# Recommended Practice for Flexible Pipe

API RECOMMENDED PRACTICE 17B
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# Contents

Page



Figures

Page



Tables

## Introduction

Users of this recommended practice should be aware that further or differing requirements might be needed for individual applications. This recommended practice is not intended to inhibit a vendor from offering, or the purchaser from accepting, alternative equipment or engineering solutions for the individual application. This may be particularly applicable where there is innovative or developing technology. Where an alternative is offered, the vendor should identify any variations from this recommended practice and provide details.

# Recommended Practice for Flexible Pipe

## 1 Scope

API 17B provides guidelines for the design, analysis, manufacture, testing, installation, and operation of flexible pipes and flexible pipe systems for onshore, subsea, and marine applications. API 17B supplements API 17J and API 17K, which specify minimum requirements for the design, material selection, manufacture, testing, marking, and packaging of unbonded and bonded flexible pipes, respectively.

API 17B applies to flexible pipe assemblies, consisting of segments of flexible pipe body with end fittings attached to both ends. Both bonded and unbonded pipe types are covered. In addition, API 17B applies to flexible pipe systems, including ancillary components.

The applications covered by API 17B are sweet and sour service production, including export and injection applications. API 17B applies to both static and dynamic flexible pipe systems, used as flowlines, risers, jumpers, downlines, and other temporary applications of flexible pipe. API 17B does cover in general terms, the use of flexible pipes for offshore loading systems. Refer also to API 17K and Bibliographic Item [54] for offshore loading systems.

API 17B does not cover flexible pipes for use in choke and kill line or umbilical and control lines.

## 2 Normative References

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

API Recommended Practice 17C, *Recommended Practice on TFL (Through Flowline) Systems*

API Specification 17J, *Specification for Unbonded Flexible Pipe*, 2014

API Specification 17K, *Specification for Bonded Flexible Pipe*

DNV OS-C501 [1], *Composite Components*, October 2010

NACE MR0175 [2], *Petroleum and natural gas industries—Materials for use in $H_2S$-containing environments in oil and gas production—Part 1: General principles for selection of cracking-resistant materials.*

## 3 Terms, Definitions, Acronyms, Abbreviations, and Symbols

### 3.1 Terms and Definitions

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

**3.1.1**
**ancillary components**
Components that are attached to the flexible pipe in order to perform one or more of the following functions:

a) to control the flexible pipe behavior;

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[1] DNV GL, Veritasveien 1, 1322 Hovik, Oslo, Norway, www.dnvgl.com.

[2] NACE International (formerly the National Association of Corrosion Engineers), 1440 South Creek Drive, Houston, Texas 77084-4906, www.nace.org.

b) to provide a structural transition between the flexible pipe and adjacent structures;

c) to avoid excessive curvature;

d) to attach other structures to the flexible pipe, or the flexible pipe to other structures, or to connect flanges or proprietary connectors to the flexible pipe (e.g. stud bolts and nuts and clamps);

e) to protect or repair the flexible pipe;

f) to provide a seal between the flexible pipe and an I-tube or J-tube inner wall (in order to prevent corrosion inhibited seawater escaping).

**3.1.2**
**annulus**
Space between two extruded polymer layers, for example, the internal pressure sheath and external sheath that is sealed in the end fitting.

NOTE Permeated gas and liquid are generally free to move and mix in the annulus.

**3.1.3**
**antibuckling tape**
A polymer, fabric, wire, fiber, or other reinforcement wound around the tensile armors, compressing the wires/strips against the pipe body to resist radial buckling of these wires/strips.

**3.1.4**
**antiextrusion layer**
A layer applied between an internal pressure sheath or an intermediate sheath and an armor layer to resist internal pressure or intermediate sheath deformation into gaps in the armor layer (creep failure).

**3.1.5**
**antiwear layer**
Nonmetallic layer, either extruded thermoplastic sheath or tape wrapping, normally used to minimize wear between structural layers.

**3.1.6**
**Arrhenius plot**
Log-linear scale used to plot service life against the inverse of temperature for some polymer materials.

**3.1.7**
**basket**
Device used for storage and transport of flexible pipe.

**3.1.8**
**bellmouth**
Part of a guide tube, formed in the shape of a bellmouth, and designed to prevent overbending of the flexible pipe.

**3.1.9**
**bend limiter**
Any device used to restrict bending of the flexible pipe.

NOTE Bend limiters include bend restrictors, bend stiffeners, and bellmouths.

**3.1.10**
**bend radius**
Radius of curvature of the flexible pipe measured from the pipe centerline.

**3.1.11**
**bend restrictor**
Mechanical device that functions as a mechanical stop and limits the local radius of curvature of the flexible pipe to a minimum value.

**3.1.12**
**bend stiffener**
Ancillary conical shaped component that locally reduces bending stresses and curvature of the pipe to acceptable levels; usually attached to either an end fitting or a support structure where the flexible pipe passes through the bend stiffener.

**3.1.13**
**bend stiffener latching mechanism**
A structure or mechanism that allows a riser bend stiffener to be connected to a structure allowing the bending to be transferred from the riser bend stiffener to that structure.

**3.1.14**
**bending stiffness**
The resistance to bending from an applied bending moment—product of the effective elastic modulus and moment of inertia of the flexible pipe. The bending stiffness may vary with tension, pressure, and temperature.

**3.1.15**
**birdcaging**
Radial buckling of the tensile armor wires, usually caused by extreme axial compression, which results in significant radial deformati1on.

**3.1.16**
**bonded pipe**
Flexible pipe in which the steel reinforcement is integrated and bonded to a vulcanized elastomeric material where textile material is included in the structure to obtain additional structural reinforcement or to separate elastomeric layers.

**3.1.17**
**buckling of tensile armors**
Buckling of the tensile armors in the radial (birdcaging) or lateral direction caused by axial compression (true wall compression), associated or not with pipe bending, twist, or torsion and affected by the annulus condition (flooded or dry).

**3.1.18**
**buoyancy module**
Buoy used at one or more discrete points over a section of riser to achieve wave shape riser configurations.

**3.1.19**
**burst disk**
Weak points in the outer sheath designed to burst when the gas pressure in the annulus exceeds a specified value.

NOTE The weak point is induced by reducing the thickness of the sheath over a localized area.

**3.1.20**
**carcass**
Interlocked metallic construction that is normally used as the innermost layer in rough bore pipes to prevent, totally or partially, collapse of the internal pressure sheath or pipe due to pipe decompression, external pressure, tensile armor pressure, and mechanical crushing loads.

NOTE The carcass may be used externally to protect the external surface of the pipe; this is referred to as “abrasion protection.”

**3.1.21**
**carousel**
Device used for storage and transport of very long lengths of flexible pipe and that rotates about a vertical axis.

**3.1.22**
**Chinese fingers**
Woven steel wire or fabric sleeve that can be installed over a flexible pipe and drawn tight to grip it for support or applying tension to the pipe.

**3.1.23**
**choke and kill line jumpers**
Flexible pipe jumper located between a marine drilling riser steel choke line and kill line and blowout preventer.

**3.1.24**
**composite armor**
Structural layer comprising fiber reinforced polymer (FRP). The structural layer can be either the pressure armor or tensile armor.

**3.1.25**
**connector**
Device used to provide a leak-tight structural connection between the end fitting and adjacent piping. Connectors include bolted flanges, clamped hubs, and proprietary connectors.

NOTE Connectors may be designed for diver-assisted makeup or for diverless operation using either mechanical or hydraulic apparatus.

**3.1.26**
**crossover**
Flexible flowline crossing another pipe already laid on the seabed. The underlying pipe may be a steel pipe or another flexible pipe.

NOTE It may be required to support the overlying pipe to prevent overbending or crushing of the new or existing pipes.

**3.1.27**
**crushing loads**
Compressive guidance-induced loads or localized compressive loads imposed on the pipe, during its installation (laying or retrieval operations) by typical laying equipment such as tensioners, wheel, sheave, chute, gutter, and handling collars or during the operating conditions where the line is bent under tension onto a radius such as J-tube bend, bellmouth, and mid-water arch gutter.

**3.1.28**
**design differential pressure**
The difference between design external pressure and design pressure (the maximum internal pressure, at a reference location including planned shut-in pressure and associated surge).

**3.1.29**
**design external pressure**
Maximum external pressure acting external to the sheath layer, applied to a pipe during installation, operation, or retrieval, after considering tidal and wave effects.

NOTE It can be either the full external pressure or the maximum annulus pressure acting on a sheath, whichever is larger.

**3.1.30**
**design methodology**
A consistent approach to the design of a component or system.

**3.1.31**
**design methodology verification report**
Evaluation report prepared by an independent verification agent (IVA) at the time of an initial review, for a specific manufacturer, confirming the suitability and appropriate limits on the manufacturer's design methodologies, manufacturing processes, and materials.

NOTE This report may include occasional amendments or revisions to address extensions beyond previous limits or revisions of methodologies.

**3.1.32**
**design tension**
Maximum tensile load applied to a pipe during installation, operation, or retrieval, after considering the associated internal fluid density and pressure.

**3.1.33**
**differential pressure**
The difference between the local internal pressure and the external hydrostatic pressure at each cross section.

**3.1.34**
**dry conditions**
Tested in air at conditions defined by the international standard atmosphere.

**3.1.35**
**dynamic application**
**DA**
Service in which flexible pipe is exposed to a large number of cyclically varying loads and deflections during permanent operation.

**3.1.36**
**end fitting**
Structural/mechanical device for terminating the different pipe layers in such a way as to transfer the load between the flexible pipe and the connector and seal all internal and external fluid containment layers.

**3.1.37**
**event, abnormal operation**
An event due to infrequent loads (e.g. pressures in excess of the design, accidental conditions).

**3.1.38**
**event, extreme operation**
An event that produces 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).

**3.1.39**
**event, extreme temporary**
An event of short duration due to infrequent loads (e.g. pressures and environments in excess of operating plan, accidental conditions).

**3.1.40**
**event, normal operation**
An event such as plan of operation; normal; in-place pressure testing; connected operation; and integrity, maintenance, and repair.

**3.1.41**
**event, normal temporary**
An event of limited duration, such as transport, installation, retrieval, and field test.

**3.1.42**
**event, survival**
An event involving conditions that exceed extreme design events where fluid containment is just maintained (i.e. material strength utilization is permitted to reach unity).

**3.1.43**
**fiber reinforced polymers**
**FRPs**
Materials in which reinforcing fibers are combined with a polymeric matrix material thus forming a material with superior properties over both the matrix material and the used fibers.

NOTE 1 FRPs may be based on either a thermoset or a thermoplastic matrix material.

NOTE 2 If the basic matrix material is a thermoset, curing of the thermoset is necessary before use.

**3.1.44**
**fishscaling**
Tendency of a wire or strip to not lay flat against the underlying layer, often caused by improper preforming during armor winding. Fishscaling can occur in the tensile armor, pressure armor, or carcass layers.

**3.1.45**
**flexible flowline**
Flexible pipe, wholly or in part, resting on the seafloor or buried below the seafloor, and used in a static application.

NOTE The term flowline is used in this document as a generic term for flexible flowlines.

**3.1.46**
**flexible pipe**
Assembly of a pipe body and end fittings where the pipe body is composed of a composite of layered materials that form a pressure-containing conduit and the pipe structure allows large deflections.

NOTE 1 Normally, the pipe body is built up as a composite structure composed of metallic and polymer layers.

NOTE 2 The term “pipe” is used in this document as a generic term for flexible pipe.

**3.1.47**
**flexible pipe system**
Fluid conveyance system for which the flexible pipe(s) is the primary component and which includes ancillary components attached directly or indirectly to the pipe.

**3.1.48**
**flexible riser**
A flexible pipe in a dynamic or static application, connecting a platform/buoy/ship to a flowline, seafloor installation, or another platform where the riser may be freely suspended (free, catenary), restrained to some extent (buoys, chains), totally restrained, or enclosed in a tube (I- or J-tubes).

**3.1.49**
**independent verification agent**
**IVA**
Independent party or group, selected by the manufacturer, who is responsible for the review and certification of the indicated product concept (e.g. pipe and end-fitting concept) and flexible pipe, associated design, manufacturing methodologies and criteria, material qualification and prototype performance based on the technical literature, analyses, results, and other information provided by the manufacturer to establish the range of applicability.

NOTE An agent may also be called upon to witness some measurements and tests related to material qualification, manufacturing process control, validation of design methodologies, and prototype tests.

**3.1.50**
**insulation layer**
Additional layer added to the flexible pipe to increase the thermal insulation properties, usually located between the outer tensile armor layer and the outer sheath.

**3.1.51**
**integrated pipe umbilical**
**IPU**
Structure in which the inner core is a standard flexible pipe construction and from which other small diameter components are (externally) helically or sinusoidally wound in order to add other functions such as electrical and optical signal transmission, power supply, or flow assurance (by heating the core pipe).

**3.1.52**
**intermediate sheath**
Extruded polymer layer located between internal pressure and outer sheaths, which may be used as a barrier to external fluids in smooth bore pipes or as an antiwear layer or used as a barrier from external fluids for insulation layers, avoiding water absorption and creep thus avoiding reduction in the pipe thermal exchange coefficient (TEC), and may be used in avoiding flooding of an inner annulus when an outer annulus is flooded due to an outer sheath breach.

**3.1.53**
**internal pressure sheath**
Polymer layer excluding any sacrificial layers that ensures internal-fluid integrity.

NOTE This layer may consist of a number of sublayers, excluding sacrificial layers.

**3.1.54**
**jumper**
Short flexible pipe used in subsea and topside, static, or dynamic applications.

NOTE Dynamic topside jumpers also includes the class of flexible pipe whose dynamic response derives from vessel motion only (e.g. turret applications).

**3.1.55**
**lateral buckling**
Failure mode of a flexible pipe often associated with a combination of reverse end-cap loading and localized dynamic bending, whereby the tensile armor wires buckle in the lateral or in-plane direction.

**3.1.56**
**lay angle**
Angle between the axis of a spiral wound element (e.g. armor wires) and a line parallel to the flexible pipe longitudinal axis.

**3.1.57**
**laying tension**
Maximum tensile load to which the pipe shall be subjected during installation or retrieval operations.

**3.1.58**
**load, accidental**
Loads that are a consequence of unplanned occurrences.

**3.1.59**
**load, environmental**
Loads that are imposed directly or indirectly by the ocean or atmospheric environment.

**3.1.60**
**load, functional**
Loads that are a consequence of the system's existence and use without consideration of environmental or accidental effects.

**3.1.61**
**multibore**
Multiple flexible pipes or umbilicals contained in a single construction with an outer sheath extruded over the bundle.

**3.1.62**
**multiple configuration**
Riser system with more than one riser connected at a mid-depth location.

**3.1.63**
**new pipe design**
A new pipe design is characterized by one or both of the following:

a) pipe concept whose constituting materials, design methodologies, manufacturing processes, and prototype testing results have not been reviewed and accepted by an IVA;

b) a pipe concept whose required performance, for a specific application, has not been accepted by an IVA or purchaser.

**3.1.64**
**operation plan**
Purchaser-specified plan of operation for the flexible pipe.

**3.1.65**
**outer sheath**
Polymer layer used to protect the pipe against penetration of seawater and other external environments, corrosion, abrasion, and mechanical damage.

NOTE This layer may consist of a number of sublayers.

**3.1.66**
**ovalization**
Out-of-roundness of the pipe, calculated as follows:

$$\frac{D_{\text{max}} - D_{\text{min}}}{D_{\text{max}} + D_{\text{min}}}$$

where $D_{\text{max}}$ and $D_{\text{min}}$ are maximum and minimum pipe diameter, respectively.

**3.1.67**
**overall heat transfer coefficient**
A measure of the overall ability of the pipe cross section to transfer heat; identified as the heat transferred per unit area per unit temperature.

NOTE The area is usually taken as the internal surface area over which the transfer of heat takes place.

**3.1.68**
**permanent operation**
Operational condition in which pipe is only subjected to frequent loading and where pressures are less than or equal to the design pressure.

**3.1.69**
**piggyback**
Two pipes attached at regular intervals with clamps, where either or both of the pipes can be flexible.

**3.1.70**
**pipe concept**
A pipe concept is characterized by the following combination of parameters:

a) function (intended use or application)

b) structure of layers, sequence and number of layers in the pipe body, type of wire cross section, etc.

c) end fitting’s structural body, details of sealing systems, anchoring system, and vent system

**3.1.71**
**pressure armor layer**
Structural layer with a lay angle close to 90° that increases the resistance of the flexible pipe to internal and external pressure and mechanical crushing loads; structurally supports the internal pressure sheath; and typically consists of an interlocked metallic construction, which may be reinforced by an overlying flat metallic spiral layer.

**3.1.72**
**prototype test**
Test to establish or verify a principal performance characteristic for a particular pipe design, which may be a new or established design, and to also validate manufacturer design methodology and so provide a basis for the IVA verification.

**3.1.73**
**qualification testing**
Testing by which the structural, functional, fabrication, and reliability performance of a pipe concept, its components, or materials used may be evaluated in order to demonstrate suitability for the specified service life in a specific application.

NOTE The qualification test can also be used to validate the manufacturer's design methodology for a new pipe design.

**3.1.74**
**quality**
Conformance to specified requirements.

**3.1.75**
**quality assurance**
Planned, systematic, and preventive actions that are required to ensure that materials, products, or services meet specified requirements.

**3.1.76**
**quality control**
Inspection, test, or examination to ensure that materials, products, or services conform to specified requirements.

**3.1.77**
**rapid decompression**
Sudden depressurization of a system during which gas in the pipe expands rapidly and may cause blistering or collapse of the internal pressure sheath or other gas-saturated layers.

**3.1.78**
**reel**
Large diameter structure used for storage of long lengths of flexible pipe and which rotates about a horizontal axis.

**3.1.79**
**riser base**
Seabed structure (gravity or piled) for supporting subsea buoy or arch systems or riser or flowline connections.

**3.1.80**
**riser hangoff**
Structure for supporting riser at the connection to a platform (e.g. jacket, semisub, tanker, etc.).

**3.1.81**
**rough bore**
Flexible pipe with a carcass as the innermost layer.

**3.1.82**
**service life**
Period of time during which the flexible pipe is designed to fulfil all specified performance requirements.

**3.1.83**
**service simulation test**
A test to establish or verify the performance of a pipe when subject to loads representative of in-service conditions.

**3.1.84**
**smooth bore**
Flexible pipe with an internal pressure sheath as the innermost layer.

**3.1.85**
**sour service**
Service conditions with a $H_2S$ content exceeding the minimum specified by NACE MR0175.

NOTE 1 Sour service condition in the bore does not always lead to sour service conditions in the pipe annulus.

NOTE 2 Design pressure is used to assess bore conditions; operating pressure is used to assess annulus condition.

**3.1.86**
**static application**
**SA**
Flexible pipes not exposed to significant cyclically varying loads or deflections during permanent operations.

**3.1.87**
**subsea buoy**
Concentrated buoyancy system, generally consisting of steel or syntactic foam tanks. See also **buoyancy module**.

**3.1.88**
**survival**
Survival of a component means that the component does not fail, but it can present one or more kinds of degradations that could jeopardize its specified performance or service life.

**3.1.89**
**sweet service**
Service conditions that have a $H_2S$ content less than that specified by NACE MR0175.

**3.1.90**
**tensile armor layer**
Structural layer with a lay angle typically between 20° and 55°, which consists of helically wound metallic wires and is used to sustain, totally or partially, tensile loads and internal pressure.

NOTE Tensile armor layers are typically counter-wound in pairs.

**3.1.91**
**tensioner**
Mechanical device used to apply tension or support a pipe by applying radial loads to the pipe with moving tracks during its installation or retrieval.

**3.1.92**
**thermal exchange coefficient**
**TEC**
Coefficient that provides the heat loss (expressed in Watts) of 1 m of pipe when subjected to 1 °C difference between its internal and external surfaces.

NOTE The TEC is typically determined for conditions corresponding to the design water depth and steady state annulus environment (intact and seawater flooded) and accounting for water absorption in the insulation layers.

**3.1.93**
**torsional balance**
Pipe characteristic that is achieved by designing the structural layers in the pipe, such that axial and pressure loads do not induce significant twist or torsional loads in the pipe.

**3.1.94**
**torsional limp stiffness**
The ability of a flexible pipe to resist twist when subjected to torsion loads, at constant tension, applied in the opposite direction to the lay angle of the outermost tensile armor wires.

**3.1.95**
**true wall force**
The axial force acting in the pipe wall.

**3.1.96**
**umbilical**
Bundle of helically or sinusoidally wound small diameter chemical, hydraulic, optical, and electrical conductors for power and control systems.

**3.1.97**
**unbonded flexible pipe**
A pipe construction that consists of separate unbonded polymeric and helical reinforcement layers, which allows relative movement between layers.

