluid forces are generally presented in time series. The validity of those solutions may depend on the numerical accuracy of the codes and how the physics of various flow regimes are being modeled. Prior to the application of this technology to riser analysis, validation of computer code with measured data is recommended.

6.3.5 Conditions That Affect Hydrodynamic Loads

6.3.5.1 Free Stream Turbulence

6.3.5.1.1 The effect of free stream turbulence should be identified for the design events which are dominated by strong current. The presence of turbulent cross flow can induce early transition of the boundary layer at a lower Re and a substantial reduction in spanwise correlation of vortex induced loadings.[51,52,53] At pre-transition Re, free stream turbulence has little or no effect on the hydrodynamic forces and the Strouhal frequency. After the transition, high frequency components in the fluctuating lift and drag become more pronounced in comparison with the case of uniform incident flow. This phenomenon of high-frequency random fluctuation is called buffeting.[54]

6.3.5.1.2 The Re at which the transition of boundary layer begins to occur is determined by the following empirical formula:[52]

$$T_y \, \mathrm{Re}^{1.34} = 1.72 \times 10^5 \qquad (32)$$

where

$T_y = (\hat{u}/U_\infty)(D/L_y)^{1/5}$ denotes the Taylor number.

6.3.5.1.3 The above formula is valid for $3.4 \times 10^4 < \mathrm{Re} < 1.5 \times 10^5$. The net reduction of Re resulting from the effect of free stream turbulence dictates how far the original C_d-versus-Re curve should be shifted to the left.

6.3.5.1.4 For the purpose of riser analysis, it is appropriate to set the free stream turbulence intensity $\hat{u}/U_\infty$ in the range of 0.01 to 0.03. The fine structure in a Gulf Stream Ring was found to have a length scale ranging from centimeters to meters.[55] The loop and eddy current are expected to have similar characteristics. To evaluate the effect of free stream turbulence, the lower limit of Re should be set equal to 3.4×10^4.

6.3.5.2 Surface Roughness

6.3.5.2.1 Long-term exposure of a marine riser in the ocean environment can lead to deterioration of the surface smoothness.

6.3.5.2.2 Surface roughness is defined by the dimensionless parameter k/D, where k denotes the average height of the roughened surface and D the outer diameter of a bare cylinder. For a lightly roughened cylinder (e.g., $k/D < 0.02$), the effect of surface roughness is to induce early transition of the boundary layer. The drag coefficient is in the range of 0.7 to 1.0 after the transition, depending on the roughness. The critical Re (at which the C_d reaches the minimum value) may be determined by the following empirical formula:[56]

$$\mathrm{Re} = 6000/(k/D)^{1/2} \qquad (33)$$

6.3.5.2.3 Beyond the critical Re, the angle of boundary layer separation tends to decrease with the increase of surface roughness. However, due to the increase of the turbulent intensity in the boundary layer and the near wake, the spectral amplitude of the fluctuating lift force decreases with the increase of the surface roughness.[57]

6.3.5.2.4 When the surface roughness protrudes outside the boundary layer, a disruption of the flow pattern is likely to occur. In this case, transition to turbulent boundary layer would occur upstream near the stagnation point, and the flow field demonstrates post critical phenomenon. The C_d curve is nearly flat, and its dependency on the Re is insignificant. A brief summary of this subject is given in 6.3.5.3.

6.3.5.3 Marine Growth

6.3.5.3.1 Marine growth includes barnacles, mussels, hydroids, chama, kelps, anemones, and many other organisms. They are found in the top layer of the ocean where sun light penetrates. The distribution of marine growth is dependent on site specific factors including current, water temperature, nutrients, etc. For the purpose of riser analysis, it is reasonable to assume that marine growths extend from the splash zone downward to a depth determined by the location. In general, marine growth is concentrated near the sea surface.

6.3.5.3.2 To evaluate the loading effect due to marine growths, the following parameters are required:

a. The average thickness and specific gravity of the growth. Note that it does not take a lot of growth to change the surface condition from smooth to very rough. The thickness of the growth is dependent on the time exposure between each riser cleaning cycle. The specific gravity of the growth is in the range of 1.0 to 1.4 depending on the type of organism.

b. The attached mass and the effective hydrodynamic diameter of the riser. In practice, these parameters can be derived from (a). The hydrodynamic inertia, added mass, drag, and damping forces should be evaluated based on the effective diameter.

c. Hydrodynamic coefficients obtained from model tests or field measurements. Limited field measurement data for very rough tubulars reveals that C_d and C_M approached the respective value of 1.1 and 1.3 at high Kc.[58,59,60,61]

6.3.5.3.3 The state of practice for riser analysis does not include the simulation of fluctuating lift and drag due to marine growths. In the very rough state, the turbulent intensity in the flow surrounding the riser is high, and secondary vortices may be formed behind local sharp edges. The near wake would demonstrate a high level of turbulent mixing, and its spectral density is wide-banded. In general, the effects of marine growth are detrimental because of the augmentation of the hydrodynamic loads and the attached weight of the organisms. This design disadvantage translates to higher riser stresses, shorter fatigue life and higher riser top tension requirements.

6.3.5.4 Effect of Appendages

6.3.5.4.1 Satellite Lines

Appendages such as choke and kill lines, hydraulic lines, and a mud booster line can be found on the circumference of a bare drilling riser joint. These lines are not arranged in 90 degree spacing for a typical design (see Figure 37). The presence of these satellite lines on a bare riser joint can induce significant changes for the hydrodynamic coefficients. Moreover, these coefficients are sensitive with respect to the orientation of the incident flow. At certain orientations, the flow field is asymmetric, and a significant mean lift force can be observed. In practice, these coefficients are obtained by means of model testing at full scale Re. Public disclosure of this information is rare. Available data indicates that the total drag force on the riser joint is not equal to the sum of the member forces which are computed without considering the hydrodynamic interference. To estimate the maximum drag force on the riser, an equivalent pipe model which shares the same C_d of a slightly roughened cylinder can be used. The equivalent diameter should be taken as the pitch diameter as shown in Figure 37. If the reference diameter is not based on the pitch diameter, the value of C_d should be adjusted so that the drag force of the riser remains unchanged.

For a high pressure drilling riser which is designed to operate with a surface BOP, only one optional hydraulic line may be needed to provide the control function of the bottom connector. The presence of this satellite line on the circumference of a bare riser would lead to asymmetrical flow conditions, except for two orientations at which the satellite line and the riser are lined up in the same direction with the incident flow.

The steady lift force induced by the asymmetric flow field is given by:

$$F_L = {}^1\!/_2\, \rho\, C_L\, D\, (u + U_n - \dot{x})^2 \tag{34}$$

in which the lift coefficient C_L should be determined by model testing or numerical simulation of the flow field. The sign of the lift force is imbedded in C_L.

6.3.5.4.2 Local Irregularities

Due to the presence of the riser connectors, the continuity of the riser cross section is interrupted from one joint to another. For threaded connectors, the increase of hydrodynamic forces can be accounted for by using the actual diameter. For bolted connectors, however, the local added mass and damping forces should be accounted for by modifying the hydrodynamic coefficients. These coefficients are dependent on the geometry of the connector and therefore can only be obtained through model testing. Similar treatment is applicable for estimating the fluid forces induced by anodes. In general, the effects of local irregularities are not among the primary factors which govern the global response of a riser. Because of this nature, they can be neglected during the feasibility or concept development stage of the design.

6.3.5.5 Wave Kinematics

This subject is concerned with computing wave particle velocities for design seastate conditions. Based on small perturbation theory, the domain of definition for the wave velocity potential is confined by the mean equilibrium (undisturbed) water surface. In order to extrapolate the wave particle velocity from the mean water line to the wave profile, a number of stretching techniques are available.[62,63,64] It should be pointed out that except for shallow water application, the riser response is in general not sensitive to the choice of a specific stretching technique. Crest kinematics in near breaking waves may be important for local bending in some riser configurations. In this case, either model tests or non-linear finite amplitude kinematic models can be used to determine the riser response.

6.3.5.6 Wave Amplification

Due to the presence of surface piercing columns of a TLP or a semisubmersible platform, wave interference between the columns may lead to noticeable amplification at discrete frequencies. The local wave field between the columns consists of both propagating waves and standing waves. In general, the wave amplification transfer function can be obtained by model tests or numerical simulation. The three dimensional wave profile together with the wave particle velocity can be derived based on the superposition of the incoming waves, the diffracted waves and the waves generated by the vessel motions.[65]

In order to determine whether the effect of wave amplification should be included in the design sea state, the wave amplification transfer function must be established in advance. If the peak period of the transfer function is in the feasible range of the wave spectral peak period, it should be demonstrated that the design condition does include the additional wave forces due to wave amplification. Otherwise, this phenomenon can be ignored in the design process.

6.3.5.7 Vortex Suppression Devices

Vortex suppression can be achieved based on the following two basic principles: 1) modification of the flow field by minimizing the strength of the vortices and 2) disruption of the spanwise correlation of the vortex formation. Since the fluctuating lift and drag are coupled, a suppression of one component may lead to the same effect for another. On the other hand, a disruption of the spanwise coherence may in-crease the three dimensionality of flow separation, thereby allowing a partial cancellation of the exciting forces over a finite segment of the riser. For a specific design, the effectiveness of the vortex suppression device should be demonstrated by means of credible testing.

There are a number of vortex suppression devices described in the public domain.[66,67] Among them, the following three concepts have been used for prototype deployment.

6.3.5.7.1 Wake Fairing

This concept includes various configurations ranging from hydrofoil section, splitter plate, and flag-type tail fairing. The main function of these devices is to delay the flow separation and minimize the strength of the vortices. The mean drag is also minimized as a result of modifying the flow field. One design requirement of this concept is that the fairing must be free to rotate about the axis of the riser. If the fairing is not free to rotate, dynamic instability may occur on the riser due to the unsteady lift forces on the fairing.

6.3.5.7.2 Helical Strake

The main function of a helical strake is to alter the flow separation characteristics over the cross section of the riser as well as in the spanwise direction. Its effectiveness is dependent on the pitch length of the winding and the projected height of the strake.[68] Despite the suppression of the vortex induced fluctuating lift and drag, a helical strake can also lead to a significant increase of the mean drag as well as the C_d and C_a as defined in the Morison formula.

6.3.5.7.3 Alternate Buoyancy Joints

On a riser which is designed to use syntactic foam modules or air cans for tensioning, one practical way to minimize the vortex induced vibrations is to arrange the buoyancy and bare riser joints in an alternate manner. Since the flow separation characteristics are entirely different over the bare riser joint and the joint with buoyancy material, the lock-on condition may only occur on either type of joints. The joints which do not encounter the lock-on condition provide the damping required for minimizing the vortex induced vibrations. In practice, the alternate joint arrangement is applied on the riser where strong current is expected to occur.[69]

6.3.6 Model Testing

Accuracy of results of analysis for risers subjected to wave and current forces depends upon correctness of the estimation of the hydrodynamic parameters, i.e., drag, inertia, and lift coefficients. For tubular members, these parameters are well established from previous research. However, in certain situations (e.g., when risers have appendages attached to them) such as external buoyancy and weight elements, choke and kill lines, or when a group of risers are in close proximity to each other, determination of hydrodynamic coefficients may require model testing. Both wind tunnels and wave basins or flumes can be used for the purpose, but the tests must be carefully planned to ensure that the appropriate Re are reached. Wind tunnels can reach far higher Re than the best wave basins can. However, even the best wind tunnel tests cannot predict the effect of VIV on drag forces.

The hydrodynamic parameters are affected in a complex way by Re, KC, surface roughness, steady or oscillating flow pattern, member inclination, etc. Each of these factors have to be carefully studied before planning for a model testing program.

Interference effects between a group of risers may increase or decrease the load on the group as a whole and on individual members within a group. Flow interference and degree of shielding are dependent primarily on the spacing of the cylinders and their orientation relative to the flow. Model testing may be the only means of establishing proper hydrodynamic coefficients for such systems. Information from previous model test results on groups of cylinders can be used for analysis, if appropriate.[1]

Model testing on a complete riser or riser system subjected to wave and/or current forces is extremely difficult to perform because of scaling problems for similitude. The KC number may be achieved by matching Froude numbers, but the effect of high Re is difficult to model at reduced scale because of roughness and turbulence.

6.4 GLOBAL ANALYSIS

Previous sections have discussed use of a riser analysis in design, and modeling of environmental effects lead to applied loads and vessel motions. The objective of this section is to provide general guidance on analyses techniques and modeling practices typically used in industry. The treatment is intentionally generic, because many techniques apply to a wide variety of riser configurations and can be used to generate basic data from which further detailed results (e.g., component stress, tensioner stroke, riser clearance) can be derived. More detailed guidance for specific analyses and riser types is provided in subsequent sections.

The following presents the basic equation of motion fundamental to riser analysis and covers several key issues that need to be properly addressed in every riser analysis, including effective tension, stiffness, mass, buoyancy, and hydrodynamic loads. Next, a discussion of typical boundary conditions is presented, followed by an introduction to various solution techniques. Finally, several special modeling considerations are discussed.

6.4.1 Equation of Motion

For simplicity in presentation, the following discussion is restricted to the case of planar, small angle, linear strain analysis of an initially straight riser modeled as a tensioned beam.

The static equilibrium equation for lateral displacement of a tensioned beam is:

$$\frac{d^2}{dz^2}\left[EI(z)\frac{d^2u}{dz^2}\right] - \frac{d}{dz}\left[T_e(z)\frac{du}{dz}\right] = r(z) \qquad (35)$$

where

- z = spatial coordinate along the beam axis.
- u = transverse displacement in the direction of the load.
- EI = bending stiffness of cross section.
- r = applied lateral load, not including applied hydrostatic and pressures.
- T_e = effective tension.

The beam's resistance to deformation is provided by flexural stiffness and more significantly, geometric stiffness arising from axial tension.

The dynamic equation of equilibrium can be obtained from Equation 35 by incorporating inertia forces and a mechanism for energy loss (damping). Applying D'Alembert's principle, assuming viscous damping, and simplifying leads to:

$$[m(z) + \rho A_i(z)]\frac{\partial^2 u}{\partial t^2} + c(z)\frac{\partial u}{\partial t} + \frac{\partial^2}{\partial z^2}\left[EI(z)\frac{\partial^2 u}{\partial z^2}\right] - \frac{\partial}{\partial z}\left[T_e(z)\frac{\partial u}{\partial z}\right] = r(z,t) \qquad (36)$$

where

- $A_i(z)$ = internal area.
- m = distributed mass.
- c = viscous damping coefficient.
- ρ = density of internal fluid.

This model is adequate for many riser analyses. Moreover, the description of this model can be used to introduce most of the fundamental concepts. Extensions required to cover more sophisticated modeling requirements are dealt with in subsequent sections.

In applying Equation 36 to riser analysis, the tension to be taken into account in analyzing an immersed, fluid filled tube is known as effective tension, T_e. Effective tension applies to the global analysis of:

a. All types of riser (metal, flexible, drilling, production, and catenary).

b. Risers consisting of a single tube, multibore, or tube within tube (e.g., tieback risers).

c. Risers of any cross-section, not necessarily circular (e.g., oval).

d. Risers with internal fluids of any density characteristics (not necessarily constant density).

e. Risers of any materials (not necessarily elastic), with plane sections not necessarily plane (e.g., flexibles).

f. Risers with tensioned guidelines threaded through multiple guides.

Effective tension can be formulated most clearly as:

$$T_e = \sum_n T_n + \sum_n (-P_i \times A_i) - (-P_o \times A_o)]_n \qquad (37)$$

for a riser comprising n distinct tubulars, where

- T_n = axial tensions in a structural element (pipe wall).
- P_iA_i = axial "tension" in an internal fluid column (A_i = internal sectional area, P_i = internal pressure).
- P_oA_o = axial "tension" in a displaced fluid column (A_o = external or displaced cross-sectional area, P_o = external pressure).

Lateral force at any cross section of a riser is equal to shear plus the effective tension times the slope. This calculation is valid only because it is equivalent to integrating pressure around the tube circumference and adding shear and the lateral component of tension.

It must be stressed however that effective tension only applies to the global analysis of risers. When calculating other effects of tension and pressure on tubes, such as axial strains and the load combinations that lead to failure, the complete stress field in the wall of a riser's tube must be taken into account.

6.4.1.1 Discretized Equation of Motion

Practical riser analysis requires numerical approximations to the riser differential equation to generate a system of coupled algebraic equations, which can then be solved by standard numerical solution techniques. Starting with Equation 36 and applying the finite element method[71] results in the following statement of lateral equilibrium for an individual element:

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \{r\} + \{q\} \qquad (38)$$

where $[m]$, $[c]$, and $[k]$ are element mass, damping, and stiffness matrices, respectively. Vectors $\{r\}$ and $\{q\}$ represent applied element loads and element boundary forces. $[k]$ is defined as:

$$[k] = [k_f] + [k_g] \tag{39}$$

$[k_g]$ is the geometric stiffness matrix and is a function of element length and effective tension. $[k_f]$ is the flexural stiffness matrix

An equation similar to Equation 38 can be developed for the axial direction, the primary difference being the form of the flexural stiffness terms (i.e., AE/L versus EI). Solution of the axial equations yields axial force in the riser, which is required for the lateral equilibrium equation. Thus, the two equations are coupled through the tension term and are typically solved by iteration. More discussion of tension coupling is given in 6.4.3.4.

The keys to building an accurate stiffness model of the riser system is to properly estimate the lateral bending stiffness term, $EI(z)$ and to accurately determine the effective tension distribution in the riser system. The former requires reasonable approximations for auxiliary lines, large appurtenances and changes in wall thickness. The latter requires approximating riser weight and buoyancy.

6.4.1.2 Mass Modeling

6.4.1.2.1 Proper modeling of the riser mass distribution is required for an accurate solution to the dynamic equilibrium equation. Riser mass is usually taken as a mass per unit length, distributed over regions of roughly equal properties. In finite element models, this distributed mass can be used either to develop a consistent mass matrix by the same methods used for developing the flexural stiffness matrix or a simple lumped mass matrix. The riser tube, couplings, coatings, auxiliary lines, anodes, buoyancy modules, appurtenances, and internal contents all contribute mass that must be accounted for in the dynamic model. In addition, the hydrodynamic added mass, as described in 6.3.3.1, must be included.

6.4.1.2.2 Each component of mass in the riser model contributes a gravity force at the location where the mass is attached to the riser, and all gravity forces contribute, along with buoyancy and pressure forces, to the axial tension in a riser. Riser contents exert a pressure force on internal diameter changes in the riser, as described in the following section.

6.4.1.3 Buoyancy and Pressure Forces

Buoyancy forces arise from the vertical component of pressure integrated over the submerged area and arise only for exposed horizontal surface. In the case of a completely submerged body, buoyancy force can be shown to equal the weight of the displaced fluid. For most metal riser analyses, the top surface of the riser is above the water surface, and therefore the most significant buoyancy force experienced directly by the riser is at the lower end and then only if not connected to the seafloor (e.g., during riser deployment operations).

Significant buoyancy forces occur on buoyancy modules, which are attached to riser joints for that purpose. Buoyancy modules have exposed horizontal surfaces and generate a buoyancy force greater than their gravitational force because their mass density is less than seawater. Data on buoyancy modules is typically given in terms of "net lift," which is the difference between buoyancy and weight (gravitational force).

Buoyancy forces also act on all other submerged material that is attached to the outside of the riser, including nonstructural appurtenances, riser connectors, and coatings. It is often assumed that the nominal riser pipe is the only material which is continuous along a riser, therefore all other items attached to the riser are assumed to have horizontal surfaces on which buoyancy forces act. The total buoyancy force on any length of riser can then be taken to equal the difference between the weight of water displaced by the riser and that displaced by the nominal riser tube, which is equal to the weight of water displaced by all attached items.

Finally, changes in riser diameter result in horizontal surfaces upon which pressure forces can act. Changes in outside diameter can generate a buoyancy force from external pressure, and changes in inside diameter give rise to a buoyancy force from internal pressure. In fact, proper consideration of diameter change handles the case where the riser terminates above the seafloor, exposing it to pressure force. Pressure of seawater is applied to the entire end (sealed or unsealed), and the pressure of contents, acting in the opposite direction, is applied to the inside area. If the contained fluid is seawater at the same pressure as the external fluid, as it would be for an unsealed end, the net force resultant is simply the product of hydrostatic pressure and riser tube section area. If the riser is empty and at ambient air pressure, as it would be for a sealed end with no contained fluid, the net vertical force is the product of hydrostatic pressure and cross-sectional area of the sealed tube.

6.4.2 Riser Boundary Conditions

6.4.2.1 Top End

6.4.2.1.1 Vessel Motions

Vessel motions are required to perform uncoupled dynamic riser analysis. This type of analysis is valid for both column stabilized and monohull vessels. Vessel motions important for riser design are:

a. Wave-frequency motions.

b. Low-frequency motions at the surge/sway natural periods.

c. Static offsets.

The analysis required can be summarized as follows:

a. First order motion responses in the six-degrees-of-freedom.

b. Wind and current force coefficients and slowly varying dynamic wind responses.

c. Mean wave drift forces and slowly varying wave drift responses.

d. Maximum platform offset including all motion response contributions.

This section is intended to summarize the main features of this type of analysis. Details may be found in API RP 2 FPI and API RP 2T.

The calculation of first order vessel motions is usually performed in the frequency domain for uncoupled riser analysis. The motion responses and static offsets due to the first-order wave forces, second-order, wave-drift forces, and wind and current forces are calculated separately. The maximum vessel offset and motion are estimated based on combination of the individual contributions.

The dynamic wind response of the vessel is a combination of a steady component and a time varying component. The steady component is calculated by summing the wind drag forces and moments on each member above the water line.

In addition to the steady wind forces, the vessel will exhibit a low frequency motion responses induced by wind dynamics. The total wind forces are treated as a constant or a combination of a steady component and a time varying component. The time varying component is also known as low frequency wind force. The low frequency wind force will induce low frequency resonant surge, sway and yaw motion.

The frequency distribution of wind speed fluctuation can be described by a spectrum. A wind spectrum for use in this analysis is given in the 19th edition of the API RP 2A-WSD.

6.4.2.1.1.1 Wave Frequency Motion Response

The vessel's first order wave responses in six degrees of freedom are generally calculated using 3D diffraction techniques. These are characterized by response amplitude operators (RAOs) and phase angles. TLPs require computation of a wave frequency setdown resulting from surge/sway. Heave— and roll/pitch—are usually negligible for TLP riser analysis.

6.4.2.1.1.2 Low Frequency Motion Response

A dynamic riser analysis is generally performed with the vessel offset to its mean position due to the steady environmental loads (wind, wave, and current) plus the maximum low frequency response of the vessel. The low frequency wave responses of the vessel are excited by the second order wave drift forces and moments and by wind gust forces. Although the magnitude of these forces is small compared to the first order wave forces, the frequency of the oscillating drift force may correspond very closely to the natural frequency of the moored vessel. In this case the horizontal motion of the vessel may be significant. The low frequency responses are also highly dependent on the mooring stiffness and the total damping included in the system. Both the slow-drift oscillations and the wave-frequency motion are calculated about the mean offset position described above. A simple one-degree-of freedom (surge) simulation of the vessel's behavior can be used to calculate the low frequency surge and sway motions of the vessel.[72] In this method, by knowing the vessel mass, the mooring stiffness and surge damping, the low frequency surge motion can be estimated.

6.4.2.1.1.3 Combination of Motion Components

Maximum vessel offsets are calculated as the superposition of the mean offset and the maximum dynamic excursion. For riser analysis, mean and low frequency motions are generally added to get a quasi-static offset to determine a quasi-static mean riser configuration. Wave frequency motions are then calculated about this point for by the riser analysis program.

6.4.2.1.2 Tensioner Modeling

Top tensioned risers are attached to the FPS by tensioners so that modeling of their response characteristics is important to accurately simulate the global riser response. In general, the load-displacement curve of a riser tensioner may resemble one of the following characteristics:

a. Flat curve close to constant tension with respect to tensioner stroke. In the analysis, riser top tension is maintained constant.

b. Linear relation between riser top tension and tensioner stroke. The tensioner can be modeled by a linear spring between the riser and the platform.

c. Nonlinear relation between riser top tension and tensioner stroke. Top tension response and tensioner stiffness can be modeled by a non-linear beam or truss elements. If the riser top tension increases significantly with respect to the tensioner stroke, the tension variation may change the stiffness in flexural bending of the riser. In this case, the coupling between the axial and bending response may be important.

6.4.2.2 Bottom End

6.4.2.2.1 Flex Joints

Flex joints are often used at the lower end of metal risers to allow the riser to articulate with minimal bending resistance. A flex joint can be modeled as a beam element or preferably as a linear spring having the appropriate rotational stiffness properties. Stiffness is a function of deflection magnitude, and this flex joint property can be important for fatigue. It should be ensured during the motion analysis that the design angular limits of the flex joints are not exceeded.

6.4.2.2.2 Stress Joints

Stress joints are special joints at the bottom or top of the riser designed to control the curvature and hence the stress in the riser where it attaches to a stiff support structure. They are usually tapered from a thick-walled section to a thinner-walled section with constant ID. A stress joint can be modeled for gross stiffness purposes as a number of straight-walled beam sections with decreasing wall thickness.

6.4.3 Solution Methods

A numerical solution to the equilibrium equations is typically obtained by assembling equations for each region comprising the riser into a system of equations describing the force-displacement relationships for all degrees of freedom (dof). By combining all equations for elements connected to a particular node, in a manner consistent with requirements for equilibrium at the node and compatibility between elements, equations relating forces at all global dof to displacement at each dof at the node are obtained. Assembling all such equations for N global degrees of freedom leads to a system of N coupled algebraic equations. These equations can be expressed in matrix form as:

$$[M]\{\ddot{U}\} + [C]\{\dot{U}\} + [K]\{U\} = \{R\} \tag{40}$$

where

$[M]$ = N x N system mass matrix.

$[C]$ = N x N system damping matrix.

$[K]$ = N x N system stiffness matrix.

$\{R\}$ = N x 1 system load vector.

$\{\ddot{U}\}$ = N x 1 acceleration vector.

$\{\dot{U}\}$ = N x 1 velocity vector.

$\{U\}$ = N x 1 displacement vector.

where each row represents the equilibrium equation for a global degree of freedom, obtained by adding contributions from each connected element. Matrix columns contain coefficients specifying mass, damping and stiffness coupling between the various dof. The coupling terms arise from elements which are connected between nodes at which the coupled dof are defined. The following sections address various issues pertinent to the numerical solution of the global equilibrium equation.

6.4.3.1 Discretization

6.4.3.1.1 Finite element or finite difference techniques are typically employed to reduce the differential equilibrium equations to a set of coupled algebraic equations that can be solved numerically. The riser must be discretized carefully to avoid numerical errors from too coarse a mesh while producing a model that can be analyzed with a reasonable amount of computational effort. The level of discretization that is ultimately acceptable depends on the numerical representation of tension variation, the spatial variation in physical properties of the riser and in the magnitude of applied load, frequency content of the applied load and the accuracy of the desired results. In general, coarser meshes are acceptable for determining approximate displacement solutions to problems dominated by vessel motions, while finer meshes are essential for accurately determining stresses in the splash zone or at a stress joint for fatigue analysis.

6.4.3.1.2 Finite element length is further controlled by the following considerations[93]:

a. Near a boundary, element length should not exceed: $C = \sqrt{\frac{EI}{T}}$

b. Away from boundaries, element length should not exceed

$$C = \frac{\pi}{\omega}\sqrt{\frac{T}{m}}$$

where ω is the highest lateral frequency to be included in the analysis.

c. The ratio of lengths of successive elements should not exceed about 1:2.

6.4.3.2 Small Versus Large Angle Formulation

6.4.3.2.1 The "small angle" assumption is often used when formulating riser analysis methods, particularly for vertical risers. In practice, various operational constraints, or stress limits for many types of risers are only met by keeping the maximum angle change along the riser below ten degrees. This just happens to be a generally recognized limit for the accuracy range of small angle beam theory.

6.4.3.2.2 Use of small angle theory simplifies the solution through approximation of the curvature term, at the expense of limiting its applicability. However, small angle approaches will generally be sufficient for a wide variety of design applications. Note that small angle theory does not limit the approach to small displacements, as rather large displacements of a riser in moderate water depths can be achieved without exceeding an angle change of ten degrees.

6.4.3.2.3 Note also that small angle theory is not limited to vertical risers. For example, any number of techniques (e.g., catenary equations) can be used to calculate the initial configuration of a catenary riser, whose subsequent dynamic response to environmental excitation can be calculated by small angle theory, subject to the limitation discussed above. Large rotations must be modeled, however, for certain analyses where angle changes will exceed ten degrees. This can be the case for flexible risers in extreme storms, particularly if the loading is normal to the catenary plane. For these situations, numerous approaches have been developed to accommodate large rotations.[73,74]

6.4.3.3 Planar Versus Three-dimensional Analysis

A common simplification for many riser analyses is the use of planar (two-dimensional) analysis, in which vessel motion, waves, current and any initial displacement of the riser are all assumed to be in the same plane. For many cases, especially for initially straight (vertical) risers, this is an adequate assumption that can significantly reduce the resources required for analysis. Planar analysis is therefore particularly useful for preliminary design work. Spread seas and non-collinear wave and current loads cannot be solved directly with two-dimensional techniques due to the coupling introduced by the drag force non-linearity. In many cases, reasonable approximations will still permit the use of two-dimensional formulations. However, certain problems are inherently three-dimensional and therefore require a three-dimensional analysis (e.g., stresses near the seabed for a catenary riser subjected to loading normal to the plane of the riser).

6.4.3.4 Tension Coupling

Tension in the riser has a significant influence on stiffness. For some riser designs, the temporal variation in tension relative to the mean tension is naturally small and therefore will have little effect on lateral displacement. However, risers with relatively stiff tensioning systems may experience tension variations that are significant relative to the mean tension, leading to appreciable changes in lateral stiffness. Analysis of these risers must account for the nonlinear coupling between axial tension and lateral stiffness. The coupling comes from the fact that as a riser displaces laterally, it must stretch axially and/or displace vertically. The balance between axial stretch and vertical displacement is a function of the constraint typically provided by its attachment to a vessel, which is itself a function of vessel displacement. In the general case, accurate determination of tension variation requires assessment of the coupling between lateral and axial riser displacements, constraints between the riser and vessel, and the associated vessel displacement. In some cases, pressure changes due to change in elevation of the free surface may also contribute to tension variation.

6.4.3.5 Stroke and Tensioner Stiffness

6.4.3.5.1 Calculation of tensioner stroke is necessary if nonlinearities in the tensioner stiffness are to be accounted for in the tension calculation. Stroke calculations are also often desired for tensioner design. Stroke of direct-acting tensioners is simply the relative displacement between the tensioning ring and the vessel. Stroke of other tensioner designs depends on the particular geometry of their attachment to the tensioning ring as well. In any case, vertical riser displacement due to lateral motion and low frequency and wave frequency vessel displacements should be considered, as should nonlinear setdown of a vertically-moored vessel (TLP).

6.4.3.5.2 In many cases where tension changes due to stroke are relatively small, modeling of the tensioner stiffness is not important. However, for detailed design of the tensioning ring or tensioning attachment hardware, forces due to stroke may be important. Also, in cases where a tensioner is relatively stiff, or in extreme cases when a tensioner is stroked out, accurate stiffness modeling of tensioners may be important. In these cases, tensioners can be modeled as inclined scalar springs with the appropriate stiffness characteristics. Accurate prediction of forces local to the tensioning ring may require considering large vessel rotations when formulating the spring (i.e., stiffness changes with instantaneous vessel position).[75]

6.4.3.6 Stability

Low, or even negative, effective tension over a portion of the riser does not imply the riser is unstable, nor does it cause the riser to instantaneously experience Euler buckling. The direct consequence of low or negative effective tension is low lateral stiffness, the result of which is adequately estimated by the standard global riser analysis if changes in effective tension are accounted for.[76]

6.4.3.7 Nominal Forces and Stresses

6.4.3.7.1 Nominal internal forces and stresses on the riser cross section can be calculated directly from the dynamic equilibrium equation for a riser element using the results from global analysis. Such nominal forces and stresses can then be used directly in design, where called for by Section 5, or they can be used as input to more detailed analysis of riser components as described in 6.5.

6.4.3.7.2 Local equilibrium of a riser element leads directly to the following expression gotten by solving Equation 38 for internal forces $\{q\}$:

$$\{q\} = [m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} - \{r\} \qquad (41)$$

6.4.3.7.3 Contributions to internal force by inertia loads are represented in the mass times acceleration term. Similarly damping contributions are represented in the damping term, and curvature is the stiffness term. Note also that contributions by internal and external pressure terms are also in the stiffness term via the effective tension, as is the contribution of axial tension to shear and moment.

6.4.3.8 Frequency-Domain Analysis

6.4.3.8.1 Frequency-domain analysis is appropriate when the effects of tension coupling are known to be small, and there are no other nonlinearities significantly affecting responses. Frequency-domain analysis is often used for fatigue analysis with the objective of obtaining estimates of root-mean-square (*rms*) axial and bending stresses. Frequency-domain analysis is also useful to estimate *rms* stresses for use in strength calculations of certain components as well as estimating clearance between risers (see 6.6).

6.4.3.8.2 The principal advantage of frequency-domain analysis is a reduction in computational effort for linear systems, coupled with very simple unambiguous output. Analysis of linear systems is well understood, and the application of frequency-domain results to design criteria is straightforward. The limitation of frequency-domain analysis is the difficulties and added complexities associated with modeling nonlinear behavior.

6.4.3.8.3 Wave and current forces as modeled by Morison's equation are nonlinear in velocity. This is typically a significant force term for risers, but it can be successfully linearized as described in 6.3.4.[36,37,38,98] With a linearized drag term, the frequency-domain equilibrium equations become:

$$[A]\{U\} = \{R_L\} \tag{42}$$

where

$$[A] = -4\pi^2 f^2 [M] + i2\pi f[C] + [K]$$

$$\{R_L\} = \left|\mathrm{r}\right|_j e^{i(2\pi f + \phi_j)}$$

6.4.3.8.4 $\{R_L\}$ represents the linearized wave and current load, f is the wave frequency in Hertz and ϕ_j is the relative phase of the load at degree-of-freedom, j. $[C]$ contains terms constructed from the linearized damping force term. $[A]$ is a complex-valued coefficient matrix that may be solved directly at each frequency by standard solution techniques for simultaneous equations. The equation may also be transformed to modal coordinates, leading to response estimates for each individual dynamic mode. In either case, the solution is in terms of displacement amplitude and phase as functions of frequency, linearized to a particular seastate.