**3.1.98**
**validation test**
A test to validate predicted pipe performance and/or design tool.

**3.1.99**
**verification test**
A test to verify manufacturer’s stated pipe performance.

## 3.2 Acronyms, Abbreviations, and Symbols

| | |
|---|---|
| CIV | corrected intrinsic viscosity |
| DA | dynamic application |
| DAC | design acceptance criterion |
| DBS | dibutyl sebacate |
| FAT | factory acceptance test |
| FOS | factor of safety |
| FPSO | floating production storage and offloading |
| FRP | fiber reinforced polymer |
| FSF | fatigue safety factor |
| HDPE | high density polyethylene |
| HIC | hydrogen-induced cracking |
| ID | inside diameter |
| IPU | integrated pipe umbilical |
| IVA | independent verification agent |
| MBR | minimum bend radius |
| MDPE | medium density polyethylene |
| NBR | nitrile butadiene rubber |
| OD | outer diameter |
| PA | polyamide |
| PE | polyethylene |
| PLEM | pipeline end manifold |
| PU | polyurethane |
| PVDF | polyvinylidene fluoride |
| ROV | remotely operated vehicle |
| SA | static application |
| SBR | storage bend radius |
| SMYS | specified minimum yield strength |
| SSC | sulphide stress cracking |
| TEC | thermal exchange coefficient |
| TFL | through flowline |
| UTS | ultimate tensile strength |
| UV | ultraviolet |
| VIV | vortex-induced vibration |
| XLPE | crosslinked polyethylene |
| $C_{\mathrm{D}}$ | hydrodynamic drag coefficient |
| $C_{\mathrm{m}}$ | hydrodynamic inertia coefficient |
| $\sigma_{\mathrm{u}}$ | material ultimate stress |
| $\sigma_{\mathrm{y}}$ | material yield stress |

# 4 System, Pipe, and Component Description

## 4.1 Introduction

### 4.1.1 General

Section 4.1 provides a general overview of flexible pipe systems and pipe cross-section designs. In addition, Figure 1 gives an overview of all aspects of flexible pipe technology and identifies the sections of API 17J and API 17K to be referenced for relevant issues.

In general, flexible pipe is a custom-built product that may be designed and manufactured using a variety of methods. It is not the intent of API 17B to discourage novel or new developments in flexible pipe. On the contrary, it is recognized that a variety of designs and methods of analysis are possible. For this reason, some topics are presented in general terms to provide guidance to the user while still leaving open the possibility of using alternative approaches.

Flexible pipe technology is in a state of continuing evolution. Therefore, users shall apply care in their application of the recommended practice within this part of API 17B.

### 4.1.2 Recommended Practice and Specification Overview

API 17B provides the current best practice for design and procurement of flexible pipe and gives guidance on the implementation of the specification for standard flexible pipe products. In addition, the recommended practice presents guidelines on the qualification of prototype products.

All aspects of flexible pipe design and technology, from functional definition to installation, are addressed in API 17B or API 17J and API 17K. Some issues are addressed in several documents. The various stages in the procurement and use of flexible pipes are defined in Figure 1.

## 4.2 Flexible Pipe Systems

### 4.2.1 Definition of System

The definition of the flexible pipe system should commence at the initiation of the overall project as the field development is evolving. Aspects of the development that may heavily influence the flexible pipe system include field layout (template vs satellite wells) and production vessel type. Current limitations in flexible pipe technology, such as application range and manufacturing capability, may also fundamentally influence potential overall field development options.

Critical parameters that can affect the pipe design should be identified early on in the development and may include the following:

a) corrosive fluids, such as high $H_2S$ content (sour service);

b) severe environmental conditions (waves, wind, and current);

c) difficult installation conditions (such as extreme environment);

d) frequent large-amplitude pressure and temperature fluctuations;

e) large vessel motions (first order and vessel offset);

f) specification of installation equipment and lay method.

To define accurately all relevant parameters, interaction between the purchaser and manufacturer is important from an early stage in the field development. It is also important to identify critical system issues, such as design of interfaces required for the risers (bend stiffeners, I-tubes, etc.).

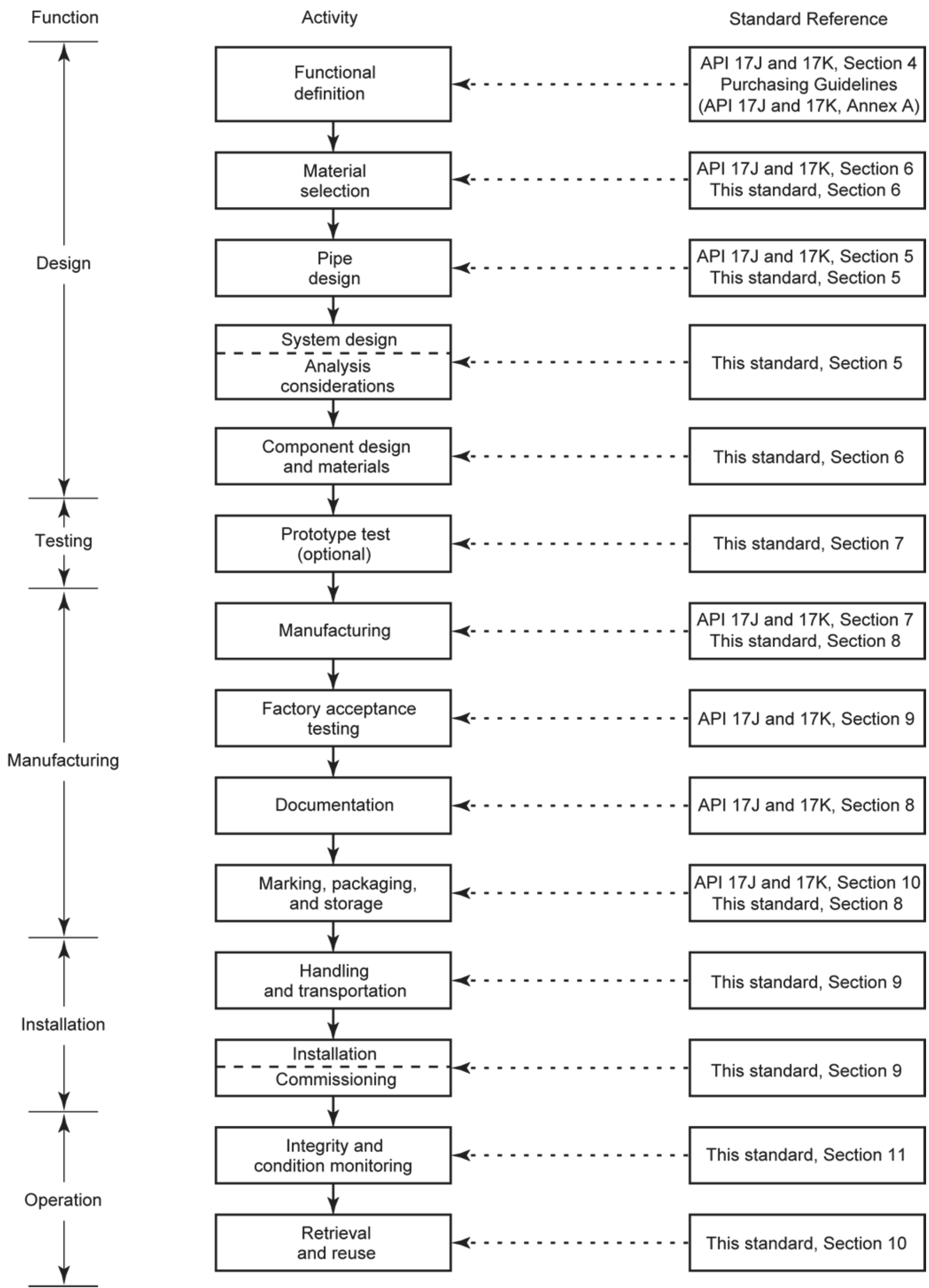



**Figure 1—Flexible Pipe Overview**

API 17J, and API 17K, provide purchasing guidelines there in, which may be used in the definition of the flexible pipe system and address all aspects from general design parameters to detailed flowline and riser specific requirements.

### 4.2.2 Applications

#### 4.2.2.1 General

Flexible pipe for offshore and onshore applications is grouped into either a static or dynamic category (Figure 2 and Figure 3). It is used for a multitude of functions, including the following:

a) production—oil, gas, condensate, water;

b) injection—water, gas, downhole chemicals;

c) export—semiprocessed oil and gas;

d) services—wellhead chemicals, control fluids.

The static and dynamic categories place different physical demands on the pipe. While both require long life, mechanical strength, internal and external damage resistance, and minimal maintenance, dynamic service pipes also require pliancy and adequate fatigue capacity.

#### 4.2.2.2 Static Applications (SAs)

SAs of flexible pipe primarily include flowline and fixed jacket riser service. Flexible pipe is used in these applications to simplify design or installation procedures or for the inherent insulation or corrosion-resistant properties. In addition, reduction of installation and end connection loads and moments may be achieved using flexible pipe.

Examples where the use of flexible pipe results in simplified flowline design or installation include the following (see Figure 2):

a) subsea flowline end connections where expensive or difficult operations, such as exact orientation measurements for spool pieces or the use of large alignment equipment to reposition the flowline, can be eliminated;

b) situations involving gross movements and damage to flowlines because of mudslides can be reduced through the use of compliant sections of flexible pipe;

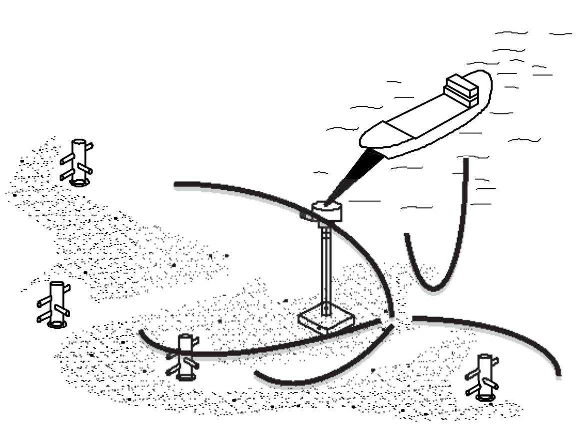
c) applications in which field hardware and flowline location change with the field's production characteristics, which may necessitate the recovery and reuse of flowlines;

d) applications with uneven seabed to avoid seabed preparation;

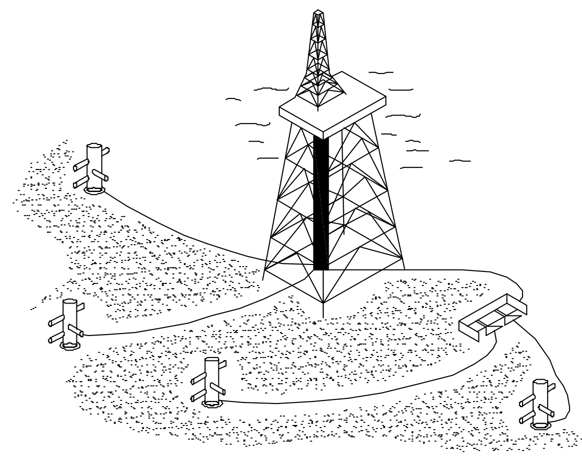
e) in deepwater or severe environment applications, where flexible pipe installation is economically attractive relative to rigid pipe installation.

Flexible pipe flowlines generally range in internal diameter from 0.05 m to 0.5 m (2 in. to 20 in.), although some low pressure bonded flexible pipes, such as oil suction and discharge hoses, have internal diameters up to 0.91 m (36 in.). Section lengths are limited by transport capabilities, and diameter is limited only by current manufacturing capability.

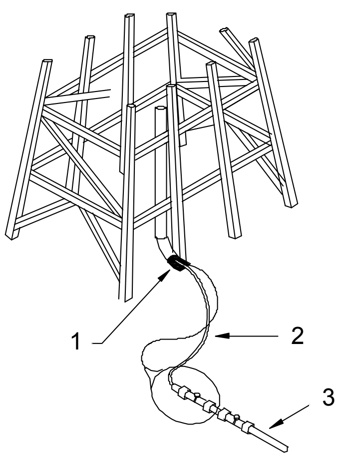
The functional requirements of a flexible pipe flowline are generally the same as for a steel pipe flowline. Significant dynamic loading or motions are generally not experienced, so the flexibility properties of flexible pipe simplify the project transport and installation phases.



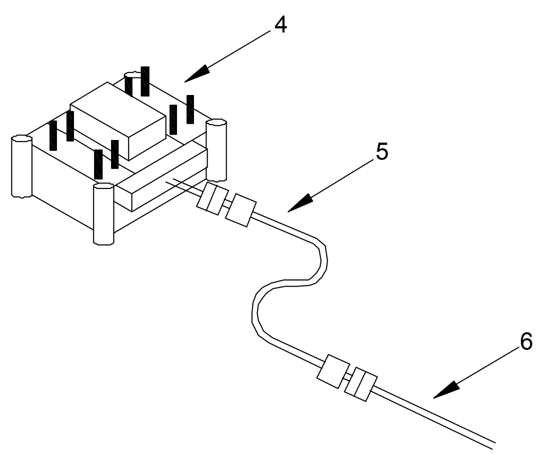
a) **Early Field Production Scheme**



b) **Flowlines Repositioned for Mature Field Production Scheme**




c) **Flexible Pipe Connected to a J-tube**




d) **Flexible Pipe Connected to a Manifold**

**Key**

1 J-tube

2 Flexible pipe

3 Rigid pipe

4 Manifold

5 Flexible pipe spool piece

6 Rigid steel flowline

**Figure 2—Examples of Static Applications for Flexible Pipe**

#### 4.2.2.3 Dynamic Applications (DAs)

Dynamic applications usually involve an offshore floating production facility or terminal connected to another floating facility, fixed structure, or fixed base (Figure 3). Examples of dynamic applications include the following:

a) flexible pipe risers for offshore loading systems,

b) flexible pipe riser connections between floating production facilities and subsea equipment.

Figure 4 presents schematics of the dynamic riser configurations most commonly used.

Hybrid riser systems are also used. These typically combine a lower vertical riser section made of steel and an upper flexible pipe section (jumper) to connect to the vessel or platform.

#### 4.2.2.4 Jumper Lines

In addition to flowlines and risers, jumper lines made of flexible pipe may be used for static or dynamic applications. Examples of flexible pipes used in jumper applications include the following (see Figure 5).

a) Static applications:

    i) intrafield connection of wellheads and manifolds (typically in lengths less than 100 m).

b) Dynamic applications:

    i) connection of wellhead platforms and floating support vessels,

    ii) lines in floating production storage and offloading (FPSO) turret motion transfer systems,

    iii) connection of topside wellheads and platform piping on tension leg platforms.

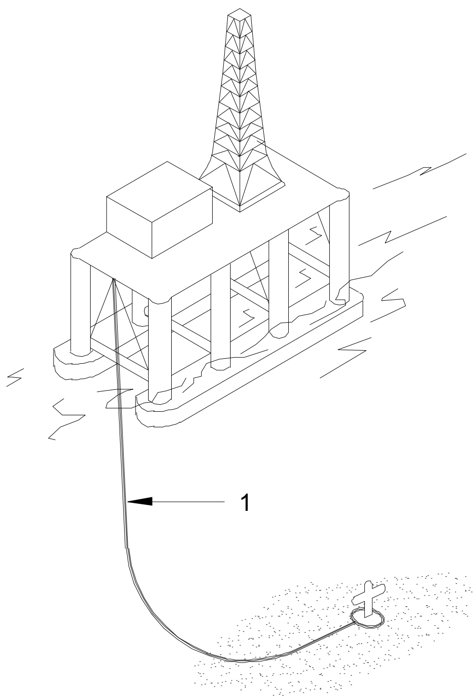
The functions of dynamic jumpers (excluding internal turret lines) are similar to riser systems. Their operation, however, is somewhat different. Jumpers are generally more exposed to wave loading, and the configuration varies between the connected condition and the standoff condition. This loading imposes extra requirements on the end connectors and bend stiffeners. The performance of these components should be evaluated carefully for dynamic jumper line applications.

## 4.3 Flexible Pipe Description

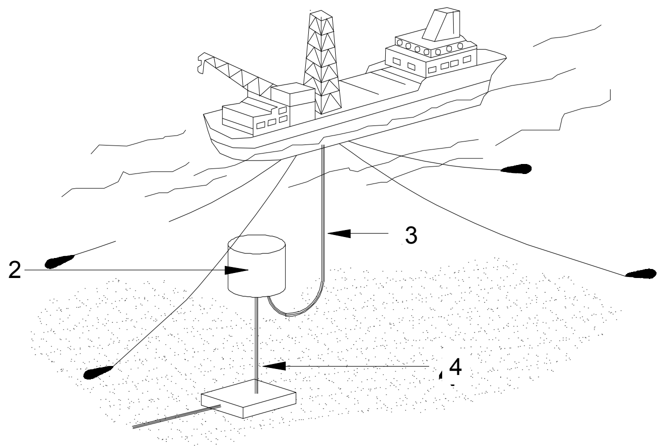
### 4.3.1 General

API 17B does not apply to flexible pipes for use in choke and kill lines, mud lines, cement lines, or umbilical applications. API 16C [8] or API 7K [6] may be applicable to those applications.

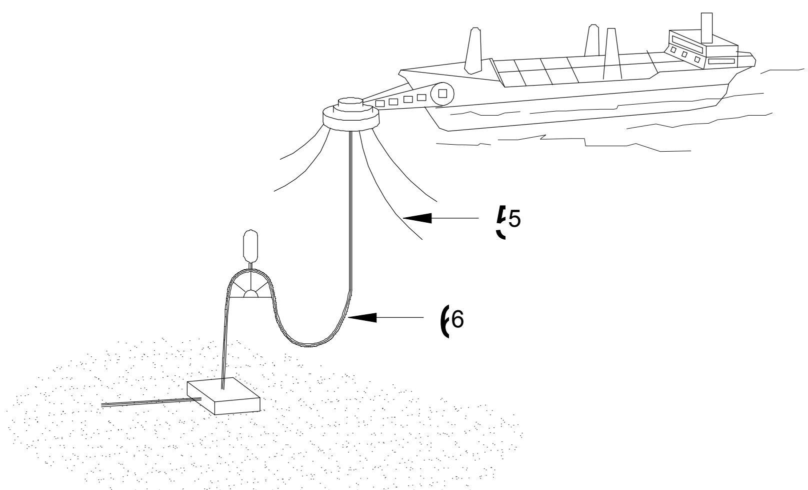
A flexible pipe generally combines low bending stiffness with high axial tensile stiffness, which is achieved by a composite pipe wall construction. This is more applicable to unbonded rather than bonded flexible pipe. The two basic components are helical reinforcement layers and polymer sealing layers, which allow a much smaller radius of curvature than for a steel pipe with the same pressure capacity. The helical reinforcement layers are commonly carbon steel armoring as specified in API 17J. Composite reinforcement materials are also employed by some manufacturers. Generally, a flexible pipe is designed specifically for each application and is not an off-the-shelf product, although flexible pipes may be grouped according to specific designs and hence applications. This allows the pipe to be optimized for each application.




**a) Floating Production System**




**b) Floating Production System**




**c) Floating Tanker/Terminal Mooring**

**Key**

1 Flexible riser

2 Subsea buoy

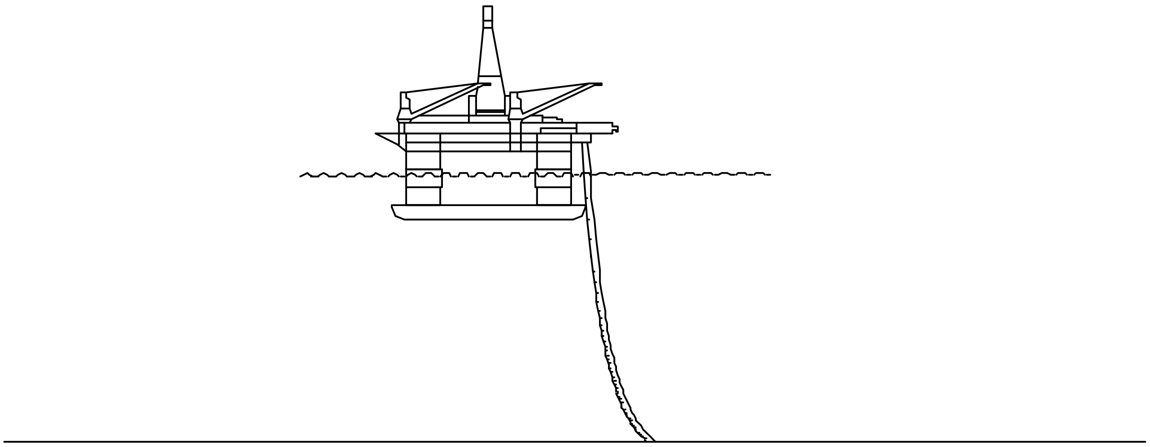
3 Flexible riser

4 Rigid riser

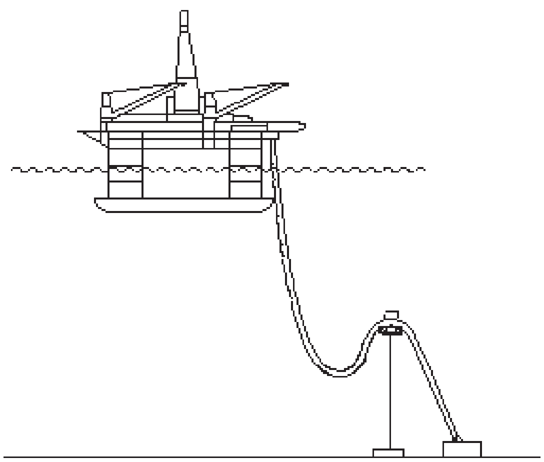
5 Mooring line

6 Flexible riser

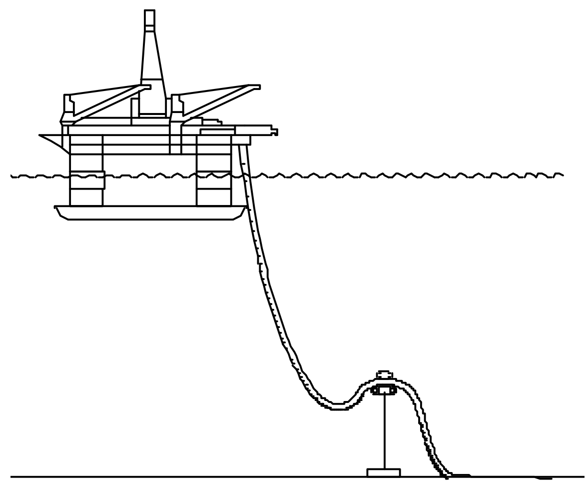
**Figure 3—Examples of Dynamic Applications for Flexible Pipe**