6.4.3.8.5 When displacement amplitudes are divided by the wave amplitudes used to generate the loads, the results are termed frequency response functions (RAOs) or transfer functions. The transfer functions can then be used to generate response estimates for a variety of environmental conditions, although frequently the analysis will be linearized to a variety of seastates of different intensities to keep the linearization error reasonably small. There are several good references that summarize the frequency-domain analysis method for offshore applications.[77,78,79] There are also several applications of the method to riser analysis in the literature.[80,81,82]

6.4.3.8.6 In addition to properly linearizing the drag force, careful selection of analysis frequencies is essential to adequately model riser response. Frequencies used in the analysis should result in adequate definition of 1) the wave energy spectrum, 2) vessel response characteristics, and 3) natural frequencies of the riser.

6.4.3.9 Time-Domain Analysis

Time-domain analysis is typically used when accurate representation of nonlinear behavior is important to meeting the analysis objective. Nonlinear effects encountered for some riser analyses such as tension coupling, large rotations, nonlinear loading or foundation stiffness can be directly modeled in the time-domain.[83,84] In addition, time-domain analysis is used to analyze transient events such as disconnecting with overpull on a drilling riser or loss of station keeping ability. Finally, time-domain analysis can be used to assess the relative accuracy of equivalent frequency-domain analyses and calibrate them for use in design.

Time-domain analysis requires defining the environment as a function of time, typically simulating wave time histories. Vessel motions may be calculated from the simulated waves and vessel frequency response functions (uncoupled vessel/riser analysis) or they may be calculated in the time-domain along with riser response (coupled vessel/riser analysis). Time-domain analysis is essentially satisfying static equilibrium, including inertial, damping, and applied loads, at particular points in time.

6.4.3.9.1 Integration Approach

Direct integration methods integrate the equilibrium equation in time, with the objective of satisfying dynamic equilibrium at discrete times. The general form for such methods is:

$$[A]_t \{U\}_{t+\Delta t} = \{R\}_t \tag{43}$$

for explicit integration methods such as central difference or for implicit methods, such as the Newmark method.

$$[A]_{t+\ddot{y}t} \{U\}_{t+\ddot{y}t} = \{R\}_{t+\Delta t} \tag{44}$$

where

A = coefficient matrix.

U = function of mass, stiffness, and damping.

R = function of load, mass, stiffness, damping, and the solution at previous time steps.

The primary difference between the two classes of integration methods is that explicit methods are derived from the equilibrium equation at time t and implicit methods at $t + dt$. This has implications on the numerical effort required to perform the integration. Explicit methods typically require fewer computations per time step but often require shorter time steps to achieve an accurate solution. Implicit methods often require substantial numerical effort at each time step (like decomposition of the coefficient matrix) but can often utilize larger time steps. Selecting a method is usually a trade-off between accuracy and economy. A variety of methods are available from the literature.[85,86]

Stability and accuracy of the time integration should be carefully considered when setting up the time-domain analysis run. Most popular methods are conditionally stable, meaning that the time step size must be below a certain threshold for the analysis to yield meaningful results. One of the most popular methods is the Newmark Constant Average Acceleration method, which is stable for any time step (i.e., unconditionally stable). However, all methods require that the time step be small enough to accurately reflect important frequencies in the load or response. This is analogous to proper spatial discretization of the model and careful selection of frequencies in the frequency-domain method. Large time steps may result in a quicker analysis that is accurate for the frequencies represented but may miss important higher frequency contributions.

All methods have some degree of integration error that is associated with frequency and amplitude of the integrated response. In certain situations, slight errors in frequency alone can accumulate and lead to numerical "beating" of the response. It is important to recognize and understand these errors when performing time-domain analysis, particularly for the purpose of simulating long time histories and developing statistics for extremes.

6.4.4 Special Modeling Considerations

6.4.4.1 Equivalent Pipe Model

Global analyses of multiple tubular riser systems are generally performed using an equivalent pipe model. The equivalent pipe models are generated using the assumption that the riser section properties can be calculated from a compound section. Using this assumption, which ignores non-isometric properties, the riser properties are obtained by adding the areas, moments of inertia, effective tensions and masses of all of the tubulars together along the length of the riser. This implies that the tubulars are in continuous contact with each other and that the displacements (and thus the curvatures) of all of the tubulars along the length of the riser are identical. In reality the tubulars are not in constant contact with each other, and therefore, the displacements of the tubulars are not identical. As a result, the global displacements describe the general or approximate displacements along the length of the riser tubulars. The closer the riser system configuration is to the compound section assumed for the global analysis, the closer the global displacements are to the actual displacements of the tubulars.

6.4.4.2 Coupled Vessel/Riser Analysis

6.4.4.2.1 Riser simulations are usually conducted as uncoupled analyses using assumed quasi-static offsets and wave-frequency motions computed from RAOs from separate moored-vessel analyses. Some programs permit solution of the total vessel/riser/moorings problem wherein the latter are represented by finite elements. This is called coupled analysis and it is usually done in the time-domain. It is useful when:

a. Risers can significantly influence the response of the vessel.

b. A more complete representation of vessel motions is desired that includes, for example, slowly varying motions or more accurate setdown effects.

6.4.4.2.2 Coupled analyses are more computationally intensive since many more degrees of freedom are being solved for at each time step.

6.4.4.3 Design Statistics and Transfer Functions

Riser analyzes are run either to: 1) determine maximum values or 2) develop transfer functions, usually for fatigue analyses or for spectral computation of extremes. Quite different techniques are required in each case.

6.4.4.3.1 Frequency Domain

6.4.4.3.1.1 Extreme Values

Frequency-domain analysis results in root-mean-square, X_{rms}, and zero-crossing period, T_{zr}, for stresses and deflections for a particular seastate according to:

$$m_n = \int_0^{\infty} f^n S(f) df \tag{45}$$

$$X_{rms} = \sqrt{m_0} \tag{46}$$

$$T_{zr} = \sqrt{\frac{m_0}{m_2}} \tag{47}$$

where

m_n = nth spectral moment.

f = frequency, Hz.

$S(f)$ = power spectrum of the response.

To predict the maximum values, these must be multiplied by an extreme factor computed from the distribution of peaks. Many analyses have assumed Gaussian responses so that the extreme value is obtained from:

$$X_{max} = X_{mean} + X_{rms} \cdot F \tag{48}$$

$$F \approx \sqrt{2 ln[D/(T_{zr} P_e)]}$$

where

P_e = exceedence probability.

X_{mean} = mean value of response.

D = duration of condition (often 3 or 6 hours).

While adequate for relatively mild conditions, such as for fatigue analysis, drag dominated responses are generally non-gaussian and are not well represented by this type of analysis in extreme conditions. This is particularly true in the splash zone, where the effects of intermittent wetting are important for the statistics.

6.4.4.3.1.2 Transfer Functions

Transfer functions can be obtained directly from frequency domain analysis programs.

6.4.4.3.2 Time-Domain

6.4.4.3.2.1 Extreme Values

Regular (design) wave simulation. These results are relatively simple to interpret for finding maximum responses to that particular wave, although relating that condition to a design seastate is problematical. Such an approach cannot be recommended when there is substantial dynamic response to frequencies near the design waves. The use of spectral analysis (based on transfer functions appropriate to the seastate to analyze) described in the following, is therefore preferred.

Random-wave simulation. Time series from random-wave simulations must be processed to obtain extreme values. One approach is to fit a distribution, such as the Weibull 3-parameter distribution, to the peak values and to compute the extreme value for the storm duration of interest. This method is particularly attractive for long simulations up to the length of the storm's duration. While computationally intensive, such an approach is well within today's hardware capabilities. Statistical uncertainty can be reduced by increasing length of simulation time.

6.4.4.3.2.2 Transfer Functions

When developing transfer functions from regular wave analysis, such results may contain unwanted higher harmonics that must be removed by filtering.

Random wave simulation results in time series that can be post-processed to develop transfer functions via Fast Fourier Transforms (FFT). One commonly used definition is:

$$RAO(f) = \sqrt{\frac{S(f)}{S_w(f)}} \tag{49}$$

where

$S_w(f)$ = wave spectrum at f.

$RAO(f)$ = response amplitude operator, response per unit wave amplitude at f.

6.5 COMPONENT ANALYSIS

This section addresses the detailed analysis of the riser components using the results obtained in the global analysis.

6.5.1 Individual Riser Tubulars

6.5.1.1 The objective of analyzing individual tubulars is to evaluate them with regard to the appropriate design criteria and to generate loads and displacements required to evaluate their components. The analyses of the individual tubulars begins with the global analyses. Such analysis takes results obtained in the global analysis and generates the information required to satisfy this objective.

6.5.1.2 For riser systems which have one tubular that provides most of the riser stiffness (i.e., drilling risers, production risers with small inner tubes, etc.) the global displacements provide an accurate description of the predominant tubular's displacements. It may also be possible to determine the tensions, bending moments and stresses in the predominant tubular without additional analysis. However, in some cases additional analyses are required to determine the loads and stresses in the predominant tubular. In these riser systems, additional analyses may also be required to determine the loads and stresses in tubulars other than the predominant tubular. For riser systems which do not have one predominant tubular, additional analyses are usually required to accurately estimate the loads, stresses, and displacements in individual tubulars.

6.5.1.3 The additional analyses are aimed at evaluating the interaction of the riser tubulars and determining the loads, stresses, and displacements in each tubular. These may be obtained directly from the additional analyses or may be obtained using a procedure derived from the results of the global analysis and the analysis of the individual tubular. In most cases it is not practical to perform a specific analysis of each individual tubular for each load case to be evaluated. For these situations a procedure may be developed which relates the loads, stresses and displacements in the individual tubes to the loads, stresses and displacements generated in the global analyses.

6.5.1.4 The tubulars interact with each other through contact loads which occur at discrete points along the length of the riser. The frequency and size of the contact loads between the tubulars depends on the global riser displacements, the clearances between the tubulars (and tubular components) and the lateral stiffnesses of the tubulars. These discrete contact loads may occur anywhere along the length of the tubulars. The most likely points of contact are at the locations of centralizers, clamps, connectors, etc.

6.5.1.5 Finite element or finite difference computer programs are generally used to analyze the individual tubulars. Depending on the riser configuration and the particular objective of the analysis, it may be desirable to include all of the tubulars in a solution with each tubular modeled individually, or it may be desirable to model one tubular in a solution and perform one solution for each tubular. For some riser systems, a combination of both methods may be required. For both methods static solutions are used to perform the analyses. These analyses are used to obtain factors relating the responses of the individual tubulars to the global responses of the riser system. These factors are then used in conjunction with the global analyses to estimate the loads, stresses and displacements of the individual tubulars.

6.5.1.6 Because the lateral stiffness of an individual tubular is dependent on the tubular's effective tension, along with the cross-sectional properties of the tubular, it is important to accurately model the effective tension distribution. Some of the factors which should be considered when determining the tubular's effective tension distribution are listed below:

a. Weight of the tubular.

b. Densities of the fluids inside and outside the tubular.

c. Internal and external tubular pressures.

d. Temperature of the tubular.

e. Boundary conditions at the ends of the tubular.

f. Tubular installation procedure to determine the initial tubular tensions.

g. Distance between the centerline of the tubular and the assumed centerline of the global riser model.

h. Special joints (i.e., sliding or telescoping joints).

i. Relative axial stiffnesses of the riser tubulars.

6.5.1.7 It is also very important to accurately model the free space or distance between the tubulars. The models should include free space reductions which may occur at the locations of centralizers, clamps, connectors, or other components. Care must be taken when discretizing the model of the tubular to ensure that in critical areas, the response of the tubular between the components can be accurately determined. For top tensioned metal risers, these critical areas generally occur at the top and bottom of the riser and in regions where the effective tension of the tubular is low enough to allow buckling of the tubular.

6.5.1.8 Centralizers are used on tubulars inside larger tubulars to control the displacements of the inner tubulars. The more centralizers that are used, the more closely the riser behaves like the equivalent pipe riser model used for the global analysis. Centralizers are used to provide the inner tubulars with additional stability, control the locations where inter-tubular contact may occur and to protect other components. For such riser systems, optimization of the centralizer spacing is generally one of the tasks to be performed. This generally requires an iterative process in which a number of responses are evaluated to determine the optimum centralizer spacing.

6.5.1.9 The results which should be generated from the analyses will vary depending on the type of riser being analyzed and the objective of the analysis. Some of the results which may be generated include:

a. Estimation of the axial and transverse displacements of the tubulars. The axial displacements can be used to generate information on the relative sliding between tubulars and to generate stroke information for tubulars with sliding (stab-in) connections or telescoping joints. The lateral analyses are used to generate the load distributions and to determine the clearances between tubulars.

b. Estimation of the load distributions along the length of the tubulars. These load distributions are used for the analyses of the tubular connectors and to determine the stresses along the length of the tubulars. The loads obtained at the ends of the tubulars are used for the analyses of the components connected to the ends of the tubulars.

c. Estimation of the stresses along the length of the tubulars. These stresses are used to evaluate the tubulars with regard to the allowable stress and fatigue criteria.

d. Optimization of the centralizer and/or clamp spacing.

e. Estimation of the contact loads between tubulars. These contact loads can be used to design centralizers and evaluate wear.

6.5.2 Connectors and Stress Joints

6.5.2.1 The objective of these analyses is to assure structural integrity and performance of these components as a part of the overall riser system. Analysis is intended to demonstrate that they are resistant to yielding and failure due to fatigue.

6.5.2.2 The following analysis procedures are recommended:

a. Global analysis: Determine the net loads by global analysis. In global analysis the stress joint should be modeled appropriately with its varying stiffness. If flowlines and their guide tubes share bending loads with the stress joint, it may be assumed that there is a common radius of curvature for all these tubes. The bending stiffness of the guide tubes and the flowlines are then added to that of the stress joint. Connectors are usually represented by adding the weight and mass to the tubular distributed properties. Such global analyses include all possible seastate and riser configurations, and the worst riser response is then determined. From the global analysis, determine loadings and displacements on the stress joint or connector, calculate stresses along various cross sections of the stress joints and compare with allowable stresses criteria.

b. Finite element analysis: Detailed finite element analysis (FEA) is then usually performed. A two or three-dimensional model may be used. Symmetry of the component can be utilized in deter-mining the stress state by using a two-dimensional axisymmetric FEA model. For such two-dimensional analyses the equivalent tension concept (API Spec 16 R) can be used to account for the bending load in element types which allow only axisymmetric loadings. Element formulations which allow axisymmetric modeling with asymmetric loading are also available and may provide improved results. Depending on the finite element model, displacements and rotations rather than forces and moments may be used to transfer the loadings from the global model to the local model.

c. Boundary conditions: A fixed boundary condition may be used at the end of a stress joint attached to a foundation that is significantly stiffer than the stress joint. The flexibility of either the riser base or the upper riser package should be included using appropriate spring elements. Interface elements can be used to model the interactions between the stress joint and the lower connector package. This provides a method to determine the load at which separation of the faces of the connection between these two components initiates.

d. Stresses: Once stresses are available from the FEA, they should be compared to the design allowables defined in Sections 4 and 5.

e. Fatigue: Connectors and stress joints are critical members where fatigue loading should be analyzed. Either FEA based analysis or global analysis results may be used to calculate the fatigue life. In the case where the global results are used, stress amplification factors (SAFs) should be used for localized high stress regions.

6.5.3 Flex Joints

Local analyses as outlined for the stress joint can be conducted for the flex joint. The purpose of the local analysis is to determine high local stresses and life of the joint under fluctuating loads. Therefore, the model should include stiffness of the elastomers between spherical shaped steel rings and appropriate contact elements. Such models must include highly non-linear behavior of the rubber layers and call for specialized analyses capabilities.

6.5.4 Effect of Appendages on Local Stress

Examples of appendages that will have an effect on local stresses and may need to be analyzed are:

a. Choke and kill lines.

b. Anodes.

c. Buoyancy.

6.5.5 Tensioning System

Tensioner design requires information on maximum loads, stroke, and angles. Loads comprise tensions in each component, for example: cylinder tensions and centralizing reactions. Stroke information determines the overall dimensions of the tensioner unit and will generally be quite different for up and down-stroke directions. Since such responses are likely to be non-gaussian in large seastates, care should be taken in developing extreme values from time series.

6.6 SPECIAL PURPOSE ANALYSES

6.6.1 Clearance

Clearance between risers, between a riser and a moving obstruction (e.g., a FPS pontoon), or between a riser and a stationary obstruction (e.g., subsea wellhead) is typically assessed by performing a global riser analysis and calculating mean clearance and relative motions. Statistics on minimum clearance and impact velocity can then be developed. Environmental conditions that are usually checked in clearance analyses are storms and high currents.

6.6.1.1 Waves

6.6.1.1.1 Clearance can be estimated for wave-induced motions in the frequency domain by calculating mean clearance and estimating relative displacements due to slow-drift and wave-frequency responses. Statistics for minimum clearance, contact rate, and potential collision velocities can then be estimated based on reasonable simplifying assumptions and standard formulas for extreme values.

6.6.1.1.2 Mean clearance can be estimated as the average clear distance between risers with the vessel at its mean slow-drift offset. If riser natural frequencies are well separated from vessel drift frequencies, then the standard deviation of relative displacement due to slow drift of the vessel can be estimated as the change in clearance that occurs as the vessel moves from its mean slow drift offset to the mean plus slow drift standard deviation position. This will often be an adequate representation for connected risers. However, some risers may exhibit appreciable dynamic response to vessel drift during installation or retrieval operations (e.g., running a subsea BOP without guidelines). For these cases, a dynamic analysis is appropriate to determine a relative displacement spectrum due to slow-drift, using the vessel motion slow-drift spectrum as a dynamic boundary condition. Finally, the standard deviation of relative displacements at wave frequencies is estimated by differencing the wave-frequency displacement transfer functions of the two risers. These transfer functions must be linearized about a particular vessel position, due to the effect of vessel motion on riser tension.

6.6.1.1.3 A complete description of clearance in the frequency domain includes the mean clearance plus a relative displacement response spectrum, which typically comprises response due to vessel slow-drift and wave-frequency motions and loadings. There are no generally accepted procedures for calculating extreme response statistics for a combined slow-drift and wave-frequency relative displacement process. However, the general approach is to develop an envelope function for the combined process and then estimate extreme values of the envelope using classical level-crossing techniques.[87,88,89] There are no specific examples for riser clearance analysis in the literature at this time, but the extreme response of a vessel is an analogous problem that has been studied extensively.[90]

6.6.1.1.4 Similar quantities may be calculated via time-domain analysis, in which case the calculation of relative displacement is straightforward if both slow-drift and wave-frequency vessel motions are included in the simulation. Relative velocities are typically computed via numerical differentiation of the relative displacement.

6.6.1.2 Currents

6.6.1.2.1 Basic Wake Formulae

Because of potentially large static deflections in high currents, the risk of collisions in riser systems should be evaluated. Large static deflection of a riser does not necessarily represent a problem as long as it is approximately equal for all risers in the array. However, for risers, even relatively small difference in deflection can exceed the top and bottom end spacings and lead to mechanical contact or collision between adjacent risers.

Thus it becomes necessary to calculate the deflection of each riser in the array to determine if any two will collide or if there will be collision with mooring lines, platform pontoons, etc. In this calculation it is recommended to account for the shielding effect of risers situated upstream in the current field.

For calculating the shielding effect, the theoretical formulation for fully developed turbulent wakes is recommended.

The wake field behind a cylinder in homogeneous flow is: [94,95]

$$b = k_1(C_d D x_s)^{1/2} \tag{52}$$

$$U_o = k_2 V(C_d D/x_s)^{1/2} \tag{53}$$

$$u = U_o \exp(-0.693(y/b)^2) \tag{54}$$

$$x_s = x + 4D/C_d \tag{55}$$

where

b = wake half-width (see Figure 38).

C_d = effective drag coefficient, any expected VIV to be taken into account by increasing its typical stationary flow value.[91]

D = diameter of riser generating the wake.

x = distance in flow direction from center of riser.

y = transverse distance from center-line of wake.

U_o = wake velocity at y=0.

u = wake velocity at arbitrary downstream coordinates x,y.

V = inflow velocity to upstream riser.

k_1 and k_2 empirical constants having approximate values k_1 = 0.25 and k_2 = 1.0.

As an example of the practical consequences of this formulation consider two cylinders of equal diameter, one sitting directly behind the other in the direction of the current. If the center-to-center spacing is 5 diameters, the drag force on the downstream cylinder is reduced by 45 percent compared to the upstream cylinder. If the spacing is 30 diameters the corresponding reduction will be 27 percent and at a spacing of 100 diameters the reduction is still as large as 16 percent. It is generally accepted that the potential flow field induced by a cylinder is negligible at distances of the order of 5 diameters or more. However, as can be seen from the above examples, the shielding effect produced by the upstream cylinder is significant even at much larger distances.

The evaluation of risk of collision in top-tensioned riser arrays can be done in three phases as follows:

Phase 1: The static deflection due to current drag is calculated for each riser in the array, neglecting any hydrodynamic interaction between them, i.e., assuming the inflow velocity for each riser to be equal to the current at the relevant level. If the riser deflections as calculated above do not exceed significantly the average of top and bottom spacings in the riser array, one can safely conclude that there will be no collisions between the risers due to the current, and no further analysis is necessary. On the other hand, if the deflections as calculated are much larger than the spacings, more accurate analysis is recommended as described in the following phase.

Phase 2: This calculation procedure takes wake interaction into account. The procedure consists in calculating the deflection of each riser, starting with the far upstream riser, and continuing with each riser in the sequence of their position in downstream direction.[96] The essential feature is that when calculating the local inflow velocity, the wakes generated by all upstream risers are taken into account by the formulae shown above.

If the deflections determined by the Phase 2 calculations show that no collisions will occur, then no further analysis is necessary. However, if the direction of the current varies for different levels down the risers, or if the stiffness of the tensioning devices is such that it significantly reduces the deflection, there is still hope that collisions will not occur, even if the Phase 2 calculation showed that they would. In this situation it is recommended that one proceeds to the more complete analysis of Phase 3.

Phase 3: This more complete analysis accounts for variations of current direction for different levels down the riser and for the stiffness of the tensioning device of each riser. The riser curvature and deflections in the two horizontal directions (x and y) are determined accordingly. The drag force is calculated, correcting the inflow for the wakes generated by all the other risers, using the geometry of the other risers determined in the previous current step.

If the deflections of the different risers according to this calculation procedure are such that they collide, the designer has two options:

a. Change the spacings or other parameters of riser system in order to avoid collisions.

b. Verify that mechanical contact between risers will be acceptable

If the second is chosen, one will have to evaluate possible damage due to two effects:

a. Risers at different angles making continuous mechanical contact, producing additional bending moments at the position of contact.

b. Risers vibrating due to VIV, producing dynamic impact forces at the points of collision, thus producing additional bending moments as well as possible damage to the surface of the risers. In this case a maximum possible impact velocity will be $2\omega A$, where ω and A are the frequency and amplitude of the VIV, respectively.

6.6.1.2.2 Flexible Risers of Arbitrary Geometry

The numerical procedures described above refer primarily to a vertical or nearly vertical riser. For this type of riser, the numerical procedures up to and including Phase 2 calculations have been verified by experiments.[95] For conditions typically referring to Phase 3 calculations, there is so far no experimental verification available, and the reliability of the results of the calculations should be judged with this limitation in mind.

Table 5—Values of k_3 for Different Velocity Profiles and Different Riser Top Tension to Bottom Tension Ratios

T_t/T_b Profile	12.0	5.5	3.3	1.6	1.0
Rectangular	1.14	1.07	1.03	1.00	1.00
h/H = 1.0	0.274	0.282	0.291	0.316	0.342
h/H = 0.8	0.193	0.196	0.212	0.237	0.262
h/H = 0.6	0.121	0.128	0.136	0.157	0.178
h/H = 0.4	0.0622	0.0663	0.0717	0.0852	0.0991
h/H = 0.3	0.0392	0.0423	0.0460	0.0555	0.0653
h/H = 0.2	0.0213	0.0231	0.0252	0.0307	0.0369
h/H = 0.1	0.00893	0.00967	0.0106	0.0131	0.0160

For flexible risers of arbitrary, wave-type geometry the basic wake formulation is still applicable. Again there is no experimental verification available, and practical experience from this type of calculations is still very limited.

6.6.2 Hydrostatic Collapse

6.6.2.1 Collapse of Metal Pipe

6.6.2.1.1 The formulas given below may be used to analyze collapse resistance. These formulas should be used with the criteria given in 5.4.1.

6.6.2.1.2 The collapse pressure for round pipe, P_o, is given by:

$$P_o = P_e P_y (P_e^2 + P_y^2)^{-1/2} \tag{57}$$

6.6.2.1.3 The minimum collapse pressure for imperfect pipe, P_c, including the effect of bending strain, is given by:

$$P_c = P_o (g - s/s_o) \tag{58}$$

where

D,t = nominal pipe outside diameter and wall thickness less any corrosion allowance.

D_{max} = maximum outside diameter of pipe.

D_{min} = minimum outside diameter of pipe.

E,u = modulus of elasticity and Poisson's ratio.

σ_y = specified minimum yield stress.

A = cross sectional area of pipe = $\pi(D^2)/4$.

a = cross sectional area of wall = $\pi [D^2 - (D - 2t)^2]/4$.

T_e = effective tension on tubular.

G = unit weight of water.

H = water depth.

P_i = internal pressure.

P = net external pressure = $GH - P_i$.

S_a = mean axial stress = $(T_e - PA) / a - P_i$.

Y_r = reduced yield stress = $\sigma_y \{[1 - 3(S_a / 2\sigma_y)^2]^{1/2} - (S_a / 2\sigma_y)\}$.

P_y = yield pressure with simultaneous tension = $2Y_r t / D$.

P_e = elastic buckling pressure = $[2E / (1 - \nu^2)] (t / D)^3$.

p = plastic to elastic collapse ratio = P_y / P_e.

O_i = initial ovality = $(D_{max} - D_{min}) / (D_{max} + D_{min})$.

f = out-of-roundness function = $[1 + (O_i D / t)^2]^{1/2} - O_i D / t$.

g = imperfection function = $(1 + p^2)^{1/2} / (p^2 + f^2)^{1/2}$.

b = strain reduction factor = 1.5 for API pipe.

s_o = critical bending strain = $t / 2bD$.

s = bending strain experienced by tubular.

6.6.2.1.4 Langner[92] provides more detailed information on the analysis methods suggested in this section.

6.6.2.2 Collapse Propagation

6.6.2.2.1 An acceptable method of calculating the net external pressure under which a pipe buckle can propagate P_p is to use the following formula:

$$P_p = 24\sigma_y (t / D)^{2.4} \qquad (59)$$

6.6.2.2.2 This formula should be used with the criteria in 5.4.

6.6.2.3 Commentary

The following points have been considered in developing the criteria in 5.4 and 6.6.2.1:

a. Unless more accurate methods are used, the analysis procedures given in this section and the criteria provided in 5.4 should be applied to demonstrate that metal tubulars used in FPS risers will not collapse under external hydrostatic pressure. While based on a substantial amount of test data, these criteria may benefit from further refinement as additional tests are performed. For example, additional data may be beneficial to define the performance of DSAW pipe and the effects of pipe eccentricity and residual stress. Sections 5.4 and 6.6.2 are intended to apply to metal tubulars of steel, aluminum, or titanium.

b. Little data exists to allow comparison of the results of this approach with experimental results for titanium. An alternative approach using the equations derived by Timoshenko and considering ovality may be used to verify predictions for this material but may require higher safety factors to yield the same degree of conservatism.

c. The design factor is introduced to allow for variation in the criteria based on factors such as the following:

1. Manufacturing methods, type of pipe.
2. Consequences of failure.
3. Service conditions.

d. The reduced yield stress is calculated based on von Mises' failure theory to allow the incorporation of tension into the analysis. The reduced yield stress is introduced in place of the yield stress in the hoop pressure formula to give the yield pressure with simultaneously acting tension. This approach is conservative and results in predictions that agree well with experimental results.

e. An alternative is to normalize the axial stress with the ultimate stress in the reduced yield stress formula. This approach offers even closer agreement between predictions and experiments performed to date but is not necessarily conservative.

f. The strain reduction factor, b, has been taken as 1.5 for API grade pipe. Given a measured stress strain curve that is always increasing, a smaller value may be appropriate. Likewise, for non-API pipe with high yield stress or large wall thickness tolerances, a larger value of b may be warranted.

6.6.3 Vortex-Induced Vibrations

6.6.3.1 For long cylindrical structures such as risers, the following basic model typifies an analysis for VIV:

a. Natural frequencies and mode shapes for bending are determined as accurately as possible.

b. Vortex shedding frequencies are determined (along the riser span) from the Strouhal relationship $f_s = VSt/D$ (where V is the local free stream velocity).

c. Vortex shedding frequencies are compared with the fundamental natural frequencies to see if VIV is possible and to estimate the highest mode in the response (if VIV is not possible, then no further analysis is necessary).

d. If VIV is possible, then the VIV responses are determined from an appropriate model.

e. VIV responses are used to compute the stress amplitudes and corresponding fatigue damage.

f. If required, estimates of the mean drag coefficient for the vibrating riser are obtained.

6.6.3.2 For highly-tensioned risers, a tensioned cable approximation is usually sufficient and conservative for completion of Step a. Otherwise, bending rigidity of a riser must be taken into consideration. Both Steps a and b can be performed for both the in-line (in-line with the flow) and transverse (normal to the flow) directions, however the transverse direction usually experiences somewhat higher bending stresses. Note that *St* is a function of several variables, including *Re*, surface roughness and the level of free stream turbulence.

6.6.3.3 Step c requires the comparison of the highest vortex shedding frequency, F_s,with the lowest natural frequency in bending, f_{n1}. If $F_s/f_{n1} > 0.2$, then in-line VIV is possible. If $F_s/f_{n1} > 0.6$, then transverse VIV is possible. For transverse VIV of a long tensioned riser, the F_s/f_{n1} ratio may be rounded upwards (to the nearest whole number) to estimate the highest transverse bending mode in the response. Note however, that higher harmonics have been observed in some experiments with test cylinders, but none to date are known to have been observed for a marine riser experiencing VIV.

6.6.3.4 Step d is the most difficult step in a VIV analysis. The VIV response depends upon numerous parameters, including *Re*, mass ratio, structural and hydrodynamic damping, the shape of the current profile, the specific modes responding, the riser roughness, etc. Numerous models exist for VIV amplitude prediction of risers experiencing VIV in uniform flows (uniform along the span) and for which the highest response mode is less than about 5. The best of these models are summarized by Blevins,[40] who notes that the predicted amplitudes of the various models differ by only about 15 percent. For low mode response, the response frequency may be conservatively assumed to be equal to the natural frequency of the highest mode excited. For higher mode response, and for situations in which the current is nonuniform or sheared along the riser span, the low mode models are usually overly conservative and accurate prediction of the response is complex. While there is not an accepted way of modeling high mode or sheared flow VIV, several conceptual models have been proposed, including those by Wang and Dalton[50] and Vandiver.[41,42,45] These models account for the possibility of multiple bending modes being excited by a sheared current but require calibration with substantial model or field data before they can be used to confidently make responsible predictions. These models also attempt to properly account for hydrodynamic damping; however, the user must also include the correct structural damping which, for flexible pipe, can sometimes be substantial. The effects of adjacent tubulars should also be considered.

6.6.3.5 Once the VIV response is known, the bending stresses can be easily and accurately determined using common formulas for stress and strain. The bending stresses can then be combined with additional structural information, such as weld types and locations to produce fatigue life estimates. Analysis of wear may also be required for flexible pipe.

6.6.3.6 The predicted VIV amplitudes and frequencies can be used to obtain estimates of the local mean drag coefficients by use of an empirical formula. Blevins reports some of the more common formulas used to estimate these drag coefficients.[40] All of the formulas are in effect an empirical coefficient (which accounts for the vibration) that is multiplied by the local steady drag coefficient for a stationary riser.

6.7 SERVICE LIFE

6.7.1 Fitness-for-Service

A fundamental requirement of any engineering structure is that it should not fail during its service life. Depending on the operating environment and the nature of the applied loading, a structure can fail by a number of different modes. In the case of FPS risers the failure modes of most concern are fracture (brittle fracture, ductile fracture, plastic collapse, etc.), fatigue, and environmental cracking.

The flaw acceptance standards included in the majority of fabrication and construction codes are based on good workmanship practices. More recently, a number of fracture mechanics-based assessment procedures have been developed which enable the significance of weld discontinuities to be assessed on a "fitness-for-service" basis. Using this concept, a structure is considered to be fit-for-service provided it can be operated safely throughout its design life. The adoption of fitness-for-service concepts in several codes has resulted in the development of more rational flaw acceptance criteria.

Fitness-for-service assessment procedures can also be used to assess the significance of flaws or cracks in a structure which may have escaped detection during original fabrication or have developed in service (e.g., fatigue cracks or environmental cracks). These procedures enable operators not only to assess the significance of flaws in structures but determine remaining life, inspections intervals, and inspection sensitivity requirements.

6.7.1.1 Fracture Mechanics Assessment Procedures

6.7.1.1.1 Fracture mechanics seeks to relate the three parameters which combine to control the process of fracture. These parameters are:

a. Size of discontinuity.

b. Material toughness.

c. Applied stress.

6.7.1.1.2 If any two of the three parameters are known, it is then possible (using the principles of fracture mechanics) to estimate the value of the third parameter which will give rise to failure of the structure. Alternatively, if all three parameters are known, it is possible to predict if the structure is fit-for-service and, if so, the margin of safety.

6.7.1.1.3 Figure 40 summarizes the different loading paths that can result in the failure of a statically loaded structure (assuming creep and corrosion effects are not significant). The loading paths range from brittle fracture under nominally elastic loading (applied stresses well below yield) to plastic collapse (overload of remaining ligament).

6.7.1.1.4 In cases where brittle fracture occurs at low applied stresses, the concept of linear elastic fracture mechanics (LEFT) can be applied, i.e., a stress intensity factor (K) approach. At the other extreme when the failure mechanism is plastic overload, assessments should be performed using limit load or plastic collapse analyses.

6.7.1.1.5 Between these two extremes, elastic plastic fracture mechanics (EPFM) methods can be applied to assess the integrity of structures. The two most common EPFM fracture characterizing parameters are the crack-tip opening displacement (CTOD) and J-integral (J). Fitness-for-service methodologies have been developed using both of these parameters.

6.7.1.1.6 A number of different fitness-for-service assessment methodologies for calculating allowable or critical flaw sizes are currently in use throughout the world. Nevertheless, the most widely used assessment methodology for offshore structures is BSI PD6493. This document includes detailed fracture and fatigue assessment procedures for welded structures.

6.7.1.1.7 Fitness-for-service design philosophies can be applied to welded structures in several different ways. The first and most widely used approach is to develop relaxed flaw acceptance criteria which are typically derived assuming a minimum toughness level which is incorporated in a weld procedure qualification. Nevertheless, fitness-for-service concepts can also be used to develop inspection criteria including sensitivity and probability of detection. In addition, fitness-for-service concepts can be used to demonstrate that flaws, which may escape detection, will not impair overall structural integrity even under accident or overload conditions.

6.7.1.2 Fatigue Design

In general, the fatigue life of a component can be broken down into two phases: Crack initiation and propagation. In the case of unwelded components (e.g., machined components), the crack initiation period represents the bulk of the total fatigue life. This is particularly noticeable at high fatigue lives where the fatigue crack initiation period may exceed 95 percent of the fatigue life. In the case of machined components, once a fatigue crack has grown to a detectable size, the component is virtually at the end of its useful life and would normally be withdrawn from service.

In the case of welded joints, there is practically no crack initiation period due to the presence of weld toe discontinuities which behave as preexisting cracks. As a result, the bulk of the fatigue life of a welded joint can be attributed to fatigue crack propagation.

The difference in the fatigue behavior of parent material and welded joints (i.e., the difference in the crack initiation phase) has significant effects on overall fatigue performance and fatigue design. In general, the fatigue strength of unwelded components increases with material tensile strength due to the in-creased initiation life associated with higher strength materials. In the case of welded joints however, the fatigue strength is relatively unaffected by material tensile strength because the bulk of the fatigue life of a welded joint is spent in the propagation phase, and although crack propagation rates can change from one material to another there is no consistent trend with regard to tensile strength.

6.7.1.2.1 S-N Curve Approach

6.7.1.2.1.1 Parent Material S-N Curves

The S-N curve approach is probably the most widely used approach to assess the fatigue performance of parent material. Since the fatigue behavior of parent material components is dependent on a number of parameters including parent material properties (e.g., strength), microstructure, environment, mean stress, etc., it is difficult to develop general fatigue design guidelines to cover parent material components (e.g., castings, changes in section, threaded connections, etc.). If fatigue data does not exist for the material and testing environment under consideration, then the designer must either develop fatigue data on a case by case basis or use a lower bound design S-N curve (e.g., Class B S-N curve in the *U.K. Department of Energy Guidance Notes*, 1990).

Parent material fatigue properties are influenced by mean stress. High mean stress will increase the fatigue damage and reduce the fatigue life. Commonly accepted methods used to account for the effect of the mean stress on the fatigue damage include the Goodman mean stress correction method and the Gerber mean stress correction method. Many fatigue curves have been adjusted for or inherently include the effects of mean stress and no further adjustment is required when using these curves. However, if the fatigue curve being used does not account for the effects of mean stress, then an adjustment of the mean stress effects should be included in the analysis.

6.7.1.2.1.2 Welded Joint S-N Curves

The fatigue behavior of welded structures is reasonably well understood and comprehensive fatigue design rules have been established. The majority of fatigue design codes present a series of S-N curves for different weld joint geometries which have been derived from constant amplitude fatigue test data. The design S-N curves incorporate the effect of the stress concentration due to the weld, and as a result the stress adopted in a design assessment is the nominal far field stress.

A classification system is used to relate details of the welded joint (i.e., weld joint geometry) and the appropriate design S-N curve. In general, the classification depends on the joint type, joint geometry, form of applied loading, and the testing environment. Since these parameters will control the local stress distributions at welded joints, the different design S-N curves can be viewed as a method of accounting for local stress effects arising from weld joint geometry and the form of applied loading. Unlike parent material S-N curves, S-N curves for welded joints are in general, not influenced by mean stress, because the bulk of the fatigue life is spent in the crack propagation phase. In addition, weld residual stress always exists to some extent.

6.7.1.2.2 Fatigue Crack Growth Assessment Procedures

Since the majority of the fatigue life of a welded joint is spent in the crack propagation phase, the analysis of fatigue cracking in welded joints is well suited to fracture mechanics. It can be used to predict the fatigue strength of nominally sound welds by considering the propagation of a fatigue crack from the inherent discontinuities that exist at the weld toe and the weld root. Although the size of these discontinuities is not well defined, it is recommended that a discontinuity depth of 0.2 mm is adopted unless there is a technical justification to adopt a different value. One of the advantages of a fracture mechanics approach is that this method can be used to predict S-N curves for welded joints which do not readily fit into the existing weld joint classifications. In such cases, the user can predict fatigue performance by undertaking a finite element analysis of the welded joint under consideration assuming an initial crack size and compute the anticipated fatigue life.

Fracture mechanics assessment procedures can also be used to predict the life of a joint with a weld discontinuity or a parent material component (e.g., casting of forging) which contains a flaw. The most widely used fatigue crack growth relationship is the Paris Law:

$$da / dN = C(K)^m \qquad (60)$$

where:

K = applied stress intensity factor range.

a = crack size.

N = number of cycles.

C and m = constants which depend on the material and environment.

For design purposes, it is sometimes necessary to estimate the limiting flaw size which will not extend by fatigue during service. The limiting crack size below which fatigue crack growth will not occur can be calculated using fatigue threshold concepts. This information can be useful in defining the required sensitivity of NDT equipment and also drawing up inspection criteria.

Fracture mechanics-based fatigue assessment procedures can also be used to define inspection criteria and in particular inspection intervals. This is achieved by assuming the maximum flaw size which may escape detection and specifying a critical crack size which should be detected to avoid unnecessary damage to the structure or the risk of failure.

6.7.1.2.3 Stresses For Fatigue Assessment

For riser components, both the S-N and fracture mechanics design approaches require knowledge of the magnitude and probability of occurrence of the expected loads applied during either the riser's life or the recommended inspection interval. These expected loads are generated from global riser analyses. The loads used to estimate the fatigue damage generated by the primary wave frequencies are obtained from dynamic global analyses of the riser for the seastates expected during the riser's life or the recommended inspection interval. The expected seastates, along with the probability of occurrence of each, form the "Fatigue Weather Scatter Diagram."

The loads used to estimate the fatigue damage generated by the low frequency wave drift are obtained from global analyses of the riser using the low frequency wave-induced motions of the FPS. These loads can be generated using static or dynamic global analyses, depending on the frequency of the motion. Dynamic analyses should be performed if the inertial loads generated by the low frequency wave-induced motions are significant. The loads generated by VIV must be obtained from a VIV analysis of the riser.

It is important to remember that all of the loads that contribute to fatigue damage of the riser components are cyclical in nature. A number of cycles or probability of occurrence for each type of load must be known to estimate the expected fatigue damage. For the primary wave cycle damage, this information is usually given in the terms of number of wave cycles for a deterministic analysis and number of storms for a spectral (stochastic) analysis.

When assessing parent material components or welded joints in the post-weld heat-treated condition, the stress range required for a fatigue assessment is the total stress range if the stress range is entirely tensile. In situations where the stress range is partly compressive, then the stress range for the fatigue analysis should be taken as the entire tensile stress range plus 60 percent of the compressive stress range. For welded joints in the as-welded condition, the stress range to be used in fatigue assessments should be based on the full stress range regardless of whether the stress range is partly or wholly compressive.

In the S-N fatigue approach, peak stress ranges are calculated for each bin in the fatigue weather scatter diagram. These peak stress ranges are equal to the product of the dynamic pipe wall stresses obtained from the global riser analysis and the stress amplification factors (SAFs) calculated for the riser components. The dynamic pipe wall stresses are calculated from the dynamic bending moments and the dynamic tension variations. The SAFs are derived by local finite element analysis of a structural component. The SAFs represent the stress increase caused by geometry, three-dimensional effects and load paths through the structural component.

In cases of variable amplitude loading, the Miner cumulative damage summation is used to sum the damage from the different loads. As long as all of the load cycles are included in the analysis, the total damage obtained using the cumulative damage summation is not affected by the sequence in which the loads are applied to the riser component. The method used to estimate the fatigue damage is different for the deterministic and spectral analysis methodologies. See API RP-2A for a description of the deterministic and spectral fatigue analysis methodologies. The estimated fatigue life is equal to the inverse of the annual damage generated by the fatigue loads. The total fatigue damage is equal to the combined damage generated by the fatigue loads (i.e., combined primary wave frequency, low frequency wave drift, and FPS offset-induced damage plus VIV damage) if the installation damage is negligible. (See 6.2.5.4.)

Care must be taken in calculating the stresses and SAFs to be used in the fatigue analysis. Relatively small changes in the stresses and SAFs can result in large differences in fatigue life. Fatigue life is proportional to the stress ranges and SAFs, each raised to the power of the S-N curve inverse slope (from 3 to 5). It can be demonstrated that, for an S-N slope of 5, doubling of either the stress range, SAF, or any product of these, decreases fatigue life by a factor of 32. For example, if the structural component had a fatigue life of 100 years, doubling the product of the stress range and SAF would reduce the fatigue life to 3 years.

6.7.1.3 Environmental Cracking

Environmentally-assisted cracking is common in components which operate in aggressive (e.g., sour) environments. Environmentally-assisted cracking or degradation can take many forms ranging from local thinning caused by global corrosion attack to stress corrosion cracking and hydrogen-induced cracking or hydrogen blistering. The form of cracking or degradation is dependent on a number of factors including the material, chemical composition and microstructure, weld metal and properties of the heat effected zone (including hardness), weld geometry, level of welding residual stresses, operating conditions, and environment.

When assessing environmentally-assisted cracking on a fitness-for-service basis, the user must first identify the cause of cracking or damage and assess the possibility of further growth or damage, i.e., is the cracking associated with original fabrication defects or previous operating conditions which were more severe than current conditions (e.g., upset conditions or a change in operating conditions). If the possibility of further growth or damage exists, the user must estimate remaining life and determine appropriate inspection intervals or develop an on-stream monitoring approach. The basic options for treating a component which has experienced environmentally-assisted cracking are as follows:

a. Prevent further cracking or damage.

b. Predict remaining life using appropriate crack growth law and determine appropriate inspection intervals.

However, before proceeding with any of the above options, the engineer must first assess the limiting crack or flaw size which could result in failure of the component. The limiting flaw size should then be compared with the cracks or flaws that have been detected to determine the maximum allowable crack growth.

6.7.1.3.1 Prevention of Further Cracking

Prevention of further crack growth can be addressed by either changing the operating conditions (e.g., downrating) or increasing the resistance to further environmental attack through the use of protective coatings, etc. One of the most important assessment parameters for components operating in aggressive environments is the threshold stress intensity factor to prevent further crack growth, frequently referred to as KISCC. Assessments can be performed using KISCC to predict acceptable combinations of crack size and applied stress, i.e., combinations which will not give rise to subsequent crack growth in service. This concept can also be applied in design to ensure that original fabrication flaws will not extend in service. Unfortunately, KISCC is dependent on both material and operating conditions and appropriate values can be difficult to obtain.

The fatigue stress intensity factor threshold should also be considered when assessing the possibility of subsequent crack growth. It should be noted that the fatigue stress intensity factor threshold is also very sensitive to the environmental conditions.

6.7.1.3.2 Predict Remaining Life Using Crack Growth Law and Determine Inspection Intervals

If further crack growth in service cannot be ruled out, a remaining life assessment should be performed. The first step in performing a remaining life assessment is to predict the limiting crack or flaw size which could result in failure of the component. The limiting flaw size is then compared with the cracks or flaws that have been detected to determine the maximum allowable crack growth.

Depending on the material and the operating conditions, environmental crack growth relationships can take several forms. In most cases, the rate of crack growth is a function of the applied stress intensity factor although there are some forms of environmental cracking which are simply a function of time. With this in mind, it is essential that the user selects an appropriate crack growth relationship for the component and operating conditions under consideration. This can be a major problem since crack growth rates can be very sensitive to changes in the process environment. Nevertheless, assuming an appropriate crack growth relationship is available, the user can calculate the number of cycles or time required for the existing cracks to increase to a critical size. This information can then be used to set inspection intervals to monitor crack growth and enable the user to decide when to take remedial action or withdraw the component from service.

6.7.2 Wear

Wear and friction must be considered together as wear causes surface damage which can act as initiation sites for fatigue cracks to develop. On its own, wear is not considered a problem structurally, as the loss of material is often insignificant for stress considerations. However, its effect on fatigue can be to greatly accelerate it, often causing fretting fatigue failure. Fretting fatigue is particularly important for risers having two metal armor layers in contact with each other. All calculations for wear must be considered as approximate since wear process is not fully understood. However, from limited data available, it appears to be a strong function of friction and the strengths of the material on either side of the interface.

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6.9 NOMENCLATURE FOR SECTION 6.3

A = Cross sectional area of the riser.

Ax = In-line oscillating amplitude.

A_y = Transverse oscillating amplitude.

A_x/D, A_y/D = Amplitude ratio.

C_a = Added mass coefficient.

C_d = Mean drag coefficient.

C_d' = Fluctuating drag coefficient.

C_L = Mean lift coefficient.

C_L' = Fluctuating lift coefficient.

C_M = Hydrodynamic inertia coefficient.

C_{dn}, C_{dt} = Normal and tangential drag coefficients of an inclined cylinder.

D = Riser outer diameter or drag diameter.

Du/Dt = Material derivatives of u: =ˈu/ˈt + uˈu/ˈx + v ˈu/ˈy + w ˈu/ˈz.

f = Riser oscillating frequency.

f_s = Vortex shedding frequency.

F = Generalized loading function.

F_I, F_D = Hydrodynamic inertia and drag forces per unit length.

F_L = Hydrodynamic lift force per unit length.

$G(\theta)$ = Wave spreading function.

H_s = Significant wave height.

k = Height of surface roughness.

k_n = Wave number associated with frequency ω_n.

KC = Keulegan-Carpenter number (u_{max} T/D) or ($\dot{x}_{max}$ T/D).

L_y = Transverse length scale of free stream turbulence.

Re = Reynolds number ($U_\infty D/\nu$) or ($u_{max} D/\nu$) or ($\dot{x}_{max} D/\nu$).

St = Strouhal number ($f_s D/U_n$).

$S(\omega)$ = Wave spectral density.

T = Period of wave motion.

T_p = Peak period of the wave spectrum.

T_z = Zero crossing period.

$\hat{u}$ = Root mean square of free stream turbulence fluctuation.

u_{max} = Maximum value of u normal to the riser axis.

u, v, w = Wave particle velocity components in local coordinates (Figure 34).

U_∞ = Free stream current velocity.

U_n = Normal component of free stream current.

$U_n/(fD)$ Reduced velocity.

V = Wave particle velocity in global coordinates.

x = In-line displacement of the riser.

$\dot{x}$, $\ddot{x}$ = Lagrangian velocity and acceleration of the riser in local coordinates.

X = Longitudinal centerline spacing of two risers.

Y = Transverse centerline spacing of two risers.

ρ = Mass density of the sea water.

$\sigma(\,)$ = Standard deviation of ( ).

ν = Kinematic viscosity.

θ_o = Main direction of the waves.

θ = Wave spreading angle.

ω = Wave frequency.

ε = Random phase distributed between 0 and 2π.

α = Inclination angle of the riser about the horizontal plane.

η = Wave profile.

Γ = Gamma function.

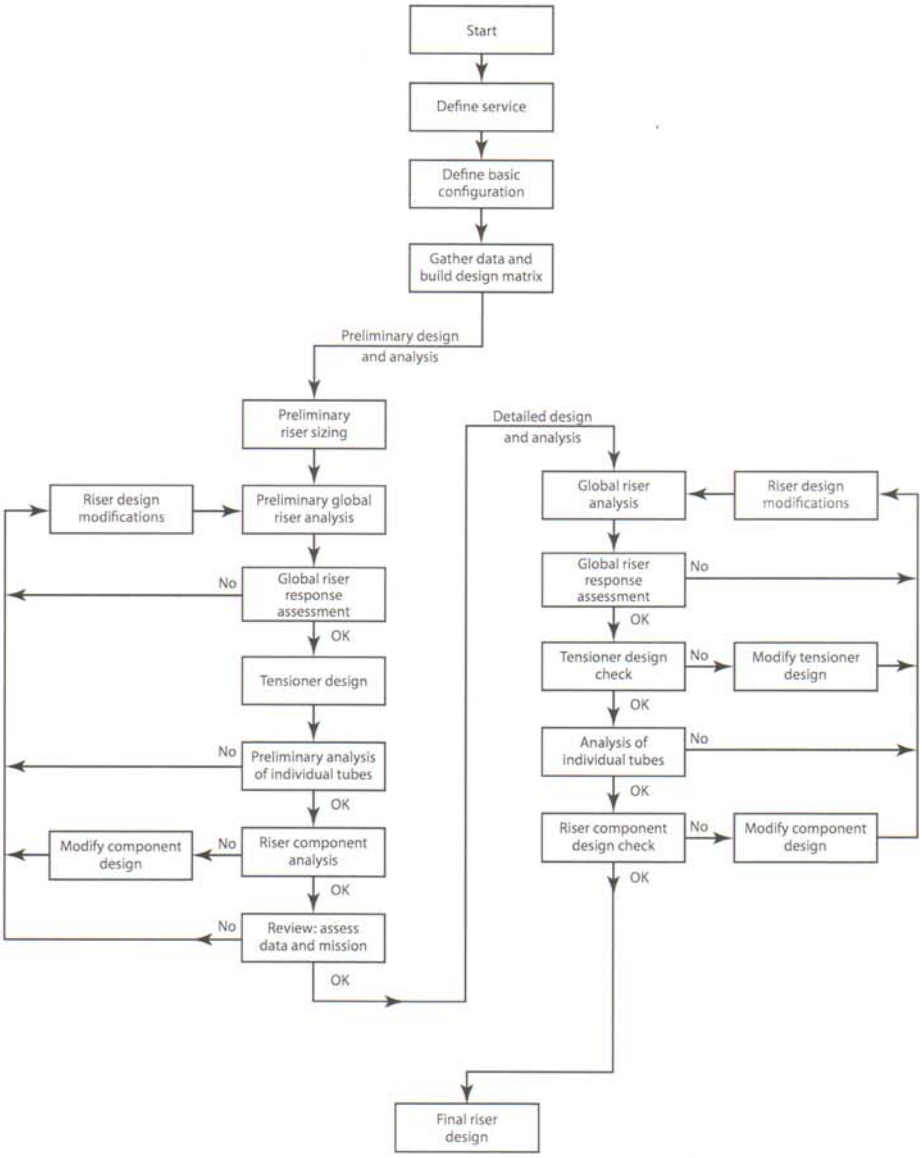

Figure 29—Design/Analytical Procedure for Top Tensioned Risers

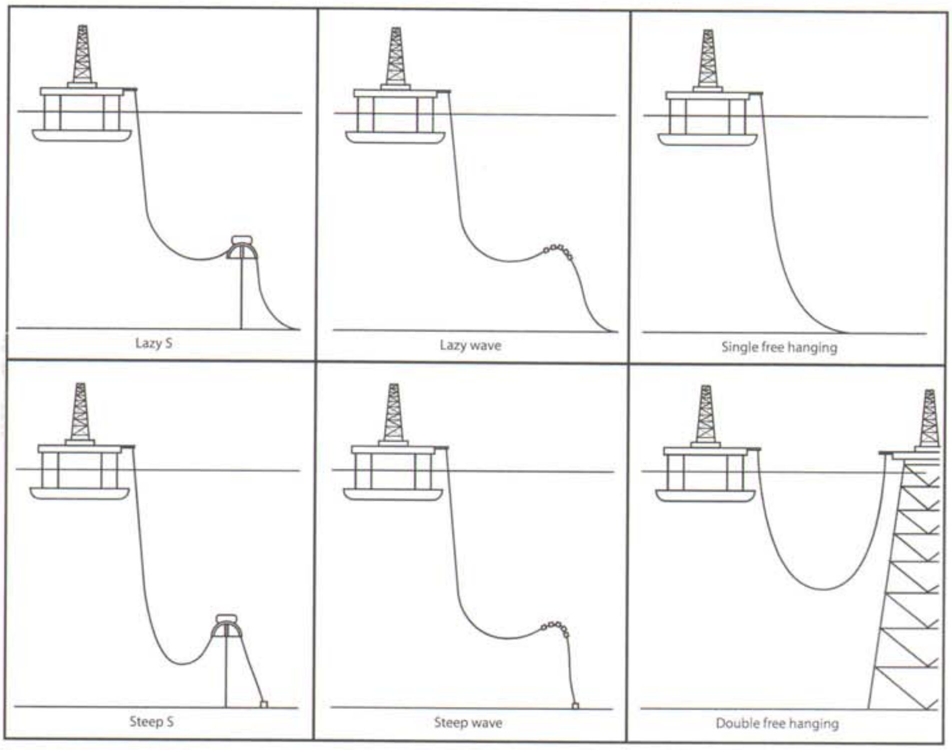

Figure 30—Flexible Riser Applications

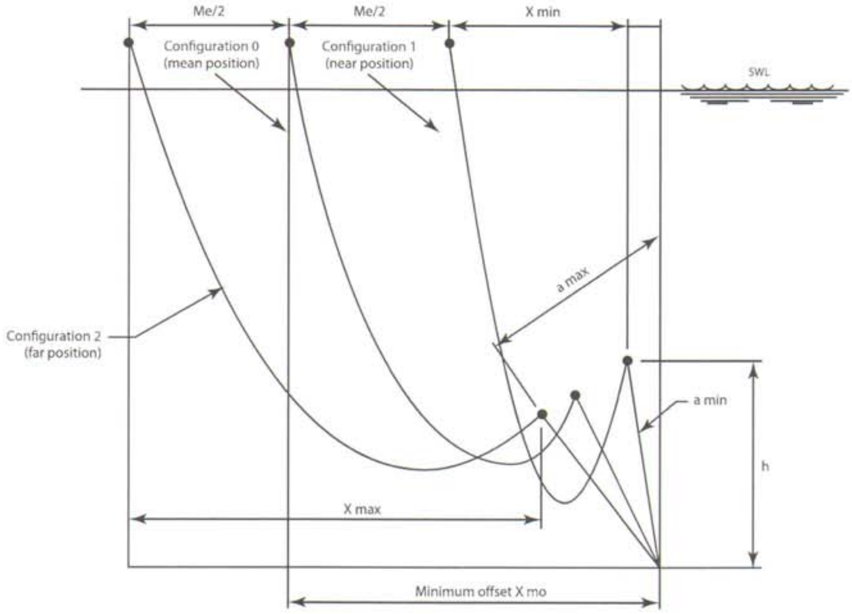

Figure 31—FPF Static Offset

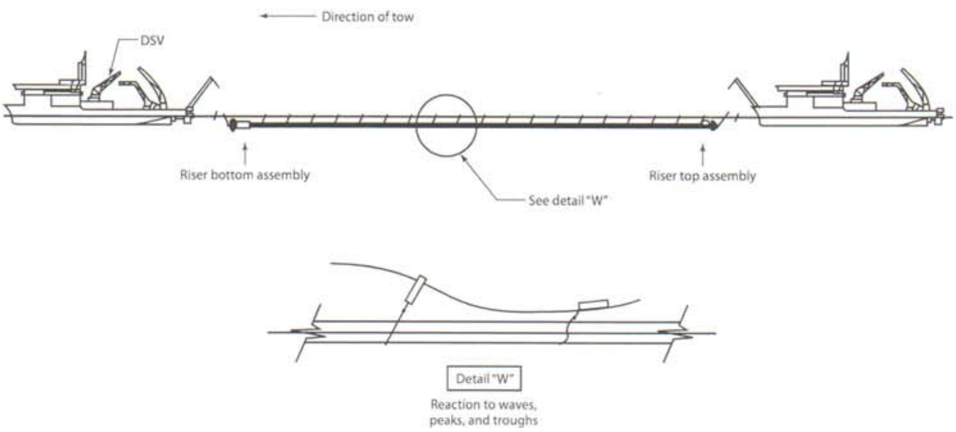

Figure 32—Hybrid Riser Tow-out Option

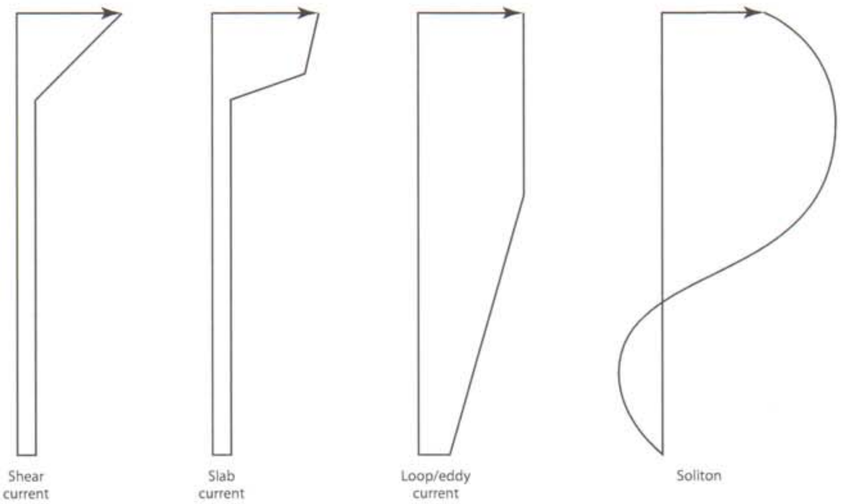

Figure 33—Current Profiles

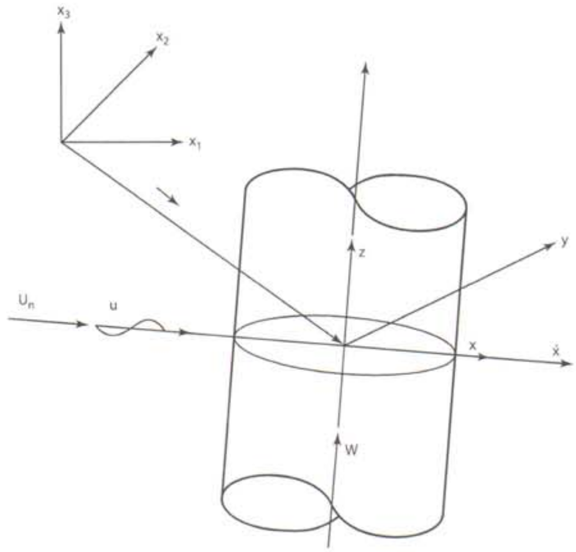

Figure 34—Local Coordinate System (x,y,z) vs. Global Coordinate System (x_1,x_2,x_3)

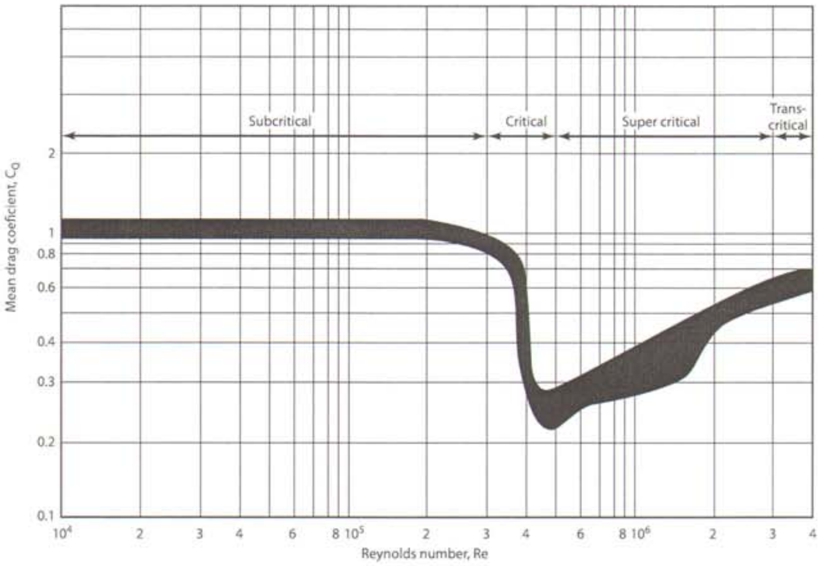

Figure 35—Drag Coefficient of a Smooth Circular Cylinder

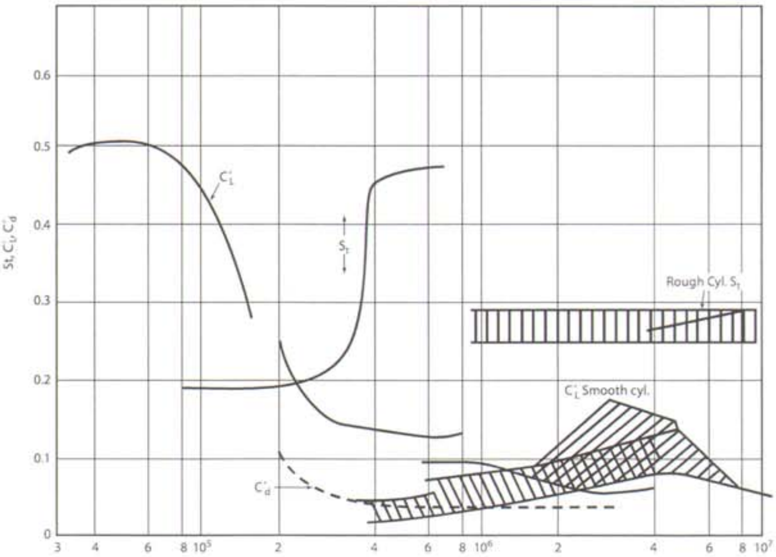

Figure 36—Variations of C_L, C_d, and S_t

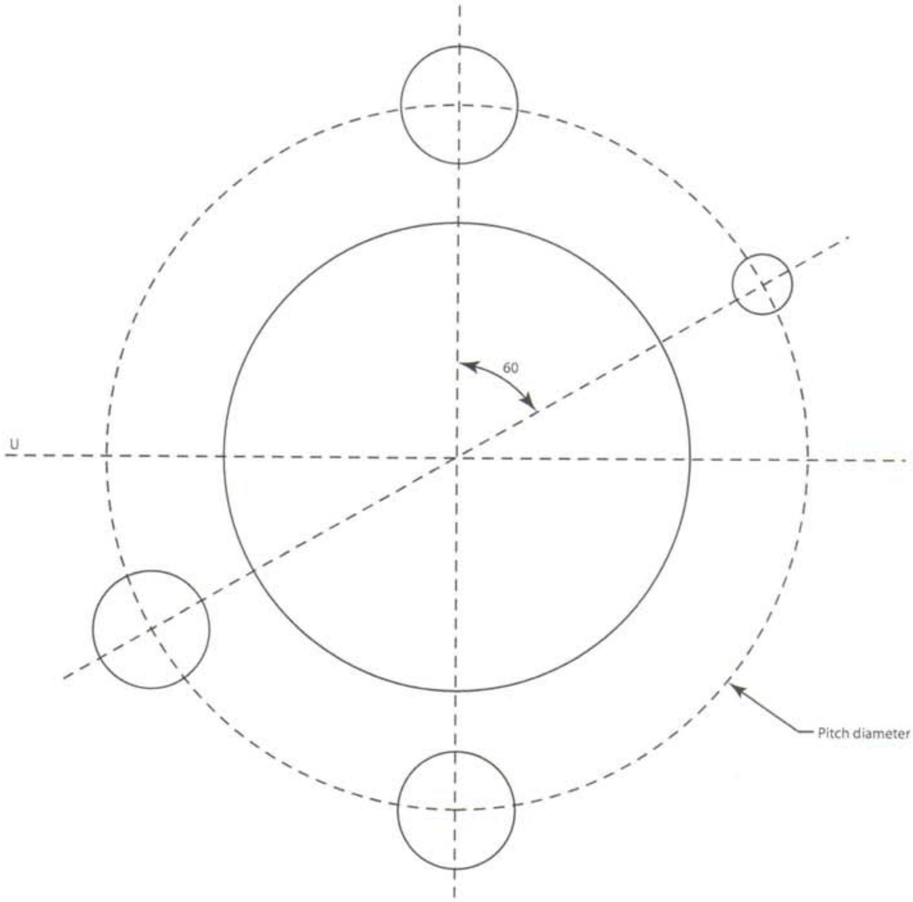

Figure 37—Satellite Lines on Circumference of a Bare Drilling Riser

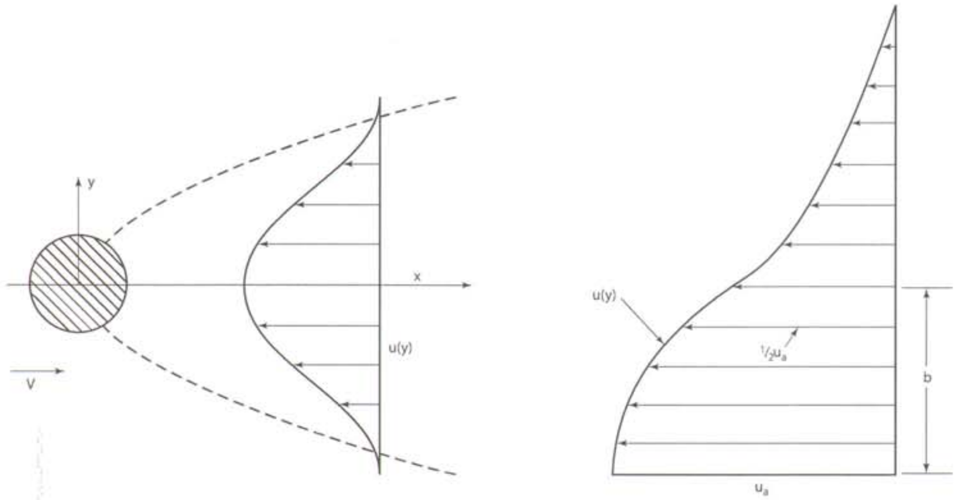

Figure 38—Wake Profile Behind a Cylinder in Stationary Flow (Left) and Definition of Wake Half Width (Right)

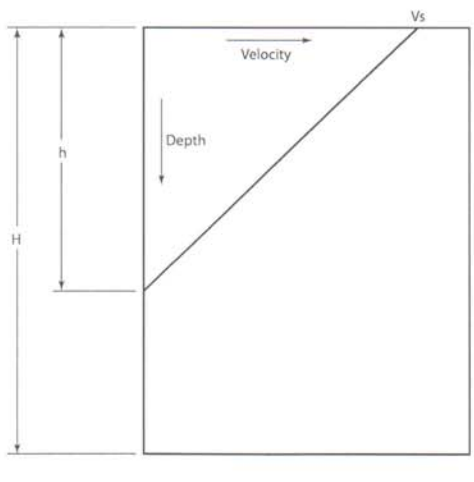

Figure 39—Definition of Current Profile Parameters

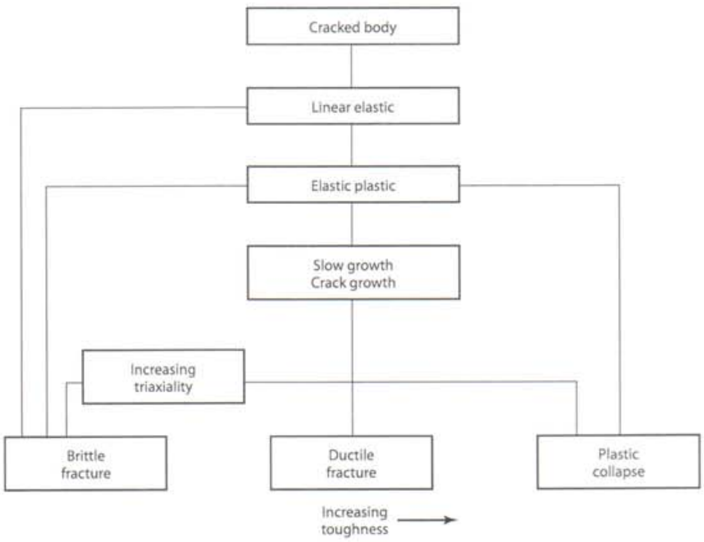

Figure 40—Summary of Loading Paths to Static Failure

7 Materials

7.1 SCOPE AND PURPOSE

This section defines the materials, their processing, and performance characteristics appropriate for use in FPS riser design. Steel, titanium, and the material components of flexible (non-bonded) pipe are covered. Other materials, such as aluminum, are not excluded if risers built using these materials can be shown to be fit for purpose. Running and handling tools are not covered in this section.