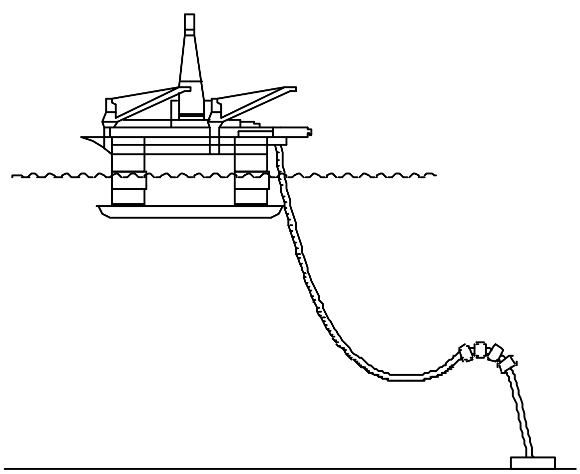
a) Free-hanging Catenary



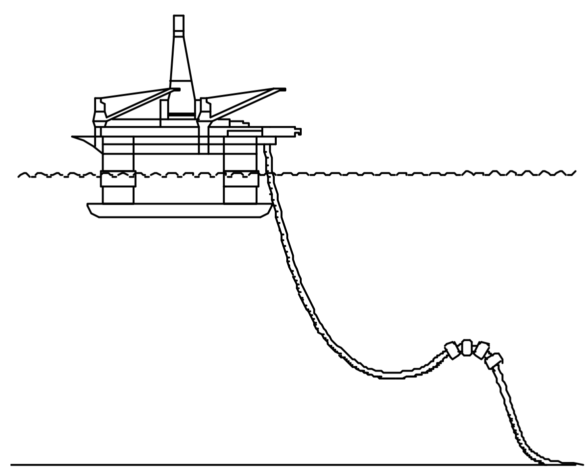
b) Steep-S



c) Lazy-S

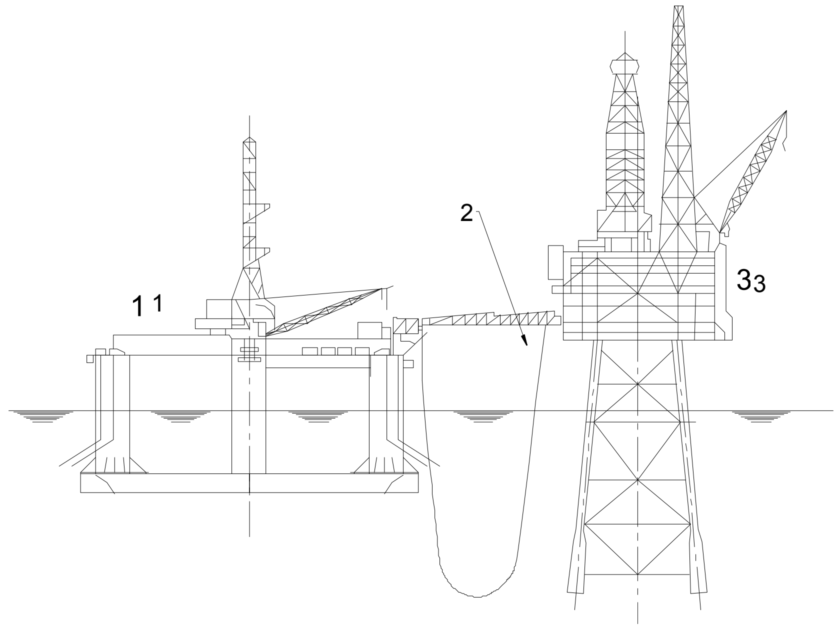


d) Steep Wave

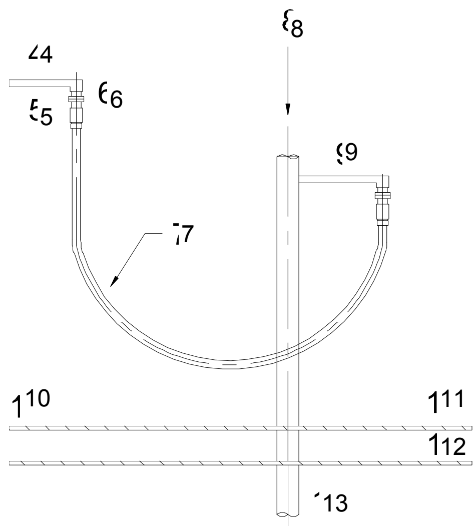


e) Lazy Wave

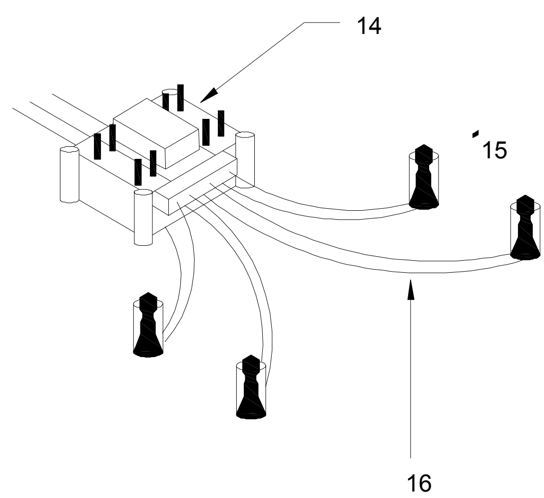
**Figure 4—Examples of Common Flexible Riser Configurations**




**a) Flexible Pipe as a Fluid Transfer Line**




**b) Flexible Pipe Connected to Christmas Tree**




**c) Flexible Pipe Connected to Manifold**

**Key**

| | | | |
|---|---|---|---|
| 1 | Support vessel | 9 | Moving end |
| 2 | Flexible jumper | 10 | Wellbay |
| 3 | Wellhead platform | 11 | Grated deck |
| 4 | Fixed end | 12 | Tree deck |
| 5 | Topsides piping | 13 | Rigid riser |
| 6 | End fitting | 14 | Manifold |
| 7 | Flexible jumper | 15 | Wellheads |
| 8 | Christmas tree | 16 | Flexible jumper |

**Figure 5—Examples of Flexible Pipe Jumper Line Applications**

#### 4.3.2 Unbonded Flexible Pipe Construction

Table 1 describes the function of each layer of a typical flexible pipe. Figure 6 shows a typical cross section of a flexible pipe.

#### 4.3.3 Bonded Flexible Pipe Construction

A typical bonded flexible pipe consists of several layers of elastomer either wrapped or extruded individually and then bonded together through the use of adhesives or by applying heat and/or pressure to fuse the layers into a single construction. Figure 6 shows an example of a bonded pipe construction. The primary layers are as follows.

a) The liner is a wrapped or extruded elastomer layer that provides internal fluid integrity.

b) The reinforcement layer typically comprises helically wound steel cables in an embedding elastomer compound used to sustain tensile and internal pressure load on the pipe. The steel cables are typically laid at an angle of 55° to obtain a torsionally balanced pipe in addition to equivalent hoop and longitudinal forces in the layer due to pressure. However, this angle may increase or decrease depending on the required strength characteristics of the pipe. For example, a higher angle may be used if increased strength in the hoop direction is required at the expense of tensile capacity and axial stiffness of the pipe.

c) The outer layer is a wrapped or extruded elastomer layer that provides external fluid integrity and protection against external environments, corrosion, abrasion, and mechanical damage.

#### 4.3.4 Classification of Flexible Pipe

Unbonded flexible pipes are generally classified into three distinct families. These classifications are identified in Table 2.

Product family II contains no pressure armor; instead, the tensile armor layers are cross wound at an angle close to 55° to obtain a torsionally balanced pipe and to balance hoop and axial loads. Product family III contains a pressure armor that is wound close to 90° to resist hoop stress.

Distinctions exist between pipes for static and dynamic applications within these families, with the main distinction being the use of antiwear layers for DAs if they are required to achieve service life criteria.

The classifications for bonded flexible pipe are identified in Table 3. Smooth bore flexible pipes (product family I, unbonded and product family IV, bonded) are typically restricted to conveying fluids with no gas content in order to prevent internal pressure sheath collapse. Therefore, they are typically used for water injection. If special measures have been taken to assure against liner collapse during the service life, then smooth bore pipes can be used for dead crude or low pressure production riser applications.

#### 4.3.5 End Fittings

Figure 8 illustrates a typical unbonded pipe end fitting. End fittings may be assembled during pipe manufacture or installed in the field on flexible pipe that has previously been subjected to factory acceptance testing (FAT). The two purposes of a flexible pipe end fitting are to:

a) terminate all the strength members in the pipe’s construction so that axial loads and bending moments can be transmitted into the end connector without adversely affecting the fluid-containing layers,

b) provide a pressure-tight transition between the pipe body and the connector.

**Table 1—Overview of Unbonded Flexible Pipe Layers**

| Layer | Function | Description |
|---|---|---|
| Carcass | To provide collapse resistance. | The carcass is manufactured from a thin metallic strip, typically stainless steel, fabricated into an interlocked or corrugated tube.<br>Flexible pipes with a carcass layer are known as rough bore pipe. |
| Internal pressure sheath | To contain the process fluid within the pipe bore. | The internal sheath is manufactured from an extruded polymer material. A range of polymer materials can be used, including polyamide (PA), polyvinylidene fluoride (PVDF), polyethylene (PE), and crosslinked polyethylene (XLPE). |
| Pressure armor wire(s) | To partially support the internal sheath and internal pressure loads.<br>Pressure armors provide additional radial capacity to radial compressive loads. | Pressure armor layers are manufactured from an interlocked metallic layer. The profile of the pressure armor wires varies between manufacturers. The pressure armor is wound at an angle close to 90° to the longitudinal axis of the pipe. To increase the internal pressure capacity, additional wires with rectangular cross section may be used.<br>Figure 7 shows the typical profiles of pressure armor wires.<br>This layer supports partially the internal pressure in the radial direction and also increases the pipe capacity against external radial compressive loads. |
| Anticollapse sheath | To increase the pipe collapse resistance by preventing seawater pressure from acting directly on the internal pressure sheath in the event of a breach of the outer sheath or end-fitting outer sheath seal leakage. | The anticollapse sheath is manufactured as an extruded polymer layer sealed in the end fittings and can be used in both smooth bore and rough bore pipes. A range of polymer materials can be used, including PA, PVDF, PE, and XLPE.<br>Typically used in pipe conveying fluids with no gas content, which eliminates the risk of a pressure buildup between the internal and anticollapse sheaths that can trigger pipe collapse when the pipe is depressurized. |
| Intermediate sheath | To improve pipe thermal insulation properties or serve as an antiwear layer. | The intermediate sheath is manufactured from an extruded polymer material and is located between the internal pressure sheath and the outer sheath. A range of polymer materials can be used, including PA, PVDF, PE, and XLPE. |
| Antiwear layer | To prevent metal-to-metal contact. | Antiwear layers are manufactured from polymer materials and are applied as a tape or an extruded layer. |
| Tensile armor wire | To provide tensile strength and to contain end-cap loads.<br>Tensile armors also provide partial pipe resistance against internal pressure. | Tensile armor layers are manufactured from thin rectangular high strength metallic wires in two or four layers, cross wound for torsional balance, at a typical lay angle of 20° to 55° to the longitudinal axis.<br>Where no pressure armor layer is used the tensile armor wires are typically cross wound at an angle close to 55° to obtain a balanced resistance to hoop and axial loads on the pipe. |

| Layer | Function | Description |
|---|---|---|
| Antibuckling | To provide resistance against radial expansion of the tensile armor wires. | Antibuckling layers typically are manufactured from a high strength composite material such as aramid fiber.<br>The purpose of the antibuckling layers is to prevent excessive bending or buckling of the armor wires. This can happen in two scenarios as follows:<br>a) radial buckling or “birdcaging,”<br>b) lateral buckling. |
| Insulation | To provide thermal insulation for bore fluid. | Insulation layers typically are manufactured from foam or solid insulation and are located between the tensile armor layers and outer sheath. |
| Outer sheath | To keep the tensile armors in position after forming, prevent the ingress of seawater and other external environments into the annulus of the flexible pipe, and protect steel wires from corrosion, abrasion, and mechanical damage. | The outer sheath is manufactured from a polymer material extruded over the tensile armor layers.<br>A pipe may have more than one outer sheaths in order to fulfill each of the functions mentioned. |
| Annulus | Provides a path through which permeated gases and liquids can be vented at the end fittings. | The annulus is the space between any two sheath layers, typically the internal pressure sheath and outer sheath.<br>A gas-venting system is provided to prevent pressure buildup in the annulus and between layers. |

End connectors can be an integral part of or attached to the end fitting. A variety of end connectors exist, such as bolted flanges, clamp hubs, proprietary connectors, and welded joints (two end fittings welded together to join pipe segments into a longer segment). The selection of end connector depends on operational and service requirements.

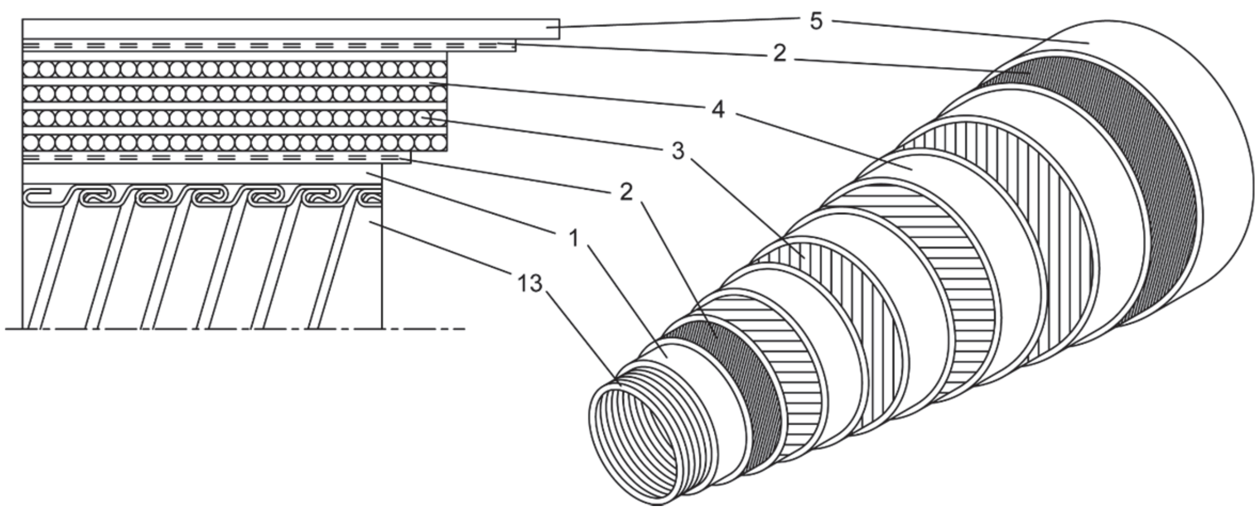
#### 4.3.6 Integrated Pipe Umbilicals (IPUs)

The functionality of flexible pipes can be combined with umbilicals to form an IPU. Figure 9 is a schematic of a typical IPU. The inner core is a standard flexible pipe construction and provides the axial load-bearing capacity of the structure. The umbilical components (electrical, hydraulic, optical, and control lines) are helically wound around the core pipe.

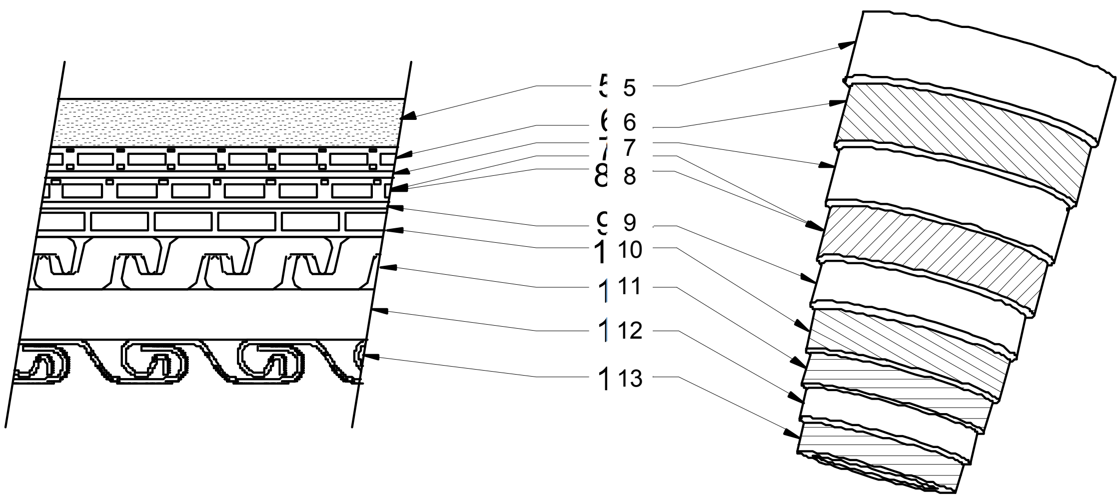
Spacers (fillers) are included between the umbilical lines to increase the crushing load resistance of the IPU. The assembly is covered by a protective outer sheath. In some cases, a layer of helical or sinusoidal armoring is applied between the control lines and the outer sheath. This layer increases the weight-to-diameter ratio of the IPU, which reduces the dynamic motions, thereby minimizing the potential for interference with adjacent risers. This layer also protects the control lines against external damage.

The end terminations of an IPU are complex constructions. The core of the termination is the end fitting of the central flexible pipe, around which the terminations of the control lines are grouped. This assembly is integrated in a steel housing or frame, which may also carry the bend stiffener and transfer bending loads. The detailed design of the termination is governed by the installation and tie-in strategy.

Stainless steel conduits may also be used in the IPU. These overcome the problem of fluid diffusion through the polymer hoses (in particular methanol) and reduce response time in control systems. However, stainless steel conduits can be sensitive to fatigue in DAs and installation loads.




**a) Bonded Flexible Pipe**

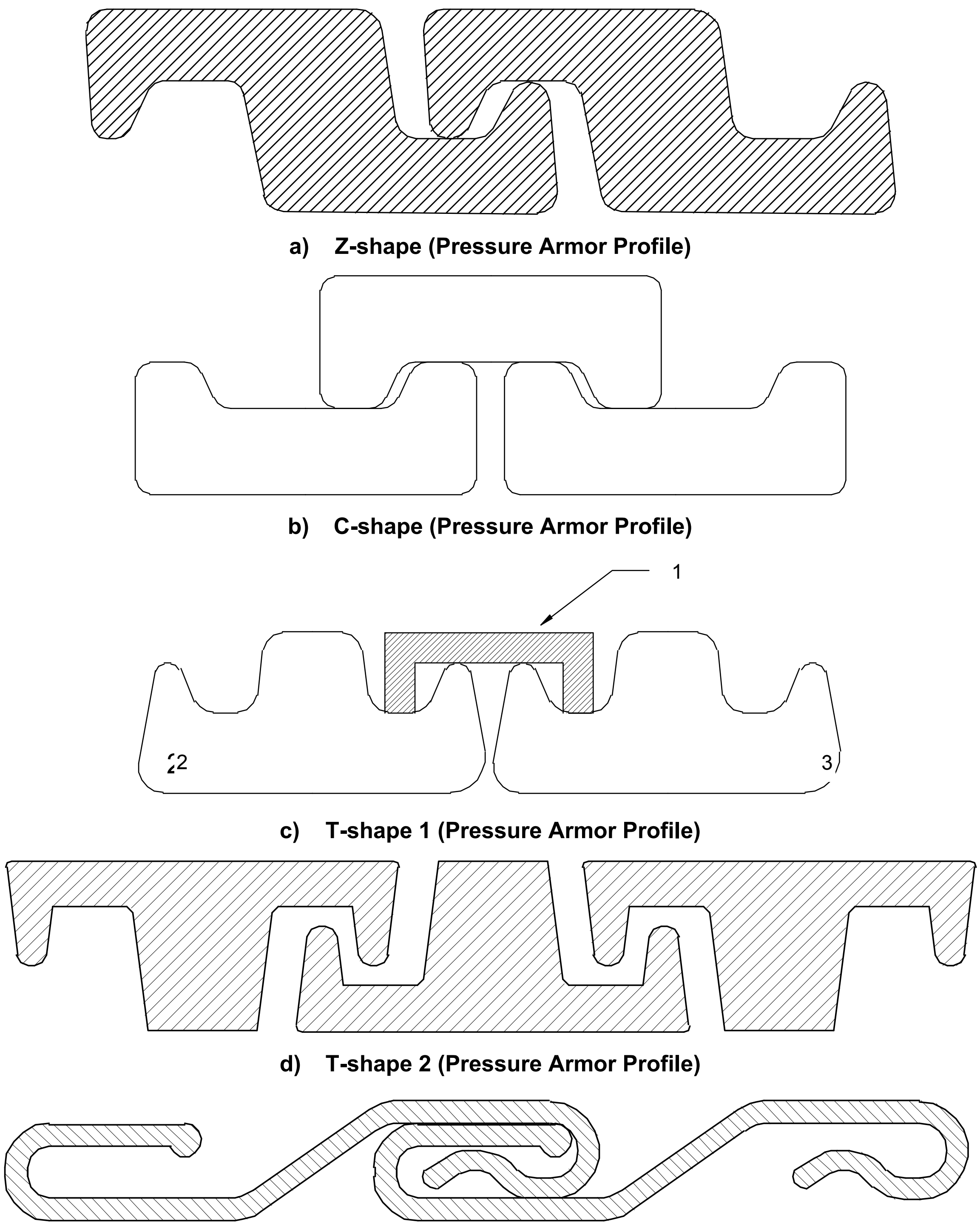



**b) Unbonded Flexible Pipe**

**Key**

1 Liner
2 Breaker layer(s)
3 Reinforcement layers
4 Cushion layer (filler)
5 Outer sheath
6 Outer tensile armor
7 Antiwear layer
8 Inner tensile armor
9 Antiwear layer
10 Backup pressure armor (noninterlocked)
11 Pressure armor (interlocked)
12 Internal pressure sheath
13 Carcass
14 Antibuckling layer

**Figure 6—Schematics of Typical Bonded and Unbonded Flexible Pipe Cross Sections**




**a) Z-shape (Pressure Armor Profile)**

**b) C-shape (Pressure Armor Profile)**

**c) T-shape 1 (Pressure Armor Profile)**

**d) T-shape 2 (Pressure Armor Profile)**

**e) Carcass Profile**

**Key**

1 Clip

2 T. Wire

3 T. Wire

**Figure 7—Typical Pressure Armor and Carcass Interlock Profiles (Unbonded Pipe)**

**Table 2—Description of Standard Flexible Pipe Families—Unbonded pipe**

| Function | Primary Function | Product Family I—Smooth Bore Pipe | Product Family II—Rough Bore Pipe | Product Family III—Rough Bore Reinforced Pipe |
|---|---|---|---|---|
| 1 | Prevent collapse | Pressure armor layer(s) | Carcass | Carcass |
| 2 | Internal fluid containment | Internal pressure sheath | Internal pressure sheath | Internal pressure sheath |
| 3 | Hoop stress resistance | Pressure armor layer(s) | Cross wound tensile armors | Pressure armor layer(s) |
| 4 | Increase the pipe collapse resistance by preventing seawater pressure from acting directly on the internal pressure sheath | Anticollapse sheath | — | — |
| 5 | Tensile stress resistance | Cross wound tensile armors | Cross wound tensile armors | Cross wound tensile armors |
| 6 | Protect steel wires from corrosion, abrasion, mechanical damage, and external environment | Outer sheath | Outer sheath | Outer sheath |
| 7 | Insulation (optional) | Insulation layer | Insulation layer | Insulation layer |
| 8 | Prevent birdcaging | Antibuckling layer | Antibuckling layer | Antibuckling layer |
| 9 | Protection (abrasion, fire resistance, etc.) | Outer layer | Outer layer | Outer layer |

NOTE 1 All pipe constructions may include various nonstructural layers, such as antiwear layers, tapes, manufacturing aid layers, etc.