7.1.1 Specifications

7.1.1.1 The material should conform to an established specification and to the minimum strength level, group, and class in accordance with the design. In situations where an appropriate ASTM, API, ASME, AWS, or other equivalent specification does not exist, a materials or fabrication specification should be developed, subject to preproduction qualification and used as appropriate for each situation.

7.1.1.2 For metallic structures, certified mill test reports or certified reports of tests made by the fabricator or a testing laboratory in accordance with DIN 50049 or equivalent constitutes evidence of conformity with the specification. Nonmetallic structures should be certified to comparable standards.

7.1.2 Material Considerations

Factors that should be considered when selecting materials include:

7.1.2.1 Tensile Properties

The riser analysis will determine the tensile characteristics that should be specified for the material. Tensile characteristics can include yield strength, ultimate strength, modulus of elasticity, Poisson's ratio, elongation, reduction of area, and strain-to-failure.

7.1.2.2 Fracture Toughness

The minimum fracture toughness of the material should be such that brittle fracture is avoided at the expected stress levels over the anticipated service life and at the lowest anticipated service temperature (LAST). Fracture mechanics-based flaw-tolerance considerations are appropriate. Toughness and fracture avoidance considerations are usually more critical for highly-loaded members, at areas of stress concentration, at regions of material inhomogeneities such as welds, and at low service temperatures. Caution should be exercised in comparing results from one method of fracture toughness testing (Charpy, CTOD, drop weight tear tests, etc.) to another. Material (steel, titanium, etc.) and material form (tubing, piping, forging, plate, etc.) may dictate the best testing technique.

7.1.2.3 Service Temperature

The environmental conditions will determine the temperature ranges in which the material is expected to function. The LAST will determine the toughness characteristics that should be specified for the material. Test loads should also be considered when selecting material strengths.

7.1.2.4 Fatigue Resistance

The fatigue resistance of the material should be compatible with the expected fatigue stresses over the anticipated service life. The environmental loadings usually cause the greatest fatigue related loading in a riser. It is important that good environmental information and surface vessel response data are used to predict the fatigue life.

7.1.2.5 Internal Erosion or Wear

Internal erosion or wear can be caused by abrasive elements (e.g., sand) in the produced fluid and passage or rotation of downhole equipment. It can also be caused by a high flow rate with turbulent flow characteristics at flow area changes in the riser. This should be taken into account when selecting materials that will be in contact with the flow. API RP 14E provides guidance on erosional velocity constraints.

7.1.2.6 H_2S

Sulfide stress cracking can cause many materials to fail prematurely and catastrophically. If H_2S is present in the fluids, NACE MR0175 should be consulted to determine acceptable materials for use in these conditions.

7.1.2.7 Internal Corrosion

Internal corrosion can be caused by the fluid chemically reacting with the material (e.g., chlorides, CO_2, H_2S, completion or treatment fluids). This can be addressed in different ways including inhibitor injection in the flow, material selection, or coating the surfaces that are subjected to the corrosive environment.

7.1.2.8 External Corrosion

External corrosion can be caused by numerous conditions. Depending upon the mode of corrosion, the preventative action can vary. Possible solutions include: placement of sacrificial anodes, material selection, and coating the material.

7.1.2.9 Welding

The final properties of welded areas should be taken into consideration. Acceptance criteria should be established for all weld joints.

7.1.2.10 Code Requirements

Materials which are to be used in components requiring regulatory agency review may require certification in accordance with the appropriate design code.

7.2 MATERIAL CLASSIFICATION

This section defines and classifies materials appropriate for use in the design and construction of FPS riser systems. All materials, components and joints between components should be designated according to three design classes. The design classes are: Primary, Secondary, and Tertiary. These design classes form the basis for selection of structural metallic materials and riser components and identification of appropriate inspection and maintenance programs.

In addition, seals may form a separate class. Metal or elastomeric elements that maintain pressure integrity but serve no other role in the riser system should be designated as a Seal Class. An example of such applications are the ring gaskets in collet connectors and the O-rings in subsea wellhead systems.

7.2.1 Primary Class

7.2.1.1 Structural materials or riser components (or parts thereof) for which failure may induce a complete failure in the riser system or interruption in production, should be designated as a Primary Class.

7.2.1.2 Material fracture toughness characteristics for this class should be suitable for the conditions of service.

7.2.1.3 This class includes materials suitable for use at subfreezing temperatures and for critical applications involving adverse combinations, where cold work, stress concentration, impact loading, or lack of redundancy indicate the need for improved material toughness characteristics.

7.2.1.4 This class may also include materials involving limited thickness, moderate forming, low restraint, and a small or modest stress concentration factor, where the lack of redundancy of the riser system may cause a catastrophic failure due to an isolated fracture of the material.

7.2.1.5 Examples of such applications are main components in subsea wellhead systems, stress joints, riser joints, and mechanical connection in tie-back production systems, riser bottom connectors, casings and transition spools in surface wellhead systems and main components of tensioning systems.

7.2.2 Secondary Class

7.2.2.1 Structural materials, riser components, or parts of components and welds of reduced criticality should be designated as a Secondary Class. This class includes materials for components that have enough structural redundancy. In this case the fracture of the material or the failure of the component does not cause an interruption in production or the catastrophic failure of the riser system.

7.2.2.2 Materials that might normally be considered critical in application may be identified as a Secondary class if the design is determined to be sufficiently robust.

7.2.3 Tertiary Class

Materials, riser components, or parts of components that are not considered structurally critical should be designated as Tertiary Class. This class may include attachments such as anodes, temporary welds, etc.

7.3 MATERIAL FORMS

7.3.1 Tubulars

7.3.1.1 General

7.3.1.1.1 This section covers steel and titanium tubulars and flexible (non-bonded) pipe. Tubulars should be procured in accordance with a written procurement specification which clearly defines all performance criteria and required properties of the tubulars. The general requirements of a Quality Assurance System should be implemented by the tubular manufacturer. As a minimum, tubulars should be manufactured and tested in accordance with the requirements of API SPEC 5L, API SPEC 5CT, or equivalent industry standards for metallic tubulars and API Spec 17J or equivalent industry standard for flexible pipe.

7.3.1.1.2 Manufacturing procedure specification and quality plan—It is recommended that tubulars be manufactured in accordance with a Manufacturing Procedure Specification (MPS) that has been reviewed and approved by both the manufacturer and operator. An MPS is defined as a detailed written step-by-step plan for manufacture, describing specific methods, materials, equipment, and activities which the manufacturer shall use specific to the particular order of tubulars.

7.3.1.1.3 It is recommended that quality control testing and inspection of tubulars be conducted in compliance with a Quality Plan (QP) that has been reviewed and approved by both the manufacturer and operator. A QP is defined as a written document setting out specific quality practices, resources, and sequence of activities relevant to quality control testing and inspection of the tubulars, specific to the particular order of tubulars.

7.3.1.2 Materials Selection and Process of Manufacture

The specific chemical composition should be mutually approved between the tubular manufacturer and operator after thorough review of performance criteria, manufacturing method, required properties and fabrication method (e.g., upset and threaded, girth welded, etc.). For girth-welded tubulars, special attention should be paid to control of elements affecting weldability and subsequent HAZ properties.

Steel and titanium tubulars may be manufactured by either a seamless or a seam-welded process. In case of seam-welded processes, special attention should be paid to both the process controls and NDT employed for the seam weld in order to reliably ensure required properties are met and that defects are controlled to within specified levels.

7.3.1.2.1 Steel

Steel tubulars should be manufactured by either the seamless process, electric-resistance welded (ERW), or double-submerged arc welded (DSAW) seam-welded processes.

It is recommended that tubulars be manufactured by a steel making process that includes vacuum degassing resulting in a fully-killed steel and a fine (ASTM 7 or finer) grain structure.

7.3.1.2.2 Titanium

Titanium alloys may be generally classified as alpha, alpha-beta, or beta type alloys, depending on the extent and type of alloying elements added. Some examples of commercial titanium alloys which are potential candidates for marine riser tubular service are given in Table 6.

Specific compositional limits and tensile property minimums for these and other titanium alloy tubular products may be found in ASTM B-337 and ASTM B-338 tubular product specifications.

In general, titanium tubulars are produced via the same methods utilized for steel tubulars, but special precautions must be employed. During processing, titanium absorbs oxygen and hydrogen that will degrade mechanical properties. Oxygen contamination is surface related and can be minimized via coatings during hot working. During pipe finishing, this case layer must be removed either by chemical cleaning or mechanical methods.

7.3.1.2.3 Flexible (Non-Bonded) Pipe

A non-bonded flexible pipe is a multilayer structure composed of thermoplastic and structural steel layers as described in Section 2.4.2.3.2.

7.3.1.2.3.1 Thermoplastic Materials

Thermoplastic materials used in flexible pipe manufacture are often made of high density polyethylene; cross-linked polyethylene; nylons 6, 11, and 12; polyvinyldene fluoride (PVDF) and polypropylene. Selection of material types, grades and additives should be guided by functional requirements. Data on candidate grades should be reviewed for the following:

a. Internal/external fluid tightness.

b. Long term allowable strains.

c. Wear resistance.

d. Fluid and chemical compatibility.

e. Creep resistance under service conditions.

f. Modulus stability.

g. Aging resistance and change in properties for anticipated service conditions over service life.

In order to select the thermoplastic material, manufacturer and operator should review the following information:

a. Fluid composition.

b. Service temperature and anticipated temperature excursions.

Table 6—Titanium Alloys for Riser Use

Alloy type	Alloy	ASTM grade (UNS number)	Minimum yield strength MPa (ksi)
alpha	Ti-0.3Mo-0.8Ni	12 (R53400)	345 (50)
near-alpha	Ti-3Al-2.5V	9 (R56320)	483 (70)
	Ti-3Al-2.5V-0.05Pd	18	
	Ti-3Al-2.5V-0.1Ru	—	
alpha-beta	Ti-6Al-4V	5 (R56400)	759-827 (110-120)
	Ti-6Al-4V ELI	23	
	Ti-6Al-4V-0.05Pd	24	
	Ti-6Al-4V-0.1Ru	—	
beta	Ti-3Al-8V-6Cr-4Zr-4Mo	19	793-1172 (115-170)

c. Frequency and duration of exposure to fluids used for temporary operations (e.g., well stimulation acids, oxygen scavengers, inhibitors, etc.).
d. Operating pressure and depressurization frequency and rate. Qualification testing is advisable where new material grades are being used or where the service conditions are outside the experience base. Qualification test requirements should be agreed upon by manufacturer and operator.

7.3.1.3 Materials Qualification

Qualification of materials used in metallic tubulars and flexible pipe are outlined in this section. It is recommended that tubular materials be qualified in accordance with a documented qualification plan that has been reviewed and approved by both the manufacturer and operator.

7.3.1.3.1 Metallic Tubulars

7.3.1.3.1.1 Qualification Test Samples (QTS)

This section refers to qualification test samples (QTS) for metallic tubulars. QTS for tubulars should take the form of test rings which are suitable for subsequent extraction of mechanical test specimens cut from tubulars in their final as-rolled or heat-treated condition. A QTS should be cut from one tubular at approximately the midpoint of each production lot. For these purposes a production lot is defined as all tubulars heat treated together either as a batch or sequentially in an uninterrupted continuous operation with the same nominal dimensions from the same heat.

7.3.1.3.1.2 Mechanical Properties

Tensile test specimens should be extracted and tested from QTS representing each production lot. As a minimum, the following tensile properties should comply with design requirements:

a. Yield strength.
b. Ultimate strength.
c. Percent elongation.
d. Percent reduction of area.

7.3.1.3.1.3 Fracture Toughness (Tubulars)

Fracture toughness testing of production material is recommended (e.g. as per ASTM E1290, ASTM E992, ASTM E399, ASTM E813 or equivalent). Test temperatures for fracture toughness tests should be according to Table 7. Toughness values are to be specified by owner or operator consistent with the design and fitness-for-purpose practices.

For titanium alloys, the plane-strain fracture toughness tests (per ASTM E-399 or equivalent) are recommended. (See Table 7 for test temperatures.)

7.3.1.3.2 Flexible Pipe

7.3.1.3.2.1 Polymeric Materials

The adequacy of polymers in relation to phenomena such as aging, fatigue, creep, environmental stress cracking, swelling due to water/oil absorption, UV light degradation, wear/abrasion, and blistering shall be considered for qualification testing. Samples for testing shall be taken from material extruded on to a flexible pipe with representative dimensions or an equivalent procedure. It is recommended that qualification test requirements for the polymer sheath layers, antiwear layers and tapes, and insulation be reviewed and approved by both the manufacturer and operator.

7.3.1.3.2.2 Metallic Materials

As a minimum, the following tensile properties should comply with design requirements:

a. Yield strength.
b. Ultimate strength.
c. Percent elongation.
d. Percent reduction of area.

In addition, the material grade designation, heat treatment, surface treatment, and lubricator (where relevant) shall be documented.

7.3.1.4 Inspections

7.3.1.4.1 Metallic Tubulars

As a minimum all riser tubulars should be ultrasonically examined over 100 percent of the pipe body in accordance with API Spec 5CT SR2 ($12^1/_2$ percent reference notch), for both longitudinal and transverse defects. Depending upon design requirements (i.e., fracture mechanics fatigue predictions) a more severe reference notch or side-drilled hole may be warranted. The ends of upset tubulars and coupling stock should also be inspected with ultrasonics to equivalent criteria. In addition, the ends of all tubulars, whether upset or not, and all coupling stock should be magnetic particle inspected for both transverse and longitudinal defects.

For additional references regarding the ultrasonic inspection of titanium tubulars, the user may refer to AMS 2236 or MIL STD 2154. MIL STD 6866 is a common standard used when performing liquid penetrant inspection of titanium components.

7.3.1.4.2 Flexible Pipe

Inspection requirements for flexible pipe shall be in accordance with API Spec 17J or as agreed upon by manufacturer and operator.

Table 7—Toughness Testing Recommendations

Service Class —>		Primary		Secondary	
Material Form		Toughness Testing Recommended	Test Temperature	Toughness Testing Recommended	Test Temperature
Metallic Tubulars	Steel	Fracture Toughness	<=LAST if not girth-welded <=LAST –36°F (–20°C) if girth welded	Charpy V-notch	<=LAST –18°F (10°C)
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST
Forgings and Extrusions	Steel	Fracture Toughness	<=LAST	Charpy V-notch Impact	<=LAST –18°F (10°C)
		Drop-Weight Tear	<=LAST –50°F (–28°C)	Drop Weight Tear	<=LAST
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST
Castings	Steel	See Note 5		Charpy V-notch Impact	<=LAST –18°F (10°C)
				Drop Weight Tear	<=LAST
	Titanium			Fracture Toughness	<=LAST
Structural Shapes and Plates	Steel	Fracture Toughness	<=LAST –36°F (20°C)	Charpy V-notch Impact	<=LAST –36°F (20°C)
		Drop Weight Tear	<=LAST –50°F (28°C)	Drop Weight Tear	<=LAST
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST

Notes:
1. Tertiary Service Class—Toughness Testing Not Required
2. Fracture Toughness testing for steels per ASTM E1290, E992, E399, E813 or equivalent; for titanium per E399.
3. Charpy V-notch tests per ASTM E23 or equivalent.
4. Drop Weight Tear Test per ASTM E208 or equivalent.
5. Castings generally are not recommended for primary service. However, if deemed suitable, toughness requirements should be specified by owner.

7.3.2 Forgings and Extrusions

7.3.2.1 General

This section covers steel and titanium forgings and extrusions. Forgings and extrusions should be procured in accordance with a written specification and Quality Assurance System. The following text identifies elements to be considered in development of the written specification.

7.3.2.2 Alloy Selection and Process of Manufacture

The specific chemical composition should be mutually approved between the tubular manufacturer and operator after thorough review of performance criteria, manufacturing method and required properties.

The designer should consult with manufacturers and experts as to the appropriate specifications for the desired application. When selecting a suitable composition, designers and metallurgists should as a minimum, consider the following:

a. Will the forging or extrusion contain structural weldment?
b. Will repair welding be allowed?
c. Will there be stress relief after welding?
d. Will the selected composition achieve specified mechanical properties (including toughness) in the critical cross section and in the HAZ for forgings to be welded?

7.3.2.2.1 Steel

It is recommended that all primary service class forgings and extrusions be manufactured by a steel making practice that includes vacuum degassing or argon-oxygen decarburization resulting in a fully killed steel and a fine (ASTM 5 or finer) prior austenitic grain structure.

A range of chemical composition specifications may be considered suitable for forgings and extrusions, depending on the design requirements. The following chemical composition specifications may be considered for forgings and extrusions:

a. AISI 41xx.
b. AISI 43xx.
c. AISI 86xx.
d. ASTM A182 Grade F22.
e. ASTM A336 Class F22.

Table 7—Toughness Testing Recommendations

Service Class —>		Primary		Secondary	
Material Form		Toughness Testing Recommended	Test Temperature	Toughness Testing Recommended	Test Temperature
Metallic Tubulars	Steel	Fracture Toughness	<=LAST if not girth-welded <=LAST –36°F (–20°C) if girth welded	Charpy V-notch	<=LAST –18°F (10°C)
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST
Forgings and Extrusions	Steel	Fracture Toughness	<=LAST	Charpy V-notch Impact	<=LAST –18°F (10°C)
		Drop-Weight Tear	<=LAST –50°F (–28°C)	Drop Weight Tear	<=LAST
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST
Castings	Steel	See Note 5		Charpy V-notch Impact	<=LAST –18°F (10°C)
				Drop Weight Tear	<=LAST
	Titanium			Fracture Toughness	<=LAST
Structural Shapes and Plates	Steel	Fracture Toughness	<=LAST –36°F (20°C)	Charpy V-notch Impact	<=LAST –36°F (20°C)
		Drop Weight Tear	<=LAST –50°F (28°C)	Drop Weight Tear	<=LAST
	Titanium	Fracture Toughness	<=LAST	Fracture Toughness	<=LAST

Notes:
1. Tertiary Service Class—Toughness Testing Not Required
2. Fracture Toughness testing for steels per ASTM E1290, E992, E399, E813 or equivalent; for titanium per E399.
3. Charpy V-notch tests per ASTM E23 or equivalent.
4. Drop Weight Tear Test per ASTM E208 or equivalent.
5. Castings generally are not recommended for primary service. However, if deemed suitable, toughness requirements should be specified by owner.

7.3.2 Forgings and Extrusions

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This section covers steel and titanium forgings and extrusions. Forgings and extrusions should be procured in accordance with a written specification and Quality Assurance System. The following text identifies elements to be considered in development of the written specification.

7.3.2.2 Alloy Selection and Process of Manufacture

The specific chemical composition should be mutually approved between the tubular manufacturer and operator after thorough review of performance criteria, manufacturing method and required properties.

The designer should consult with manufacturers and experts as to the appropriate specifications for the desired application. When selecting a suitable composition, designers and metallurgists should as a minimum, consider the following:

a. Will the forging or extrusion contain structural weldment?
b. Will repair welding be allowed?
c. Will there be stress relief after welding?
d. Will the selected composition achieve specified mechanical properties (including toughness) in the critical cross section and in the HAZ for forgings to be welded?

7.3.2.2.1 Steel

It is recommended that all primary service class forgings and extrusions be manufactured by a steel making practice that includes vacuum degassing or argon-oxygen decarburization resulting in a fully killed steel and a fine (ASTM 5 or finer) prior austenitic grain structure.

A range of chemical composition specifications may be considered suitable for forgings and extrusions, depending on the design requirements. The following chemical composition specifications may be considered for forgings and extrusions:

a. AISI 41xx.
b. AISI 43xx.
c. AISI 86xx.
d. ASTM A182 Grade F22.
e. ASTM A336 Class F22.

f. ASTM A350 Grade LF6 and LF787.
g. ASTM A508 Class 2, 2a, 3, 3a, 4, 4b, 5, and 22B.
h. ASTM A541 Class 2,2a,3,3a,4,7,7B,8,22B, and 22.
i. ASTM A707 Grade L3,l4,l5,l8.
j. ASTM A739 Grade B22.
k. ASTM A859.
l. MIL-S-23009 (HY80, HY100).

For primary service class forgings and extrusions, steel cleanliness should be verified by magnetic particle step-down tests (e.g., AMS 2300 or 2301) or by microcleanliness tests such as ASTM E45 or equivalent.

7.3.2.2.2 Titanium

It is recommended that all primary service class forgings be manufactured using the guidelines of ASTM B 381. It should be noted that some of the titanium alloys are proprietary to specific manufacturers.

7.3.2.3 Materials Qualification

7.3.2.3.1 Qualification Test Samples (QTS)

For primary service class forgings and extrusions, qualification test samples (QTS) should be used to qualify mechanical properties after final heat treatment. The QTS should be sized to realistically represent the forging or extrusion at the critical cross section. QTS may take the form of prolongations, sacrificial forgings, trepanned or cored samples, or separately forged test bars. Separately forged test bars should have a forging reduction representative of the actual forgings or extrusions to be qualified and should be heat treated together with the forgings or extrusions they are to represent. Separately forged test bars should have an equivalent round (ER, as defined by AS-1260 for example) greater than or equal to the forgings they are to represent; however, ER need not exceed 10 inches (254 mm).

Mechanical properties for secondary service class forgings or extrusions should be verified by testing QTS meeting the guidelines of API Spec 6A, Section 407.

7.3.2.3.2 Mechanical Properties

Mechanical Properties should be confirmed for base-metal, weld-metal and heat-affected-zone for forgings or extrusions which will be welded.

As a minimum, the following mechanical (tensile) properties should be confirmed for forgings or extrusions by tests performed on the QTS:

a. Yield strength.
b. Ultimate tensile strength.
c. Percent elongation.
d. Percent reduction of area.

7.3.2.3.3 Fracture Toughness Tests (Forgings and Extrusions)

Primary service class steel components—fracture toughness tests and dropweight tests (DWT) are recommended (e.g., as per ASTM E1290, ASTM E992, ASTM E399, or ASTM E813 or equivalent, and DWT per ASTM E208 or equivalent). Test temperature for fracture toughness tests should be per Table 7.

Secondary service class steel components—Charpy V-notch (CVN) impact tests with minimum values for both absorbed energy and percent shear area are recommended (e.g., as per ASTM E23 and DWT tests per ASTM E208 or equivalent). Test temperature should be per Table 7.

For both primary and secondary class titanium components, the plane-strain fracture toughness tests (per ASTM E-399 or equivalent) are recommended. Test temperature should be per Table 7.

Tertiary service class components—fracture toughness testing is not required.

7.3.2.3.3.1 Heat-Treatment Controls

Quality heat treatment should be performed in furnaces meeting the calibration and uniformity guidelines of BSI M54; AMS 2750; API Spec 6A Appendix H; or equivalent.

7.3.2.3.3.2 Nondestructive Testing

All forgings and extrusions should be ultrasonically (UT) examined and should have their finish-machined surfaces examined by the magnetic-particle (MT) or liquid penetrant method.

7.3.2.3.4 Steel

Applicable standards for steel forgings and extrusions are ASTM A388 or MIL-STD-2154 or equivalent for UT and ASTM A275 or MIL-STD-1907 or equivalent for MT.

For primary service class steel components, UT acceptance criteria should, as a minimum, be in compliance with ASTM A745 PL-1 or MIL-STD-2154 Class A, and MT acceptance should be in compliance with ASME BPV Sec. VIII Div.1 App.6 or MIL-STD-1907 Grade A (or their equivalents).

For secondary service class steel components, UT acceptance criteria should, as a minimum, be in compliance with ASTM A745 PL-2 or MIL-STD-2154 Class B, and MT acceptance should be in compliance with ASTM A788 S18 or MIL-STD-1907 Grade B (or their equivalents).

7.3.2.3.5 Titanium

Applicable standards for titanium forgings and extrusion are AMS 2236 or MIL STD 2154 or equivalent for UT and MIL STD 6866 or equivalent for liquid penetrant inspection.

7.3.3 Castings

7.3.3.1 General

Castings should be procured in accordance with a written specification and Quality Assurance System (API Spec Q1, or equivalent). Castings should not in general be used for primary service class unless NDT and mechanical properties recommended in 7.3.2.1 for primary service class forgings and extrusions can be verified. The general guidance of ASTM A703 for steels and ASTM B367 for titanium should be complied with. Additional elements to be considered in development of the written specification include:

7.3.3.2 Alloy Selection and Process of Manufacture

The specific chemical composition should be mutually approved between the tubular manufacturer and operator after thorough review of performance criteria and required properties. The designer should consult with manufacturers and experts as to the appropriate specifications for the desired application.

The following questions can be of primary importance when selecting a suitable composition:

a. Will the casting contain structural weldments?

b. Will repair welding be allowed?

c. Will there be stress relief after welding?

d. Will the selected composition achieve specified mechanical properties in the critical cross section?

7.3.3.2.1 Steel

A range of chemical composition specifications may be considered suitable for castings and extrusions, depending on the design requirements. General chemical composition specifications considered suitable for castings are:

a. AISI 41xx.

b. AISI 86xx.

c. ASTM A352 All Grades.

d. ASTM A487 All Grades.

e. MIL-S-23008 (HY80, HY100).

It is recommended that all castings be manufactured by a steel making practice that includes vacuum degassing or argon-oxygen decarburization.

7.3.3.2.2 Titanium

ASTM B367 may be used as a guideline specification for titanium castings. Castings should be done under vacuum. After casting, the parts should be hot-isostatic press (HIP) treated to minimize voids and porosity.

7.3.3.3 Material Qualification

7.3.3.3.1 Qualification Test Samples (QTS)

Qualification test samples (QTSs) should be used to qualify the mechanical properties of all castings after final heat treatment on a heat and heat-treat lot basis. The location and configuration of the QTS shall be by agreement between customer and manufacturer to assure that the properties of the QTS will be representative of the entire cast part.

For steels, the QTS shall comply with ASTM A703 Supplementary Requirement S26 (or equivalent), except that the thickness upon which the dimensions of the QTS are based should be defined as the diameter of the largest circle that can be inscribed within the critical cross section of the casting at quality heat treatment.

7.3.3.3.2 Mechanical Properties

As a minimum, the following mechanical properties should be confirmed for the castings by tests performed on the QTS:

a. Yield strength.

b. Ultimate tensile strength.

c. Percent elongation.

d. Percent reduction in area.

7.3.3.3.3 Fracture Toughness (Castings)

Primary service class—As mentioned in Table 7, for primary service, castings should be very carefully evaluated, particularly if welding is involved.

Secondary service class—For steels, Charpy V-notch (CVN) impact tests with minimum values for both absorbed energy, percent shear area and/or lateral expansion are recommended (e.g., as per ASTM E23 or equivalent). Test temperature should be per Table 7.

For titanium alloys, fracture toughness tests (per ASTM E399 or equivalent) are recommended. Test temperatures should be per Table 7.

Special attention should be given to welding procedures (see 7.4).

7.3.3.4 Heat-Treatment Controls

Quality heat treatment should be performed in furnaces meeting the calibration and uniformity guidelines of MIL-H-6875; MIL-STD-1684; BSI M54; AMS 2750; API Spec 6A, Appendix H; or equivalent.

7.3.3.5 Inspection

All castings should be either radiographically (RT) or ultrasonically (UT) examined and should have their finish-machined surfaces examined by the magnetic-particle (MT) method to accepted standards.

For steel castings, ASTM A703 Supplementary Requirements S5 or S7 and ASTM A703 Supplementary Requirement S6 may be used as reference for RT, UT, and MT respectively.

For titanium castings, AMS 2236 or MIL STD 2154 or equivalent and MIL STD 6866 or equivalent may be used as reference for RT or UT and liquid penetrant inspection, respectively.

Acceptance criteria for RT should, as a minimum, be in compliance with Severity Level 3 in low-stressed areas and ASME BPV Code Section VIII Division I Appendix 7 for critical areas (or their equivalents). Acceptance criteria for UT should be Quality Level 3 in non-critical regions and Quality Level 1 in highly stressed or fatigue hot-spot regions. Acceptance criteria for MT should be in compliance with ASTM E125 Severity Degree 2 for surface indication Types II through V and $^3/_{16}$" maximum for Type I linear indications in non-critical regions (or equivalent standards). MT acceptance criteria for critical regions should be in compliance with ASME BPV Code Section VIII Division I Appendix 7 (or equivalent).

7.3.4 Structural Shapes and Plates

7.3.4.1 General

Structural shapes and plates should be procured in accordance with a written specification which clearly defines performance and acceptance criteria. The general requirement of a Quality Assurance System should be implemented by the manufacturer. Certified mill test reports or certified reports of tests made by the fabricator or a testing laboratory constitute evidence of conformity with the specification. Unidentified materials should not be used.

7.3.4.2 Alloy Selection and Process of Manufacture

Steels and titanium alloys are available in a wide range of compositions and properties. The designer should select a specification which provides the required strength level while also addressing:

a. Weldability, including the use of special welding procedures, if required.
b. Fatigue problems which may result from the use of higher working stress.
c. Notch toughness in relation to other elements of fracture control, such as fabrication, inspection procedures, service stresses, temperature, and corrosion environment.

7.3.4.2.1 Steel

The following is a partial listing of specifications for steel shapes and plate that have been used successfully in offshore structures and marine risers:

a. ASTM A36.	
b. ASTM A131	Grades A, B, D, E, CS, AH32, AH36, DH32, DH36, EH32, EH36.
c. ASTM A516	Grade 65.
d. ASTM A537	Classes I and II.
e. ASTM A572	Grades 42, 50.
f. ASTM A709	Grades 36T2, 50T2, 50T3.
g. ASTM A710	Grade A Class 3.
h. API 2H	Grade 42.
i. API 2W	Grades 42, 50, 50T, 60.
j. API 2Y	Grades 42, 50, 50T, 60.

Additional steel specifications that might be of interest are listed in documents such as API RP 2A.

7.3.4.2.2 Titanium

The plate specification most commonly referenced to manufacture and test product is ASTM B 265.

Titanium plate is produced from intermediate slab product and hot rolled to the required dimensional tolerances. Plate product is then low-temperature annealed to minimize the hot rolling stresses. Titanium forms a tightly adhering scale and a thin, tough, oxygen-rich, surface layer known as alpha case. This surface layer must be removed by shot-blasting or machine-grinding and chemically etching. An alpha-case-free surface enhances the ability to form, machine and weld titanium.

Heat treating—Several of the alpha beta (Grades 5, 23, 24, and 25) or beta titanium alloys (Grades 19, 20, and 21) are heat treatable, reaching mechanical properties above those stated in ASTM. A common heat treating specification is MIL-H-81200.

7.3.4.3 Materials Qualification

7.3.4.3.1 Mechanical Properties

As a minimum, the following mechanical properties should be specified and confirmed:

a. Yield strength.
b. Ultimate strength.
c. Percent elongation.
d. Percent reduction of area.

7.3.4.3.2 Fracture Toughness (Structural Shapes and Plates)

Fracture toughness is recommended and test temperatures should be per Table 7.

7.3.4.4 Inspection

Application and service environment will influence the NDT requirements. Typically, higher alloyed alpha beta and beta grades require an ultrasonic inspection to AMS 2631 Class A. Finish material surfaces are routinely dye penetrant inspected to MIL-I-6866.

7.4 WELDING

7.4.1 General

7.4.1.1 Scope

This section establishes the recommended practices for arc welding of wrought and cast steel and titanium materials for risers and attachments thereto. For steels, welding should be conducted in accordance with 7.4 and API Std 1104 and supplements. Unless otherwise specified in the contract documents, longitudinal weld seams in the manufacture of steel pipe are acceptable provided they comply with the applicable pipe specification. For sour service, NACE MR0175 should apply.

7.4.1.2 Welding Terms

Welding terms and definitions pertaining to welding as used in this document conform to the standard definitions of AWS A3.0 and supplemented by API Std 1104 for steels.

7.4.2 Quality Control

Detailed written procedures should be established for control of welding quality. The following procedures are recommended prior to starting fabrication:

a. Welding and weld repair.
b. Storage, control, and identification of welding consumables.
c. Welder qualification records.
d. Inspection/NDE.
e. Monitoring the progress and quality of welding.

7.4.2.1 Welding Processes and Consumables—Steel

7.4.2.1.1 Low Hydrogen

Excluding the root pass, all welding of steel with a nominal yield strength of 40 ksi or more, or a weld throat thickness in excess of $^1/_2$ inch, should be accomplished with low hydrogen processes (i.e., less than 15 ml/100g).

7.4.2.1.2 Gas Metal Arc Welding—Short Circuit Arc

GMAW-S welding should be limited to secondary and tertiary welds or root passes in one-sided butt welds without backing.

7.4.2.1.3 Consumables

Filler metal, fluxes, and shielding gases should comply with the requirements of API STD 1104.

7.4.2.2 Welding Processes and Consumables—Titanium

7.4.2.2.1 Gas Tungsten Arc Welding

GTAW welding should be used whenever possible. Process variations such as hot wire filler metal additions or buried arc may be used when qualified in accordance with this section.

7.4.2.2.2 Plasma Arc Welding

PAW welding may be used when qualified in accordance with this section and approved by the user.

7.4.2.2.3 Other Processes

Titanium is readily welded by other conventional processes including laser (LBW), electron beam (EBW), friction (FRW), and flash welding (FW).

7.4.2.2.4 Consumables

Filler metal shall comply with ANSI/AWS A5.16. The user should specify the level of testing per ANSI/AWS A5.01, Schedule J (chemistry only for each lot shipped) or Schedule K (tests specified by the purchaser for each lot shipped). Filler metals shall be selected to nominally match base metal chemistry.

When mounting or removing titanium spools, the wire surface shall not be handled other than with lint-free, clean gloves. Wire which has been improperly handled shall be removed from the spool and discarded. Manually-fed titanium wire or rod shall be wiped with a clean, acetone-soaked cloth before welding and handled thereafter with clean, lint-free gloves. Prior to reinitiating welding, titanium wire or rod shall be cut back approximately one-half inch.