NOTE 2 The pressure layer may be subdivided into an interlocked layer(s) and backup layer(s).

NOTE 3 The number of cross wound armor layers may vary, though generally is either two or four.

NOTE 4 The internal pressure and outer sheaths may consist of a number of sublayers.

NOTE 5 Product family III is generally used for higher pressure applications than II.

NOTE 6 The intermediate sheath for smooth bore pipes is optional if there is no external pressure or external pressure is less than the collapse pressure of the internal pressure sheath for the given application.

NOTE 7 Pipes for deepwater applications or pipes subjected to bending and high axial compression loads may use high strength antibuckling tapes (aramid fiber tape) to prevent birdcaging and buckling of tensile armors due to compressive and bending loads.

**Table 3—Description of Standard Flexible Pipe Families—Bonded Pipe**

| Function | Primary Function | Product Family IV—Smooth Bore Pipe | Product Family V—Rough Bore Pipe |
|---|---|---|---|
| 1 | Prevent collapse | N/A | Carcass |
| 2 | Internal fluid integrity | Liner | Liner |
| 3 | Hoop and tensile load resistance | Reinforcement layer(s) | Reinforcement layer(s) |
| 4 | External fluid integrity and protection | Cover | Cover |
| 5 | Insulation (optional) | Insulation layer | Insulation layer |
| 6 | Outer protection (abrasion, fire resistance etc.) (optional) | Outer layer | Outer layer |
| NOTE 1 All pipe constructions may include various nonstructural layers, such as filler layers and breaker fabrics. | | | |
| NOTE 2 The number of cross wound reinforcement plies may vary, though generally is either two, four, or six. | | | |

The IPU design may be governed by multiple specifications. API 17J or API 17K may govern for the inner core and API 17E [10] may govern for the design of the umbilical components. It is recommended that the IPU manufacturer clearly identify which standards apply to each of the components and provide a specification of the requirements for the overall IPU structure and end fitting that are not clearly defined in governing component standards. The manufacturer shall also provide a specification of the requirements applicable to the components (electrical cables, fiber optics, etc.) that might influence their performance due to the interaction with the IPU structure, such as those that may cause high contact pressures induced by a heavier pipe surrounded by delicate components, especially during manufacturing, handling, and installation (crushing loads). The supplementary requirements should be comprehensive and cover design methodology, prototype testing, manufacturing process, and FAT.

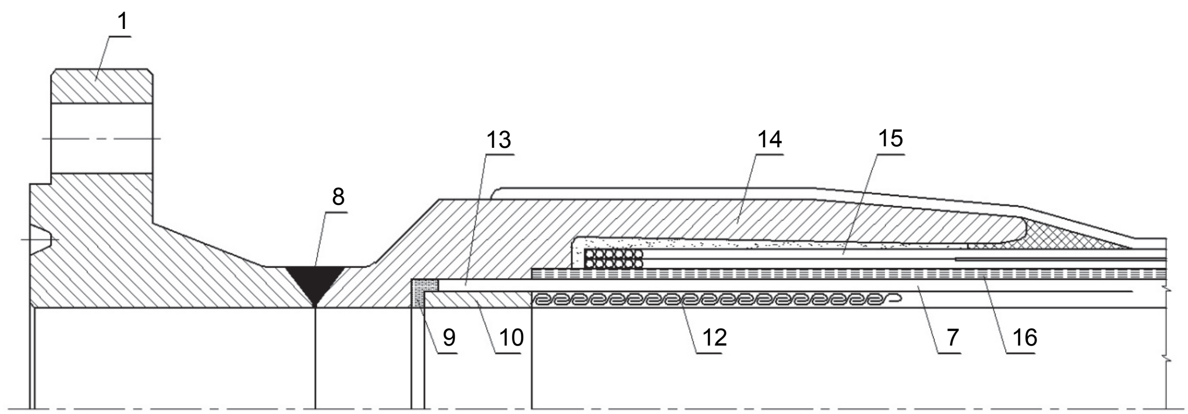
### 4.3.7 Multibores

The multibore concept involves combining multiple flexible pipes and/or umbilical components into a single construction, thus reducing the number of lines in a field development and thereby simplifying the field layout and installation requirements. It can also reduce the number of I-tubes or J-tubes required for some development options.

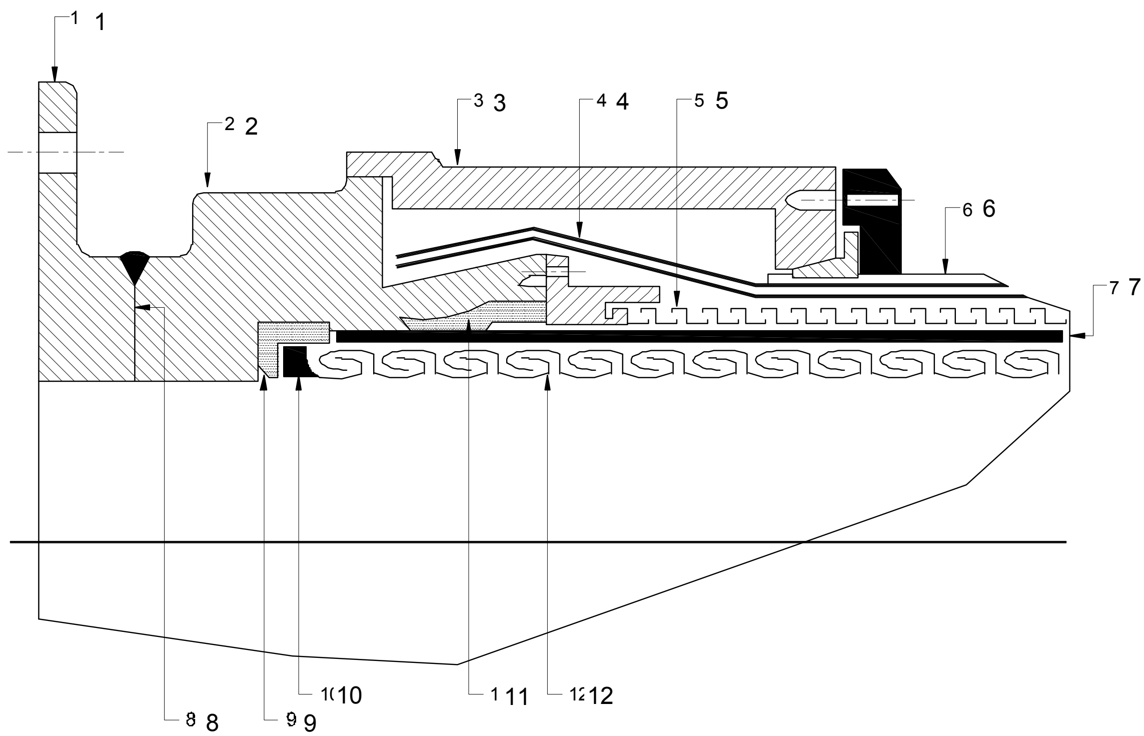
Figure 10 illustrates some examples of multibore constructions. The individual pipes are helically or sinusoidally wound and filler/spacer materials are used to obtain a circular cross section. External armoring may be applied outside the bundle. A polymer sheath is extruded over the bundle and provides structural integrity and protection.

The design of a multibore construction is much more complex than a single bore. Important considerations are described as follows.

a) The most desirable shape in a multibore structure is a circular cross section, since this results in optimal hydrodynamic performance, efficient space utilization, and easy handling during installation and retrieval.




**a) Bonded High Pressure Flexible Pipe End Fitting**

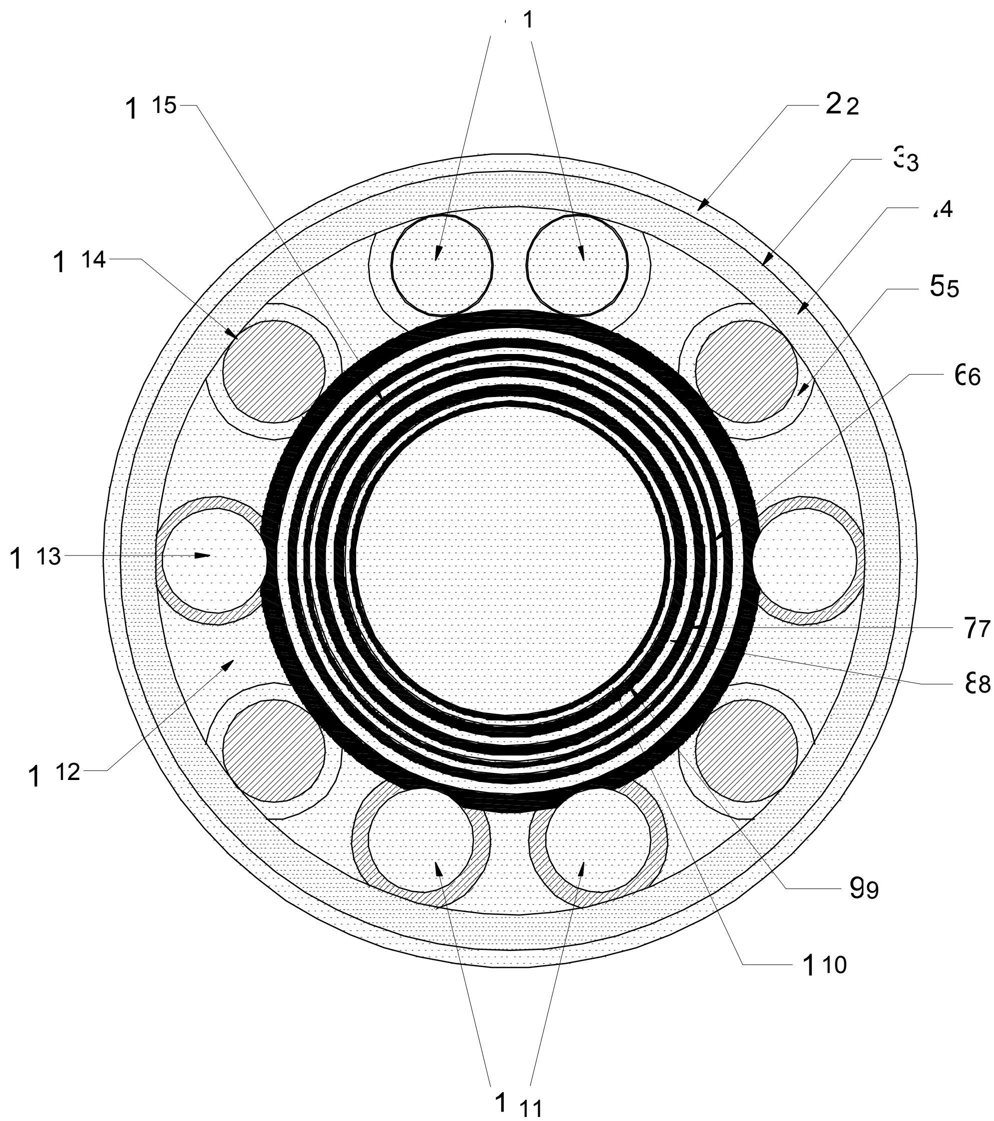



**b) Unbonded Flexible Pipe End Fitting**

**Key**

1 Mounting flange
2 End-fitting housing (inner casing)
3 End-fitting housing (outer casing)
4 Tensile armors (embedded in epoxy)
5 Pressure armor layer
6 Outer sheath
7 Internal pressure sheath (and sacrificial layers)
8 End-fitting neck
9 Insulator
10 Carcass end ring
11 Seal ring
12 Carcass
13 Sealing
14 Coupling body
15 Reinforcement layers
16 Breaker layers

**Figure 8—Example of Bonded and Unbonded Flexible Pipe End Fittings**




**Key**

| | | | |
|---|---|---|---|
| 1 | Electric power cable | 9 | Internal pressure sheath |
| 2 | Outer sheath | 10 | Carcass |
| 3 | Tape | 11 | Electrical signal cable |
| 4 | Pipe outer sheath | 12 | Filler material |
| 5 | Tape | 13 | Fiber optical cable |
| 6 | Tensile armor layer | 14 | Hydraulic hose |
| 7 | Internal tensile armor layer | 15 | Antiwear tape |
| 8 | Pressure armor layer | | |

**Figure 9—Schematic Drawing of an Example Integrated Pipe Umbilical**

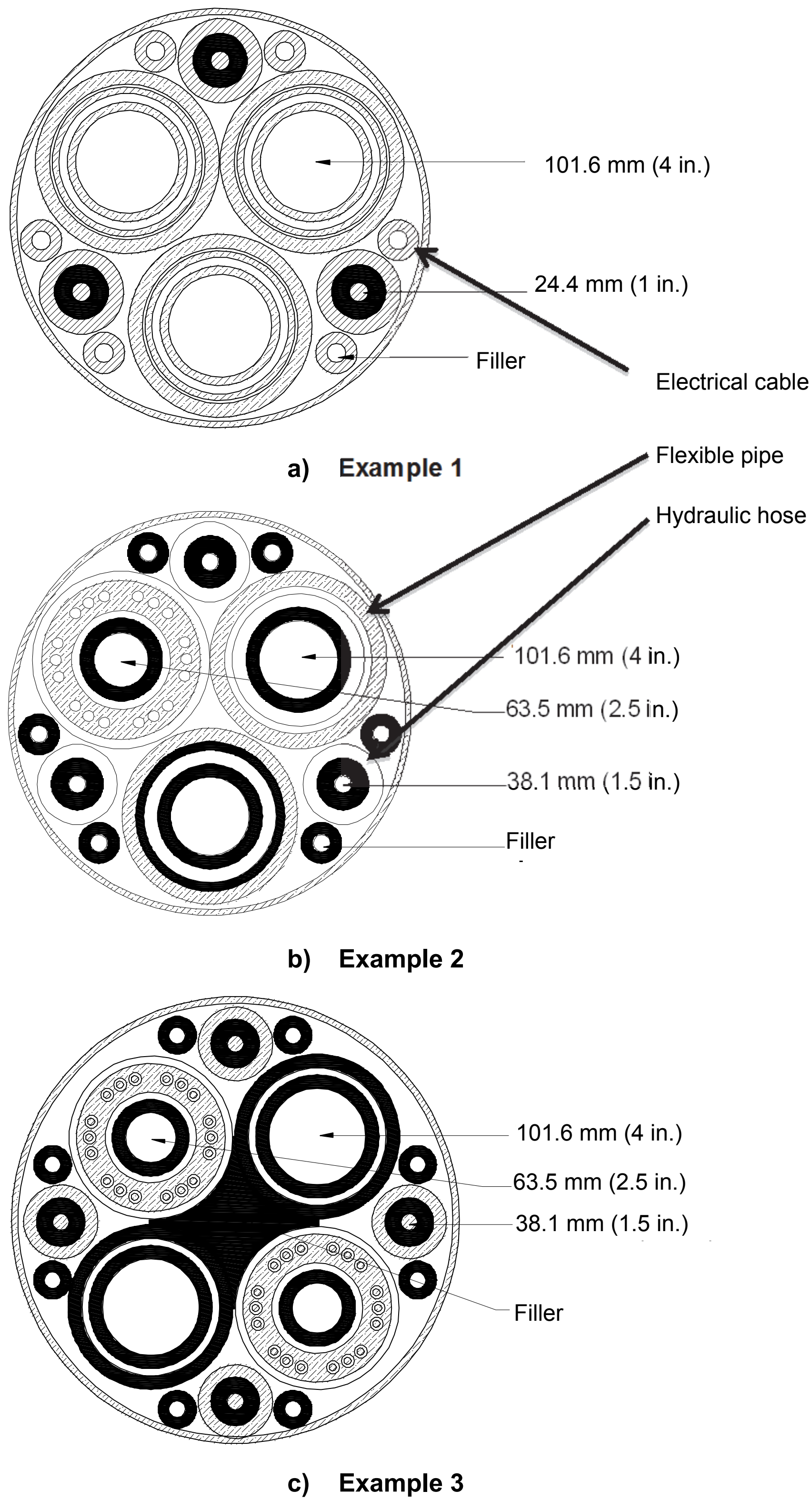



**Figure 10—Examples of Multibore Constructions**

b) Standard components (flexible pipes and umbilicals) are recommended to be used as much as possible.

c) The internal components can be designed to provide the axial load capacity of the structure, depending on the manufacturing process. The axial load capacity or additional capacity can be provided by armor layers. The structural stability (differing elongations in the components) and torsional balance of the multibore under various loading conditions (unequal pressure levels and bending) should be evaluated.

d) The crushing resistance of the multibore should be large enough to allow for flexibility in installation methods.

e) The maximum outer diameter (OD) is limited by the extrusion capability of the manufacturer for the outer sheath.

f) Care should be taken during winding to minimize torsion loads induced in the individual components.

g) A symmetrical construction is recommended to ensure uniform mechanical properties and to prevent structural rearrangement under dynamic loading.

h) The end termination for the multibore construction would typically use standard end fittings, contained within a box type structure.

The multibore design may be governed by multiple specifications. API 17J or API 17K may govern for the individual flexible pipe elements, and API 17E [10] may govern for the design of the umbilical components. It is recommended that the multibore manufacturer clearly identify which standards apply to each of the components and provide a specification of the requirements for the overall multibore structure and end fitting/termination that are not clearly defined in governing component standards. The manufacturer shall also provide a specification of the requirements applicable to the umbilical components that might influence their performance due to the interaction with the multibore structure such as those that may cause high contact pressures induced by heavier pipes surrounded by more delicate components, especially during manufacturing, handling, and installation (crushing loads). The supplementary requirements should be comprehensive and cover design methodology, prototype testing, manufacturing process, and FAT.

## 4.4 Ancillary Components

Ancillary components for flexible pipe systems are described in detail in Section 4.2 of API 17L2 [12]. Ancillary components commonly used in flexible pipe systems are as follows:

— bend stiffeners;

— bend restrictors;

— bellmouths;

— buoyancy modules and ballast modules;

— subsea buoys;

— tethers for subsea buoys and tether clamps;

— riser and tether bases, clamping devices;

— piggyback clamps;

— repair clamps;

— I/J-tube seals;

— pull-in heads/installation aids;

— connectors;

— load transfer devices;

— mechanical protection and fire protection.

# 5 Pipe Design Considerations

## 5.1 General

Section 5 provides guidance on flexible pipe design consistent with the requirements of API 17J and API 17K. Section 5 addresses the following specific issues:

a) system design requirements,

b) design overview and process,

c) pipe structural failure modes,

d) design criteria,

e) design load cases,

f) analysis methods and best practice.