7.4.2.2.5 Shielding Gas

Conventional welding processes, such as GTAW, hot wire GTAW, and PAW, need not be performed in a chamber, provided proper shielding is provided. Protection should be provided to all titanium surfaces above 800°F in order to prevent contamination by air. Separate gas supplies are needed for primary shielding (weld torch) of the molten puddle, secondary shielding (trailing) of the cooling weld and heat-affected base metal and backside shielding of the weld and base metal. Backside shielding may be accomplished with either a purge or backing shield. Argon or mixtures of argon and helium are preferred as shielding gas. Inert shielding gases should be at least 99.995 percent pure and capable of providing a dew point of –40°F at the work piece. Shielding gas hoses shall be new or shall not have been used to carry anything except weld gases. Rubber hoses are prohibited. All gas lines and equipment should be prepurged prior to use.

The effectiveness of shielding should be evaluated prior to production welding. An arc should be struck on scrap metal. The color of the weld can be used as an indicator of shielding effectiveness and indirectly, weld quality. Weld colors reflect the degree to which the weld was exposed to oxygen at elevated temperatures. A bright silvery metallic luster can generally be taken as an indication of an uncontaminated weld. Straw color indicates decreased shielding in the secondary shielding. Light straw should be removed by wire brushing. If straw coloration is observed, welding practice and shielding technique should be reviewed. Contaminated welds, as evidenced by blue, purple, gold, gray, and powdery white are contaminated, and weld properties are likely to be deleteriously affected and should be removed.

7.4.3 Qualification

7.4.3.1 General

Welding procedures and each welder or welding operator should be qualified in accordance with ASME Section IX for titanium alloys and ASME Section IX or API Std 1104 for steels and the additional recommendations of 7.4. The welding procedure should be adhered to during welding performed under this document.

7.4.3.2 Essential Variables

Welding qualifications may be based on ASME Section IX or API Std 1104 and should also comply with the essential variable range of this document:

a. A single welding procedure may cover several essential variable changes as long as separate procedure qualification exists for each essential variable or the procedure qualification incorporated the subject changes to the essential variables.

b. A change in the trailing shield or backing shield design or method constitutes an essential variable.

c. An increase in the maximum time between completion of the root bead and the start of the second bead does not constitute an essential variable.

d. The addition or deletion of post-weld heat-treatment and/or a change in post-weld heat-treatment time or temperature constitute an essential variable.

e. A change from automatic/ mechanized GTAW to manual GTAW or vice versa is an essential variable.

7.4.3.3 Material Strength/Grade

Test pieces for welding procedure qualifications should be of the same strength (yield and tensile) grade and classification as production material. Heat-treatment or manufacturing process should be similar to that used on the job. When available, actual job material should be used.

7.4.3.4 Base Metal Weld Prequalification—Tubulars

If tubulars are to be joined either to themselves or to mechanical connectors via girth welds, it is recommended that a prequalification program be conducted, in a fashion analogous to API RP 2Z. This should confirm that the heat-affected-zone of the tubulars will perform in an acceptable fashion, relative to tensile properties, fracture toughness, hardness, and delayed cracking susceptibility. Evaluation should be conducted on those HAZ in the post-weld condition that will be utilized in service (i.e., as-welded vs. post-weld heat-treated).

7.4.3.5 Material Chemistry

7.4.3.5.1 Steel

Test pieces for procedure qualification of carbon steel should be selected from the higher range of carbon equivalents. All qualified procedures are based upon the carbon equivalent (*Pcm*) of the parent metal defined in Equation 55.

$$Pcm = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (55)$$

where

Pcm = carbon equivalent.

C, Si, etc. = elements.

Procedures are qualified for welding materials with a *Pcm* up to 0.02 percent higher (by product analysis) than the material qualified. Heat/ladle analysis may be used if approved by the company when product analysis is not reported. Use of higher *Pcm* steels will require a new welding procedure qualification.

7.4.3.5.2 Titanium

Where specified by the user, chemical analysis shall be taken at the root and face surface. As a minimum, the elements of the filler metal specification should be checked. The interstitial elements in the weld metal should not exceed the limits of the filler metal and/or the base metal specification.

7.4.3.6 Reduced-Section Tension Tests

In addition to the tensile requirements of ASME Section IX for titanium and ASME Section IX or API Std 1104 for steels, transverse weld tensile tests should not fail in the weld metal. Overmatching of the weld metal is desired.

7.4.3.7 Bend Tests

Bend tests shall be performed as part of qualification requirements for steel and titanium in accordance with ASME Section IX. For steel and titanium grades with P-numbers, the mandrel diameter should comply with ASME Section IX, QW-466.1. The mandrel diameter shall be 16 times the specimen thickness for Ti-6Al-4V.

7.4.3.8 Macrosection Examination

One weld area sample should be ground, polished and etched with a suitable solution to give clear definition of the weld heat-affected-zone (HAZ) and fusion line microstructures under the microscope. For acceptable qualification, the macrotech test specimen, when inspected visually, should conform to the requirements for visual examination.

7.4.3.9 Microstructural Hardness

7.4.3.9.1 Steel

For acceptable qualification, the maximum hardness should be determined using Vickers hardness tests (ASTM E92) Hv10. Rockwell and Brinell hardness tests and conversions from Rockwell or Brinell hardness tests are not acceptable. Hardness test locations should be carried out as shown in Figure 41. Maximum acceptable hardness shall be 325 Hv10. If any individual hardness value exceeds the limit specified, two further sections should be taken, both of which should meet the specified requirements.

7.4.3.9.2 Titanium

For acceptable qualification, the maximum allowable difference between the base metal, HAZ and the weld metal averages shall not exceed 30 (Hv10) for each traverse. Hardness test locations should be carried out as shown in Figure 41. The hardness test should use the Vickers method with a 10 kg. load.

A photograph or photo macrograph of 1X to 3X magnification clearly showing the hardness indentations, HAZ and the weld zone should be included in the test results.

7.4.3.10 Toughness Testing (Welds)

Test temperatures for welded structure fracture toughness testing are given in Table 8.

7.4.3.10.1 Steel

7.4.3.10.1.1 Charpy Testing

Charpy V-notch impact testing should be performed in accordance with ASTM A370. Weld metal, fusion line, and HAZ tests are required. The Charpy test specimen locations are given in Figure 42. Only root location tests are required for base material thickness less than $^3/_4$ in. (20 mm). The absorbed energy and percent shear requirements shall be specified by the owner.

7.4.3.10.1.2 CTOD Testing

When specified by the owner, CTOD testing should be conducted in accordance with API Std 1104 paragraph A.3.2. The level of fracture toughness should be specified by the owner.

7.4.3.10.2 Titanium

Fracture toughness testing shall be conducted in accordance with ASTM E399. The fatigue crack shall be located in the weld metal and the HAZ (0 to 1 mm from the fusion line). Specimen shall be Bx2B, L-C orientation. Acceptance criteria shall be as agreed upon by manufacturer and operator.

7.4.3.10.3 Welders and Welding Operators

Welders and welding operators should be qualified in accordance with ASME Section IX or API Std 1104 for steels. Welders should be qualified for the type of work assigned and should be issued certificates of qualification describing the materials, processes, electrode classifications, positions, and any restrictions of qualification.

Welder requalification tests should be required if there is some specific reason to question a welder's ability or the welder is not engaged in the given process of welding (i.e., SAW or FCAW) for a period of 6 months or more.

7.4.4 Welding Workmanship

7.4.4.1 Tack Welds

Tack welds may be used in lieu of lineup clamps for butt welds to hold members in alignment. All tack welds should

Table 8—Toughness Testing Requirements for Welds

Service Class —>		Primary		Secondary	
Material Form		Testing Recommended	Test Temperature	Testing Recommended	Test Temperature
Steel	Base Metal	Fracture Toughness	<=LAST –36°F (20°C)	Charpy	<=LAST –36°F (20°C)
		Drop Weight Tear	<=LAST –50°F (28°C)	Drop Weight Tear	<=LAST
	Weld Metal	Fracture Toughness	<=LAST	Charpy V-notch Impact	<=LAST –36°F (20°C)
		Charpy V-notch Impact	<=LAST –50°F (28°C)		
	Fusion Line, HAZ	Charpy V-notch Impact	<=LAST –36°F (20°C)	Charpy V-notch Impact	<=LAST –18°F (20°C)
Titanium—Base Metal, Weld Metal, Fusion Line, and HAZ		Fracture Toughness	<=LAST	Fracture Toughness	<=LAST

Note:
Tertiary Service Class—toughness testing not required.

be made by qualified welders using a welding procedure for the root pass of an approved procedure. Tack welds should have the same preheat requirements as for the root pass of the appropriate structural welding procedure.

7.4.4.2 Temporary Attachments

The same care and procedures used in permanent welds should be used in welding temporary attachments.

7.4.4.3 Preheat and Interpass Temperature

Contractor should develop a general preheat control procedure. The procedure should specify the method of heat application and control, maximum temperature of the surface, and time required for each application.

7.4.4.3.1 Steel

Preheating may be accomplished by any suitable method, provided that it is uniform and that the temperature does not fall below the prescribed minimum during the actual welding operations. Pyrometer thermocouples and/or temperature-indicating crayons or equivalent should be used to assure the required temperature is obtained prior to and maintained during the welding operation.

Minimum preheat for all steel should be the greater of 38°C (100°F) or the minimum qualified by testing, whichever is higher.

Maximum preheat or interpass temperature should not exceed 232°C (500°F) unless otherwise qualified.

7.4.4.3.2 Titanium

When welding titanium, the methods of measuring the preheat and interpass temperatures shall be restricted to those that do not leave contaminants on the surface of the metal. Appropriate methods include thermocouples and contact pyrometers. Temperature indicating crayons are prohibited. Preheat and interpass temperature should be measured within approximately one inch of the weld joint edge adjacent to the area of the start of the next weld bead. Flame heating should not be used for preheating.

The minimum preheat for titanium should be greater than 60°F, or the minimum qualified by testing, whichever is higher.

The maximum interpass temperature shall not exceed 350°F unless otherwise qualified.

7.4.4.4 Welding Environment and Joint Cleanliness

7.4.4.4.1 Contractor should develop a cleaning procedure.

7.4.4.4.2 Prior to welding titanium and its alloys, it is imperative that weld joints be free of mill scale, dirt, dust, grease, oil, moisture, and other potential contaminants. Titanium reacts readily at elevated temperatures with air, moisture, oil, grease, dirt, refractories, and most other metals to form brittle compounds. Any surface of the weld joint members which will see temperatures above 600°F, or a minimum distance of two inches from the weld edge, should be cleaned with non-chlorinated solvents such as acetone. Solvents shall be new or re-distilled solvents only. Once cleaned, the cleanliness of the joint should be preserved.

7.4.4.4.3 Prior to interpass cleaning, each weld bead should be evaluated for color by the welder/welding operator. Interpass cleaning is not required as long as the weld is a bright silvery metallic luster.

7.4.4.4.4 The use of sandpaper or steel wool, which can leave particles behind, is a source of contamination and is prohibited for pre-weld and interpass cleaning. Rotary files, files, burrs, and stainless steel brushes shall be new, not previously used on any other material and degreased with acetone prior to initial use. Tools for use on titanium shall be maintained and stored from other tooling so they do not pick up contaminants.

7.4.4.4.5 When welding titanium, a clean environment is required. The area should be kept clean and isolated from dirt producing operations such as grinding, cutting, machining, and painting. During welding, the area should be free of air drafts and temperature and humidity should be controlled.

7.4.4.5 Joint Fit-Up

7.4.4.5.1 Good fit-up is more critical for titanium than for other materials. Uniform fit-up minimizes burn-through and controls underbead contour. Poor fit-up may increase the possibility of contamination from air trapped in the joint. Weld joint offset should be specified in each welding procedure. Joint offset refers to the weld land preparation mismatch.

7.4.4.5.2 Passes shall not start and stop at the same point. Passes should be staggered in such a manner as to overlap the preceding pass a minimum of 50 mm whenever possible.

7.4.4.6 Weld Defect Repair

7.4.4.6.1 Authorization for repair of welds, removal and repair of weld defects and testing of weld repairs should be in accordance with 7.4. Defects other than cracks in the root and filler beads may be repaired with prior company authorization. Defects other than cracks in the cap pass may be repaired without prior company authorization. When repairs are made in previously repaired areas, a procedure similar to that for repair of cracks shall be used. Cracked welds shall be discarded unless repair is authorized by the company. All repairs shall meet the standard of inspection set forth in 7.4.

7.4.4.6.2 For all repair welding, written procedures approved by the company shall be utilized. These may be based on company approved full-penetration groove welding procedures qualified for repairs.

7.4.4.7 Weld Repair—Castings

7.4.4.7.1 It should be anticipated that castings will have regions requiring weld repair. Weld repair procedures should be qualified in compliance with an agreed upon established industry standard (e.g., ASME BPV Code Section IX, ASTM A488, or equivalent) as a minimum. It should be demonstrated that both weld metal and heat-affected-zone regions achieve the mechanical properties and NDT specifications for the remainder of the casting.

7.4.4.7.2 Authorization for repair of welds, removal and repair of weld defects, and testing of weld repairs should be in accordance with API Std 1104.

7.4.4.7.3 For all repair welding, written procedures approved by the company should be utilized. These may be based on company approved full penetration groove welding procedures specifically qualified for repairs.

7.4.4.8 Arc Strikes

Arc strikes should be made only in the weld groove. A procedure should be established for determining the extent of any methods for repairing damage to materials resulting from inadvertent arc strikes outside of the weld groove. The methods of defining the hardened zone, presence of cracks, and surface integrity restoration should be detailed.

7.4.5 Fabrication Details

7.4.5.1 General

Fabrication tolerances should be as per contract documents.

7.4.5.2 Temporary Welds

7.4.5.2.1 Temporary welds or fabrication aids should not be made on primary members without prior company approval. Where allowed on primary members, these welds should be subject to the same welding and material requirements as other welds. These welds should not be made within 2 in. (50 mm) of other welds in secondary members.

7.4.5.2.2 All areas from which temporary attachments are completely removed should be examined by magnetic particle. Gouges deeper than allowed by the material specification thickness tolerance should be replaced or repaired.

7.4.6 Inspection/Examination

7.4.6.1 General

Inspection and nondestructive examination should comply with the requirements of ASME Section V and/or API Std 1104 for steels and the additional requirements of this specification. Each inspection or examination should be carried out using a written procedure approved by the company.

7.4.6.2 Personnel Qualifications

All inspectors should be AWS QC1 certified (or acceptable equivalent) except specialty technicians (PT, MT, UT, and RT) should be qualified and certified according to the guidelines ASNT SNT-TC-1A or equivalent. Additionally, all specialty technicians may be required to demonstrate their capabilities with a practical site test for company approval.

7.4.6.3 Inspection Requirements

Inspection Requirements should comply with Table 9. All welds should be visually examined in accordance with API STD 1104.

On titanium alloy welds, visual inspection shall include examination of the weld's color. The weld should have a bright silvery metallic luster. Blue, purple, gold, gray, powdery white, or straw-colored welds indicate contamination and should be removed.

7.4.6.4 Radiographic Examination

Welds that are subject to radiographic examination should comply with the quality level requirements of ASME Section V, Article 2 and/or API Std 1104. Wire type image quality indicators (IQI) may be used in lieu of plaque type penetrameters. Where wire penetrameters are used, the maximum wire diameter used to verify film sensitivity should comply with ASME Section V, Article 2, Table T-276.

7.4.6.5 Magnetic Particle Examination/Dye Penetrant

7.4.6.5.1 Steel welds subject to magnetic particle testing should comply with the quality level requirements of API Std 1104. Magnetic particle inspection should be by the wet method using a white background and black ink. Magnetic Particle inspection is required on both OD and ID for primary Appendix 6. If the weld ID is inaccessible, then magnetic particle inspection after root pass is laid should be done from the OD.

7.4.6.5.2 Dye penetrant inspection is required on both OD and ID for primary titanium welds in accordance with ASME Section V, with acceptance criteria as set in ASME Section 8, Div. 1, Annex 8. If the weld ID is inaccessible, then dye penetrant examination after root pass is laid should be done from the OD.

7.4.6.6 Ultrasonic Examination

7.4.6.6.1 Ultrasonic examination procedures should be established by an ASNT Level III ultrasonic specialist. The

Table 9—Inspection Requirements

Classification[a] material		Radiographic Examination	Ultrasonic Examination	Magnetic Particle/Dye Penetrant Examination
Primary	Steel	ASME Sec. VIII[b] and/or API 1104[3]	API RP 2X[b] and/or API 1104[c]	ASME Sec, VIII Div. 1., App. 6
	Titanium	ASME Sec. VIII[b] Div. 1, UW 51	AMS 2630[b]	ASME Sec. VIII Div. 1, App. 8
Secondary		API STD 1104[b]		not required
Tertiary		not required		

Notes:
[a]Material classification as defined in 8.2 of this document.
[b]Examine by either UT or RT.
[c]As defined by Company. Supplemental requirements may be specified by Company.

procedure should define equipment, techniques and methods consistent with the design requirements.

7.4.6.6.2 For ultrasonic inspection on steel welds, the essential variables listed in API RP 2X should be detailed in the written procedure, which should be submitted for company approval prior to use during trial and subsequent examinations. Variations from the proven procedure should be cause for requalification.

7.4.6.6.3 Ultrasonic inspection of titanium welds should be in accordance with AMS 2630. Both straight and angle beam techniques should be employed. An ultrasonic standard should be developed for each pipe wall thickness, with the weld included.

7.4.6.6.4 Through-thickness UT examination—Plate or pipe to be used in applications where the member is subject to substantial Z-direction loading should be ultrasonically examined. Examination and reporting requirements of A578 should apply.

7.4.6.6.5 The intersect location (footprint), including a 6-inch (150-mm) wide band, should be examined in accordance with A578 acceptance standard-level III.

7.4.6.6.6 Members with flaws that would interfere with weld inspection may be positioned so that acceptable material is located under the footprint area.

7.4.6.6.7 Weld repairs of members with unacceptable flaws up to 10 in.^{2} (6450 mm^2) may be made using a company approved weld repair procedure.

7.4.6.7 Acceptance Criteria

Company shall set acceptance criteria if different from aforementioned standards for critical welds of primary members and establish minimum sensitivity parameters for nondestructive examination of such welds. Acceptance criteria may be established based on fitness-for-purpose or engineering critical assessment procedures. For further description or reference to this approach see Reference 10.

7.4.7 Postweld Heat Treatment

When required by the owner, a written PWHT procedure should be supplied to the company for approval.

7.4.8 Reports and Records

The following reports and data sheets should be supplied to the company representative:

a. Mill test reports and certificates.

b. Company approved welding procedure package.

c. Welder and/or welding operator qualification test results.

d. Temperature charts or records for all stress relieving and/or postweld heat treating (when required by company specifications and/or regulatory authorities).

e. NDE reports and results.

f. As-built construction drawings.

7.5 BOLTING

7.5.1 General

Selection of bolting, studs, and nuts for components covered by this RP should consider the effects of a marine environment and the corrosion protection measures that may be employed at each location. Marine environments reveal that localized corrosion resistance is a common limitation of otherwise corrosion resistant materials. Threaded fasteners, by nature, create tight crevices which often result in crevice corrosion and pitting attack. Dissimilar material assembly often results in galvanic interaction, creating localized generation of hydrogen, often resulting in hydrogen embrittlement. As a minimum, the following should be considered:

a. External fluids.
b. Internal fluids.
c. Crevice corrosion.
d. Dissimilar metal effects.
e. Cathodic protection effects.
f. Coatings.
g. Preload.
h. Tensioning system.

7.5.2 Materials

7.5.2.1 Steel

7.5.2.1.1 Bolting materials manufactured from carbon or alloy steel should not be used in submerged or splash zone service at hardness levels exceeding Rockwell C 35. ASTM specifications (latest revisions) than can produce suitable bolting, studs, and nuts are:

a. ASTM A193.
b. ASTM A194.
c. ASTM A320.

7.5.2.1.2 Note that the materials defined in these specifications are more resistant to general corrosion than high strength carbon or alloy steel; however, they are all susceptible to general corrosion, crevice corrosion, pitting corrosion, stress corrosion cracking, corrosion fatigue, galvanic attack, and MIC. The above specifications or their equivalents may be applied, but careful design consideration is recommended.

7.5.2.2 Titanium

7.5.2.2.1 Titanium and titanium alloys are recommended as preferred marine fastener materials for bolts, studs, and nuts covered by this RP. These alloys are immune to ambient seawater general corrosion, crevice corrosion, pitting, stress corrosion cracking, galvanic attack, and MIC and are highly resistant to corrosion fatigue.

7.5.2.2.2 All titanium alloys listed in the latest revisions of the following ASTM specifications are suitable for all wet, splash zone or dry, bolting, studs, and nuts applications:

a. ASTM F467.
b. ASTM F467M.
c. ASTM F468.
d. ASTM F468M.

7.5.2.2.3 Optimum toughness and ductility are achieved from the ASTM Titanium Grade 19 (Beta-C®) alloy for high strength applications and ASTM Titanium Grade 4 for low and medium strength requirements. The above specifications or their equivalents should be applied.

7.5.2.2.4 Titanium bolting coatings—Titanium alloys generally require an anti-galling treatment for threaded components. The recommended practice is to pretreat the surface with a neutral bath anodize (e.g., AMS 2487 except with testing requirements as negotiated between the supplier and purchaser) and then to coat the threads with a bonded molydisulfide based solid dry film lubricant (e.g., MIL-L-46010 Type II). The coatings both mitigate galling concerns and, simultaneously, make negligible any galvanic interaction the titanium bolting may have with less noble surrounding metals. For galling mitigation it may be necessary to only coat the external thread or the internal thread. The bearing surface should be coated. Additional installation lubricants are not necessary but are not considered detrimental.

7.5.2.3 Nickel-Copper-Aluminum Alloys

7.5.2.3.1 Nickel-copper-aluminum alloy 500 and nickel-copper-alloy 400 are alternative marine environment bolting materials. These are not susceptible to general seawater corrosion, but they are susceptible to crevice corrosion, pitting, stress corrosion cracking, and galvanic attack. The latest revisions of the following ASTM specifications are suitable for bolting, studs, or nuts:

a. ASTM F467.
b. ASTM F467M.
c. ASTM F468.
d. ASTM F468M.

7.5.2.3.2 These alloys are known to have galling problems similar to the titanium alloys. Liberal application of installation lubricants or applications of a solid film lubricant is recommended. The above specifications or their equivalents should be applied.

7.6 NON-METALLIC MATERIALS FOR RISER END CONNECTIONS/TERMINATIONS

7.6.1 Flex Element Elastomers

7.6.1.1 Elastomers are used in riser systems in laminated flexelements. In laminated flexelements, rubber layers are designed to be permanently bonded to reinforcements (usually steel). The strength and durability of the bond should be shown to be adequate for the fluid, temperature, and loading conditions during the life of the project. The rubber layers should be designed to operate primarily in shear/compression to prevent bond failures and to maximize fatigue life.

7.6.1.2 There is a wide range of different elastomers available, and it is not adequate to specify by material name. A full material specification must be developed for each application and must be specific to the compound being considered. This specification should explicitly take into account: a) fluid chemical composition, b) operation and upset conditions temperatures, c) operating pressure, d) material deformations during service, e) depressurization frequency and rate, f) cyclic loading, and g) qualification test requirements.

7.6.1.3 Some commonly used elastomer categories include:

a. NR: Natural rubber.
b. CR: Chloroprene.
c. EPDM: Ethylene-Propylene-Diene.
d. NBR: Nitrile rubber.
e. HNBR: Hydrogenated nitrile rubber.
f. FKM: Fluorocarbon rubber.
g. FFKM: Tetrafluoroethylene-propylene terpolymer.

7.6.1.4 Table 10 provides some generic material properties of various categories of elastomers that can be useful in preliminary materials selection.

7.6.1.5 Final selection of an elastomer compound should be based on results of material qualification tests that are representative of service conditions. These tests should be specified in the material specification and should be approved by both user and vendor. It is advisable to review the track record/ prior experience with the candidate elastomeric compounds in flexelement service prior to making the final material selection.

7.6.1.6 It is suggested, that the material specification include:

a. Shear modulus (over a range of temperatures before and after aging).
b. Ductile-brittle transition temperature (if applicable to service conditions).
c. Bond strength to metallic reinforcement (e.g., peel adhesion strength).
d. Aging resistance (e.g., modulus stability over service life).
e. Tear strength (e.g., trouser tear to relate to extreme deformations).
f. Fatigue resistance (using project conditions of strain, temperature and fluid environment).
g. Explosive decompression resistance.
h. Creep or stress relaxation (if appropriate).
i. Swelling and equilibrium absorption in service fluids.

7.6.1.7 Proper material evaluation, selection and specification are required for a long-term, maintenance-free service. The large number of elastomeric material compositions possible gives scope for tuning the properties for optimum performance.

7.6.2 Bend Stiffener Materials

7.6.2.1 Bend-stiffener materials are typically molded solid or reinforced polyurethanes. Selection of the appropriate grade of polyurethane and care in processing during fabrication are critical for stiffener performance. Selection of material grades should be guided by functional requirements. The following data on candidate grades should be reviewed:

Table 10—Generic Material Properties for Various Elastomer Categories

Elastomer Category	Properties
NR, CR, EPDM	Low resistance to swell in hydrocarbons oil and gas. Good mechanical properties. Good low temperature properties.
NBR, HNBR	Moderate to good resistance to swell in hydrocarbons. Moderate high temperature and chemical resistance. Good mechanical properties. May stiffen at low temperatures. Poor H_2S resistance.
FKM, FFKM	High resistance to swelling in hydrocarbon oil and gas. Good chemical resistance at elevated temperatures. Poor mechanical properties. May stiffen at low temperatures.

a. Stress-strain curve, modulus at prescribed strain levels.
b. Hardness.
c. Change in properties for the anticipated service conditions over anticipated service life.
d. Property variation over thickness.

7.6.2.2 As with elastomers, polyurethane is a family of polymers that can have a wide range of properties. In some cases, specification of the supplier, the generic type, supplier's trade name, and grade may be required.

7.6.2.3 Manufacturing of polyurethanes parts, especially in large size, may require specialized equipment and experienced personnel. Special consideration should be given to quality control and previous experience of a contractor in similar types of jobs and under similar environmental conditions.

7.7 FOAM BUOYANCY

7.7.1 General

There are two basic types of foam materials used for buoyancy: closed cell and syntactic foams. The former are normally limited to shallow depths, while the latter can be used to greater depths, provided the material is correctly designed and constructed.

7.7.2 Closed Cell Foams

7.7.2.1 Several kinds of closed cell foam materials are in common use:

a. Polyvinyl chloride (PVC) foam.
b. Polypropylene foam.
c. Polyurethane foam.
d. Ionomer foam.

during service, e) depressurization frequency and rate, f) cyclic loading, and g) qualification test requirements.

7.6.1.3 Some commonly used elastomer categories include:

a. NR: Natural rubber.
b. CR: Chloroprene.
c. EPDM: Ethylene-Propylene-Diene.
d. NBR: Nitrile rubber.
e. HNBR: Hydrogenated nitrile rubber.
f. FKM: Fluorocarbon rubber.
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7.6.1.4 Table 10 provides some generic material properties of various categories of elastomers that can be useful in preliminary materials selection.

7.6.1.5 Final selection of an elastomer compound should be based on results of material qualification tests that are representative of service conditions. These tests should be specified in the material specification and should be approved by both user and vendor. It is advisable to review the track record/ prior experience with the candidate elastomeric compounds in flexelement service prior to making the final material selection.

7.6.1.6 It is suggested, that the material specification include:

a. Shear modulus (over a range of temperatures before and after aging).
b. Ductile-brittle transition temperature (if applicable to service conditions).
c. Bond strength to metallic reinforcement (e.g., peel adhesion strength).
d. Aging resistance (e.g., modulus stability over service life).
e. Tear strength (e.g., trouser tear to relate to extreme deformations).
f. Fatigue resistance (using project conditions of strain, temperature and fluid environment).
g. Explosive decompression resistance.
h. Creep or stress relaxation (if appropriate).
i. Swelling and equilibrium absorption in service fluids.

7.6.1.7 Proper material evaluation, selection and specification are required for a long-term, maintenance-free service. The large number of elastomeric material compositions possible gives scope for tuning the properties for optimum performance.

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7.6.2.1 Bend-stiffener materials are typically molded solid or reinforced polyurethanes. Selection of the appropriate grade of polyurethane and care in processing during fabrication are critical for stiffener performance. Selection of material grades should be guided by functional requirements. The following data on candidate grades should be reviewed:

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FKM, FFKM	High resistance to swelling in hydrocarbon oil and gas. Good chemical resistance at elevated temperatures. Poor mechanical properties. May stiffen at low temperatures.

a. Stress-strain curve, modulus at prescribed strain levels.
b. Hardness.
c. Change in properties for the anticipated service conditions over anticipated service life.
d. Property variation over thickness.

7.6.2.2 As with elastomers, polyurethane is a family of polymers that can have a wide range of properties. In some cases, specification of the supplier, the generic type, supplier's trade name, and grade may be required.

7.6.2.3 Manufacturing of polyurethanes parts, especially in large size, may require specialized equipment and experienced personnel. Special consideration should be given to quality control and previous experience of a contractor in similar types of jobs and under similar environmental conditions.

7.7 FOAM BUOYANCY

7.7.1 General

There are two basic types of foam materials used for buoyancy: closed cell and syntactic foams. The former are normally limited to shallow depths, while the latter can be used to greater depths, provided the material is correctly designed and constructed.

7.7.2 Closed Cell Foams

7.7.2.1 Several kinds of closed cell foam materials are in common use:

a. Polyvinyl chloride (PVC) foam.
b. Polypropylene foam.
c. Polyurethane foam.
d. Ionomer foam.

7.7.2.2 Closed cell foams are relatively lightweight (4 to 12 lb/cu.ft.), resilient and inexpensive. They can be provided with tough outer skins to resist handling damage. However, most closed cell foams are not strong enough to survive prolonged immersion beyond a depth of about 200 feet. Manufacturer's data should be closely examined before specifying closed cell foam for any deep long-term application.

7.7.3 Syntactic Foam

Syntactic foam is a composite material combining pressure-competent spheres of varying sizes and construction (e.g., macrospheres and/or microspheres) with various matrix or binder materials, such as epoxy resin. Typical syntactic foam densities are in the range of 18 to 32 lb/cu.ft. The spheres are used to occupy a large portion of the product's volume to reduce the overall density and provide a buoyant force without significant reduction of the hydrostatic strength. The size, structure, and material composition of the spheres are varied by design to generate foam products that are suitable for the targeted service water depths.

7.7.4 Specification and Procurement

7.7.4.1 A specifications document should be developed to ensure that manufactured products will provide desired buoyant lift force to the riser system at depths of service and for the duration of service required by the user. The specifications should reflect and balance these key considerations:

a. Maximum and service/operating depth.

b. Time at depth (duration of service).

c. Permissible change in buoyancy during service.

d. Total buoyancy requirements (at all phases of service).

e. Density needed to achieve buoyancy (lift force) within constraints.

f. Handling and installation loads.

g. Service environment.

7.7.4.2 The specification should include testing and qualification requirements that can demonstrate that the product's crushing strength properties, service depth, long-term average density (buoyancy), and structural stability are adequate. Such evidence is usually provided by hydrostatic testing of full-size parts or of adequately-sized samples.

7.7.4.3 In addition, all metallic hardware associated with foam buoyancy products (e.g., fasteners) should be compatible with other metals in the riser system, or appropriate anticorrosion measures should be taken. Caution is advised that surface or near-surface buoyancy components may be subject to biological attack and fouling. Appropriate coatings or surface impregnations may be required to prevent degradation of service.

7.7.5 Manufacturing, Inspection, and Testing

7.7.5.1 A Quality Assurance Plan (QAP) shall be submitted by the manufacturer and approved by the customer prior to starting production. The manufacturer shall establish a process control and record system that identifies the process variables associated with the manufacture of each individual buoyancy module. The inspection frequency, testing program, and type of test shall be defined as part of the QAP.

7.7.5.2 The minimum recommended tests for qualification and acceptance of modules to be used for buoyancy applications should be:

a. Buoyancy verification: Modules shall be immersed in water to verify buoyancy. The inspection intervals and maximum acceptance tolerance should be defined in the specifications.

b. Crush strength: The crush strength of the foam used in the modules shall be determined and shall be higher than the pressure at service depth times the appropriate safety factor.

c. Buoyancy losses: The loss of buoyancy caused by compression and water ingress shall be determined at the service depth. The minimum duration of the test shall be defined by the designer and the materials specialist and shall take into account the effect of the protective layer on the water ingress rate.

7.8 COATINGS

7.8.1 General

Corrosion of external steel surfaces may be mitigated by cathodic protection, proper material selection or by the use of protective coatings, including flame-sprayed aluminum. Whenever one of the first two options is preferred, the use of protective coatings may be useful to extend the effective life of the risers and reduce maintenance costs.

7.8.2 Coating Materials

7.8.2.1 Coating materials commonly used for steel risers include fusion-bonded or liquid epoxy, polyethylene, polypropylene, polyurethane, and synthetic rubbers (neoprene or EPDM). These materials are often combined and applied as systems in which one or more layers are applied, not only to inhibit corrosion but also to provide protection from handling damage.

7.8.2.2 Some coating materials, such as the epoxies, have excellent adhesion to steel but are somewhat brittle and are sensitive to physical abuse. These are often combined with polyethylene or polypropylene, which have poor bonding characteristics but are tough and have excellent resistance to abuse. The rubber coatings have both good adhesion and toughness.

7.8.2.3 While risers are usually coated prior to installation, coating systems designed to be applied underwater can be applied in-situ for repair and rehabilitation of damaged or deteriorating coatings. Internal surfaces are only coated where it is necessary to satisfy particular needs, such as protection from highly corrosive and/or abrasive streams, for reduction of paraffin adhesion or for stream flow enhancement. Coatings for these purposes are usually specialty materials such as baked liquid or fusion-bonded epoxies, epoxy-phenolics, or phenolics.

7.8.2.4 Temporary protection of the interior of risers may be achieved using vapor phase inhibitors or various rust-preventative oils or waxes. In each case, protection is short-lived, and protection of more than nine months should not be considered.

7.8.3 Selection of Coating System

7.8.3.1 Riser coating selection must be made based on a number of considerations, including: 1) compatibility with sea water and pressure due to water depth, 2) installation and/or in-service loads and impact (particularly at the splash zone), 3) tolerance to marine plant and animal growth (seaweed, barnacles, etc.), 4) temperature gradients between cold seawater and hot/warm steel (hot-wall effect), and 5) ultraviolet light exposure effects.