## 5.2 System Design Requirements

### 5.2.1 Transported Fluid Considerations

The fluid velocity is important, particularly if abrasive materials such as sand are present in the produced fluids that can result in wear of the pipe's internal layer. Fluid velocities of the flowline and riser system are based on system pressure drop and the internal friction parameter for the flexible pipe. The friction parameter varies significantly between smooth and rough bore pipes because of the carcass construction in a rough bore pipe. Typical values for absolute friction factor are as follows:

— rough bore pipe: ID (mm)/250,

— smooth bore pipe: 0.005 mm (0.0002 in.).

The roughness values can generally be considered to be conservative. The friction is strongly influenced by the carcass characteristics, such as ID and profile dimensions, for a rough bore pipe. A more accurate friction factor can be calculated from tests if required.

The design of flexible pipe systems should consider the effect of variations in internal fluid density over the life of the project, particularly for riser systems, where a change in fluid density can change the shape of the riser configuration. In the case of multiphase flow, the effect of slug-induced vibration should be considered.

### 5.2.2 Corrosion Protection

The metallic components of the flexible pipe system exposed to corrosive fluids should be selected to be corrosion-resistant or alternatively be protected from corrosion. Corrosion protection can be achieved by one or more of the following methods:

a) coating,

b) application of corrosion inhibitors,

c) application of special metallic materials or cladding,

d) specification of corrosion allowance,

e) cathodic protection.

The implications for overall system design of providing corrosion protection should be assessed. API 17J and API 17K contain corrosion protection requirements, and DNV-RP-B401 [34] contains guidelines on the design of cathodic protection systems. Material qualification testing should be conducted in accordance with the referenced standards to demonstrate the efficacy of the selected corrosion protection system over the service life of the pipe.

### 5.2.3 Thermal Insulation

If the fluid temperature inside the system is to be maintained at a particular level, thermal insulating layers can be added to the flexible pipe cross section to provide added thermal resistance. The insulating material used should be compatible with the annulus fluids to which it is likely to be exposed. Typically, pressure, temperature, and mechanical compression limits apply to the use of these insulating materials and should be considered in the selection process. API 17J and API 17K specify minimum requirements for the use of thermal insulating layers.

Design of a flexible pipe to meet a specified thermal resistance should include thermal resistance from the surrounding environment. Burial or trenching and backfill will provide significant thermal resistance and can minimize or avoid a requirement for thermal insulation layers.

### 5.2.4 Gas Venting—Unbonded Pipe

Gas venting enables gas that has diffused through the internal pressure sheath of the flexible pipe to escape and thus avoid excessive gas pressure in the annulus of the flexible pipe system (see 5.6.3).

A gas-venting system comprises small bore pipes or machined channels, connecting continuous flow paths in the pipe annulus to gas-relief valves in the pipe end fittings. Burst discs may also be placed along the outer sheath of the flexible pipe for flowline systems; however, burst discs are not a good solution for static or dynamic pipe applications because localized corrosion can occur. While not recommended as primary vent system, burst discs can be used as secondary flow path in case of unexpected pressure rise or malfunction of main valves. API 17J specifies that burst discs shall not be used on risers. The minimum requirements for the design of gas-relief valves and burst discs are given in API 17J. At the topside connection, the annulus gas vent system should be designed to prevent backflow of liquids or corrosive gasses into flexible riser annulus. An appropriate design can be selected (e.g. a goose-neck on topside piping, a drain pot, heat trace cables, gas-relief check valves). The gas bleed-off system should never be capped during operation to avoid excessive pressure buildup in the annulus.

### 5.2.5 Pigging and Through Flowline (TFL) Requirements

The user should specify any pigs or tools to be passed through the flexible pipe. If pigging is required for the flexible pipe system, the following are recommended, as they may have an important impact on the system layout. Design issues include whether to use loops (pipes in parallel) or subsea receivers.

Foam or polyurethane (PU) pigs can be used for smooth bore pipes. Brush, foam, or PU pigs can be used for rough bore pipes. Scraper pigs are not suitable for flexible pipes.

Flexible pipe intended for use in TFL service should be constructed with an innermost layer that will not impede or suffer significant damage from the passage of TFL tools. For TFL service, the pipe shall conform to API 17C requirements with regard to design, fabrication, and testing and to Annex A of the same recommended practice with regard to internal diameter and drift testing.

### 5.2.6 Fire Resistance

API 17J and API 17K list the issues to be considered in assessing the resistance to fire of the flexible pipe. Ultimately, fire resistance tests will possibly be required. Additional resistance against fire may be provided by the application of an insulating protective cover on the outer sheath of the pipe. Special consideration should be given to the effect of fire on the interface between pipe and end fitting.

### 5.2.7 Piggyback Lines

The flexible pipe should be sufficiently protected against pipe and steel scuffing and the potential transfer of high temperatures from the steel to the flexible pipe if a flexible pipe is piggybacked to a steel pipeline or other steel structure.

The piggyback system should be designed with the following considerations where an umbilical or smaller diameter line is piggybacked to a flexible pipe:

a) hydrodynamic interaction, including shielding, solidification, hydroelastic vibrations, lift, and marine growth;

b) relative motion between the lines;

c) relative changes in length between the two lines (particularly due to different pressure and/or thermal expansion coefficients and axial stiffness between flexible and steel lines);

d) clamp loads;

e) loads and wear of the flexible pipe;

f) creep and long-term degradation of pipe and clamp materials;

g) internal pressure, tension, external pressure, bending, and torsion-induced change in cross-section geometry of the pipe.

The method of connecting the piggybacked line at the vessel interface should be carefully designed for the case of a flexible pipe riser.

### 5.2.8 Seabed and Overland Routing

Routes should be selected with regard to the probability and consequences of all forms of pipe damage.

The following factors should be taken into account:

a) installation,

b) seabed or overland route contour and conditions,

c) trenching or rock dumping (if applicable),

d) soil stability,

e) location of other installed equipment and pipelines,

f) pipe expansion,

g) accuracy of structure positions,

h) accuracy of installation vessel positioning system,

i) as pulled-in configuration,

j) ship traffic,

k) fishing activities,

l) offshore operations,

m) corrosivity of the environment,

n) launching of lifeboats,

o) anchoring and mooring of other installations and vessels.

The selection of the pipe route should satisfy the following:

a) minimize the need for seabed preparation;

b) minimize the vertical imperfections to be crossed;

c) ensure space for individual trenching, if required;

d) minimize pipe length.

The layout [e.g. location of wellheads, manifolds, mooring lines, and pipeline end manifolds (PLEMs), etc.] will significantly influence the selection of flowline layouts and riser configurations and should be considered early in the design.

#### 5.2.9 Protection

Pipe protection against damage caused by objects such as fishing gear, anchors, and mooring lines should be considered and requirements specified in agreement by the purchaser and manufacturer.

The impact energy and geometry of objects to be considered should be defined in the project design premise (see API 17J and API 17K). Impact loads should be quantified for the intended service as normal or abnormal operations following the results of a safety analysis. The recommended requirements for pressure containment equipment (such as the pipe structure, end fittings, and connectors) are as follows:

a) normal operations: such equipment should not be permanently deformed,

b) survival conditions: such equipment should not leak.

Based upon this classification and the protection method adopted, representative calculations should show that the pipe structure, end fitting, and connector utilization conform with API 17J and API 17K.

The following should be taken into account in the evaluation of the optimum technical and economical protection method:

a) seabed or ground conditions;

b) pipe and protection facility installation;

c) pipe expansion from temperature, pressure, etc.;

d) bending as a result of upheaval buckling;

e) inspection and maintenance;

f) pipe retrieval.

### 5.2.10 On-bottom Stability

#### 5.2.10.1 General

The stability of a flowline section on the seabed or ground is directly related to its (submerged) weight, the environmental forces, and the resistance developed by the soil. A stability analysis should demonstrate that the (submerged) weight of the unburied flowline is sufficient to meet the required stability criteria. Pipeline stability is to be considered for both installation and operation conditions.

Flotation and sinking of the pipe for the most critical internal fluid conditions should be checked. Issues to be considered during the stability analysis should include the following:

a) lateral displacement from an installed position as a result of expansion, settlement, or hydrodynamic effects;

b) geometric limitations of surrounding system;

c) distance from other pipes, structures, or obstacles;

d) internal fluid density and its variation during the service life;

e) pipeline tension, curvature, and torsion;

f) interaction with lateral buckling resulting from axial forces;

g) fatigue damage;

h) wear and deterioration of outer sheath;

i) damage to sacrificial anodes;

j) loading on end connections.

The suitability of mattresses, with respect to pipe cover abrasion and damage from protrusions, should be confirmed if their incorporation is required to provide stability. The general form and size of rocks, if rock dumping is provided, should be such that no damage is sustained to the pipe during deployment.

#### 5.2.10.2 Analysis Methods

The following stability analysis methods may be employed:

a) dynamic analysis involving a full dynamic simulation of the pipeline resting on the seabed, including modelling of soil resistance, hydrodynamic forces, boundary conditions, and dynamic response;

b) generalized stability analysis based on a set of nondimensional stability curves that have been derived from a series of runs with a dynamic response model;

c) simplified stability analysis based on a quasistatic balance of forces acting on the pipe.

Further details on the above analysis are given in Bibliographic Items [35] and [1].

#### 5.2.10.3 Stability Criteria

The pipe manufacturer or designer should specify and justify stability criteria for the particular application, which may be based on guidelines in Bibliographic Items [35] and [32]. As a minimum, the design criteria specified in API 17J and API 17K should be satisfied.

### 5.2.11 Upheaval Buckling

#### 5.2.11.1 General

A flexible pipe laid in a trench can be susceptible to upheaval buckling from longitudinal expansion of the flowline caused by internal pressure and temperature loadings. Internal pressure is the dominating factor contributing to upheaval buckling of flexible pipe.

In addition, changing the lay angle of the tensile armor layers can change the pressure and thermal expansion coefficients of the pipe. Additional pairs of tensile armor can change the optimal angle significantly.

The flexible flowline may be allowed to buckle provided that the design criteria of 5.2.11.4 are not violated. The potential for upheaval buckling can be evaluated by analytical or experimental methods. The parameters that influence the upheaval behavior of a flexible flowline and that should be incorporated into any investigation of upheaval buckling include the following:

a) operational pressure and temperature distributions along the flowline, including hydrotest conditions;

b) vertical imperfections in the flowline foundation;

c) variations in uplift resistance along the line, such as varying soil cover height and conditions, soil longitudinal friction, soil rotational stiffness, and its contribution to bending resistance of the pipe;

d) uplift resistance as a function of pipe uplift displacement;

e) stiffness properties of the pipe cross section as a function of pressure and temperature; in particular, axial compression stiffness and bending stiffness of the pipe;

f) relaxation with time of the initial lay pretension stresses in the pipe.

#### 5.2.11.2 Methods of Prevention

Measures to prevent or limit the extent of upheaval buckling include the following:

a) burying the pipe in a trench,

b) rock dumping,

c) wide and open trench and/or a meandering trench path to allow horizontal snaking,

d) laying the pipe with internal pressure to provide initial pretension in the line prior to burial,

e) optimize tensile armor lay angle.

A feasible way of pretensioning a flexible pipeline is to restrain the pipe (e.g. by rock dumping) while it is subjected to axial expansion due to internal pressure. Consider the following when evaluating the resulting effective pretension in the line:

a) residual axial compression loads due to the frictional resistance between the pipe and the seabed,

b) relaxation of pretension loads because of possible straightening of formed loops (lateral buckles),

c) creep of pipe materials over time.

#### 5.2.11.3 Analysis Methods

A linear model can be used to determine if upheaval buckling may occur. If the linear analysis indicates any potential concerns, then a nonlinear model for analysis of upheaval buckling is recommended. The nonlinear model should account for varying soil cover from imperfection geometry, nonlinear pipe/soil interaction, and geometric nonlinearities because of large deflections of the flowline. It may be assumed that the material properties exhibit a linear behavior.

An initial imperfection in the installed flowline configuration is characterized by an imperfection amplitude and a corresponding imperfection wavelength, assuming a symmetrical shape about the imperfection apex. In the unloaded condition, the pipe is assumed fully supported by the soil. Subjecting the pipe to temperature and pressure loads generates an axial compression force in the pipe, causing the pipe to buckle into a new equilibrium shape characterized by a buckling wavelength and a buckling amplitude, thereby creating a resulting uplift amplitude at the apex of the imperfection. The bending stiffness used in the calculations should be determined for the relevant internal pressure and temperature.

#### 5.2.11.4 Design Criteria

The upheaval buckling design criteria should be based on the following:

a) the pipe contains no bends below its minimum allowable bend radius;

b) the pipe does not deviate beyond the trench or berm boundaries;

c) movement restrictions imposed by the trench and infill do not result in pipe structure stresses or loads that violate the design criteria in API 17J and API 17K;

d) the upheaval buckling process does not subject the pipe to other failure modes that could cause leakage of the pipe, such as exposing the pipe to trawl board snagging;

e) adequate safety margin against snap-through buckling.

The uplift displacement is to be limited to a maximum of $0.75d_{\text{ult}}$, where $d_{\text{ult}}$ is the burial depth, to avoid an upheaval creep mechanism taking place because of variations in temperature and pressure during the service life of the line.

The distance between the prebuckling and postbuckling equilibrium curves at specified design conditions shall not be less than 0.1 m (3.94 in.) when plotted in a temperature (or pressure) versus uplift displacement plane to ensure an adequate safety margin against snap-through buckling failure.

The uplift resistance of the protection cover should be documented. Consideration is to be given to possible decrease in uplift resistance because of undrained cover or backfill or change in cover properties as a result of the installation method employed.

Following the installation of a flexible pipe that is susceptible to upheaval buckling, the design requirements should be verified with regard to the following:

a) vertical imperfections of installed line,

b) burial depth and berm height/width.

Documentation should exist verifying that the required cover is present prior to taking a trenched pipeline with natural backfill into service. The pipe configuration that results if a pipeline is situated in an open trench should be checked when the line is brought into service.

#### 5.2.12 Pipeline Crossing

Suitable protection should be placed between a flexible pipe that crosses another flexible, steel pipe or umbilical in service, unless it can be shown that the minimum bend radius (MBR) and other pipe design criteria are not violated. Protection can include sand bags, stabilization mattresses, structural bridges, or low friction matting. The number of crossovers should be minimized by the installation procedures if multiple lines are installed in a single trench.

A gas-carrying pipe should be placed above a liquid pipe if a crossover involves both liquid and gas-carrying pipes, unless the liquid pipe is lighter than the gas pipe, accounting for content. Any protection facility should take such movement into account where crossed flexibles are susceptible to movement.

Abrasion sleeves constructed of metal or polymer should be provided where a number of pipes come into contact under constant or frequent movement. The sleeves should sufficiently cover the maximum extent of relative movement and have enough thickness to account for expected wear. The sleeve requirements should be determined during the detail design of the pipe system.

## 5.3 Design Overview

### 5.3.1 General

Sections 5.3.2 and 5.3.3 give a general overview on the typical design process for flexible pipe. The design process, however, is a function of the pipe application, and a distinction is made between the process for the design of the following two generic flexible pipe applications:

a) SA—application in which flexible pipes are not exposed to significant cyclically varying loads or deflections,

b) DA—application in which flexible pipe is exposed to cyclically varying loads or deflections.

### 5.3.2 Design Stages

The main design stages for static and dynamic applications are represented in flowchart form in Figure 11 and are as follows:

a) Stage 1—material selection,

b) Stage 2—cross-section configuration design,

c) Stage 3—system configuration design,

d) Stage 4—dynamic analysis and design,

e) Stage 5—detail and service life design,

f) Stage 6—installation design.

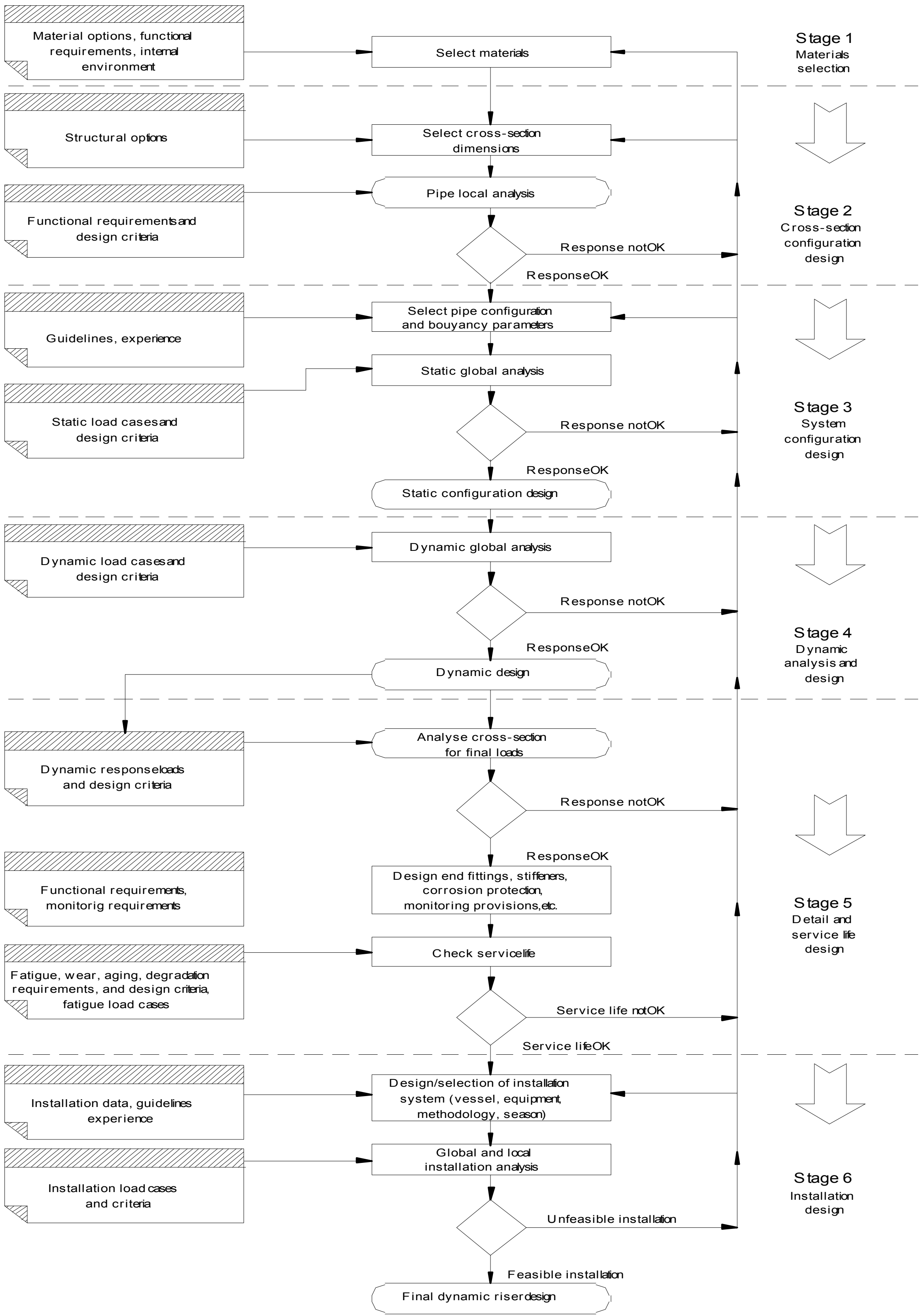



**Figure 11—Flexible Pipe Application Design Flowchart**

In Stage 1, the pipe material selection is made based on internal environment (transported fluid), functional requirements, and material options. Materials compatible with the transported product are selected. Section 6 contains guidelines for material selection. Materials should be qualified for the range of the specified functional requirements and for the range of exposures, loading, and environments predicted by the manufacturer for the materials in the product during the service life.

In Stage 2, the cross-section configuration and dimensions are selected based on the pipe's functional requirements and experience in the selection of the layer structure. Cross-section design calculations and checks typically are carried out by the manufacturer using proprietary software. The software should be validated against test data.

Stage 3 involves selection of the system configuration. This is generally a straightforward task in the case of a flowline, with the only complications typically being the design of the end sections and any requirements to accommodate the relative movement envelope. However, installation analysis, thermal analysis, upheaval buckling, and stability analysis can dictate design requirements in certain situations, as well as the field hydrostatic test of the installed system.

Stage 4 involves the dynamic design of the riser or riser system. Typically, this considers the dynamic response of the riser, subject to a series of imposed loading conditions derived from the functional, environmental, and accidental loads on the system. Issues to be addressed include possible interference with other system components, riser tension and/or compression loads throughout the riser, riser curvature (MBR), the top departure angle, and interface loads (described by tension angle or moment and shear force).

Stage 5 includes service life analysis as it applies to the pipe and components.

Stage 6 completes the design process and involves the selection and design of the installation system, including vessel, equipment, methodology, and environment conditions. Stage 6 requires detailed global and local analyses to confirm the feasibility of the selected installation system. This stage is in many cases critical for the pipe design, and it is therefore recommended that preliminary installation analyses be performed for both risers and flowlines at an early stage in the design process.

### 5.3.3 Riser Configuration

#### 5.3.3.1 General

A considerable part of flexible riser system design is the determination of the global configuration so that the riser can safely sustain the extreme seastate loadings for which it is to be designed. A safe riser design should not violate the minimum allowable bend radius or other pipe design criteria defined in API 17J and API 17K when subjected to these extreme wave and current loadings. A well-designed riser configuration accommodates vessel motions and other functional requirements in a safe and cost-effective manner. A riser that is compliant minimizes the stationkeeping requirements for the vessel and, in turn, reduces mooring costs.

Flexible risers are commonly deployed in one of five standard configurations listed below and illustrated schematically in Figure 4:

a) free-hanging catenary,

b) lazy-S,

c) steep-S,

d) lazy wave,

e) steep wave.

Other nonstandard or customized riser configurations may also be deployed.