7.8.3.2 It is recommended that the selection of a coating system should also involve:

a. Utilization of knowledgeable and experienced organizations and personnel.
b. Qualification of candidate coating systems using the track record, history and performance experience of similar materials in like service.
c. Qualification of candidate coating systems using suitable techniques under typical performance conditions. The use of standard American Society for Testing Materials (ASTM) tests to evaluate:

1. Cathodic disbondment at ambient and elevated temperatures.
2. Bending characteristics.
3. Impact resistance.
4. Resistance to abrasion.
5. Accelerated weathering.

d. Estimation of performance characteristics and coating life using analytical and mathematical tools.
e. An awareness of the sensitivity of application quality and techniques on the candidate coatings, including the need and ease of repair and/or rehabilitation of damaged or deteriorated systems.

7.8.4 Coating Systems Application

In addition to proper coating materials selection, application systems play a key part in assuring good coatings. The following factors should be considered in reviewing the application system:

a. Coating plants may be in proximity but may be completely independent of steel pipe mills, or the steel pipe mill may have its own coating system and/or coating yard. This could affect candidate coating selection and application and require additional attention.
b. Knowledge and experience of plant personnel, quality of facilities, and laboratories. A well-managed control laboratory, with good quality control procedures is desirable.
c. Good pipe storage and handling facilities are vital to minimize coating damage due to handling and transportation, often a major source of problems.

In-situ application is generally restricted to field welded joints, repair, or rehabilitation.

7.8.4.1 Surface Preparation

7.8.4.1.1 An important factor in successful coating is surface preparation. For immersion conditions, white metal blasting (ISO-8505-1, Sa 3) should be achieved, preferably using rotary blasters. Chemical treatment of the surface should be considered, particularly with systems involving epoxy or where excessive surface chemical or salt contamination is likely.

7.8.4.1.2 Surface preparation at site is performed primarily for welded joints prior to coating or for areas of coating repair. Blast-cleaning methods are likely to be manually operated, and care should be taken to avoid undesirable surface contamination. White metal blast-cleaning is advantageous, though near white (Sa $2^1/_2$) may be acceptable depending on the coating system.

7.8.4.2 Pipe-Handling

Most riser coatings systems are chosen in part, for their toughness. However, damage caused by poor handling is common and can be easily avoided. Handling equipment should be padded on all contact faces. Slings should be of nylon (or an alternate malleable material), and sharp impact of any kind should be avoided.

7.8.4.3 Quality Control

7.8.4.3.1 A detailed quality plan should be prepared and approved by both manufacturer and operator prior to commencement of work, followed by inspection to ensure that the agreed upon criteria are met.

7.8.4.3.2 Sources that address coating systems quality and recommended practices include:

a. International Standards Organization (ISO).
b. Deutches Institute fur Normung (DIN).
c. National Association of Corrosion Engineers (NACE).
d. Canadian Standards Association (CSA).
e. Steel Structures Painting Council (SSPC).
f. American Society of Testing and Materials (ASTM).

7.8.5 Field Welds (Joints)

7.8.5.1 Riser field welded joints may be protected by application of the same coating as that used for the riser pipe or by use of an alternate coating. Field joints can be protected with manually applied systems involving liquid epoxy, composite tapes and wraps, and heat shrinkable materials. The steel should be cleaned to at least Sa $2^1/_2$ (near white) or better to achieve an optimum bond.

7.8.5.2 Since field-weld joint coatings have the potential of being inferior to the pipe coating, adjustments in cathodic protection requirements should be considered to provide supplemental corrosion protection.

7.8.6 Other Considerations

Sacrificial anode assemblies are frequently used in conjunction with coatings to provide a synergistic protective system. Anode assemblies are generally attached to uncoated field joints, where the anode material provides adequate protection. If all field joints are to be coated, including those where anodes are attached, the connection should be made before final coating of the joint area, or a repair to the coating will be necessary.

7.9 FATIGUE

7.9.1 General Considerations

7.9.1.1 Fatigue cracks can originate from planar and non-planar flaws, and therefore both types are considered in fatigue assessment. Fracture mechanics principles should be used to describe the behavior of planar flaws using experimental da/dN versus ΔK (fatigue crack growth rate vs. applied stress intensity factor) data. Assessment of non-planar flaws should be done using experimental S-N (stress vs. number of cycles data).

7.9.1.2 This section applies only to fatigue assessment of steels and titanium alloys and not to the metallic components of flexible pipe.

7.9.2 Fatigue Crack Growth Rates

The rate of fatigue crack growth can be represented by Equation 60 for all values of ΔK. The recommended general procedure for use of the crack growth rate curves for planar flaws in fatigue life assessment is outlined in BS: PD6493. The values of C and m depend on material and applied conditions and can be taken as constant over a limited range of ΔK only. In addition to the material strength/ grade and test environment, the crack growth rates can depend on cycling frequency, microstructural features, R ratio (mean stress level) and test specimen configuration.

In the absence of specific data, the following subsections provide recommendations on the fatigue crack growth rate constants for steels and titanium alloys in typical marine riser service conditions. Where specific crack growth rate data are available for the material and service conditions, they can be used in accordance with the general procedure for planar flaw assessment described in PD6493.

7.9.2.1 Ferritic Steels

7.9.2.1.1 Table 11 provides the values of the crack growth rate constants C and m (taken from BS: PD6493) for da/dN (in units of in/cycle) and ΔK (in units of ksi-$\sqrt{\text{in}}$) for ferritic steels with yield strengths below 87 ksi. These provide the upper bound to published data on ferritic steels (base metal, weld, and HAZ).

Table 11—Fatigue Crack Growth Rate Constants for Ferritic Steels with Yield Strengths δ87 ksi

Service Condition	C	m
Air, cathodically protected or isolated from marine environment, temp. 212°F	4.84×10^{-10}	3.0
Splash zone/ freely corroding, temp. 68°F	3.17×10^{-9}	3.0

7.9.2.1.2 For steels with yield strengths greater than 87 ksi, specific crack growth rate data should be obtained for the material and service condition of interest, giving careful consideration to the effects of testing frequency and waveform. Careful thought should also be given to the statistical confidence which the crack growth rate data give in the overall life prediction.

7.9.2.2 Titanium Alloys

Very limited fatigue crack growth rate data on titanium alloys in marine environments is available in the open literature. It appears that titanium alloys are more sensitive to the material grade, microstructural properties, cycling frequency, etc. than steels. It is recommended that specific crack growth rate data should be obtained for the material and service condition of interest, giving careful consideration to the effects of testing frequency and waveform. Careful thought should also be given to the statistical confidence which the crack growth rate data give in the overall life prediction.

7.9.3 S-N Data

7.9.3.1 Steel

7.9.3.1.1 Weldments

In the absence of specific large scale test data allowing use of a different S-N curve, it is recommended that an appropriate S-N fatigue curve from a recognized national or international standard be the basic component S-N fatigue design curve for riser girth welds in steels: 1) with yield strengths less than 87 ksi and 2) that see service in air or are cathodically protected or isolated from the marine environment.

Fatigue performance of riser girth welds may be improved if any of the following conditions are fulfilled:

a. Welds are ground flush on the ID and OD and inspection procedures that include, as a minimum, visual inspection of the ID and OD to ensure no undercuts or suckbacks and either X-ray or volumetric ultrasonic inspection consistent with Table 9.

b. Special profile control processes (e.g., mechanized or GTAW pulsed root) and technique are used in the welding process and that: 1) minimize axial and angular misalignment, 2) minimize stress concentrations associated with reentrant angles and weld bead height, and 3) which result in no undercuts, suck-backs (internal concavity), or insufficient throat all around the circumference, followed by inspection as above.

Curves that are not in national or international standards may also be used if supported by large scale test data on welds. Caution is advised that test welds should be made as they would in service and tested under conditions representative of those in service. The component S-N curve should be determined as the lower bound of a two-sided, 95 percent prediction interval. Consideration may be given to fixing the slope in this type of statistical analysis on the basis of fracture mechanics or other mechanistic arguments.

Under freely-corroding or unprotected conditions in seawater, the basic S-N curve should be reduced by a factor of 2 on life, following guidance in UK DOE, "Offshore Installation Guidance on Design and Construction," Part II, Section 4.2.1.10.

For higher strength steels, where corrosion protection is being provided by cathodic protection systems, candidate fatigue curves should be qualified by test data under representative conditions. Caution is advised that, when coupled to cathodic protection potentials more negative than –0.8V, the fatigue resistance of higher strength steels may deteriorate due to hydrogen embrittlement.

For all welds other than the riser girth welds, the guidance on fatigue curve selection provided in AWS D1.1 or UK DOE, "Offshore Installation Guidance on Design and Construction," Part II, Section 4.2.1.10 may be used.

7.9.3.1.2 Base Metals

In the absence of specific test data allowing use of a different S-N curve, it is recommended that the DOE-B curve should be the basic component S-N fatigue design curve for steels: 1) with yield strengths less than 87 ksi, 2) that see service in air, or 3) are cathodically protected or isolated from the marine environment. Other curves may also be used if supported by test data. The component S-N curve should be determined as the lower bound of a two-sided, 95 percent prediction interval. Consideration may be given to fixing the slope in this type of statistical analysis on the basis of fracture mechanics or other mechanistic arguments.

As an alternative to using the above DOE-B curve or a stress-based approach using S-N data, specific fatigue curves for specific base metals may also be developed using strain-based approaches and strain-controlled fatigue test data on representative materials.[1]

Under freely-corroding or unprotected conditions in seawater, the basic S-N curve should be reduced by a factor of 2 on life, following guidance in UK DOE, "Offshore Installation Guidance on Design and Construction," Part II, Section 4.2.1.10.

For higher strength steels where corrosion protection is being provided by cathodic protection systems, candidate fatigue curves should be qualified by test data under representative conditions. Caution is advised that, when coupled to cathodic protection potentials more negative than –0.8V, the fatigue resistance of higher strength steels can deteriorate due to hydrogen embrittlement.

7.9.3.2 Titanium—Base Metal and Welds

7.9.3.2.1 Very limited fatigue S-N data on titanium alloys and welds in marine environments is available in the open literature. It appears that titanium alloys are more sensitive to the material grade, microstructural properties, cycling frequency, etc. than steels. It is recommended that specific S-N data should be obtained for the material and service condition of interest (e.g., air, seawater isolated from cathodic polarization, seawater exposed to cathodic polarization, etc.) giving careful consideration to the effects of testing frequency and waveform. Caution is advised that where welds are anticipated, S-N data should be obtained on representative welds made as they would be in service and tested under conditions representative of those in service. The component S-N curve should be determined as the lower bound of a two-sided, 95 percent prediction interval. Consideration may be given to fixing the slope in this type of statistical analysis on the basis of fracture mechanics or other mechanistic arguments.

7.9.3.2.2 Caution is also advised that when coupled to cathodic protection potentials more negative than –0.8V (typically used to protect steels), the fatigue resistance of some titanium alloys can deteriorate, a phenomenon related to hydrogen embrittlement or "hydriding" described in Section 8.

7.9.4 Flexible Pipe

Both the tensile armors and the hoop stress resistance layers are fatigue critical components and should be checked. Typically, both layers are made up of high strength steels (100 to 120 ksi yield) except when designed for sour service, where it is then limited by NACE guidelines. For flexible pipe stressed for functional loads and dynamic curvature variations, the procedures outlined in 7.9.2 and 7.9.3 are applicable here as well. Fatigue da/dN and S-N curves used must be supported by manufacturer-supplied or independently gathered data for the specific material and environment seen by the pipe layers.

7.10 CORROSION

External corrosion of carbon steel is best controlled by cathodic protection and/or a combination of cathodic protection and coatings, as detailed in 7.5.2. Provisions should be made to control not only internal corrosion problems but to include such problems as paraffin formation and hydrate formation. These latter problems can occur internally with all riser materials.

7.10.1 Internal

Riser materials selection and internal corrosion mitigation strategies should take into consideration compatibility with all fluids that are expected to be in contact with the riser, including:

a. Produced well fluids, including hydrocarbons, acidic gases (CO_2 and H_2S), and brines.
b. Drilling, completion and workover fluids.
c. Hydrate, paraffin and corrosion control fluids and other chemicals.

In addressing fluid compatibility, the following should be considered as a minimum:

a. Period of exposure.
b. Concentration of CO_2, H_2S, brines, etc. in the fluid.
c. Flow rates and solids production.

7.10.1.1 Steel

7.10.1.1.1 In steel risers for sweet wells, internal corrosion is typically controlled by using appropriate corrosion inhibitors. Field and laboratory test data on inhibitor effectiveness under anticipated service conditions should be reviewed by supplier and operator prior to inhibitor selection. Where such data is unavailable, inhibitor qualification testing is recommended to ensure adequate corrosion control can be achieved. When produced H_2S or souring from water flooding is anticipated, materials selection should be based on NACE MR01-75 guidelines.

7.10.1.1.2 Inhibitors that have been suitably qualified may be used to mitigate corrosion from drilling, completion and workover fluids as well. Where risers are exposed to these fluids only for a short term and/or at low temperatures, use of corrosion inhibitors may not be necessary if supported by laboratory corrosion test data or field experience under similar conditions.

7.10.1.1.3 Suppliers should be consulted on the compatibility of well control fluids and chemicals including paraffin, hydrate, and corrosion and scale control fluids.

7.10.1.2 Titanium

7.10.1.2.1 Titanium alloys are highly corrosion resistant to produced well fluids including all hydrocarbons, acidic gases (CO_2 and H_2S), elemental sulfur and sweet and sour chloride brines at elevated temperatures. Where produced H_2S or souring from water flooding is expected, titanium alloys listed in NACE specification MR01-75 should be considered. Caution is advised that, in the presence of acidified brines at temperatures exceeding ~80°C, crevice corrosion and stress corrosion cracking (SCC) susceptibility of some of the more common alloy grades is enhanced. Titanium alloys containing minor ruthenium (0.1 percent Ru)[2] or palladium (0.05 percent Pd) levels and/or containing at least 3.5 wt. percent molybdenum are reported to mitigate this susceptibility and may be considered.[1,2,3]

7.10.1.2.2 Titanium alloys are also generally resistant to well drilling and completion fluids. However, caution is advised as before. Chloride or bromide-based brine completion fluids at temperatures exceeding ~80°C enhance susceptibility to crevice corrosion and SCC, and careful alloy selection must be made.

7.10.1.2.3 Titanium alloy riser components may also be periodically exposed to well workover fluids. For acidizing treatments, exposure of titanium alloys to hydrofluoric (HF) containing acids should always be avoided due to rapid metal dissolution. Alternative acidizing solutions include 10 to 12 wt. percent HCl solutions inhibited with an appropriate oxidizing species (i.e., 1 percent sodium molybdate) or uninhibited organic acids (i.e., 10 percent acetic or formic acids) are suitable.

7.10.1.2.4 Methanol injected downhole to dissolve hydrates must contain at least 2.5 wt. percent water to prevent stress corrosion cracking of titanium alloys components. Anhydrous methanol grades should be avoided or sufficient water should be added prior to injection. Commercially available, less-flammable methanol solvent grades containing 2.5 to 30 wt. percent water are recommended.

7.10.2 External

7.10.2.1 Steel

7.10.2.1.1 Corrosion of external steel surfaces may be mitigated by cathodic protection or by the use of protective coatings.[4,5,6] Weight is often a significant factor in floating and tension-leg platform, and the use of coatings combined with cathodic protection results in significantly reducing the weight requirement for sacrificial anodes. Additionally, it has been shown that the sphere of influence of a given anode is markedly enhanced for well-coated pipelines, allowing for additional weight savings. The splash zone of the riser, generally from mean sea level to about the plus ten foot elevation is the most severe environment encountered from the standpoint of external corrosion. Areas that are periodically wet, that is not totally immersed, are not protected by cathodic protection and thus must be protected by other means, such as corrosion allowance, monel sheathing, vulcanized rubber or high build epoxy systems.

7.10.2.1.2 Caution is advised that high strength steels may be susceptible to hydrogen embrittlement under cathodic polarization conditions at potentials more negative than –0.8 V(SCE). Qualification testing under cathodic conditions to ensure hydrogen embrittlement resistance of base material and welds is advisable.

7.10.2.2 Titanium

7.10.2.2.1 Titanium alloys are resistant to corrosion and erosion-corrosion, uniform attack, pitting attack and microbiologically-influenced corrosion (MIC) in natural seawater due to the protective surface oxide film. Similarly, weld and heat-affected-zone metal (performed per approved processes and procedures) may be expected to exhibit corrosion resistance equivalent to that of wrought base metal.

7.10.2.2.2 Long-term hydrogen absorption and possible embrittlement in titanium alloys exposed to high cathodic potentials from cathodic protection systems intended for neighboring steel components need careful consideration in terms of alloy selection and mitigation measures. The lower strength α alloys are more susceptible to hydrogen embrittlement than the α-β and β alloys. Depending on the riser component and application, total electrical isolation of the riser or component, using monolithic insulating joints or commercially available insulating flange gaskets and flange bolt sleeve/washer kits may be considered. The insulating/isolation joints must be demonstrated to be suitable for the service conditions, including pressure, temperature, and dynamic loading conditions where applicable. Where electrical isolation is not achievable or practical, the application of insulating OD surface coatings of proven, seawater-resistant polymers such as 6 to 10 mm thick polyurethane, polychloroprene rubber, and EPDM rubber coatings, may be considered. Caution is advised that the experience base with these options to mitigate hydrogen embrittlement is limited, and prototype testing to demonstrate electrical isolation, serviceability, and integrity over service life is recommended.

7.11 WEAR

7.11.1 Steel

7.11.1.1 The internal erosion or wear can be caused by abrasive elements in the produced fluid, such as sand and passage or rotation of downhole equipment. It can also be caused by a high flow rate and turbulent flow characteristics at flow are changes in the riser. This should be taken into account when selecting materials that will be in contact with the flow.

7.11.1.2 Risers with multiphase flow, or flow of fluids containing particles (such as sand or proppant), must be able to resist erosion. Some guidelines are provided for gas-liquid flows in API RP 14E. For liquids carrying particles, less guidance is available in the open literature. Resistance to erosion under the expected conditions should either be demonstrated experimentally or be analyzed using a calculation procedure that has been sufficiently verified with experimental results.

7.11.2 Titanium

Titanium alloys may exhibit higher wear rates than steel in situations of high bearing load contact with rotating, sliding or reciprocating steel components [2]. These situations may exist during drilling or well workover operations involving contact with steel drill strings or wire lines. Although casual and/or light contact is permissible, sustained high contact load wear can be mitigated through the use of wear resistant surface linings or rubber drill string collars. Wear resistant surface linings or coatings include polymers (rubbers and thermoplastics), hard and/or soft metal electro- or electroless-plated coatings or plasma-sprayed hard coatings. Coating/liner selection will depend on the specific component and application, relative to wear and fatigue performance requirements.

7.11.3 Wear of the Flexible Pipe Plastic Layers

Wear in plastic materials constituting the flexible pipe is due to an abrasion process. Abrasion can take place in two different locations:

a. Wear of innermost layer.
b. Wear of external layer.

7.11.3.1 Wear of Innermost Layer

7.11.3.1.1 Under certain conditions, the well flow may contain sand and other types of abrasive particles. For a flexible pipe with a thermoplastic inner layer, even small amounts of sand can cause some local material losses due to abrasion.

7.11.3.1.2 Manufacturers and designers should ensure that local decreases in thickness do not affect the service life of the whole system.

7.11.3.2 Wear of External Layer

7.11.3.2.1 The flexible pipe sections resting on the sea-bed can move from their as-installed position due to functional and environmental forces (including movements due to expansion and settlement).

7.11.3.2.2 Limitations on allowable deterioration or abrasion of the external layer due to interaction with the sea-bed can determine limits on allowable displacements.

7.11.3.2.3 The manufacturer/designer should determine if any predicted abrasion is acceptable on the basis of the geotechnical data provided by the operator, as well as the thermoplastic properties.

7.12 MARINE GROWTH AND BIOLOGICAL CONSIDERATIONS

7.12.1 Marine organisms will often attach to risers, increasing riser weight and cross-sectional area. Marine growth thickness increases with time until a "climax" thickness is reached. When the climax thickness is reached portions of the marine growth break off due to its own weight or loading induced by water currents, and new growth begins until the climax thickness is reached again. Climax thickness can vary from a few centimeters to almost one meter depending on the location. Marine risers should be designed with necessary strength to handle loads that occur when marine growth reaches climax thickness, or means of controlling the marine growth thickness should be implemented.

7.12.2 Marine growth build up can be controlled by routine cleaning, use of materials and/or coatings that inhibit marine growth adhesion to the riser and combinations of cleaning and use of fouling resistant materials. There are two general classes of fouling resistant materials: toxic release materials that release materials toxic to the marine organism and low surface energy materials that provide a surface to which marine organisms cannot attach. The best economic approach may be some combination of an antifouling system and routine cleaning.

7.12.3 Anti-fouling materials may be provided in the form of a coating that releases materials toxic to marine organisms at a controlled rate such as copper or tin compounds. Metallic copper coating-based systems are effective only as long as they continue to release the toxic material and therefore have a finite service life (commonly on the order of three years). Some of the toxic release systems are not permitted in certain areas of the world. Local regulations should be consulted. Metallic copper systems offer service in excess of 10 years and commonly consist of 90/10 copper-nickel sheets with an elastomeric backing that electrically insulates the copper-nickel from the steel riser. The elastomeric material may provide corrosion protection with the overlying copper-nickel sheath providing resistance to marine fouling. Other variations may apply copper particles or thermally sprayed copper over an electrically insulating coating. Care should be taken to assure electrical isolation of the copper based materials from the riser and the cathodic protection system. Cathodic protection will retard copper corrosion such that copper ions due to corrosion are no longer released, and the copper surface will foul. Also the use of copper systems in the vicinity of aluminum or aluminum coating may cause accelerated corrosion of the aluminum.

7.12.4 Low surface energy coatings function by presenting a surface to which the marine organisms cannot readily attach. This approach is a developing technology and does not have the problems associated with toxic release systems. However, service life may be limited relative to the structural materials and metallic toxics. Further, the nature of these coatings are such that they are not as resistant to mechanical damage as corrosion protective coatings like as epoxies.[7,8,9]

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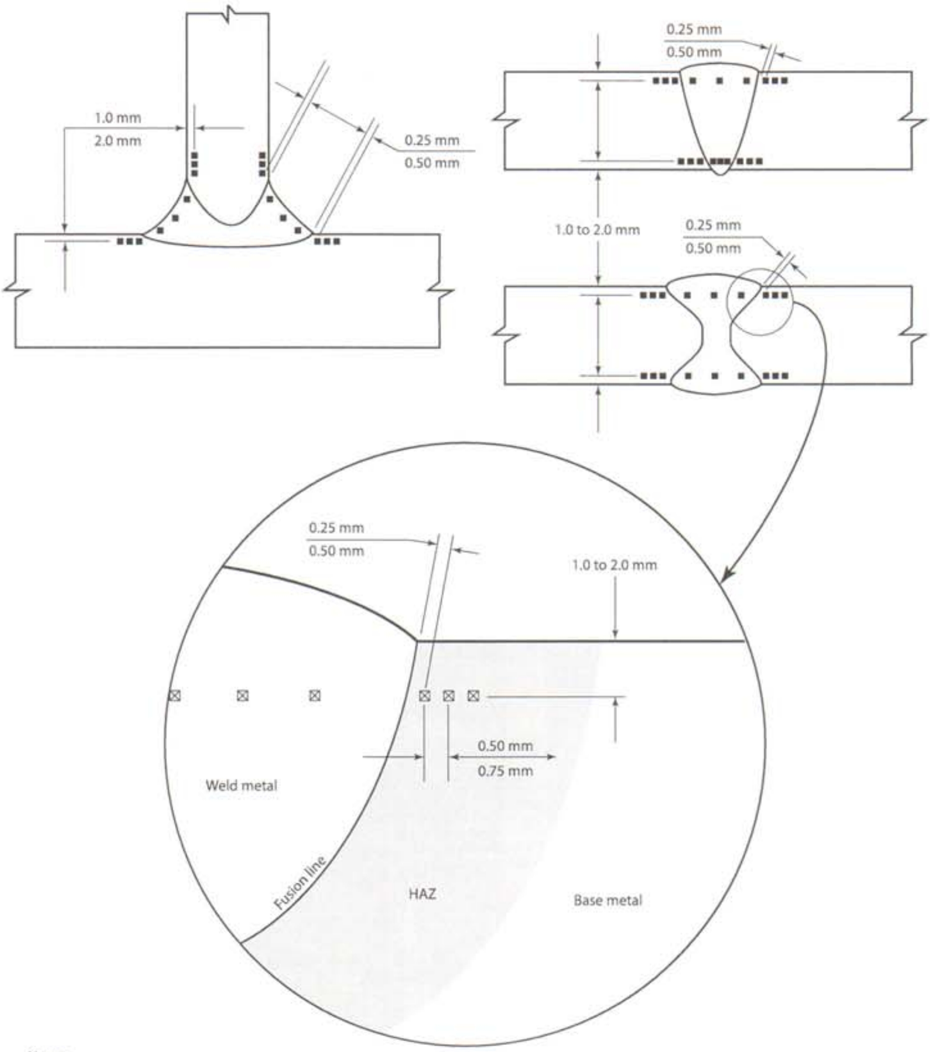
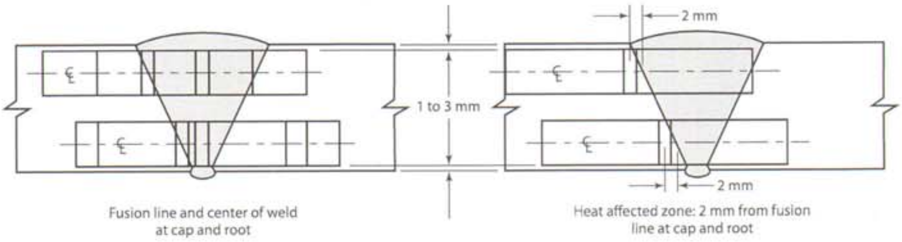


Notes:

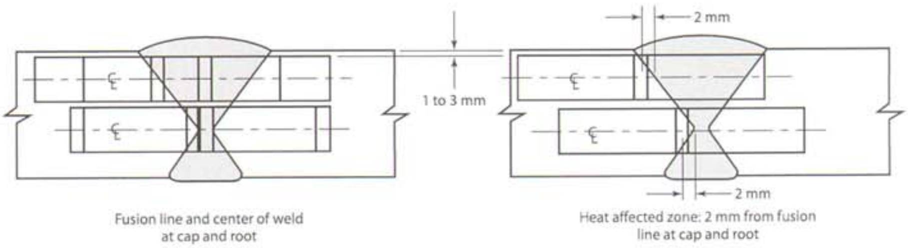
1. Test load shall be 10-kgf or less.
2. Indentations to be located as shown on the figures and as detailed below:
   HAZ: Starting at 0.25 to 0.50 mm from the fusion line with three (3) indents at 0.50 to 0.75 mm intervals. Specimen shall be polished well enough to clearly show the fusion line under magnification.
   Weld Metal: A minimum of three equally spaced indents for each hardness traverse.
3. Hardness traverse on fillet welds shall be as detailed for T-connections above.

Figure 41—Vickers Hardness Test Location

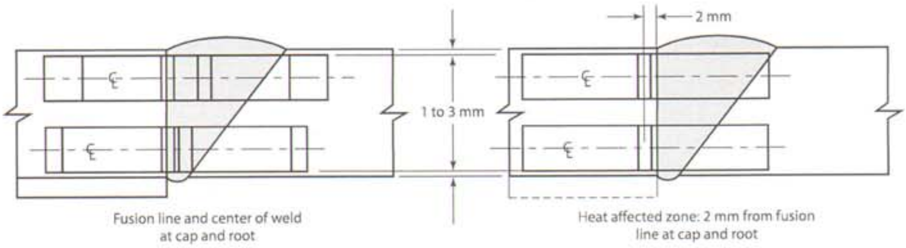
Location of Charpy Test Bar Notches for All Single Sided Groove Welds



Location of Charpy Test Bar Notches for All Double Sided Groove Welds



Location of Charpy Test Bar Notches for All Single-Bevel Groove Welds



Note: For base material thicknesses less than 19 mm ($^3/_4$ inch) only root location tests are required.

Figure 42—Charpy Test Specimen Location for Welding Procedure Qualification

ANNEX A—(INFORMATIVE)

A.1 Glossary

As a starting point for the compilation of a glossary for this RP, the definitions are essentially taken from API RP 16Q: *Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems*, November 1, 1993. In some cases, revisions have been made to accommodate both drilling and production risers.

The goal of this glossary is to focus on those terms specific to risers of floating production systems and tension leg platforms. Particular attention is given to the many acronyms found in the text.

A.1.1 accumulator (riser tensioner): A pressure vessel charged with gas (generally nitrogen) over liquid with pressure on the gas side maintained by its connection with high-pressure gas reservoirs (bottles). High pressure hydraulic fluid from the liquid side of the accumulator is used to energize a riser tensioner cylinder.

A.1.2 air can buoyancy: Tension applied to the riser string by the net buoyancy of an air chamber created by a closed-top, open-bottom cylinder forming an air-filled annular space around the outside of the riser pipe.

A.1.3 apparent weight: Weight minus buoyancy (commonly referred to as weight in water, wet weight, net lift, submerged weight, or effective weight).

A.1.4 auxiliary line: A conduit (excluding choke and kill lines) attached to the outside of the riser main pipe. Examples include: Hydraulic supply line, buoyancy control line, and mud boost line.

A.1.5 ball joint: A ball and socket assembly having central through passage equal to or greater than the riser internal diameter that may be positioned in the riser string to reduce local bending stresses.

A.1.6 bend restrictor: A device that prevents a flexible pipe from being bent below a given radius (e.g., a tapered conical inner surface through which the flexible pipe passes).

A.1.7 bend stiffeners: Device used to increase and distribute bending stiffness in localized areas of flexible pipe. They are often made of polymeric molded material surrounding the pipe and attached to the end fitting.

A.1.8 BOP stack: An assembly of well control equipment including BOPs, spools, valves, hydraulic connectors, and nipples that connects to the subsea wellhead. Common usage of this term sometimes includes the Lower Marine Riser Package (LMRP).

A.1.9 breech-block coupling: A coupling which is engaged by small-angle rotation of one member into an interlock with another member.

A.1.10 buoyancy control line: An auxiliary line dedicated to controlling, charging, or discharging air-can buoyancy chambers.

A.1.11 buoyancy equipment: Devices added to riser joints to reduce their apparent weight, thereby reducing riser top-tension requirements. The devices for risers typically take the form of syntactic foam modules or metal open-bottom air chambers.

A.1.12 charpy V-notch (CVN): Type of fracture toughness test.

A.1.13 Chinese lantern: A flexible pipe geometry.

A.1.14 choke and kill (C&K) lines: External conduits, arranged laterally along the riser pipe, and used to circulate fluids into and out of the well bore to control well pressure.

A.1.15 control pod: An assembly of subsea valves and regulators which when activated from the surface will direct hydraulic fluid through special porting to operate BOP equipment.

A.1.16 crack-tip opening displacement (CTOD): A measure of crack severity which can compared against a critical value at the onset of unstable crack propagation.

A.1.17 cumulative fatigue damage analysis: Fatigue life prediction method based on use of a stress vs. number of cycles curve (S-N) and the Palmgren-Miner Rule for damage computation under variable amplitude loading.

A.1.18 design environmental case: Set of environmental conditions included in a particular Design Case.

A.1.19 design fatigue life: The life predicted by cumulative fatigue damage ratio calculations.

A.1.20 design load: Load governing a design.

A.1.21 design pressure: Pressure governing a design.

A.1.22 dog-type coupling: A coupling having wedges (dogs) that are mechanically driven between the box and pin for engagement.

A.1.23 drape hose: A flexible line connecting a choke, kill or auxiliary line terminal fitting on the telescopic joint to the appropriate piping on the rig structure. A U-shaped bend or "drape" in this line allows for relative movement between the outer barrel of the telescopic joint and the vessel.

A.1.24 drift off: An unintended lateral move of a dynamically positioned vessel off of its intended location relative to the wellhead, generally caused by loss of stationkeeping control or propulsion.

A.1.25 drive off: An unintended move of a dynamically positioned vessel off location driven by the vessel's main propulsion or stationkeeping thrusters.

A.1.26 drop weight test (DWT): Type of fracture toughness test.

A.1.27 dynamic positioning (automatic station keeping): A computerized means of maintaining a vessel on location by selectively driving thrusters.

A.1.28 effective hydraulic cylinder area: Net area of moving parts exposed to tensioner hydraulic pressure.

A.1.29 effective tension: The axial tension calculated at any point along a riser by considering only the top tension and the apparent weight of the riser and its contents.

A.1.30 effective weight: See apparent weight.

A.1.31 elastic plastic fracture mechanics (EPFM): A type of fracture mechanics analysis suitable for predicting failure in highly ductile materials. Uses such measures as CTOD or J-integral.

A.1.32 elastomer: Any of the class of materials, including natural and synthetic rubbers, which return to their original shape after being subjected to large deformations.

A.1.33 emergency shut down (ESD): To shut off operations/production and fluid flow on an emergency basis.

A.1.34 expansion bend: A bend placed in a line to provide for expansion and contraction.

A.1.35 expansion loop: See expansion bend.

A.1.36 factory acceptance testing: Testing by a manufacturer of a particular product to validate its conformance to performance specifications and ratings.

A.1.37 fail safe: Term applied to equipment or a system so designed that, in the event of failure or malfunction of any part of the system, devices are automatically activated to stabilize or secure the safety of the operation.

A.1.38 fatigue weather (or wave) scatter diagram: Table listing occurrence of seastates in terms of wave height and period.

A.1.39 fillup line: The line through which fluid is added to the riser annulus.

A.1.40 fitness-for-service: A concept that implies that an item is fit for service when it can be operated safely through out its design life.

A.1.41 flange-type coupling: A coupling consisting of two flanges joined by bolts.

A.1.42 fleet angle: In marine drilling riser nomenclature, the fleet angle is the angle between the vertical axis and a riser tensioner line at the point where the line connects to the telescopic joint.

A.1.43 flex joint: A laminated metal and elastomer assembly, having a central through-passage equal to or greater in diameter than the interfacing pipe or tubing bore, that is positioned in the riser string to reduce the local bending stresses.

A.1.44 floating production system (FPS): Any of several types of surface platforms comprising a hull and mooring system, that can support clusters of risers and production and drilling equipment.

A.1.45 gooseneck: A type of terminal fitting using a pipe section with a semicircular bend to achieve a nominal 180 degree change in flow direction.

A.1.46 guidelineless reentry: Establishment of a connection between the BOP stack and the subsea wellhead or between the LMRP and the BOP stack using a TV image and/or acoustic signals instead of guidelines to guide the orientation and alignment.