#### 5.3.3.2 Free-hanging Catenary

The free-hanging catenary is the simplest, and generally the least expensive, riser configuration. A key problem with this solution, however, is that if there are any significant first-order wave motions at the vessel connection (particularly heave), these motions are transferred directly to the seabed potentially leading to compression at the riser touchdown point. Buckling and overbending of the pipe are consequences of this effect. Furthermore, the free-hanging riser is not very compliant to vessel motions: riser top tension increases rapidly with far vessel offset, and large vessel offset motions result in correspondingly large and undesirable motions of the riser/seabed touchdown point.

However, the free-hanging configuration, because of its simplicity, is always worth considering as a potential solution, particularly for mild environments and deepwater applications. In deepwater applications, the hangoff loads on the vessel can be large due to the suspended riser length.

#### 5.3.3.3 S-configuration

In an S-configuration, the flexible pipe ascends to the floating vessel over a tethered buoy. The hydrodynamic behavior of the buoy is an important consideration in the design of these systems. In general, the steep-S riser buoy is more susceptible to torsional instability than is the lazy-S solution.

The introduction of a subsea buoy into the riser configuration has two main functions:

a) provides a filter to stop the direct transfer of dynamic motions to the seabed that occurs with the free-hanging configuration;

b) supports part of the weight of the riser, thereby reducing static tension at the vessel connection.

The change in seabed touchdown point is controlled by the lateral motion of the subsea buoy. Increasing the size of the buoy correspondingly also increases the lateral restoring force through the buoy tethers, and this in turn tends to reduce the lateral motions of the buoy. However, a larger buoy is also susceptible to increased hydrodynamic loading.

#### 5.3.3.4 Wave Configuration

The buoyancy for wave configurations is applied to the pipe in a distributed manner using discrete modules rather than as a single tank as for the S-configurations. Generally, wave configurations are more compliant to dynamic motions than the S-configurations and ascend to the floating vessel as individual lines (or clamped bundles). While the increased compliancy to dynamic motions is an advantage, the compliant nature of the riser configuration itself to environmental loading and particularly to cross-loading makes riser interference with adjacent risers or structures an important design consideration.

In general, the steep wave riser is less compliant than the lazy wave. The lazy wave riser is particularly susceptible to variations in internal fluid density, and thus may not be a suitable choice in certain scenarios, for example, where a production riser may be emptied in service conditions. However, dynamic motions of the riser may be minimized by designing a flexible pipe cross section with low drag to weight characteristics. A steep wave will perform better in terms of interference with adjacent risers, moorings, or structures.

Other variations of the wave configuration, such as the double-lazy wave, have been installed in shallow water. This configuration consists of two separate buoyancy regions but is otherwise similar to the standard lazy wave. This design may be used to accommodate significant vessel offsets in shallow water but again may not be suitable in cases where the design requires a significant variation in internal fluid density.

The tethered (or pliant) wave is a modification to the steep wave configuration. Near the seabed touchdown, the tension in the riser is transferred via a riser clamp to a tether, which is fastened to the seabed by a clump weight or suction anchor. Otherwise, the riser touches down on the seabed in a similar manner to the lazy wave configuration. The benefit of this configuration is that the position of the riser touchdown point is kept under control by the tether, similar to a lazy configuration.

#### 5.3.3.5 Customized Configurations

Many flexible riser systems have been installed as hybrids (steel and flexible) and other combinations of the basic configurations. There have also been other innovative, sometimes proprietary, flexible riser configuration designs that have been successfully deployed. When considering nonstandard riser configurations, additional care should be taken to assure that all functional loads are taken into account and that the design requirements addressed in 5.2 of this document and the appropriate API standards are met. In addition, it should be assured that the riser configuration analysis is being conducted within the limitations of the proprietary riser system analysis software package being employed, such as through validation against alternative calculations.

### 5.3.4 Riser Interference Design

The riser system design should include evaluation or analysis of potential riser interference (including hydrodynamic interaction) with other risers and between risers and mooring legs, tendons, vessel hull, seabed, or any other obstruction. Abnormal service conditions including the case of one mooring line damaged should also be considered. Interference should be considered during all phases of the riser design life, including installation, in-place, disconnected, and unusual events. The accuracy and suitability of the selected analytical technique should be assessed when determining the probability and severity of contact.

Riser systems should be designed to control interference, which can damage the risers or other parts of the system. Hydrodynamic interaction of multiple risers, including shielding, should be considered. The effect of marine growth should also be considered.

Either of two design approaches may be taken to control riser interference. One approach requires that the riser system has an acceptably low probability that the clearance between a riser and another object is less than a specified minimum value. The other approach permits contact between the riser and the other object but requires analysis and design for the effects of contact based on clashing impact test data. For example, the impact energy may be calculated and compared to an allowable value.

Interference can occur between a riser and any object that has dynamic characteristics different from those of the riser and that is sufficiently close to it. Objects can include the vessel hull, a riser of different size, a riser having different properties (such as different contents, extent of marine growth, top tension or tension distribution) or other boundary conditions, or a riser in a different flow field caused by wake effects. Clearly, this type of interference is more severe than between the risers with similar dynamic characteristics, and the size and direction of impact loads should be quantified.

Interference between adjacent wave type risers at the buoyancy section should not be allowed to occur. Interference with the mooring lines, vessel hull, or other adjacent structures should also not be allowed to occur.

Quasistatic analyses may be used to identify the critical load combinations of wind and current profiles and headings, and vessel offsets, which minimize the clearance between the riser and the adjacent structure. Dynamic analysis should be used, with the critical combinations of vessel draft, vessel orientation, wave frequency, and wave heading that maximize riser motions and deflections, in the presence or absence of currents.

The dynamic load cases are typically based on the critical load combinations determined from the quasistatic analyses. Note that the load cases for interference may be different for those that drive the extreme responses (riser tension and MBR) in terms of inner fluid densities and environmental loading. The loading conditions that cause the largest riser deflections should be considered.

### 5.3.5 End-fitting Design

#### 5.3.5.1 General

The design of the end fitting for flexible pipes is critical. Section 4.3.5 describes the end fittings used for flexible pipes, while Figure 8 shows a schematic of a typical unbonded pipe end fitting. As a minimum, the end-fitting design should meet the requirements of API 17J and API 17K.

#### 5.3.5.2 Unbonded Pipe

The end-fitting design for unbonded flexible pipes should consider the potential pipe defects identified in 11.3. Of particular relevance are high pressure, deepwater, and the potential for pull-out of the internal pressure sheath from the inner seal.

Critical issues include the following:

a) loss of plasticizer from internal pressure sheath (if applicable);

b) dimensional changes in sheath;

c) friction coefficient between seal and adjacent layers;

d) creep and stress relaxation in sheath material;

e) thermal coefficient of expansion for sheath material;

f) variation of sheath material properties over service life;

g) requirement for multiple layers in internal pressure sheath;

h) for vertical risers, potential loss of support of internal carcass weight by internal pressure sheath leading to carcass pull-out of top end fitting;

i) venting of the annulus gases;

j) number and range of temperature cycles;

k) cooldown rates during temperature cycles of end fitting and main pipe body;

l) variations in polymer material properties with temperature;

m) armor wire pull-out or rupture inside the end fitting;

n) epoxy degradation;

o) corrosion (external and internal corrosion, not limited to the end-fitting body, that is, for instance in armors or internal components due to corrosive fluid or seawater ingress)

p) pressure and tension retaining capability;

q) resistance to seawater ingress (external seal or vent valve failures);

r) resistance to outer sheath pull-out during installation.

The design of the end-fitting internal crimping/sealing mechanism, for polyvinylidene fluoride (PVDF) based pipes in particular, is critical. The effectiveness of the seal can be reduced by large temperature cycles, high thermal expansion coefficient, plasticizer loss, or use of a multiple layer construction for a PVDF internal pressure sheath. The end-fitting design should be verified with high temperature cycling tests (Annex A). These tests should be representative of service conditions, including thermal and dynamic loading, and the effect of plasticizer loss as applicable. For new designs, the prototype tests of Section 7 should also be considered. For new internal pressure sheath materials, the sealing system should be qualified as per Annex A and Annex C (midscale tests).

#### 5.3.5.3 Bonded Pipe

The end-fitting design for bonded flexible pipes should consider the potential pipe failure mechanisms identified in 11.3. Issues of particular relevance include high pressure, deepwater, the potential for pull-out of reinforcing cables, and loss of fluid seal integrity. Critical issues include the following:

a) change of pipe body, particularly liner material properties over service life,

b) dimensional changes in pipe body due to the highly elastic nature of pipe body elastomer material,

c) bonding of liner material layers and bonding of liner to remainder of flexible pipe body,

d) reinforcing armor pull-out,

e) epoxy degradation,

f) corrosion,

g) pressure and tension retaining capability,

h) resistance to seawater ingress,

i) integrated gasket integrity,

j) crimping overpressure applied,

k) number and range of temperature and pressure cycles,

l) incorporation of integrated bend stiffeners.

### 5.3.6 Load-bearing Structures

Load-bearing structures used to support flexible pipes should be designed such that the pipe is not subjected to excessive wear, bending, crushing, or point loading. Steel materials should be provided with suitable cathodic or coating protection, and all surfaces in contact with the flexible pipe should assure that the MBR for the flexible pipe is not violated.

Structures within a flexible pipe system should be designed to accommodate flexible pipe movements. Load-bearing steel components should be designed in accordance with relevant steel standards for offshore structure design.

### 5.3.7 Pipe Attachments

Interactive forces between pipe and any attachment should be determined along with resultant pipe deflections. Due consideration should be given to mid-water support buoys with respect to their overall behavior within the system to minimize dynamic effects imposed on the pipe. Other considerations should include: clamping capacity, radial expansion and contraction, friction, and safety factors.

### 5.3.8 Riser Bases

Riser bases should be located in relation to the overall system such that the pipe does not exceed design MBR in any design load case and the maximum excursion capability of the flexible pipe top end is facilitated. Installation tolerance for the riser base should be accounted for in the riser system design.

#### 5.3.9 Jumper and Spool Pieces

Each flexible pipe jumper and spool piece should be analyzed in accordance with the load cases defined in the design premise (see API 17J and API 17K). All associated equipment should be subjected to a similar level of analysis in order to establish suitability. The analysis should take account of seabed conditions and pipe stability.

The configuration of a spool piece should be such that minimal loading is imposed on the flexible pipe, with special emphasis being placed on the area immediately around the end fitting. Spool pieces and their systems should be manufactured so that pipe lengths provide sufficient flexibility during installation and operation.

#### 5.3.10 Failure Modes

It is important to have detailed knowledge of the potential degradation and failure modes for the intended application so that they can be addressed in the design. Table 4 and Table 5 provide lists of pipe failure modes that are explicitly provided for in typical unbonded and bonded pipe design, respectively, and identify relevant failure mechanisms and appropriate design strategies/solutions. The design solutions should in all cases meet the design criteria specified in API 17J and API 17K. A more complete, though not exhaustive, list of potential pipe defects for flowline and riser applications is presented in Table 30 to Table 32.

### 5.4 Design Criteria

#### 5.4.1 Unbonded Flexible Pipe

##### 5.4.1.1 Introduction

The design criteria for unbonded flexible pipes are given in API 17J in terms of the following:

a) bending strain (polymer sheaths);

b) thinning of layer due to creep (internal pressure sheath);

c) stress (metallic layers and end fitting);

d) hydrostatic collapse (buckling load);

e) mechanical collapse (stress induced from armor layers);

f) crushing collapse and ovalization (during installation);

g) compression (axial and effective);

h) service life factors (e.g. pipe, end-fitting anchoring system, end-fitting body, bend stiffener);

i) stress or strain (antibuckling tape);

j) buckling load (carcass and armor layers);

k) overbending leading to unlocking pressure armor.

Guidance on the derivation of these criteria is given in the following paragraphs. In addition, criteria are also introduced which provide for design against failure additional to the criteria specified in API 17J.

**Table 4—Checklist of Failure Modes for Primary Structural Design of Unbonded Flexible Pipe**

| Pipe Global Failure Mode to Design Against | Potential Failure Mechanisms | Application Static/Dynamic (SA/DA) | Design Solution or Variables (API 17J ) |
|---|---|---|---|
| Collapse | — Collapse of carcass and/or pressure armor due to excessive tension. | SA, DA | — Increase thickness of carcass strip, pressure armor, or internal pressure sheath (smooth bore collapse). |
| | — Collapse of carcass and/or pressure armors due to excess external pressure. | SA, DA | — Modify configuration or installation design to reduce loads. |
| | — Collapse of carcass and/or pressure armor due to installation loads or ovalization due to installation loads. | SA, DA | — Add intermediate anticollapse sheath (smooth bore pipes). |
| | — Collapse of internal pressure sheath in smooth bore pipe. | SA, DA | — Increase the area moment of inertia of carcass or pressure armor. |
| | — Collapse of carcass due to pressure buildup in multilayer pressure sheaths followed by rapid decompression. | SA, DA | — Prevent pressure buildup and rapid decompression through operational procedures. |
| | — Collapse of pipe due to carcass pull out from end fitting resulting from lack of pressure sheath support. | SA, DA | — Design end fittings to assure support of pressure sheath and carcass. |
| | — Collapse of carcass due to carcass fatigue. | SA, DA | — Assure that carcass is manufactured correctly to avoid fatigue loading. |
| Burst | — Rupture of pressure armors because of excess internal pressure. | SA, DA | — Modify design (e.g. change lay angle, wire shape, etc.). |
| | — Rupture of tensile armors due to excess internal pressure. | SA, DA | — Increase wire thickness or select higher strength material if feasible.<br>— Add additional pressure or tensile armor layers. |
| Tensile failure | — Rupture of tensile armors due to excess tension. | SA, DA | — Increase wire thickness or select higher strength material if feasible. |
| | | SA, DA | — Modify configuration designs to reduce loads. |
| | — Snagging by fishing trawl board or anchor, causing overbending or tensile failure. | SA, DA | — Add two more armor layers.<br>— Bury pipe. |
| Compressive failure | — Birdcaging or lateral buckling of tensile armor wires | SA, DA | — Avoid riser configurations that cause excessive pipe compression. |
| | — Compression leading to upheaval buckling and excess bending | SA, DA | — Provide additional support/restraint for tensile armors, such as antibuckling tape and/or additional or thicker outer sheath. |

| Pipe Global Failure Mode to Design Against | Potential Failure Mechanisms | Application Static/Dynamic (SA/DA) | Design Solution or Variables (API 17J ) |
|---|---|---|---|
| Overbending | — Collapse of carcass and/or pressure armor or internal pressure sheath.<br>— Rupture of internal pressure sheath.<br>— Unlocking of interlocked pressure or tensile armor layer.<br>— Crack in outer sheath. | SA, DA<br>SA, DA<br>SA, DA<br>SA, DA | — Modify configuration designs to reduce loads. |
| Torsional failure | — Failure of tensile armor wires.<br>— Collapse of carcass and/or internal pressure sheath.<br>— Birdcaging of tensile armor wires. | SA, DA<br>SA, DA<br>SA, DA | — Modify system design to reduce torsional loads.<br>— Modify cross-section design (e.g. change lay angle of wires, add extra layer outside armor wires, etc.) to increase torsional capacity. |
| Fatigue failure | — Tensile armor wire fatigue.<br>— Pressure armor wire fatigue. | DA<br>DA | — Increase wire thickness or select alternative material, so that fatigue stresses are compatible with service life requirements.<br>— Modify design to reduce fatigue loads. |
| Erosion | — Of internal carcass. | SA, DA | — Material selection<br>— Increase thickness of carcass<br>— Reduce sand content<br>— Increase MBR |
| Corrosion | — Of internal carcass.<br>— Of pressure or tensile armor exposed to seawater, if applicable.<br>— Of pressure or tensile armor exposed to diffused product. | SA, DA<br>SA, DA<br>SA, DA | — Material selection<br>— Cathodic protection system design<br>— Increase layer thickness<br>— Add coatings or lubricants |

The criteria specified by API 17J apply to the materials currently used in flexible pipe applications. Where new materials are proposed or used, the design criteria for the new materials should give at least the safety level specified in API 17B and API 17J. The same is applicable to conventional materials that are used outside the qualification envelope (i.e. for more severe conditions). The design criteria should consider all material characteristics, such as susceptibility to such conditions as creep, fatigue, excessive strain, and cracking.

Simplified approaches exist for the approximation of pipe characteristics (axial, bending, and torsional stiffness, etc.) and for calculating loads in the individual layers. These simplified methodologies may be used for preliminary comparison of design loads with design criteria. For final design calculations, however, a verified (with prototype tests) methodology is to be used, as defined in API 17J.

**Table 5—Checklist of Failure Modes for Primary Structural Design of Bonded Flexible Pipe**

| Pipe Global Failure Mode to Design Against | Potential Failure Mechanisms | Application Static/Dynamic (SA/DA) | Design Solution or Variables (API 17K) |
|---|---|---|---|
| Collapse | — Collapse of carcass due to excessive tension.<br>— Collapse of carcass due to excess external pressure.<br>— Collapse of carcass and due to installation loads or ovalization due to installation loads.<br>— Collapse of pipe in smooth bore pipe. | SA, DA<br>SA, DA<br>SA, DA | — Increase thickness of carcass strip or pipe body (smooth bore collapse).<br>— Modify configuration or installation design to reduce loads.<br>— Increase the area moment of inertia of carcass. |
| Burst | — Rupture of reinforcing armors due to excess internal pressure. | SA, DA | — Modify design (e.g. change lay angle, cable type, etc.).<br>— Increase cable thickness or select higher strength material if feasible.<br>— Add additional reinforcing armor layers. |
| Tensile failure | — Rupture of reinforcing armors due to excess tension.<br>— Collapse of carcass and/pipe body sheath due to excess tension.<br>— Snagging by fishing trawl board or anchor, causing overbending or tensile failure. | SA, DA<br>SA, DA<br>SA, DA | — Increase cable thickness or select higher strength material if feasible.<br>— Modify configuration designs to reduce loads.<br>— Add two more armor layers.<br>— Bury pipe. |
| Compressive failure | — Compression leading to upheaval buckling and excess bending (see also upheaval buckling failure mode, 8.3.5). | SA, DA | — Avoid riser configurations that cause excessive pipe compression.<br>— Application of antibuckling tape to increase compressive capacity. |
| Overbending | — Collapse of carcass or pipe body.<br>— Rupture of liner.<br>— Crack/tear in outer sheath. | SA, DA<br>SA, DA<br>SA, DA | — Modify configuration designs to reduce loads. |
| Torsional failure | — Failure of tensile armor wires.<br>— Collapse of carcass and/or liner.<br>— Birdcaging of tensile armor wires. | SA, DA<br>SA, DA<br>SA, DA | — Modify system design to reduce torsional loads.<br>— Modify cross-section design (e.g. change lay angle of wires, add extra layer outside armor wires, etc.) to increase torsional capacity. |

| Pipe Global Failure Mode to Design Against | Potential Failure Mechanisms | Application Static/Dynamic (SA/DA) | Design Solution or Variables (API 17K) |
|---|---|---|---|
| Fatigue failure | — Tensile armor wire fatigue. | DA | — Increase wire thickness or select alternative material, so that fatigue stresses are compatible with service life requirements. |
| | — Pressure armor wire fatigue. | DA | — Modify design to reduce fatigue loads. |
| Erosion | — Of internal carcass or liner. | SA, DA | — Material selection.<br>— Increase thickness of carcass.<br>— Reduce sand content.<br>— Increase MBR. |
| Corrosion | — Of internal carcass. | SA, DA | — Material selection. |
| | — Of pressure or tensile armor exposed to seawater, if applicable. | SA, DA | — Cathodic protection system design. |
| | — Of pressure or tensile armor exposed to diffused product. | SA, DA | — Increase layer thickness.<br>— Add coatings or lubricants. |

#### 5.4.1.2 Strain

The allowable strain is a critical parameter in the design of the internal pressure sheath, outer sheath, or other leak-proof polymeric layer (such as the anticollapse sheath). API 17J specifies allowable strain values for the most commonly used materials.

The allowable strains in API 17J have been verified by material tests performed under relevant service and ageing conditions and historical field performance. The allowable strain for materials not explicitly provided for in API 17J should be evaluated by the manufacturer by performing such tests. A safety factor is typically applied to results to derive the allowable strain of the material over its service life, accounting for material ageing and degradation in the appropriate environment.

API 17J also provides for the calculation of MBR to prevent locking of the interlocked pressure armor wires.

#### 5.4.1.3 Creep/Thinning

Under normal service conditions, the internal pressure sheath will deform or "creep" into gaps in the pressure or tensile armor layer as a result of pressure and temperature effects. If the sheath is too thin or the gap between the armors is too large, the internal pressure sheath will creep until a failure (leakage) occurs. Creep of the sheath at the end-fitting seal is also an important issue (see Table 6).

The design of the internal pressure sheath (wall thickness) should account for creep. The main factors to be accounted for are material properties, layer thickness, pressure or tensile armor geometry, gap between armors, temperature, and pressure. Two methodologies currently used to determine the wall thickness required to prevent creep failure are as follows:

a) physical tests to determine the required wall thickness;

b) finite element analyses, calibrated with gap span test data, to determine the required wall thickness.

The layer thinning design criterion specified in API 17J is based on both of these methodologies. This specifies the maximum allowable reduction in wall thickness below the minimum design value under all load conditions.

#### 5.4.1.4 Stress

The design stress criteria (utilization factors) given in API 17J or API 17K were derived to give acceptable factors of safety against failure. These factors prescribe the maximum allowable average layer stress as a proportion of the structural capacity of steel materials. The utilization factors make implicit allowance for the presence of residual wire stress.

The published utilization factors relate to steel materials that have been qualified to API 17J or API 17K. No inference can be made about allowable stress in new materials based on these values.

As stated in Section 5.3.1 of API 17J, local armor wire stresses may exceed average layer stresses. While fatigue analysis considers local wire stresses, these local stresses are usually based on operating pressure instead of the greater design or incidental pressures the pipe may be subjected to. It is important to document that the extreme local wire stresses determined for extreme and/or abnormal operating conditions do not lead to a subsequent progressive failure of the pipe. Evaluation of acceptability of local stresses and strains can be done by one of the following, after accounting for the residual stresses in wires due to manufacturing and FAT.

a) Demonstrating that maximum local stress is below yield.

b) Confirming by analysis and testing that the local stresses do not result in unacceptable deformation or crack initiation at any location in the armor wire cross section. The model and criteria should be validated by small-scale tests. For example: manufacturing and installation tolerances resulting in pipe ovality should be taken in consideration when calculating the maximum local stress; the wire sulphide stress cracking (SSC) and hydrogen-induced cracking (HIC) resistance should be retested when the maximum local stress exceeds the stress level (e.g. 90 % of yield) at which the wires have been previously tested.

c) Determining wire fatigue performance by using strain based fatigue capacity E-N curve (defined as strain range vs number of cycles to failure) if the maximum local stresses exceed the wire yield stress during a single extreme or abnormal event. The number of strain ranges should be determined from the duration of such an event in the given geographical area.

d) Full-scale dynamic fatigue tests applying the loads in the armor layers corresponding to Item c) followed by inspection of armor wire cross sections.

#### 5.4.1.5 Hydrostatic Collapse

Utilization factors that relate to buckling of the internal carcass under hydrostatic pressure are specified in API 17J. API 17J states that the buckling load utilization for the carcass is calculated from dividing the differential pressure by the (external) hydrostatic pressure, where the differential pressure is defined as the difference between the local internal pressure and the external hydrostatic pressure of the pipe.

Hydrostatic collapse calculations should be performed for both an intact outer sheath and a breached outer sheath (such as seawater penetrated into the annulus), with the hydrostatic collapse resistance taken as the minimum of the two collapse pressure values. Analytical methods for calculating collapse resistance should be based on an assumed initial ovalization. This ovalization should be selected by the manufacturer, based on manufacturing tolerance limits and residual ovalization from the installation process. A minimum ovality of 0.2 % should be used if no other data exists.

The collapse resistance for smooth bore pipes should also be calculated based on the resistance of the internal pressure sheath only, and standard analytical methods may be used. If the collapse to design ratio is below the required value, then it should be specified that sufficient internal pressure be maintained to prevent collapse (such as by ensuring line is full of liquid at hydrostatic pressure). Alternatively, an intermediate anticollapse sheath should be provided to ensure that the pressure armor provides the required collapse resistance.

FPS 2000 [40] and Bibliographic Item [27] contain recommended procedures for calculating the hydrostatic buckling load (collapse pressure) of a carcass. However, these procedures are for the carcass layer alone. In pipe designs that include a pressure armor layer, this layer assists the carcass and significantly increases the collapse strength of the pipe. When used, methodologies for calculating the collapse strength (design water depth) of a flexible pipe with contribution from the pressure armor layer should be verified by documented prototype tests.

Bibliographic Items [26] and [62] describe some of the recent developments regarding collapse resistance prediction methodologies (numerical models) and the correlation with results from collapse tests for both bent and straightened pipe.

#### 5.4.1.6 Mechanical Collapse

The utilization factor for mechanical collapse of the internal carcass is specified in API 17J. The contribution of all supporting steel layers may be taken into account when designing against mechanical collapse.

#### 5.4.1.7 Torsion

The flexible pipe should have a torsional strength sufficient to withstand torsional loads induced during installation and service conditions without any structural damage. The torsional stiffness indicates the resistance of a flexible pipe to rotation around its axis under a torsional moment and is a performance characteristic of the pipe.

The maximum acceptable torsion derives from the following two scenarios (depending on the direction of the applied torsion).

a) The outer tensile armor layer is turned inward and pressed against the internal layer (in which case the allowable tension causes overstressing of the tensile armor) by inducing a stress corresponding to its structural capacity (defined by API 17J multiplied by the utilization factor specified in API 17J ).

b) The outer tensile armor layer is turned outward and pressed against the outer layers, leading to a gap between the two tensile armor layers, in which case the damaging torsion induces a gap between tensile armor layers, equal to half the thickness of the tensile armor wire. The allowable torsion for this case should be calculated from the damaging torsion using a safety factor not less than 1.0. If the twisting acts to tighten the inner armor the stress utilization in the inner armor should be checked.

#### 5.4.1.8 Crushing Collapse and Ovalization

During conventional laying operations, the tension in the flexible pipe is generally controlled with a tensioner or with a laying winch. The load applied to the flexible pipe, when tightening it in a tensioner or unreeling/reeling the flexible pipe under tension (possibly over a V-shaped sheave), has to be controlled to avoid sudden collapse (or significant ovalization) of the structure or overstressing of the metallic layers. The tension loads and crushing effect on the structure during installation should be accounted for in the design of the flexible pipe.

The feasibility of installing the flexible pipe with the selected procedure should be evaluated, considering the following effects:

a) crushing of the flexible pipe under radial compression in a tensioner,

b) crushing effect on a laying pulley or sheave,

c) damaging pull of the flexible pipe at the top of the catenary.

The collapse load should be calculated based on the resistance of the internal carcass and supporting pressure layers (pressure armor and flat steel spiral), as applicable. For rough bore pipes, Table 8 of API 17J states that the stress in either the carcass or the pressure armor can meet the material yield stress, provided that the allowable utilization is not exceeded in the other layer at the same time.

The two following alternative approaches, which have been calibrated against full-scale tests, are recommended for the collapse calculation:

a) finite element analysis,

b) analytical/empirical formulae.

The following load cases should be investigated, as applicable:

a) reeling/unreeling on a sheave of a flexible pipe subjected to design maximum axial load,

b) radial compression in a tensioner of a flexible pipe subjected to design maximum axial load.

The compressive radial loads and axial loads induced by the installation procedure should be limited such that the design criteria specified for installation in Table 8 of API 17J are met. In particular, the maximum allowable installation tension should be established as the value that meets the applicable criteria in API 17J, Table 8.

In addition, the maximum permanent ovalization of the pipe for both installation methods should be less than the value of initial ovalization used for hydrostatic collapse calculations (see 5.4.1.5).

#### 5.4.1.9 Compression

A flexible pipe may be subjected to two types of compression as follows:

— effective compression (negative effective tension),

— axial (true wall) compression.

Effective compression can lead to a lack of stability in risers under dynamic loading conditions, potentially causing overbending or other effects of instability. Axial (true wall) compression can potentially cause birdcaging or lateral buckling of the tensile armor layer. The behavior of flexible pipe under compressive loading is also dependent on the pipe temperature.

The potential for both types of compression to occur should be checked during the design of the flexible pipe system. In particular, compression is often an issue in the design of risers (e.g. at seabed touchdown), and effort should be made to design the riser in such a way to minimize compression. If compression is predicted to occur in the pipe, the maximum value predicted should be checked against the criteria specified in Table 8 of API 17J (refer to tensile armors buckling and antibuckling tape) and against the criteria specified by the manufacturer for allowable compression in the pipe body and MBR.

#### 5.4.1.10 Service Life Factors

Section 5.7.11 presents a more detailed discussion of service life analysis, including fatigue calculations. The criteria for fatigue calculations are specified in API 17J. Furthermore, permissible levels of degradation should be defined for the service life analysis. Recommendations on these are given in Table 6.

**Table 6—Recommended Allowable Degradation for Unbonded Pipes**

| Component | Degradation Mode | Recommendation |
|---|---|---|
| Carcass | Corrosion | Limited corrosion acceptable provided structural capacity and functional requirements are maintained. |
| | Erosion | Same as for corrosion. |
| Internal pressure sheath | Creep | Limited creep acceptable provided:<br>— structural capacity to bridge gaps maintained,<br>— no cracks,<br>— no locking of carcass or pressure armor layers,<br>— no leakage,<br>— sealing maintained at end fittings. |
| | Thermal/chemical degradation | Capacity at design life to remain within specified usage factors with maximum gaps between layers. No leakage allowed. Increased permeation allowed if system has been designed for the increased level of permeation. Important considerations are increased damage rates (corrosion, hydrogen-induced cracking, sulphide stress cracking) for armors and limits on gas-venting system capacity. Strain capacity sufficient to meet the design requirements of API 17J. |
| | Cracking | No cracking is allowed. |
| Pressure and tensile armors | Corrosion | Only general corrosion accepted. No crack initiation acceptable. |
| | Disorganization or locking of armoring wires | No disorganization of armoring wires when bending to minimum bend radius. |
| | Fatigue and wear | See 5.7.11. |
| Antiwear layer | Wear | No through thickness wear of the layer over its service life. |
| Intermediate (anticollapse) sheath | Thermal degradation | Functional requirements are maintained. |
| Thermal insulation | Thermal degradation | Insulation capacity to be maintained equal to or above minimum specified value. |
| Outer sheath | General degradation | Strain capacity sufficient to meet the design requirements of API 17J. |
| | Radial deformation (loosening) | No loosening that will cause disorganization of armor wires or strain failure of outer sheath material. |
| | Breaching | No breaching allowed unless pipe design under flooded annulus conditions can be shown to meet the design requirements and remaining service life requirements. |
| End fitting and armors/carcass/sheath interface | Corrosion | No corrosion acceptable that results in reduction of capacity, possibility for leakage, or damage to any sealing or locking mechanism.<br>No rupture or pull out of tensile armors is allowed. |

### 5.4.2 Bonded Flexible Pipe

#### 5.4.2.1 Introduction

The design criteria for bonded flexible pipes are shown in API 17K in terms of the following:

a) strain (elastomer layers);

b) stress and load (reinforcement layers, carcass, and end fitting);

c) hydrostatic collapse (buckling load);

d) mechanical collapse (stress induced from reinforcement layers);

e) crushing collapse and ovalization (during installation);

f) service life factors.

These criteria are discussed further in 5.4.2.2 to 5.4.2.8, which give some guidance on their derivation. Criteria are also introduced that provide for design against failure additional to the criteria specified in API 17K.

The criteria specified by API 17K apply to the materials currently used in bonded flexible pipe applications. If new materials are proposed or used, the design criteria for the new materials should give at least the safety level specified in API 17B and API 17K. The design criteria should consider all material characteristics, such as ageing, fatigue, and excessive strain.

Simplified approaches exist for the calculation of pipe characteristics (axial, bending and torsional stiffness, etc.) and for calculating loads in the individual materials of the pipe (reinforcing cables, elastomer body, etc.). These simplified methodologies may be used for preliminary comparison of design loads with design criteria. A verified (with prototype tests) methodology should be used, as defined in API 17K, for final design calculations.

Due to the composite nature of bonded flexible pipes, the verified design methodology should account for interaction between metallic and elastomer components and for load sharing between different layers and components in particular at and adjacent to the end fitting.

Two distinctly different types of design methodology are used by bonded flexible pipe manufacturers. Some manufacturers use analytical or finite element methods to account for the load sharing between the various components making up the bonded pipe. Others use standard analytical methods derived from geometrical considerations of the pipe in conjunction with empirical efficiency factors. The efficiency factors are calculated based on prototype tests, for example, burst and tensile tests.

#### 5.4.2.2 Strain

API 17K specifies allowable strain values for elastomer layers as a maximum of 50 % of design maximum strain for aged material. Due to the typically large strain capacity of elastomer materials used in the manufacture of bonded flexible pipes, this design criterion is not necessarily as critical as it is for the thermoplastic materials used in the manufacture of unbonded flexible pipe.

API 17K provides for the calculation of MBR to prevent damage to the interlocked inner or outer carcass, if present.

#### 5.4.2.3 Stress/Load

The design stress and load criteria (utilization factors) given in API 17K were derived to give acceptable factors of safety against failure. These factors prescribe the maximum nominal applied stress or load as a proportion of the structural capacity of steel materials (defined by API 17K). The utilization factors make implicit allowance for the presence of residual wire stress.

The published utilization factors relate to steel materials. No inference can be made about allowable stress in new materials based on these values.

#### 5.4.2.4 Hydrostatic Collapse

Utilization factors that relate to buckling of the internal carcass under hydrostatic pressure are specified in API 17K as a function of water depth, with a higher permissible utilization factor (smaller safety factor) allowed for deepwater applications. The safety factor (the reciprocal of the utilization factor) is related to the absolute, rather than relative, margin between collapse and design depth.

Analytical methods, if used for calculating collapse resistance, should be based on an assumed initial ovalization. This ovalization should be selected by the manufacturer, based on manufacturing tolerance limits and residual ovalization from the installation process. A minimum ovality of 0.2 % should be used if no other data exists.

The collapse resistance for smooth bore pipes should be calculated based on the resistance of the pipe body, and standard analytical methods may be used. If the collapse-to-design ratio is below the required value and if the pipe is not designed to be collapsible, then it should be specified that sufficient internal pressure be maintained to prevent collapse (such as by ensuring line is full of liquid at hydrostatic pressure).

The hydrostatic buckling load (collapse pressure) of a carcass should be calculated per FPS 2000 [40] and Bibliographic Item [27].

#### 5.4.2.5 Mechanical Collapse

See 5.4.1.6.

#### 5.4.2.6 Crushing Collapse and Ovalization

See 5.4.1.8.

#### 5.4.2.7 Compression

See 5.4.1.9.

#### 5.4.2.8 Service Life Factors

Section 5.7.11 presents a more detailed discussion of service life analysis, including fatigue calculations. The criteria for fatigue calculations are specified in API 17K. Furthermore, permissible levels of degradation (see Table 7) should be defined for the service life analysis.

**Table 7—Recommended Allowable Degradation for Bonded Pipes**

| Component | Degradation | Recommendation |
|---|---|---|
| Carcass | Corrosion | Limited corrosion acceptable provided structural capacity and functional requirements are maintained. |
| | Erosion | Same as for corrosion. |
| Liner | Blistering, delamination | No blistering, delamination or leakage paths because of gas rapid decompression. Damage due to dissection process should be ignored. |
| | Thermal/chemical degradation | No leakage allowed. Increased permeation allowed, if system has been designed for the increased level of permeation. Limited degradation acceptable provided sealing is maintained at end fitting in addition to the above. |
| | Cracking, fatigue | No through thickness cracking and no leakage allowed. |
| Reinforced layers | Corrosion | No corrosion that results in increase in utilization of cables in reinforcing layer to beyond allowable values shown in API 17K, Table 7, is allowed. |
| | Fatigue and wear | See 5.7.11. |
| Cover | General degradation | Strain capacity sufficient to meet the design requirements of API 17K, Table 7. |
| End fitting | Corrosion | No corrosion that results in reduction of capacity, possibilities for leakage, or damage to any sealing or locking mechanism is allowed. |

## 5.5 Load Cases

### 5.5.1 General

The flexible pipe should be designed to satisfy its functional requirements under loading conditions corresponding to the internal environment, external environment, system requirements, and service life defined by the purchaser of the pipe.

All potential load cases for the flexible pipe system in the design premise are specified by API 17J and API 17K. The design premise should specify a load case matrix that defines all operating, nonoperating, survival, and fatigue loading conditions according to requirements specified by the purchaser in API 17J, Annex B and API 17K, Annex A.

All stages of the design process involve either global or local (cross-section) analyses of the flexible pipe. The primary objectives of the global analyses are to verify that the main design criteria are satisfied (such as MBR, allowable tension, and stability of dynamic motions) and to identify critical load combinations. Local analysis is then performed to verify that these critical global load combinations do not exceed the criteria specified in API 17J and API 17K.

### 5.5.2 System Configuration Design

Input to this stage includes all static loads relating to the system design. The pipe is analyzed under all functional, environmental, and accidental loading combinations deriving from the internal environment (pressure, temperature, fluid composition) and the static components of the external environment, defined in API 17J and API 17K. In this context, functional, environmental, and accidental loads are defined by API 17J and API 17K.

Examples of the global static analysis load cases that form an input to this process include upheaval buckling load cases (trenched or buried static flowlines only), on-bottom stability load cases (static flowlines only), and/or static global configuration load cases. Table 8 presents a typical example of the global static analysis load cases relating to this stage of design. Local analyses are generally only required for SAs in this phase of the design. The local analyses for DAs are performed in Stage 4 of Figure 11. Local analysis load cases for SAs should include all relevant test, installation, and operational load cases. For static design, functional, environmental, and accidental loads are defined by API 17J and API 17K.

### 5.5.3 Selection of Load Cases

The design load conditions to be analyzed are specified by API 17J and API 17K as follows:

a) permanent operation (normal and extreme);

b) abnormal events;

c) temporary events;

d) survival events;

e) fatigue;

f) temporary conditions (e.g. testing, installation, abandonment and recovery, handing and storage).

The load case matrix constitutes the full set of loading conditions examined as part of the structural analysis and design process. Specific load cases form inputs to five stages in the overall pipe design, as follows:

a) cross-section configuration design (local analyses),

b) system configuration design (static global and local analyses),

c) dynamic analysis and design (global analyses for dynamic riser design only),

d) detail and service life design (final local and service life analyses),

e) installation design (global and local analyses).

The classification of loading cases for flexible pipe design is presented in Table 6 of API 17J. The table provides a detailed framework of the applicable loading cases for design and also provides an associated combined probability of occurrence, $P_c$. For example, $P_c \leq 10^{-2}$ is applicable for an "abnormal operating" load case. The probability of occurrence is based on a combination of the annual probability of the environmental conditions and any accidental events that are being considered.

The requirement for considering accidental events should be based on an assessment of the probability of the events occurring. The accidental events typically considered for SAs include impact from trawl boards and dropped objects. For DAs, accidental events typically considered include one or more mooring lines broken and partial loss of buoyancy.

Careful consideration is required when choosing the environments for extreme design.

### 5.5.4 Dynamic Analysis Cases and Design

Load cases for this stage relate only to dynamic riser (or jumper) applications and include all dynamic loads for the global system design. The pipe is again analyzed under all functional, environmental, and accidental loading combinations deriving from the internal and external environment. For static design, functional, environmental, and accidental loads are defined by API 17J and API 17K.

All dynamic operational and accidental load cases, typically combining static internal with dynamic external environmental conditions (such as wave, current, and riser top motions) are considered as part of the dynamic analysis. Sufficient load cases should be analyzed to cover the complete envelope of response, in terms of motions and forces. Sensitivity studies should be performed to evaluate the effect of variations in critical parameters, including internal fluid, marine growth, wave periods, vortex-induced vibration (VIV) effects, etc. The load case matrix will depend largely on site specific conditions.

Table 8 presents a typical set of static load cases applicable to static and dynamic applications. Table 9 contains a typical example of a global dynamic analysis load matrix for a set of load cases in accordance with API 17J.

**Table 8—Typical Static Global Analysis Load Cases—Operating Conditions**

| Load Case | Description | Application Static/Dynamic (SA/DA) |
|---|---|---|
| A | Global static analysis at design pressure, operating internal fluid, mean vessel offset, no current | DA |
| B | Global static analysis at design pressure, operating internal fluid, 100-year return inline near current, 100-year near vessel offset | DA |
| C | Global static analysis at design pressure, operating internal fluid, 100-year return far current, 100-year far vessel offset | DA |
| D | Global static analysis at design pressure, operating internal fluid, 100-year return cross-current, 100-year cross vessel offset | DA |
| E | Thermal analysis | SA, DA |
| F | On-bottom stability analysis | SA |
| G | Upheaval buckling analysis | SA |
| H | In-place tie-in configuration analysis | SA |

### 5.5.5 Cross-section Configuration Design

The results of initial local analyses (to determine burst pressure, response to FAT pressure, MBR, collapse depth, damaging tension, thermal properties, apparent weight in seawater, drag to apparent weight ratio, etc.) provide information that can be compared with design requirements (such as water depth and design pressure) and experience to arrive at a preliminary cross-section design. This initial cross-section design can be subsequently modified based on the results from the remaining stages in the design process. In particular, installation loads should be considered at the start of the design process for deepwater applications.

### 5.5.6 Interference Design

A set of load cases should be performed to evaluate potential interference between different system components. Guidance on the issue of interference is given in 5.3.4. Further guidance may be found in DNV RP F203 [36] and API 2RD [4]. The load cases should include normal operation (1-year and 100-year conditions) with relevant accidental loading conditions.

**Table 9—Example of Dynamic Load Cases**

| Load Condition (1) | | Load Type | Design Criteria (2) | MBR Criteria (3) |
|---|---|---|---|---|
| Operating | Permanent (normal) | Functional and environmental | Refer to API 17J and API 17K | Refer to API 17J and API 17K |
| | Permanent (extreme) | Functional, environmental, and accidental | | |
| | Abnormal | Functional, environmental, and accidental | | |
| Nonoperating | Temporary (normal) | Functional and environmental | | |
| | Temporary (extreme) | Functional, environmental, and accidental | | |
| Survival | | Functional, environmental, and accidental | | |

NOTE 1 The definition of permanent, abnormal, and temporary conditions should be based on regulatory or contractual requirements applicable to the pipe design.

NOTE 2 The stress criterion is permissible utilization as a function of structural capacity.

NOTE 3 The MBR criterion is based on a) a factor of safety applied to the locking radius of the pipe and b) maintaining the bend radius of the pipe above the storage radius.