A.1.47 handling tool (running tool): A device that joins to the upper end of a riser joint to permit lifting and lowering of the joint and the assembled riser string in the derrick by the elevators.

A.1.48 hang-off: Riser when disconnected from seabed.

A.1.49 heat affected zone (HAZ): Region around a weld that has been affected during welding.

A.1.50 heave: Vessel motion in the vertical direction.

A.1.51 hot-spot stress: Highest stress in the region or component under consideration. The basic characteristic of a peak stress is that it causes no significant distortion and is principally objectionable as a possible initiation site for a fatigue crack. These stresses are highly localized and occur at geometric discontinuities. Sometimes referred as Local Peak Stress.

A.1.52 hydraulic connector: A mechanical connector that is activated hydraulically and connects the BOP stack to the wellhead or the LMRP to the BOP stack.

A.1.53 hydraulic supply line: An auxiliary line from the vessel to the subsea BOP stack that supplies control system operating fluid to the LMRP and BOP stack.

A.1.54 instrumented riser joint (IRJ): A riser joint equipped with sensors for monitoring parameters such as tension in the riser pipe wall, riser angle, riser internal fluid temperature, pressure, etc.

A.1.55 J-lay: A pipe laying technique in which the pipe departs the vessel at a near-vertical angle.

A.1.56 JONSWAP spectrum: A wave spectrum normally used to describe seas in fetch-limited conditions. It has three governing parameters, significant wave height, peak period, and peakedness factor.

A.1.57 jumper hose: A flexible section of choke, kill, or auxiliary line that provides a conduit around a flex/ball joint that can accommodate the angular motion at the flex/ball joint.

A.1.58 keelhauling: A technique for handling major pieces of equipment offshore by transferring the item under the keel of the vessel as opposed to bringing it aboard topside.

A.1.59 key seating: The formation of a longitudinal groove in the bore of a riser system component caused by abrasion and wear of the rotating drillstring on the riser component.

A.1.60 kill line: See choke and kill line.

A.1.61 landing joint: A riser joint temporarily attached above the telescopic joint and used to land the BOP stack on the wellhead when the telescopic joint is collapsed and pinned.

A.1.62 landing shoulder: A shoulder or projection on the external surface of a riser coupling or other riser component for supporting the riser system or well control equipment during riser deployment and retrieval operations. Sometimes referred to as Riser Support Shoulder.

A.1.63 linear elastic fracture mechanics (LEFT): A method of predicting crack growth based on the assumption of elastic material behavior.

A.1.64 load and resistance factor design (LRFD): A design approach separate factors are assumed for each load and resistance term.

A.1.65 lower marine riser package (LMRP): The upper section of a two-section subsea BOP stack consisting of the hydraulic connector, annular BOP, ball/flex joint, riser adapter, jumper hoses for the choke, kill and auxiliary lines, and subsea control pods. This interfaces with the BOP stack.

A.1.66 lowest anticipated service temperature (LAST): temperature used in establishing temperatures for fracture toughness testing.

A.1.67 local peak stress: See hot-spot stress.

A.1.68 lock-in: Synchronization of vortex-shedding frequency and structural vibration frequency producing resonant flow induced vibration.

A.1.69 low frequency motion: Motion response at frequencies below wave frequencies typically with periods ranging from 30 to 300 seconds.

A.1.70 madeup length: The net length contributed to a riser string by a made-up riser component (overall joint length minus box/pin engagement).

A.1.71 marine drilling riser: A tubular conduit serving as an extension of the well bore from the equipment on the wellhead at the sea floor to the floating drilling vessel.

A.1.72 maximum environmental condition: Maximum condition for designing risers.

A.1.73 maximum operating condition: Maximum condition in which normal operations are carried out.

A.1.74 microbiologically-influenced attack: (MIC).

A.1.75 minimum bending radius (MBR): A governing criteria for flexible pipe risers limiting the radius of curvature.

A.1.76 mobile offshore drilling unit (MODU): A drilling rig used exclusively to drill offshore wells and that floats on the water when being moved from location to location.

A.1.77 mud boost line: An auxiliary line which provides supplementary fluid supply from the surface and injects it into the riser at the LMRP to assist in the circulation of drill cuttings up the marine riser, when required.

A.1.78 net lift: See apparent weight.

A.1.79 nominal stress: Stress calculated using the nominal pipe wall dimensions of the riser at the location of concern.

A.1.80 porch: The top most part of a pontoon or similar hull structure.

A.1.81 post-weld heat-treatment: (PWHT).

A.1.82 preload: Compressive bearing load developed between box and pin members at their interface. This is accomplished by elastic deformation developed during makeup of the coupling.

A.1.83 pup joint: A joint of pipe or tubing shorter than standard length.

A.1.84 quick connect/disconnect connectors: (QCDC).

A.1.85 rated load: A nominal applied loading condition used during riser design, analysis, and testing based on maximum anticipated service loading.

A.1.86 response amplitude operator (RAO): For regular waves, it is the ratio of a vessel's motion to the wave amplitude causing that motion and presented over a range of wave periods.

A.1.87 riser adapter: Crossover between riser and flex/ball joint.

A.1.88 riser annulus: The space around pipe (drillpipe, casing, or tubing) suspended in a riser; its outer boundary is the internal surface of the riser main pipe.

A.1.89 riser connector (LMRP connector): A hydraulically operated connector that joins the LMRP to the top of the BOP stack.

A.1.90 riser disconnect: The operation of unlatching of the riser connector to separate the riser and LMRP from the BOP stack.

A.1.91 riser hang-off system: A means for supporting a disconnected riser from the drilling vessel during a storm without inducing excessive stresses in the riser.

A.1.92 riser joint: A section of riser main tube having ends fitted with coupling elements and includes choke, kill, and (optional) auxiliary lines and their support bands.

A.1.93 riser main tube (riser pipe): The seamless or electric welded pipe which forms the principal conduit of the riser joint. For example, in reference to a drilling riser, the riser main tube is the conduit for containing the return fluid flow from the well and for guiding drill string, logging tools, casing, etc. into the well.

A.1.94 riser recoil system: A means of limiting the upward acceleration of the riser when a disconnect is made at the riser connector.

A.1.95 riser spacer frame: A purpose designed frame to maintain lateral separation among risers.

A.1.96 riser spider: A device having retractable jaws or dogs used to support the riser string on the uppermost coupling support shoulder during deployment and retrieval of the riser.

A.1.97 riser string: A deployed assembly of riser joints.

A.1.98 riser support shoulder: A shoulder or projection on the external surface of a riser coupling or other riser component for supporting the riser system or well control equipment during riser deployment and retrieval operations. Sometimes referred to as Landing Shoulder.

A.1.99 riser tensioner: Means for providing and maintaining top tension on the deployed riser string to help control lower flex element angle, to reduce pipe bending stress, and to prevent pipe buckling.

A.1.100 riser tensioner ring: The structural interface of the telescopic joint outer barrel and the riser tensioners.

A.1.101 rotary kelly bushing (RKB): Commonly used vertical reference from the drillfloor.

A.1.102 running tool: Specialized tools used to run equipment in a well, such as a wireline running tool or various types of tubing-type running tools.

A.1.103 service life: The length of time that a component will be in service assumed in design.

A.1.104 spar: A spar-buoy shaped FPS hull.

A.1.105 slip joint (telescopic joint): A riser joint having an inner barrel and an outer barrel with a sealing means between. The inner and outer barrels of the telescopic joint move relative to each other to compensate for the required change in the length of the riser string as the riser bends and the vessel experiences surge, sway and heave.

A.1.106 specified minimum yield strength: The tensile stress at 0.5 percent elongation of the specimen gage length.

A.1.107 stab: A mating box and pin assembly that provides pressure-tight engagement of two pipe joints. An external mechanism is normally used to keep the box and pin engaged. For example, riser joint choke and kill stabs are retained in the stab mode by the make-up of the riser coupling.

A.1.108 standard riser joint: A joint of typical length for a particular drilling vessel's riser storage racks, the derrick V-door size, riser handling equipment capacity or a particular riser purchase.

A.1.109 steel catenary riser (SCR): A prolongation of a subsea pipeline attached to a FPS in a catenary shape.

A.1.110 storm choke: See subsurface safety valve.

A.1.111 storm disconnect: A riser disconnect to avoid excessive loading from vessel motions amplified by inclement weather conditions.

A.1.112 strakes: Helically wound appendages attached to the outside of the riser to suppress vortex induced vibrations (also helical strakes).

A.1.113 stress amplification factor (SAF): Equal to the local peak alternating stress in a component (including welds) divided by the nominal alternating stress in the pipe wall at the location of the component. This factor is used to account for the increase in the stresses caused by geometric stress amplifiers which occur in the riser component.

A.1.114 stress concentration factor (SCF): Equal to the local peak alternating stress divided by the nominal stress in the component.

A.1.115 stress joints: A stress or taper joint provides a means of distributing riser curvature arising from bending at either end.

A.1.116 strumming: The in-line or transverse oscillation of a riser in a current induced by the periodic shedding of vortices.

A.1.117 submerged weight: See apparent weight.

A.1.118 subsea fillup valve: A special valve that allows the riser annulus to be opened to the sea. To prevent riser collapse, the valve may be opened by an automatic actuator controlled by a differential-pressure sensor.

A.1.119 subsurface controlled sub-surface safety valve: (SSC).

A.1.120 subsurface safety valve (SSSV): A device installed in the tubing string of a producing well that shuts in the flow should it exceed a preset rate.

A.1.121 support brackets: Brackets positioned at intervals along a riser joint that provide intermediate radial and lateral support from the riser pipe to choke, kill, and auxiliary lines.

A.1.122 surge: Vessel motion along the fore/aft axis.

A.1.123 sway: Vessel motion along the port/starboard axis.

A.1.124 syntactic foam: Typically a composite material of hollow spherical fillers in a matrix or binder.

A.1.125 telescopic joint (slip joint): See slip joint.

A.1.126 telescopic joint packer: The means of sealing the annular space between the inner and outer barrels of the telescopic joint.

A.1.127 tension leg platform (TLP): A column stabilized platform that has vertical prone motions restrained by tendons.

A.1.128 terminal fitting: The connection between a rigid choke, kill or auxiliary line on a telescopic joint and its drape hose, effecting a nominal 180 degree turn in flow direction.

A.1.129 thrust collar: A device for transmitting the buoyant force of a buoyancy module to the riser joint.

A.1.130 type certification testing: Testing by a manufacturer of a representative specimen (or prototype) of a product to qualify the design and to validate the integrity of other products of the same design, materials, and manufacture.

A.1.131 upper/lower riser connector package: (UPRC/LRPC).

A.1.132 vortex induced vibration (VIV): The in-line and transverse oscillation of a riser in a current induced by the periodic shedding of vortices.

A.1.133 wave frequency motion: Motion of the FPS at the frequencies of incident waves.

A.1.134 wellhead connector (stack connector): A hydraulically operated connector that joins equipment to the subsea wellhead (e.g., BOP stack "stack connector," subsea production or injection tree or "tree connector," production or injection risers or "riser connectors").

A.1.135 wet weight: See apparent weight.

A.1.136 working stress design: Design based on not exceeding allowable stresses as distinguished from a load-and-resistance factor design.

ANNEX B—(INFORMATIVE)

Detailed Functional Considerations by Riser Type

The functional considerations for each of the principal types of risers (production, injection service, export/sales, drilling, and workover) are listed below:

B.1 Production Risers

B.1.1 Are required to transfer the produced (oil, gas, water, or a combination of these) fluids from the subsea wellhead and Christmas tree or manifold, to the floating production vessel.

B.1.2 Transfer well completion, workover, or kill fluids and other remedial fluids from the floating production system to the subsea production equipment.

B.1.3 Provide and maintain the necessary control of the wells and produced fluids at all times and under all operating and emergency conditions.

B.1.4 Provide a smooth, unobstructed passage for mechanical tools and pigs to and from the subsea production equipment. The design of the production riser should facilitate in-line service and maintenance functions, such as conventional pigging.

B.1.5 Minimize the number of flow restrictions and the pressure drop between the subsea equipment and the floating production system.

B.1.6 Are able to withstand the maximum operating pressure of the subsea equipment and process equipment on the floating production system.

B.1.7 Facilitate installation, maintenance, and abandonment operations.

B.1.8 Provide means for integrity monitoring and visual inspection while installed and in service.

B.1.9 Meet the required design operating life.

B.1.10 Withstand the design loads under normal operating, emergency, and survival conditions.

B.1.11 Minimize the maintenance requirements in terms of frequency, involvement, complexity or costs.

B.2 Injection Service Risers

B.2.1 Are required to transfer high pressure water or gas from the floating production system to the sub-sea wellheads for reservoir pressure maintenance and other production management purposes.

B.2.2 Provide and ensure that the necessary control of the injection wells and other production service functions are maintained at all times and under all operating and emergency conditions.

B.2.3 Provide a smooth, unobstructed passage for inspection tools to and from the subsea equipment. The design of the injection riser should facilitate in-line service and maintenance functions.

B.2.4 Minimize the number of flow restrictions and the pressure drop between the floating production system and the subsea equipment.

B.2.5 Withstand the full working pressure of the booster pumps or compressors on the floating production system and the subsea completion.

B.2.6 Facilitate the installation, maintenance, and abandonment operations.

B.2.7 Provide means for integrity monitoring and visual inspection while installed and in service.

B.2.8 Meet the required design operating life.

B.2.9 Withstand the design loads under normal operating, emergency and survival conditions.

B.2.10 Minimize the maintenance requirements in terms of frequency, involvement, complexity, or costs.

B.3 Export Risers

B.3.1 Transfer the processed (oil, gas, water, or combination of these) fluids from the floating production system to another facility, which may include a fixed drilling/production platform, a floating, processing, and/or storage vessel, or a shuttle tanker.

B.3.2 Provide a smooth, unobstructed passage for inspection tools and pigs between the floating production system and the processed fluid receiving facility. The design of the export riser should also facilitate in-line service and service functions, such as conventional pigging.

B.3.3 Minimize the number of flow restrictions and the pressure drop between the floating production system and the processed fluid receiving facility.

B.3.4 Prevent excessive formation of paraffin deposits on the internal wall surfaces.

B.3.5 Prevent the formation of hydrates in the line.

B.3.6 Withstand the full working pressure of the transfer pumps and/or compressors and the process equipment on the receiving facility.

B.3.7 Facilitate the installation, maintenance, and abandonment operations.

B.3.8 Provide means for integrity monitoring and visual inspection while installed and in service.

B.3.9 Meet the required design operating life of the field.

B.3.10 Withstand the design loads under normal operating, emergency, and survival conditions.

B.3.11 Minimize the maintenance requirements in terms of frequency involvement, complexity, or costs.

B.4 Drilling Risers

B.4.1 Provide a continuation of the drilling wellbore from the subsea BOP stack to the floating drilling vessel.

B.4.2 Provide a continuation of the wellbore from the marine housing to the BOP stack on the floating vessel.

B.4.3 Provide a conduit to contain drilling fluids and allow their circulation to and from the wellbore.

B.4.4 Act as a guide for drilling tools being run into or pulled out of the wellbore.

B.4.5 Provide a containment of the drilling string while it is being rotated under normal drilling.

B.4.6 Allow controlled circulation of drilling fluids through the choke and kill lines during well-control operations.

B.4.7 Provide a means of connecting the subsea BOP stack to the pressure control manifold on the floating vessel by means of choke and kill lines.

B.4.8 Provide containment for uncontrolled flow of shallow gas and allow safe diverting of the uncontrolled flow away from personnel and the drilling vessel.

B.4.9 Support external conduits such as choke and kill lines.

B.4.10 Support external BOP control lines for guideline-less drilling operations.

B.4.11 Provide a means for circulating drilling fluid through the drilling riser to increase riser annular fluid velocity while drilling.

B.4.12 Serve as a running and retrieving string for the BOP and LMRP.

B.4.13 Allow means of connecting riser joints together in safe and convenient manner on the drill floor.

B.4.14 Allow a means of attaching hoists or slings to the drilling riser for safe handling on the drilling vessel.

B.4.15 Allow a means of storing the drilling riser on the drilling vessel without damage to external lines.

B.4.16 Provide for the attachment of buoyancy modules to assist in supporting the riser and reduce operating tension requirements.

B.4.17 Provide for the attachment of spoilers or strakes to reduce the drag and vibration in the drilling riser by high currents.

B.5 Workover and Completion Risers

B.5.1 Provide a continuation of the wellbore from the subsea tree to the floating workover vessel.

B.5.2 Provide a conduit from the individual bores of a subsea tree to the surface workover vessel.

B.5.3 Allow unobstructed access to single or multiple tubing bores and the wellbore annulus from the workover vessel.

B.5.4 Provide a conduit to contain completion of workover fluids and allow their circulation to and from the wellbore.

B.5.5 Act as a guide for workover tools being run into or pulled out of the wellbore.

B.5.6 Allow means of connecting workover riser joints together in a safe and convenient manner on the drill floor.

B.5.7 Allow means of adjusting the relative lengths of dual tubing strings.

B.5.8 Serve as a running string for the subsea tree.

B.5.9 Serves as a running string for the tubing hanger.

B.5.10 Allow for running the completion riser through the drilling riser and well head system.

B.5.11 Act as a guide for the passage of tools and plugs to and from the wellbore by wireline.

B.5.12 Provide a means for attaching external or connecting internal control lines to the subsea tree or running tools.

B.5.13 Allow for the injection of chemicals at or below the subsea tree if required.

ANNEX C—(INFORMATIVE)

C.1 Design Criteria Example Problem

C.1.1 The following is an example problem that demonstrates how to use the design criteria provided in Section 5 for rigid risers. The example is a simple cylindrical pipe with a uniform internal diameter and a step increase in outside diameter. The pipe is loaded with internal pressure and external force. All pertinent stresses were calculated using a finite element model, since this is currently the most commonly used method of stress analysis. Although it is not necessary to use a finite element model to calculate stresses, this method is recommended for all but very simple geometries and loads where hand calculations are accurate. Note that the bending referred to in this Annex is the local bending across a cross section and not the global bending computed by global riser analysis.

C.1.2 Figure C-1 shows the geometry and dimensions of the example problem. The nomenclature for the dimensions is:

R_o = outside radius.

R_o = 2.5 inches.

R_i = inside radius.

R_i = 1.0 inches.

R_m = intermediate radius.

R_m = 1.5 inches.

C.1.3 The loads are shown Figure C-2. The values and nomenclature for the loads are:

P = internal pressure.

P = 10000 psi.

U = axial tension.

F = 100000 lbs.

C.1.4 It is assumed that these are the loads during the maximum operating load design case, and the material yield strength is:

σ_y = 60,000 psi

C.1.5 Figure C-3 shows the element grid, loads, and boundary conditions for the finite element model of the tube. As the figure shows, the model was axisymmetric and applied the axial forces as a uniform pressure on the ends of the tube. The nodes on the small end were axially fixed to prevent rigid body movements that might be caused by computer round-off of the two pressure end loads. The ANSYS finite element program and the PLANE42 element type were used. Notice that the grid was not fine enough at the transition to yield accurate peak stresses. This is acceptable, since a fatigue analysis is not being performed in this example.

C.1.6 Figure C-4 shows the Von Mises effective stress contours in the vicinity of the thickness where the stresses will be a maximum.

C.1.7 The following allowable stresses are given in 5.2.3:

C_f = design case factor (see 4.4).

C_a = $^2/_3$ for steel.

C_f = 1.0 for maximum operating design case.

for primary membrane:

$$\sigma_p < C_a C_f \sigma_y$$

$$\sigma_p < 40{,}000 \text{ psi}$$

for primary membrane plus bending:

$$\sigma_p + \sigma_b < 1.5\, C_a C_f \sigma_y$$

$$\sigma_p + \sigma_b < 60{,}000 \text{ psi}$$

for primary plus secondary:

$$(\sigma_p + \sigma_b + \sigma_q)_e < 3.0\, \sigma_a$$

$$\sigma_p + \sigma_b < 120{,}000 \text{ psi}$$

C.1.8 Section 5.2.1 requires that the principal stresses at all critical sections be calculated and classified as either primary membrane, primary bending or secondary. Figure C-5 shows the two critical sections in the example. Section AA is critical, because it is the minimum section away from any discontinuities. This is the critical section from the standpoint of primary stresses. Section BB is critical, because it is the section at the discontinuity where primary plus secondary stresses will be largest. This is verified by the stress plot shown in Figure C-4.

C.1.9 Figures C-6 and C-7 show the calculated values of hoop, axial and radial stress components across sections AA and BB. These stresses were taken directly from the finite element output. Notice that since there is no transverse shear force or torsional moment on the sections, these stress components are also the principal stresses.

C.1.10 The primary and secondary stresses that are compared with the allowables are the von Mises equivalent stresses calculated from the stress components after they are linearized across sections. Figures C-8 and C-9 show the linearized stresses in the hoop, axial and radial directions across sections AA and BB. The ANSYS linearizing commands were used to generate these curves. Most finite element programs have linearizing routines that will adequately perform the linearizing function. However, if a finite element program does not have this capability or stresses were calculated using some other technique, linearizing can be adequately performed using hand calculations or curve fitting programs.

C.1.11 The stresses are then separated into membrane and bending components. For linear stresses across a section, the membrane and bending components are calculated using the following equations:

σ_m = membrane stress $\qquad$ σ_d = bending stress

$\sigma_m = (\sigma_o + \sigma_i)/2 \qquad \sigma_d = (\sigma_o - \sigma_i)/2$

where

σ_o = stress at outside surface.

σ_i = stress at inside surface.

C.1.12 First consider section AA:

in the hoop direction:

$$\sigma_{ih} = 24{,}750 \text{ psi}$$

$$\sigma_{oh} = 15{,}230 \text{ psi}$$

$$\sigma_{mh} = \frac{\sigma_{ih} + \sigma_{oh}}{2}$$

$$\sigma_{mh} = 19{,}990 \text{ psi}$$

$$\sigma_{dh} = \frac{\sigma_{ih} - \sigma_{oh}}{2}$$

$$\sigma_{dh} = 14{,}760 \text{ psi}$$

in the axial direction:

$$\sigma_{ia} = 25{,}420 \text{ psi}$$

$$\sigma_{oa} = 25{,}510 \text{ psi}$$

$$\sigma_{ma} = \frac{\sigma_{ia} + \sigma_{oa}}{2}$$

$$\sigma_{ma} = 25{,}465 \text{ psi}$$

$$\sigma_{da} = \frac{\sigma_{ia} - \sigma_{oa}}{2}$$

$$\sigma_{da} = 45 \text{ psi}$$

in the radial direction:

$$\sigma_{ir} = -9882 \text{ psi}$$

$$\sigma_{or} = 30 \text{ psi}$$

$$\sigma_{mr} = \frac{\sigma_{ir} + \sigma_{or}}{2}$$

$$\sigma_{mr} = -4926 \text{ psi}$$

$$\sigma_{dr} = \frac{\sigma_{ir} - \sigma_{or}}{2}$$

$$\sigma_{dr} = -4956 \text{ psi}$$

C.1.13 The membrane stresses, σ_m, are primary membrane stresses, and the bending stresses, σ_d, are primary bending stresses. Also, all of the membrane and bending stresses calculated in the preceding page are principal stresses. Hence, the three principal primary membrane stresses at section AA are:

$\sigma_1 = \sigma_{ma} \qquad \sigma_1 = 25{,}465$ psi

$\sigma_2 = \sigma_{mh} \qquad \sigma_2 = 19{,}990$ psi

$\sigma_3 = \sigma_{mr} \qquad \sigma_3 = -4926$ psi

and the von Mises membrane stress is:

$$\sigma_{me} = \frac{\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}}{\sqrt{2}}$$

$\sigma_{me} = 28{,}057$ psi $\quad$ The allowable for this stress is 40,000 psi, thus it is acceptable.

The three principal primary membrane plus bending stresses at the inside surface are:

$\sigma_1 = \sigma_{ma} + \sigma_{da} \qquad \sigma_1 = 25{,}420$ psi

$\sigma_2 = \sigma_{mh} + \sigma_{dh} \qquad \sigma_2 = 24{,}750$ psi

$\sigma_3 = \sigma_{mr} + \sigma_{dr} \qquad \sigma_3 = -9882$ psi

and the von Mises membrane plus bending stress is:

$\sigma_{be} = 34{,}972$ psi $\quad$ The allowable for this stress is 60,000 psi, thus it is acceptable.

C.1.14 The three principal primary membrane plus bending stresses at the inside surface are:

$\sigma_1 = \sigma_{ma} - \sigma_{da}$ $\quad \sigma_1 = 25{,}510$ psi

$\sigma_2 = \sigma_{mh} - \sigma_{dh}$ $\quad \sigma_2 = 15{,}230$ psi

$\sigma_3 = \sigma_{mr} - \sigma_{dr}$ $\quad \sigma_3 = 30$ psi

and the Von Mises membrane plus bending stress is:

$\sigma_{be} = 22{,}203$ psi The allowable for this stress is 60,000 psi, thus it is acceptable.

C.1.15 Next consider section BB. This section is next to the transition and will include primary and secondary stresses. The following are the linearized stresses taken from Figure C-9.

in the hoop direction:

$\sigma_{ih} = 26{,}820$ psi

$\sigma_{oh} = 20{,}550$ psi

$$\sigma_{mh} = \frac{\sigma_{ih} + \sigma_{oh}}{2}$$

$\sigma_{mh} = 23{,}685$ psi

$$\sigma_{dh} = \frac{\sigma_{ih} - \sigma_{oh}}{2}$$

$\sigma_{dh} = 3135$ psi

in the axial direction:

$\sigma_{ia} = 16{,}330$ psi

$\sigma_{oa} = 33{,}460$ psi

$$\sigma_{ma} = \frac{\sigma_{ia} + \sigma_{oa}}{2}$$

$\sigma_{ma} = 24{,}895$ psi

$$\sigma_{da} = \frac{\sigma_{ia} - \sigma_{oa}}{2}$$

$\sigma_{da} = -8565$ psi

in the radial direction:

$\sigma_{ir} = -9521$ psi

$\sigma_{or} = -841$ psi

$$\sigma_{mr} = \frac{\sigma_{ir} + \sigma_{or}}{2}$$

$\sigma_{mr} = -5181$ psi

$$\sigma_{dr} = \frac{\sigma_{ir} - \sigma_{or}}{2}$$

$\sigma_{dr} = -4340$ psi

and the Von Mises membrane plus local bending stress is:

$\sigma_{be} = 30{,}007$ psi The allowable for this stress is 120,000 psi, thus it is acceptable.

C.1.16 The membrane stresses, σ_m, are primary membrane stresses, and the bending stresses, σ_d, are primary bending stresses. Notice that the geometry and dimensions are identical for sections AA and BB. The only difference is that section BB is near a discontinuity which causes secondary stresses. Thus, the primary bending stresses in section BB are the same values as those in section AA which have already been shown acceptable. Also, all of the membrane and bending stresses calculated in the proceeding page are principal stresses. Hence, the three principal primary membrane stresses at section BB are:

$\sigma_1 = \sigma_{ma}$ $\quad \sigma_1 = 24{,}895$ psi

$\sigma_2 = \sigma_{mh}$ $\quad \sigma_2 = 23{,}685$ psi

$\sigma_3 = \sigma_{mr}$ $\quad \sigma_3 = -5181$ psi

and the Von Mises membrane stress is:

$\sigma_{me} = 29{,}490$ psi The allowable for this stress is 40,000 psi, thus it is acceptable.

C.1.17 The three principal primary membrane plus bending stresses at the inside surface are:

$\sigma_1 = \sigma_{ma} - \sigma_{da}$ $\quad \sigma_1 = 26{,}820$ psi

$\sigma_2 = \sigma_{mh} - \sigma_{dh}$ $\quad \sigma_2 = 16{,}330$ psi

$\sigma_3 = \sigma_{mr} - \sigma_{dr}$ $\quad \sigma_3 = -9521$ psi

and the Von Mises membrane plus bending stress is:

$\sigma_{be} = 32{,}396$ psi The allowable for this stress is 120,000 psi, thus it is acceptable.

C.1.18 The three principal primary membrane plus bending stresses at the inside surface are:

$\sigma_1 = \sigma_{ma} - \sigma_{da}$	$\sigma_1 = 33{,}460$ psi
$\sigma_2 = \sigma_{mh} - \sigma_{dh}$	$\sigma_2 = 20{,}550$ psi
$\sigma_3 = \sigma_{mr} - \sigma_{dr}$	$\sigma_3 = -841$ psi

and the von Mises membrane plus bending stress is:

$\sigma_{be} = 30{,}007$ psi The allowable for this stress is 120,000 psi, thus it is acceptable.

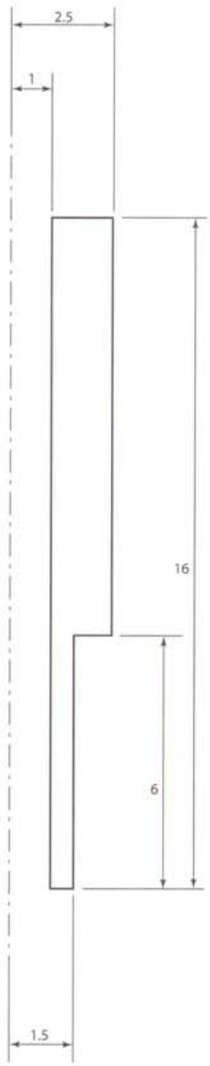


Figure C-1—Geometry

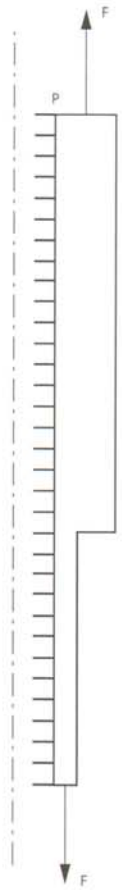


Figure C-2—Loads

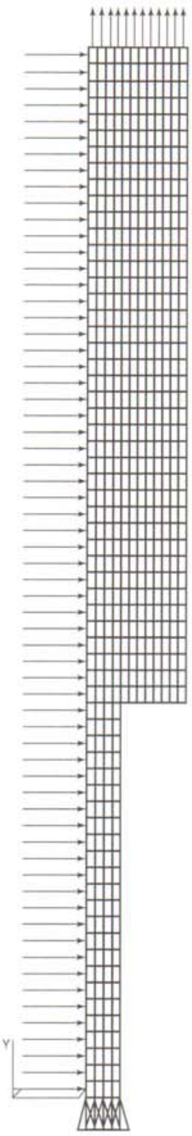


Figure C-3—Finite Element Model

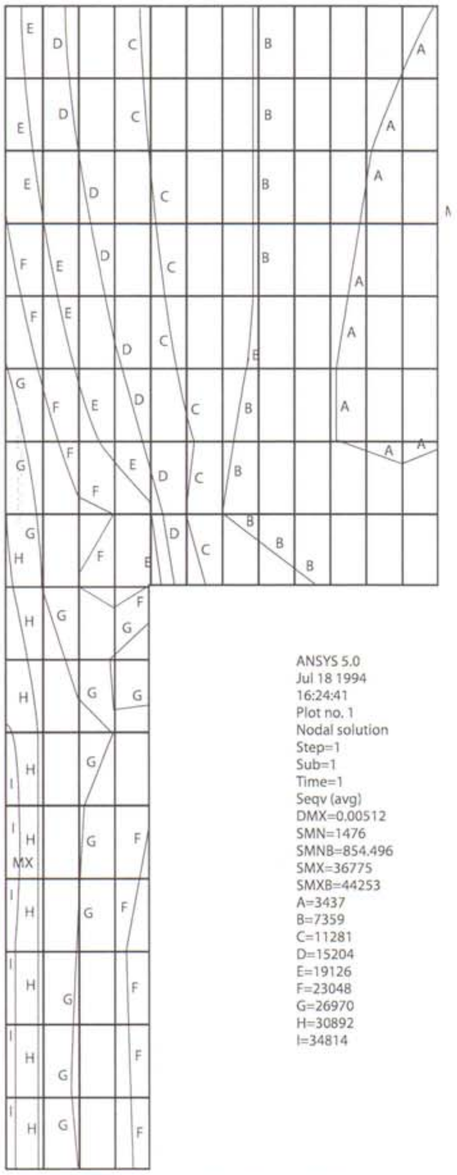


Figure C-4—von Mises Stresses

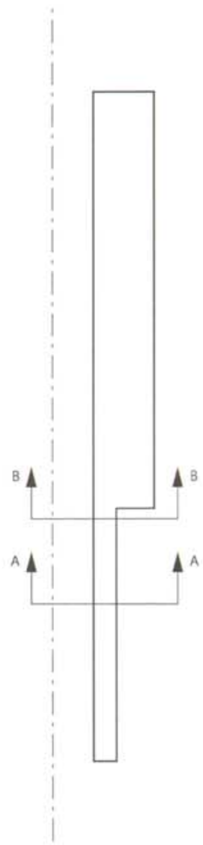


Figure C-5—Critical Section

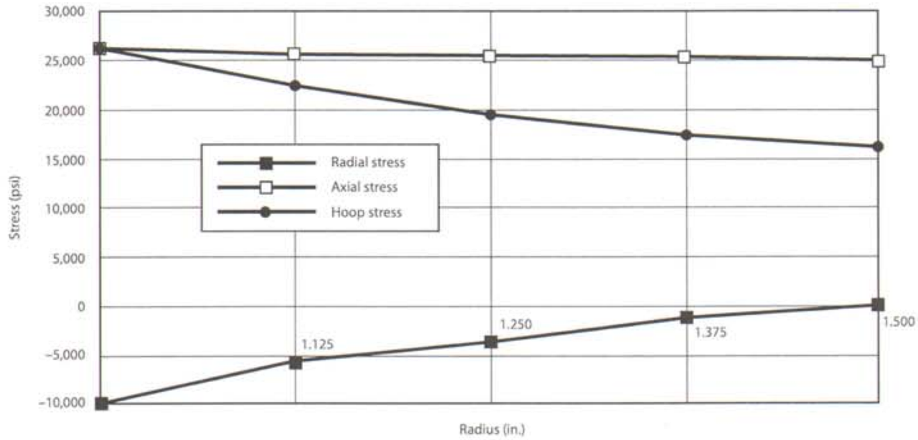


Figure C-6—Stress in Section AA

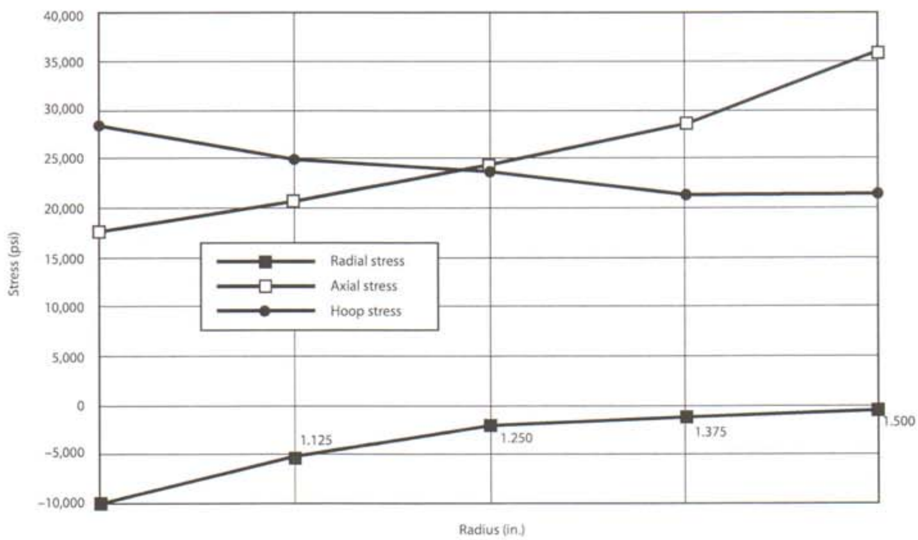


Figure C-7—Stresses in Section BB

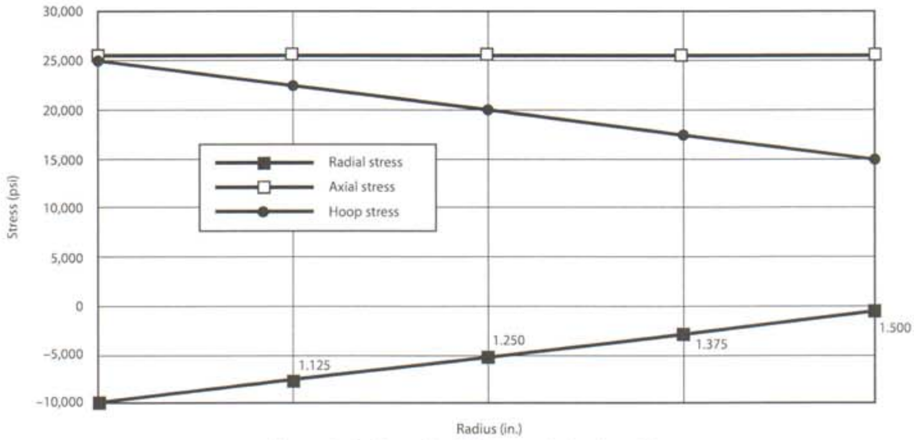


Figure C-8—Linearized Stresses in Section AA

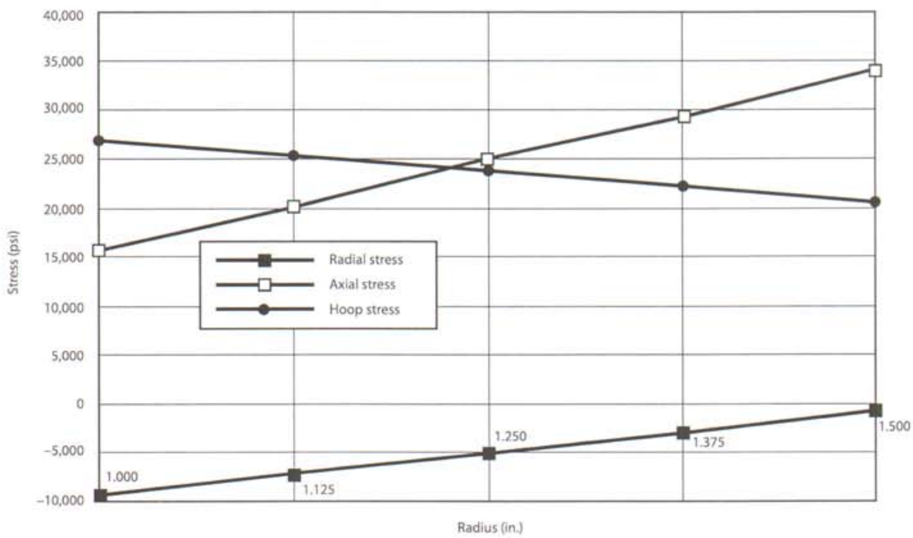


Figure C-9—Linearized Stresses in Section BB

ANNEX D—(INFORMATIVE)

Composite Riser Design

D.1 General

High performance composite materials have been used in the aerospace industry for many years for applications where high strength and low weight are required. Their application to deepwater risers has been a topic of research since the early 1980s. Such research has intensified in recent years.

D.2 Definition

The term "High Performance Composites" is used here for those long continuous fibrous composites used in the construction of heavily loaded structural components. Failure of these structural components is often governed by the failure of the high performance composites in the fiber direction.

D.3 Composite Riser Joint Components

A riser joint of high performance composites will generally include the following four components:

a. A high performance composite tube body made of multiple layers of continuous fibers embedded in a resin matrix. The fibers in each layer may be of various types, such as high strength carbon fiber, high modulus carbon fiber, aramid fiber, S-glass, and E-glass fibers. More than one type of fiber may be used in each layer. Fibers in different layers may orient at different angles to the composite tube axis. The resin matrix can be of either thermoset or thermoplastic.

b. Tube metal end pieces, with connectors to allow easy make up of riser joints.

c. An internal liner.

d. An external liner.

D.3.1 TUBE BODY ANALYSIS

The global stiffness of the high performance composite tube and the stresses induced in different layers within the tube body due to either applied loads and/or thermal effects should be calculated based on thick-walled anisotropic composite cylinder analysis. Finite element methods which can account for thick-walled effect can also be used.

D.3.2 STRESS LIMITS FOR FIBERS

The allowable design stress of the fibers used in the construction of the high performance composite tube will need to be clearly specified. In establishing the allowable fiber design stress, care should be taken to account for the effect of the operating environment, temperature, loading history, service life requirements, etc.

D.3.3 STRESS LIMITS FOR THE MATRIX

D.3.3.1 The high performance composite tube can be designed to allow micro-cracking of the resin matrix to occur during its service life. In this case, the wall of the composite tube will no longer be water-tight. Pressure barriers such as internal and external liners will need to be used. It should be pointed out that micro-cracking of the resin matrix will not cause structural failure of the high performance composite tube. The structural integrity of the high performance composite tube is governed by the integrity of the long continuous fibers.

D.3.3.2 If the high performance composite tube is required to maintain water-tightness during its entire service life, the allowable design stress limits of the matrix dominated stress components will need to be established. They can be determined either through long term testing of the high performance composite tube or through validated analytical methods utilizing well characterized material properties and appropriate anisotropic failure criteria.

D.3.4 END PIECE DESIGN

The tube end piece will normally be made from metal to allow for easy coupling to other riser joints. Stresses in the end piece should be analyzed using the finite element method.

D.3.5 TUBE/END PIECE CONNECTION

The interface between the high performance composite tube and the metal end piece is critical to the structural integrity of the composite riser. Structural connection can be achieved by various means such as pinning, bonding, etc. Care should be taken to avoid localized high stresses at the tube to metal end piece interface which could jeopardize the integrity and service life of the composite riser.

D.3.6 INTERNAL LINER

The internal liner can be used to provide a pressure barrier for the high performance composite tube. The internal liner must be compatible with the fluids and gases that will be encountered during the entire service life of the composite riser. The liner can be installed before or after the fabrication of the high performance composite tube. If the liner is installed before the fabrication of the composite tube, it must be capable of withstanding all mechanical and thermal loads during all phases of the fabrication process. Depending on the service environment, the liner might need to be bonded to the composite tube body. Note that the internal liner considered here does not include any resin rich liner that is fabricated in-situ with the composite tube. The resin rich liner is considered as part of the composite tube.

D.3.7 EXTERNAL LINER

The external liner can be used to provide a pressure barrier for the high performance composite tube. The external liner must be compatible with the surrounding fluid and be able to provide some protection against accidental damage due to handling the high performance composite tube.

D.3.8 LINER/END PIECE JUNCTIONS

The junctions between the liners and the tube end pieces are critical items requiring special attention. They must be designed to remain pressure tight during the entire life of the tube. The junctions should be designed to avoid excessive large local strains in the liner at the transition between the composite tube body and the metal end piece.

D.4 Loads and Constraints—Some Particular Points

D.4.1 EXTERNAL PRESSURE

The design must consider the possibility of a sudden loss of internal pressure in the riser during work-over or other operations, when the internal pressure may fall to atmospheric pressure. Either the composite tube must be designed to resist the resulting differential external pressure, or equipment such as a fill-up valve must be incorporated into the riser system to ensure that external differential pressure can never exceed a specified value, which the riser must be designed to resist.

D.4.2 AXIAL STRAIN

Composite production risers may be used with production tubings made from other materials, such as steel, with very different elastic characteristics. It is important to ensure that the axial strain of the composite riser does not lead to the over stressing of the production tubings. It may be necessary to equip the latter with expansion joints. This is particularly likely to be the case if the composite risers are designed to be connected to the platform without tensioners.

D.4.3 PLATFORM/RISER CONNECTION

For TLPs in deep water, composite risers can be designed to operate without compensating tensioners. If this option is adopted it is important for the designer to verify the effects of changes of internal pressure or temperature. These can lead to axial stretch of the riser and hence to a reduction in effective tension. The designer has three options. He can incorporate a tension adjustment system at the top end of each riser; he can verify that the riser stretch and associated reduction in effective tension are acceptable; he can exploit the special features of composites and design the tube to have small (or even negative) axial stretch under the effect of internal pressure and temperature.

D.4.4 FATIGUE/AGING/CORROSION

The effects of fatigue, aging, and corrosion on composites are important and complicated subjects requiring further research. The effects are very different according to the types of composites used and to the operational environment.

D.4.5 INSPECTION AND NON-DESTRUCTIVE TESTING

The recommendations given in 5.7.3 of the main body of this document should form the basis for inspection and non-destructive testing of the composite riser.

D.4.6 DEVELOPMENTS FOR SPECIFIC APPLICATIONS

Composite risers will continue to remain as a research subject. However, serious considerations should be given to evaluate this technology for specific applications. Development of advanced design concepts and reliability analysis techniques are essential to the advancement of composite riser technology. For composite risers to be a reality for deep water applications, work must begin to qualify composite risers for specific applications.

ANNEX E—(NORMATIVE)

E.1 References

E.1.1 API—AMERICAN PETROLEUM INSTITUTE

RP 2A-LRFD	*Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Load and Resistance Factor Design*, Twentieth Edition, July 1, 1993
RP 2A-WSD	*Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms Working Stress Design*, Twentieth Edition, July 1, 1993
RP 2FPI	*Recommended Practice for Design, Analysis, and Maintenance of Moorings for Floating Production Systems*, First Edition, February 1, 1993
RP 2T	*Recommended Practice for Planning, Designing and Constructing Tension Leg Platforms*, First Edition, April 1987 (Supplement 1 to first edition RP 2T, April 1, 1992) ANSI/API RP 2T-1992)
RP 2X	*Recommended Practice for Ultrasonic Examination of Offshore Structural Fabrication and Guidelines for Qualifications of Ultrasonic Technicians*, Second Edition, September 1, 1988 (ANSI/API RP 2X-1992)
RP 2Z	*Recommended Practice for Preproduction Qualification for Steel Plates for Offshore Structures*, Second Edition, July 1, 1992 (ANSI/API RP 2Z-1992)
RP 14E	*Recommended Practice for Design and Installation of Offshore Production Platform Piping Systems*, Fifth Edition, October 1, 1991 (ANSI/API RP 14E-1992)
RP 16E	*Recommended Practice for Design of Control Systems for Drilling Well Control Equipment*, First Edition, October 1, 1990 (ANSI/API RP 16E-1992)
Bull 16J	*Bulletin on Comparison of Marine Drilling Riser Analyses*, First Edition, August 1, 1992 (ANSI/API Bull 16J-1992) (Formerly Bulletin 2J)
RP 16Q	*Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems*, First Edition, November 1, 1993 (Formerly RP 2Q and RP 2K)
Spec 16R	*Specification for Marine Drilling Riser Couplings*, First Edition, October 1986
RP 17A	*Recommended Practice for Design and Operation of Subsea Production Systems*, First Edition, September 1, 1987
RP 17B	*Recommended Practice for Flexible Pipe*, First Edition, June 1, 1988 (ANSI/API RP 17B-1992)
RP 17G	*Recommended Practice for Design and Operation of Completion/Workover Riser Systems*, First Edition, January 1, 1995
Spec 17J	*Specification for Unbonded Flexible Pipe*, First Edition
RP 750	*Management of Process Hazards*, First Edition, January 1990
RP 1111	*Developing a Pipeline Supervisory Control Center*, Second Edition, March 1993
Spec 2H	*Specification for Carbon Manganese Steel Plate for Offshore Platform Tubular Joints*, Seventh Edition, July 1, 1993
Spec 2W	*Specification for Steel Plates for Offshore Structures, Produced by Thermo-Mechanical Control Processing (TMCP)*, Third Edition, July 1, 1993
Spec 2Y	*Specification for Steel Plates, Quenched-and-Tempered, for Offshore Structures*, Third Edition, July 1, 1993
Spec 5CT	*Specifications for Casing and Tubing (US Customary Units)*, Fifth Edition, April 1, 1995
Spec 5L	*Specification for Line Pipe*, Forty-First Edition, April 1, 1995
Spec 6A	*Specifications for Wellhead and Christmas Tree Equipment*, Seventeenth Edition, February 1, 1996
Spec 17D	*Specification for Subsea Wellhead and Christmas Tree Equipment*, First Edition, October 30, 1992 [Supplement 1 (March 1, 1993) to the first edition of Spec 17D, October 30, 1992]
Spec 17E	*Specification for Subsea Production Control Umbilicals*, First Edition, November 1, 1994
Spec 17J	*Specification for Unbonded Flexible Pipe*.
Spec Q1	*Specification for Quality Programs*, Fifth Edition, December 1, 1994.
Std 1104	*Welding of Pipelines and Related Facilities*, Eighteenth Edition, May 1994 (ANSI/API Std 1104-1994)

E.1.2 SAE-AMS—SOCIETY OF AUTOMOTIVE ENGINEERS, AEROSPACE MATERIAL SPECIFICATION

AMS 2236	
AMS 2300G	*Premium Aircraft-Quality Steel Cleanliness Magnetic Particle Inspection Procedure*
AMS 2301G	*Magnetic Particle Inspection, Aircraft Quality Steel Cleanliness*
AMS 2487	*Anodic Treatment of Titanium and Titanium Alloys, Solution pH 12.4 Maximum*
AMS 2630B	*Inspection, Ultrasonic Product Over 0.5 inch (12.7 mm) Thick*
AMS 2631B	*Ultrasonic Inspection, Titanium and Titanium Alloy Bar and Billet*
AMS 2750C	*Pyrometry*

E.1.3 ANSI—AMERICAN NATIONAL STANDARDS INSTITUTE

E.1.4 ASME INTERNATIONAL

ASME Boiler and Pressure Vessel Code
ASME Pressure Vessels & Piping

ASME QW 466.1	*Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators*

E.1.5 ASNT—AMERICAN SOCIETY FOR NONDESTRUCTIVE TESTING

SNT-TC-1A	*Recommended Practice—Personnel Qualification*

E.1.6 ASTM—AMERICAN SOCIETY FOR TESTING AND MATERIALS

A36/A36M	*Carbon Structural Steel*
A131/A13	*Structural Steel for Ships*
A182/A18	*Forged or Rolled Alloy-Steel Pipe Flanges, Forged Fittings, and Valves and Parts for High-Temperature Service*
A193/A19	*Alloy-Steel and Stainless Steel Bolting Materials for High-Temperature Service*
A194/A19	*Carbon and Alloy Steel Nuts for Bolts for High-Pressure and High-Temperature Service*
A275/A27	*Magnetic Particle Examination of Steel Forgings*
A320/A32	*Alloy Steel Bolting Materials for Low-Temperature Service*
A336/A33	*Alloy Steel Forgings for Pressure and High-Temperature Parts*
A350/A35	*Carbon and Low-Alloy Steel Forgings, Requiring Notch Toughness Testing for Piping Components*
A352/A35	*Steel Castings, Ferritic and Martensitic, for Pressure-Containing Parts, Suitable for Low-Temperature Service*
A370	*Mechanical Testing of Steel Products*
A388/A38	*Ultrasonic Examination of Heavy Steel Forgings*
A487/A48	*Steel Castings Suitable for Pressure Service*
A488/A48	*Steel Castings, Welding, Qualifications of Procedures and Personnel*
A508/A50	*Quenched and Tempered Vacuum-Treated Carbon and Alloy Steel Forgings for Pressure Vessels*
A516/A51	*Pressure Vessel Plates, Carbon Steel, for Moderate-and Lower-Temperature Service*
A537/A53	*Pressure Vessel Plates, Heat-Treated, Carbon-Manganese-Silicon Steel*
A541/A54	*Quenched and Tempered Carbon and Alloy Steel forgings for Pressure Vessel Components*
A572/A57	*High-Strength Low-Alloy Columbium-Vanadium Structural Steel*
A703/A709	*Steel Castings, General Requirements, for Pressure-Containing Parts*
A707/A70	*Forged Carbon and Alloy Steel Flanges for Low-Temperature Service*
A709/A70	*Carbon and High-Strength Low-Alloy Structural Steel Shapes, Plates, and Bars and Quenched-and-Tempered Alloy Structural Steel Plates for Bridges*
A710/A71	*Age-Hardening Low-Carbon Nickel-Copper-Chromium-Molybdenum-Columbium Alloy Structural Steel Plates*
A739	*Steel Bars, Alloy, Hot-Wrought, for Elevated Temperature or Pressure-Containing Parts, or Both*
A745/A74	*Ultrasonic Examination of Austenitic Steel Forgings*
A788	*Steel Forgings, General Requirements*
A859/A85	*Age-Hardening Alloy Steel Forgings for Pressure Vessel Components*
B265	*Titanium and Titanium Alloy Strip, Sheet, and Plate*
B337	*Seamless and Welded Titanium and Titanium Alloy Pipe*
B338	*Seamless and Welded Titanium and Titanium Alloy Tubes for Condensers and Heat Exchangers*
B367	*Titanium and Titanium Alloy Castings*
B381	*Titanium and Titanium Alloy Forgings*
E23	*Notched Bar Impact Testing of Metallic Materials*
E45	*Determining the Inclusion Content of Steel*
E92	*Vickers Hardness of Metallic Materials*
E125	*Magnetic Particle Indications on Ferrous Castings*

E208	*Conducting Drop-Weight Test to Determine Nil-Ductility Transition Temperature of Ferritic Steels*
E399	*Plane-Strain Fracture Toughness of Metallic Materials*
E813	*JIC, A Measure of Fracture Toughness*
E992	*Determination of Fracture Toughness of Steels Using Equivalent Energy Methodology*
E1290	*Crack-Tip Opening Displacement (CTOD) Fracture Toughness Measurement*
F467	*NonFerrous Nuts for General Use*
F467M	*NonFerrous Nuts for General Use [Metric]*
F468	*Nonferrous Bolts, Hex Cap Screws, and Studs for General Use*
F468M	*Nonferrous Bolts, Hex Cap Screws, and Studs for General Use [Metric]*

E.1.7 AWS—AMERICAN WELDING SOCIETY

AWS A3.0	*Standard Welding Terms and Definitions*
AWS A5.01	*Filler Metal Procurement Guidelines*
AWS D1.1	*Structural Welding Code-Steel*

E.1.8 BSI—BRITISH STANDARD INSTITUTE

BS: PD6493	*Guidance on Methods for Assessing the Acceptability of Flaw in Fusion Welded Structures*
M54	

E.1.9 DOE—DEPARTMENT OF ENERGY (U.K.)

DOE	*Offshore Installation Guidance on Design and Construction*

E.1.10 ISO— INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

8505-1

9002

E.1.11 MIL. STD—MILITARY STANDARD (DEPARTMENT OF DEFENSE)

H 6866	*Inspection, Liquid Penetrant*
H 81200B	*Heat Treatment of Titanium and Titanium Alloys*
L 46010D	*Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting*
S23008D	*Steel Castings, Alloy, High Yield Strength (HY-80 and HY-100)*
S23009C	*Steel Forgings, Alloy, High Yield Strength (HY-80 and HY-100)*
STD 1907	*Inspection, Liquid Penetrant and Magnetic Particle, Soundness Requirements for Materials, Parts and Weldments*
STD 2154	*Inspection, Ultrasonic, Wrought Metals, Process for Department of Defense*
STD 6866	

E.1.12 NACE INTERNATIONAL

MR-01-75	*Metallic material requirements for resistance to sulfide stress cracking (SSC) for petroleum production, drilling, gathering and flowline equipment, and field processing facilities to be used in H_2S-bearing hydrocarbon service*
RP-0176-83	*Control of Corrosion for Steel, Fixed, Offshore Platforms Associated with Petroleum Production*
TM0177-90	*Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking in H2S Environments*
TM0284-87	*Evaluation of Pipelines Steels for Resistance to Stepwise Cracking*

ANNEX F—(INFORMATIVE)

F.1 Design Considerations for Hybrid Risers

This annex outlines the most important design considerations for hybrid risers.

F.1.1 BUOYANCY

F.1.1.1 The buoyancy used to support the riser may come from three sources:

a. Syntactic foam buoyancy modules.
b. Air filled structural member.
c. Near surface air tanks.

F.1.1.2 All forms of buoyancy have reduced effectiveness at increased depth as shown below. It may therefore appear preferable to mount the buoyancy near the top of the riser. This approach results in larger tensile loads being applied over much of the riser than if the buoyancy is distributed along the entire length. A further consideration is that while syntactic foam is the most expensive of the three buoyancy types, it is arguably the simplest form of buoyancy to implement offshore and can reduce the cost of offshore operations. However, the limitations of installation handling equipment are such that neither excessive weight nor buoyancy can be experienced at any stage of installation. The optimum system is therefore likely to consist of a combination of all three forms of buoyancy, with the distribution of each varying according to the application and installation method. Some of the factors influencing selection are now discussed.

F.1.1.3 Buoyancy from the near surface air tanks or the central structural member may be provided by air at ambient pressure or a pressurized air-up type system, fed from the base of the can. Air at ambient pressure offers the simplest solution. However, at increased water depths the increase in external pressure loads require increased can wall thickness which gives reduced upthrust. The pressurized system offers the advantage of enabling the cans to be designed for relatively small hydrostatic pressures throughout the water column, though with increased design complexity. As a result, air tanks mounted at the top of the riser are likely to provide the least expensive form of upthrust.

F.1.1.4 A small diameter structural member is well suited to use of air at ambient pressure. This is the most simple form of air-can, and offers the benefit of providing the facility for internal inspection. At larger depths, where external pressure starts determining the wall thickness, it may be beneficial to flood the lower portion of the can. Where a larger diameter structural member is warranted, an air up type system with many bulkheads along the riser length, possibly every joint, may be more appropriate. Application of this type of system at larger depths or harsher environments may not be feasible as the process of pressurizing the buoyancy system as the riser is lowered through the water column may limit the speed of installation.

Table F-1—Relative Density of Different Types of Buoyancy

Depth (feet)	Syntactic Foam	*Air at Hydrostatic Pressure
1500	0.40	0.06
3000	0.45	0.11
4500	0.50	0.16

Note:
*Excludes weight of can.

F.1.1.5 Syntactic foam buoyancy is the most expensive of the three types of buoyancy but serves a number of functions apart from providing upthrust to the riser. These include, guidance for the peripheral lines during installation, thermal insulation and protection of the peripheral lines from directly applied hydrodynamic loads, and local vortex shedding effects. For installation either by tow-out or running from the production vessel, syntactic foam buoyancy can simplify installation procedures. The buoyancy modules also provide a convenient surface for mounting vortex induced vibration suppression devices. As with other forms of buoyancy, the effectiveness of the syntactic foam buoyancy is reduced at increased water depth. However, when considering the comparative densities in Table F-1, the relative reduction in effectiveness at increased depth is less than that of a pressurized air can type system. At greater depths, when the weight of air cans are taken into consideration, similar effectiveness may be produced from syntactic foam and air-can buoyancy systems.

F.1.2 INSTALLATION

F.1.2.1 Hybrid risers may be installed by running from the production vessel in the same manner as a drilling riser or by tow-out and upending as used for flowline bundles and TLP tethers. The selected method has a significant impact on the design of the riser. Whichever method is adopted the design process must produce a low effective riser weight at all stages of installation, needed for safe handling while ensuring that satisfactory hydrodynamic response is maintained.

F.1.2.2 The differences between the two processes consist of the stages involved in getting the assembled riser string vertically orientated below the production vessel. For installation by tow-out this consists of launch, by lifting the riser from the beach or pulling off a runway, trimming, involving ballasting of peripheral lines and attachment of drag chains or floats so the riser is at the correct depth for towing, tow-out, and upending. For installation by running the process consists of the joint make-up procedure which involves connecting the structural member flange, coupling peripheral lines (if not installed later), fitting vortex vibration suppression strakes where needed and flooding the central member (if peripheral lines not installed) to control weight and upthrust. The joint make-up procedure and ballasting operations required for running result in a longer offshore operations than tow-out.

F.1.2.3 Installation by tow-out probably offers the lowest weight design solution which in turn offers lowest buoyancy cost. Other potential benefits may also be realized but these must be weighed against the associated disadvantages which are not found in installation by running. These include the following:

a. All-welded construction and greater reliability of flowline connections versus possible need to use lower grade steel piping and inability to replace individual lines.
b. Smaller installation weather windows versus accumulation of fatigue damage during tow-out.

F.1.2.4 The advantages and disadvantages of each method vary from application to application. In harsh environments with short installation weather windows, installation by tow-out may be the most favorable. In mild environments, or where the riser has a small number of lines, running may be more appropriate.

F.1.2.5 The final stages of installation are similar with both tow-out and running. The FPS is prepared by attachment of the flexible hoses to the pontoons with free ends tied back in the moonpool area. The riser is positioned vertically such that the top assembly is at a convenient point for attachment of flexible hoses to the goosenecks. When all flexible lines are in place the riser is lowered and latched to the riser base.

F.1.3 VESSEL INTERFACE

F.1.3.1 The interfaces between a hybrid riser and the vessel consist of the flowline connections to the hull and a tensioning or tethering arrangement to maintain compatibility between the lateral movements of the vessel and the riser. The one existing hybrid riser is used with a semisubmersible vessel, but the required interfaces can also be provided by a tanker type FPSO.

F.1.3.2 Hybrid risers are generally considered most suitable for use with semisubmersible vessels. The main difference between semisubmersible and FPSO interfaces is the difference in offtake circumference provided at the vessel, which is smaller for an FPSO. The dimensions of the semisubmersible pontoons provide greater spacing between jumper hoses than offered by the turret of an FPSO, which can make satisfactory configuration of the jumper hoses more difficult, particularly if severe surface currents must be accommodated. In harsh environments, with both severe wave and surface current loading, an offset riser may be needed to produce a satisfactory flexible jumper hose arrangement.

F.1.3.3 Tethering or tensioning of the riser from a semisubmersible can be conveniently achieved with the drilling riser tensioner or guidewire tensioners, if the production vessel is a drilling rig conversion. Modification of these devices may be needed or alternative methods of tethering may be more suitable, depending on design requirements. These include long-term tether load, capacity to lift the EDP, stroke, the need for tether release if simultaneous drilling or workover is to be conducted, space limitations in the turret of an FPSO, and low load variation with stroke to minimize stress fluctuations and fatigue damage in the riser.

F.1.4 SIMULTANEOUS OPERATIONS AND RISER POSITION

F.1.4.1 The opportunity for conducting workovers or drilling on a well while producing from adjacent wells can be a driving factor for the selection of a hybrid riser system and have a significant impact on design of the vessel and seabed interfaces. At the seabed, the riser may be connected to the well template, as opposed to a stand-alone base. This may simplify flowline connections and enable cost reduction through use of a multifunction base structure. The requirement for simultaneous operations can also be a factor in determining the level of tensioning or tethering provided by the vessel and the position of the vessel relative to the riser. Three basic approaches can be followed:

a. Centrally located below the vessel moonpool and tethered.

b. Offset from vessel moonpool, but tethered beneath the vessel.

c. Offset from vessel and freestanding.

F.1.4.2 In the first option, the riser must be able to free-stand in mild environmental conditions. This enables the tether to be disconnected and the vessel winched to a suitable position for operating on the template wells. The second option is similar to the first with the advantage that the riser need not be untethered and offers extended scope for conducting workover operations. The second option has the disadvantage that the jumper hose layout is more restricted if the moonpool area is to kept clear. The third option may offer further improvement in scope for conducting well operations while producing. However, the large offsets that are experienced by FPSs can result in long jumper hoses being needed. This adds to weight, increases the buoyancy requirement and adds to cost which must be traded off with the additional opportunities for well operations that may be achieved by adopting the offset design.

F.1.5 PERIPHERAL LINES

F.1.5.1 The peripheral flowlines are conventionally located on the outside of the structural member in guide tubes running through the syntactic foam buoyancy. The lines contribute to the bending stiffness and combined effective tension of the riser as a whole by way of the lateral restraining forces provided by the guides. To accommodate differences in temperature and end cap pressure extension between different line types and the structural member the lines are free to move axially within the guides. Lines may be supported at either the top or base of the riser. If top supported, the structural member must be designed for the compressive load applied by the lines. Axial movements are accommodated at the base of the riser and the design of the upper flowline terminations is simplified as no axial movement need be accommodated. When bottom supported, the peripheral lines must be designed for self-weight compression and buckling resistance at the base. The base piping interface is simplified as no thermal movements must be accommodated and the jumper hose interface is more complex due to the axial movements that must be accommodated. In very deep water applications, the support loads may be considerable and the thermal movements and end cap pressure extension may be difficult to accommodate at one end of the riser. In such situations supports and expansion loops may be needed at a number of points along the riser length in order to rationalize the design of the structural member and lateral restraining loads for which the guide tubes must be designed.

F.1.5.2 As an alternative to locating the flowlines on the outside of the structural member, a design has been proposed whereby the flowlines are contained within the structural member in the same way as a flowline bundle.[3] This approach may require different methods of accommodating relative extension between different line types and supporting the peripheral lines.

F.1.6 RISER BASE

The riser is attached to the base foundation by way of a stress joint or flex-joint and hydraulic connector. Titanium has been used for the base stress joint, as this provides greater flexibility than steel, thus reducing the required stress joint size and base loading.[1] Loading on the base can also be reduced with an all steel design by reducing the diameter of the structural member just above the stress joint, allowing smaller radii of curvature to be accommodated along the stress joint and giving reduction in base loading. Much greater reduction to bending loads applied to the connector and foundation can be achieved if a flex-joint is implemented instead of a stress joint. However, the concentration of rotation at a single point creates greater difficulty in design of the transition from the vertical peripheral lines to the riser base piping.

F.2 Bibliography

1. Fisher, E. and Holley, P., "Development and Deployment of a Freestanding Production Riser in the Gulf of Mexico," OTC 1995, Paper No. OTC 7770.

2. Hatton, S.A., "Hybrid Risers—A Cost Effective Deepwater Riser System?" The 2nd Annual International Forum on Deepwater Technology, DEEPTEC'95, Aberdeen. IIR, London, March 1995.

3. Smith, I. and Langrock, D., "A Riser System for Very Deepwater Applications," The 2nd Annual International Forum on Deepwater Technology, DEEPTEC'95, Aberdeen. IIR, London, March 1995.

ANNEX G—(INFORMATIVE)

G.1 Differences From Other Codes

G.1.1 The methods of design by analysis specified in the ASME Pressure Vessel Code, Section VIII, Division 2 are utilized in this document with four important differences:

a. Component stresses are combined using the von Mises failure theory instead of the maximum shear stress.
b. The basic allowable stress is $^2/_3$ the minimum yield strength and is independent of the ultimate strength whereas the ASME Code limits it to the lesser of $^2/_3$ of yield or $^1/_3$ of the ultimate.
c. The allowable stress is modified by a design case factor.
d. The criterion for local primary membrane stress has been eliminated.

G.1.2 The reasons for making these changes to the methods in the ASME code are as follows.

G.1.3 The von Mises failure theory was adopted instead of the maximum shear stress theory because experimental data shows it more accurately predicts the onset of yield for ductile materials. The ASME code uses the maximum shear stress theory even though it is slightly less accurate, because it is easier to use and is always conservative compared to von Mises.

G.1.4 This recommended practice does not consider the ultimate strength in setting the basic allowable stress. Instead, rupture is prevented by not allowing the use of brittle materials that might be susceptible to rupture.

G.1.5 The ASME code, on the other hand, specifies the basic allowable stress as the lessor of $^2/_3$ the yield or $^1/_3$ the ultimate. The $^1/_3$ ultimate limit prevents rupture.

G.1.6 The design case factor was introduced to modify the allowable stress based on the probability of occurrence of a design case and the consequences of a failure for the conditions of the design case. This type of factor is common in design codes. For example, API RP 2A-WSD permits a $^1/_3$ increase in allowable stresses (from $0.6\sigma_y$ to $0.8\sigma_y$) for stresses due in part to design environmental conditions.

G.1.7 The ASME Pressure Vessel Code does not use a factor like this, because the predominate loads are operational and not environmental. Thus, the loads on pressure vessels are not as random as those on some other systems like FPS risers.

G.1.8 The ASME criterion for local primary membrane stresses was eliminated, because these stresses do not normally occur in risers, and they will not cause failure.

G.1.9 For several reasons, the allowable stresses in this RP differ from those in API RP 16Q, which is for marine drilling risers used on floating drilling vessels. The typical marine drilling riser is used in many water depths and different environments during its life. This makes it very difficult for an analyst to predict lifetime loads and thus to estimate the riser's fatigue life. Moreover, drilling risers are retrieved frequently and can be inspected on deck for fatigue cracks. They are also usually retrieved, or at least disconnected from the well, for the worst storms. On the other hand, FPS risers operate for a long time at one location. In addition, most FPS risers remain in place through all storms and are retrieved infrequently if at all before final removal.

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ERRATA

Page 53, Section 5.2.3.1, Equation 4, replace the equation with the following:

$$(\sigma_p + \sigma_b + \sigma_q)_e < 3.0\sigma_a \quad \text{(see Ref. 1 and Annex C)} \tag{4}$$

Page 54, Section 5.2.4.3, Equation 9, replace the first line and Equation (9) with the following:

5.2.4.3 Substituting Equations 6, 7, and 8 into Equation 5 gives, following a little algebra,

$$\sigma_e^2 = \left[\frac{\sqrt{3}(P_i - P_o)D_o D_i}{2(D_o + D_i)t}\right]^2 + \left[\frac{T_{eff}}{A} \pm \frac{M(D_o - t)}{2I}\right]^2 \le (C_f S_a)^2 \tag{9}$$

Page 145, Section C.1.7, equation for "primary plus secondary", replace the first equation with the following:

$$(\sigma_p + \sigma_b + \sigma_q)_e < 3.0\sigma_a$$

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