### 5.5.7 Detail and Service Life Design

The final local analysis load cases, for DAs, are checked using loads that have been determined using global dynamic analyses. Local analyses should be performed for all critical locations along the pipe, considering loads calculated in the global analyses for all relevant conditions during the life of the pipe (such as FAT, installation, and normal and abnormal operation). Critical locations of interest typically include loading interfaces such as bend stiffeners, riser base or PLEM, riser top connection, seabed touchdown zone, midline connection interfaces, and buoyancy tank.

Service life calculations to be performed relate to the polymer degradation, to the corrosion of metallic layers and to fatigue analysis. Unless the stresses in the pressure and tensile armors (unbonded) and reinforcing cables (bonded) are below the endurance limit (and if it is proven that this endurance limit really exists for the predicted annulus environment) for all load cases, a fatigue analysis will be required.

For the fatigue analysis, the pipe is analyzed under the fatigue loading combinations specified in the design premise. The combinations are derived from the internal environment and the fatigue (typically seastate) components of the external environment. The selected seastates should represent the wave scatter diagram for the location and should be shown to be conservative. It may be desirable to perform a directional analyses (e.g. eight directions around the compass) to reduce conservatism of the fatigue results.

The fatigue damage is calculated by using Palmgren Miner's rule and design S-N curves defined per ASTM E739 with 97.5 % probability of survival.

For detailed guidance on performing a fatigue analysis of a dynamic riser, refer to Annex G.

### 5.5.8 Installation Design

The flexible pipe is analyzed to check the feasibility of the proposed installation method and determine suitable weather windows for installation. The load cases should account for all relevant functional, environmental, and accidental loads as applicable to the installation method, vessel, season, test pressure, etc. Consideration should be given to upheaval buckling requirements and to the possible need to pressurize prior to burial if flowlines are to be trenched and back-filled. Table 10 shows a typical set of installation load cases.

The load cases for riser systems should cover all phases in the installation process. For example, in the case of a wave configuration, this could include analyses of the initial bare riser section, after buoyancy modules paid out, and during final connection. The installation internal fluid conditions should be in agreement with the purchaser and defined in the design premise. Consideration may be given to flushing the lines with seawater for normal or extreme environment installation conditions, if the material of the innermost layer is suitable.

A critical set of local installation load cases, based on the results of the global analyses, should be selected. Table 11 shows an example set of local load cases. The results of these analyses should be compared with the design criteria specified in API 17J and API 17K for installation conditions.

**Table 10—Example Global Analysis Load Cases for Installation Conditions**

| Load Cases | Description |
|---|---|
| A | Static analysis, field hydrotest pressure |
| B (1) | Static analysis, installation internal fluid conditions, maximum installation current, equivalent vessel offset |
| C (1) | Dynamic analysis, installation internal fluid conditions, maximum installation current and extreme wave, equivalent vessel offset |
| D (1) | Dynamic analysis, hydrotest pressure, maximum current and extreme wave at hydrotest conditions, equivalent vessel offset |
| E | Static analysis, post installation plough operation |
| NOTE 1 | Typically performed for a number of loading directions, such as 0°, 45°, 90°, 135°, and 180°. |

## 5.6 Analysis Techniques

### 5.6.1 Software Validation

Any software tool used for local cross-section analysis of flexible pipe analysis should be:

a) verified against closed form analytical solutions;

b) validated by a range of numerical tests that the generic model/software tool is internally consistent and that it does not contain detectable flaws;

c) calibrated against full-scale tests by means of manipulating the independent variables of the software model to obtain a match between the observed and simulated distributions of the dependent variables;

d) confirmed to predict values within the [−p %, +q %] accuracy range from the observed values of the full-scale tests.

A report summarizing the verification, validation, and confirmation of the version of the software tools intended for use should be available for purchaser's review and approval. This report needs to be updated with consequent major software version releases that add key functionality or modify methodology and numerical schemes.

**Table 11—Example Local Analysis Load Cases for Installation Conditions**

| Load Cases | Description |
|---|---|
| A | Field hydrotest pressure, maximum top tension at hydrotest conditions |
| B | Installation internal fluid conditions, maximum installation top tension, installation MBR |
| C (1) (2) | Maximum top tension, maximum radial compression over chute or at tensioners |
| D (1) (3) | Maximum top tension, minimum radial compression from tensioners |

NOTE 1 Load Cases C and D are used to check two critical load conditions for vertical installation with tensioners.

NOTE 2 Checks for potential collapse of the carcass.

NOTE 3 Checks for slippage of the pipe due to insufficient friction between the outer sheath and the outer tensile armor layer (unbonded pipe only).

### 5.6.2 Local Analysis

Local cross-section analysis is a complex subject, particularly for combined loads, because of the composite layer structure of a flexible pipe. Local analysis is required to relate global loadings to stresses and strains in the pipe. The calculated stresses and strains are compared to the specified design criteria (API 17J and API 17K list relevant criteria) for the load cases identified in the project design premise (see 5.5 for guidelines on selection of load cases).

The simplified formulae given in FPS 2000 [40] may be used for a preliminary check of loads on flexible pipe and are fully acceptable for some failure modes. For detailed design, more refined analysis techniques that account for all relevant effects are required. The required analysis can be performed by a number of software packages. Minimum requirements for the cross-section analysis methodology are provided in API 17J and API 17K.

Load effects in pipe wall sections may be documented by prototype testing. Numerical analysis methods also may be used to predict local stresses. Under numerical analysis, the analysis results may be validated by prototype testing.

Design formulae should be related to the specific type of pipe design and can be validated for those specific designs by strain gauge results from prototype tests. Justification for extrapolation of results should be documented. The actual load situation in the pipe should be considered, especially with regard to combined loading when considering use of analytical methods.

### 5.6.3 Analysis of Pipe Wall Environment

For purposes of this section, the region of either a bonded or unbonded pipe, containing the reinforcing wires, will be called the "pipe wall."

The analysis of the pipe wall environment of a flexible pipe is an important consideration, particularly for the determination of gas release requirements and metallic material failure modes. The following pipe wall environment characteristics should be considered for the design of the flexible pipe:

a) permeated gas and liquids,

b) external fluid ingress (seawater).

The polymers used for the internal pressure sheath allow fluids in the pipe to permeate the pipe wall. This permeation rate (leakage) is negligible with regard to pipe performance (flow capacity). The pipe system design, however, should allow for safe escape of the permeated gas. Gas permeation from the conveyed fluid into the pipe wall should be calculated using a qualified procedure. The permeation rate is a function of internal and external pressures, surface areas, sheath thickness, and permeability coefficient. The permeability coefficient depends on material, level of material degradation, gas component, and temperature.

$H_2S$ gas permeation into the pipe wall environment determines if a particular application is to be considered as sweet or sour service. The pressure in the pipe wall and the concentration of $H_2S$ in the pipe wall should be calculated to make this determination. In addition, $CO_2$ permeation rates are required to determine the annulus pH level.

After a transient period, an equilibrium condition is reached in which the partial pressures in the pipe wall will be lower or at a maximum equal to the partial pressures in the pipe bore, with the actual value dependent on pressure, temperature, polymer materials, etc.

The partial pressure of $H_2S$ in the pipe wall can be assumed, as an initial approximation, to be the same as in the pipe bore. Differences can exist between the fluid composition in the pipe bore and pipe wall because of the different permeation rates of $H_2S$ and other components.

Parameters that influence the actual partial pressure of $H_2S$ in the pipe wall are discussed in Bibliographic Item [39]. The partial pressure should then be used to check against NACE TM0177 [48] requirements. If testing is required, the partial pressure of $H_2S$ used in testing should be greater than or equal to the calculated pipe wall pressure.

The pipe wall of an unbonded flexible pipe intended for static service should be assumed flooded with seawater. The outer sheath for unbonded flexible pipe intended for dynamic service should be qualified as watertight. In addition, the service life, with the pipe wall flooded with seawater, should be calculated and specified in the operation manual. If specified by the purchaser, the dynamic risers design can comply with the requirement of operation for the deaerated seawater flooded annulus condition, for the whole service life, with a mutually agreed corrosion-fatigue safety factor.

### 5.6.4 Global Analysis

Global analysis is performed to evaluate the global load effects on the pipe during all stages of installation, operation, and retrieval, as applicable. The static configuration and extreme response of displacement, curvature, force, and moment from environmental effects should be evaluated in the global analysis.

Global load effects generally should be documented by numerical analysis methods, such as the finite element method. The analysis should account for three-dimensional dynamic response, stochastic response (irregular sea), and nonlinear effects. The computer model and results should be fully documented.

Static and quasistatic analysis methods may be used for preliminary configuration design. However, all time-varying loads (such as waves) should be modelled with dynamic analyses in the detailed design stage of a project to accurately account for inertia effects.

Critical phases during installation and operation may be analyzed by a stepwise time integration procedure. Very large changes in the riser configuration require a nonlinear solution procedure. Nonlinear time domain simulations are required for dynamically sensitive structures. The wave conditions to be considered can be described by deterministic or stochastic methods. Structural damping may be taken into account with a proportional type damping used without the inertia component.

Pipe characteristics and operational data should be considered in the analysis. For some applications the bending stiffness characteristics of the pipe will be critical, such as light lines that are subject to severe dynamic motions or the seabed touchdown region in the lower catenary section of a lazy-S configuration. The bending stiffness in such cases will need to be assessed accurately to determine if buckling is occurring or if MBR design criteria are being violated. Parameters relevant to the pipe bending stiffness include number, thickness (including tolerances) and material in polymer layers, mean temperature in the layers (pipe will be stiffer at lower temperatures), nonlinear material characteristics, and internal pressure and friction among adjacent layers.

Interaction is required for riser configurations with a part of the riser resting on the seafloor. A complete nonlinear formulation should be used if the local behavior close to the seafloor is of particular interest.

It is preferable in most scenarios to maintain positive effective tension in flexible pipe to minimize buckling or instability issues. This can be an issue particularly with dynamic risers. Refer to 5.4.1.9 for design guidance regarding compression in flexible pipe.

## 5.7 Calculation of Riser Loads

### 5.7.1 Regular vs Irregular Wave Approach

This section presents recommendations on the application regular and irregular wave approaches to extreme analysis. For guidance on application of regular wave methods to fatigue analysis, see Annex G. The wave modelling approaches used to predict the extreme dynamic loads on a flexible riser system can be categorized into either the regular wave or irregular wave analysis approaches.

The regular wave approach is a deterministic description of the wave environment using a single maximum wave height and wave period. These parameters are usually derived from the wave statistics of the associated environment. The advantage of this approach is that interpretation of results is straightforward, giving periodic output with no further requirement for statistical postprocessing.

The limitation of the regular wave approach is that the results can be difficult to interpret for systems whose response is strongly dependent on frequency. It is often impossible to determine whether the result is conservative or unconservative, particularly in the case of flexibles where estimation of the natural periods can contain significant uncertainties. In some situations an irregular wave approach may be required.

It is therefore common practice to perform a frequency screening of the system to identify critical response periods for the riser system. However, this approach may give overconservative results, depending on the type of system and the associated responses. In this case, an irregular sea verification analysis should be performed to confirm the level of conservatism.

The irregular sea approach is based on a stochastic description of the wave environment. The seastate is modelled as a wave spectrum with energy distributed over a range of frequencies. The most common spectra used are the Pierson-Moskowitz (fully developed sea) and the JONSWAP (developing sea) spectra. However, statistical postprocessing is often necessary to identify the peak responses.

The extreme response for the irregular wave should be found by either:

a) using a recognized, most-probable maximum extrapolation technique (e.g. Rayleigh or Weibull),

b) performing multiple realizations of the seastate to generate a conservative peak response

In the case of Item a) above, normally a 3-h irregular wave duration should be considered. Otherwise, it should be demonstrated that the duration of the simulation is sufficiently long to generate steady state response statistics, so that reliable extreme values may be extrapolated. For example, in some cases a one-hour realization may be sufficient to generate steady state statistics. It is recommended that caution is applied when interpreting the results in these cases.

In the case of Item b) above, normally a 3-h duration should be considered. However, if the characteristics of the system are well known, it may be possible to analyze shorter portions of the seastate to capture peak responses. The duration of the analysis should be carefully selected in order to ensure peak responses are captured.

### 5.7.2 Modal Analysis

A modal analysis may be performed to determine the mode shapes and natural frequencies of the riser system to obtain information needed for either a global VIV analysis or for selecting appropriate wave periods for global analysis. In detail, it may be used for the following:

a) calculation of the natural frequencies of the riser system for analysis of global VIV response due to current. The number of modes should be sufficient to determine riser response for the full range of VIV frequencies;

b) as a basis for selecting the wave periods for strength/interference/fatigue/installation analyses when considered with the motion/velocity/acceleration RAOs at the riser hangoff.

An important consideration in modal analyses is the modelling of nonlinearities, such as the effect of the seabed for “lazy” riser configurations.

### 5.7.3 Modelling Considerations

#### 5.7.3.1 Model Discretization

Typically, finite element or finite difference techniques are employed to model the riser system. Element lengths should be selected carefully to avoid numerical errors resulting from too coarse a mesh while producing a model that can be analyzed with a reasonable amount of computational effort.

It is recommended that short elements be used in regions that undergo significant bending (e.g. seabed touchdown and hangoff regions) as applicable.

#### 5.7.3.2 Irregular Wave Modeling

Irregular waves are simulated by superposition of a number of sinusoidal components, each having a constant amplitude, unique frequency, and a random phase.

Selection of the number of wave components and their frequencies should be based on capturing: about 99 % of the input seastate spectrum energy, both swell and wind-sea peaks of bimodal spectra, and resonant responses of the riser system in the wave-frequency range defined in the metocean criteria and in the vessel-RAO-motion range. Equal energy, equal frequency spacing, geometric progression, and other spectrum discretization methods can be used to achieve these objectives.

The realized spectrum (from the wave elevation time history) should be compared to the input spectrum. The accuracy of the realized spectrum should be demonstrated by sensitivity runs that show convergence of up to the fourth spectral moments with the number of wave components.

The recommended simulation time for extreme analyses is the full duration of the extreme storm event, while for fatigue analyses it should be determined from sensitivity analyses that show fatigue-damage convergence with time. The simulation time should be increased with a time period at the end of which the transient riser response has decayed to a negligible value, which in turn can be determined from regular wave runs until convergence or riser response (e.g. tension and curvature). The transient riser response shall be excluded from postprocessing.

### 5.7.4 Effective Tension

Effective tension is a key output of a riser analysis. The effective tension, not the true wall tension, is usually of interest for riser design. The effective tension ($T_e$) is expressed as follows:

$$T_e = T_a + P_o A_o - P_i A_i \tag{1}$$

where

$T_a$ is the axial (true wall) force or tension;

$P_i$ is the internal pressure;

$P_o$ is the external pressure;

$A_i$ is the internal cross-sectional area of pipe;

$A_o$ is the external cross-sectional area of pipe.

It is convenient to treat effective tension as a physical quantity; however, it is not a physical tensile or compressive force. It is the resultant of the forces acting on the pipe in the axial direction.

A detailed discussion in relation to effective tension in flexible pipe is given by Sparks [57].

### 5.7.5 Hydrodynamic Loads

When calculating hydrodynamic loads, it is first necessary to define the wave-induced water particle velocities and accelerations, (the wave kinematics). Common practice in deepwater riser analysis is to model the wave using linear Airy wave theory. In some cases, particularly in shallow water, Stoke's fifth-order wave theory may be used. See API 2A or Bibliographic Item [3] for guidance on the appropriate wave theory to use.

Linear wave theory calculates only the kinematics for infinitesimal wave heights. Stretching techniques may be used to extend the theory to finite wave heights.

Significant amplification of the wave kinematics can occur adjacent to large structures (such as the columns of a semisub) and where relevant this may need to be considered in the riser design. One method for modelling this amplification is to use increased hydrodynamic coefficients at the relevant location.

### 5.7.6 Morison's Equation

The general practice for modelling of hydrodynamic forces on flexible pipes is to use the Morison formulation [51]. The formula was originally derived on a semiempirical basis for calculating the hydrodynamic forces on vertical, shallow water, fixed piles with only wave loading. It has since been extended to apply to arbitrary orientation moving structures (such as risers) with both wave and current loading.

See Bibliographic Item [25] for general information relating to application and limitations of Morison's theory.

### 5.7.7 Drag and Inertia Coefficients

The drag ($C_D$) and inertia ($C_m$) coefficients incorporated into Morison's formulation are empirical coefficients that have been derived from a large body of reported experiments. These experiments have shown good agreement between measured forces and forces calculated from Morison's equation.

As a function of Reynold's number, Keulegan-Carpenter's number, structure geometry and surface roughness the drag and inertia coefficients can be determined exactly from published test data for regular waves. For irregular waves, these coefficients can only be determined experimentally. Using a bounding approach is recommended for irregular waves, where these coefficients are selected equal to the upper and lower bounds determined with regular wave tests, the impact of the bounds determined on the riser response, and the most conservative with respect to riser response values of the drag and inertia coefficients are consequently used in riser analysis. It is common practice to use varying coefficients along a riser in order to model aspects such as buoyancy modules or marine growth. The selection of hydrodynamic coefficients tends to introduce a source of uncertainty in the accuracy of global analysis results. FPS 2000 [40], DNV-OS-C101 [29], and Rodenbusch and Kalstrom [56] provide recommendations on the selection of drag and inertia coefficients for flowlines and risers. In flexible pipe analyses, $C_{\mathrm{m}}$ is usually taken to be 2.0, while $C_{\mathrm{D}}$ varies between 0.7 and 1.2. In most cases, it is normal practice to take 1.2 for extreme analysis and 0.7 for fatigue analysis. However, other coefficients may be used if a justification is available (e.g. Re number dependency). It is recommended that sensitivity studies always be performed to investigate the effect of the selected coefficients. Guidance on selection of drag coefficients is also given in DNV-RP-C205 [33].

The riser system dynamic response can be sensitive to the selection of hydrodynamic coefficients for large system components (such as buoyancy tanks) and should be carefully evaluated. For a riser with buoyancy modules, the buoyancy region will be subject to significant tangential hydrodynamic loads. Some recommendations on the selection of tangential hydrodynamic coefficients for buoyancy module riser sections are given in Bibliographic Item [41].

Consideration should also be given to the potential effect of external VIV and marine growth on hydrodynamic loading coefficients. Note that marine growth can also affect the hydrodynamic loading on the pipe in the tangential direction.

### 5.7.8 Gravity and Buoyancy Loads

The analysis should include the gravity and buoyancy loads from all components of the system, including flexible pipe, buoys, and clump weights.

Gravity and buoyancy loads resulting from marine growth and ice accumulations should also be modelled if applicable.

### 5.7.9 Internal Fluid Loading

The mass of the internal fluid should be included in all analyses, and variation in the density should be considered where applicable. Changes in the internal fluid density over the design life can significantly affect some riser configurations, particularly the wave configurations. It also could be necessary, for some applications, to consider the effect of slugs (liquid and gas) on the system. The loads induced by slugs, which should be accounted for in the analysis, are gravity, inertia, centrifugal forces, and Coriolis loads.

### 5.7.10 Seabed and Soil Interaction Loads

The effects of the seabed, including frictional loads, should be included where relevant. In particular, these will be required for flowline stability analyses and motion analysis for riser sections lying on the seabed. FPS 2000 [40] lists representative soil stiffness and friction coefficients for flexible pipes in contact with the seabed. The soil stiffness and friction coefficients are reproduced in Table 12.

The axial and lateral resistance to movement of the pipe at the soil interface is usually modelled by either a constant friction model or a hysteresis model. The friction force in a hysteresis model is gradually built up as the pipe slides on the seabed, up to the maximum value depending upon the normal force and the friction coefficient; if the movement is reversed, the buildup starts in the opposite direction. However, the hysteresis model is difficult to apply in practice because the history of loading is required. For this reason, a constant friction may be used if a proper hysteresis model is not available. In this case, it is recommended that the accuracy of the results be evaluated using sensitivity studies.

**Table 12—Typical Soil Stiffness and Friction Coefficients for Flexible Pipes**

| Seabed Type | Direction | Stiffness kN/m$^2$ | Friction Coefficient |
|---|---|---|---|
| Clay | Axial | 50 to 100 | 0.2 |
| | Lateral | 20 to 40 (1) | 0.2 to 0.4 (3) |
| | Vertical | 100 to 5,000 (1) | — |
| Sand | Axial | 100 to 200 | 0.6 |
| | Lateral | 50 to 100 | 0.8 |
| | Vertical | 200 to 10,000 (2) | — |

NOTE 1 Value increases with increasing undrained soil shear strength.
NOTE 2 Value increases with increasing soil density.
NOTE 3 Value increases with decreasing soil shear strength.

### 5.7.11 Service Life Analysis

#### 5.7.11.1 General

The pipe design service life should be specified and documented. Design service life may be based on specific project or application duration or may be related to a replacement program. Consideration is to be given in the design of flexible pipe to service life or replacement of components/ancillary equipment as part of an overall service life policy.

Specification of pipe service life may also be related to an in-service inspection program. The inspection method and inspection interval should be documented and justified with respect to suitability for the specific application (see Section 11).

Evaluation of service life should address the following, as a minimum:

a) metallic material corrosion and other failure modes (SSC, HIC, erosion, hydrogen embrittlement),

b) wear of metallic material,

c) fatigue of metallic material,

d) polymer/elastomer material degradation,

e) wear/abrasion of polymers/elastomers,

f) end-fitting and pipe/end-fitting interface structural and seal integrity over the service life.

The wear and fatigue failure modes are generally only applicable to DAs. The metallic materials can be selected so as not to corrode or alternatively the corrosion rate is calculated based on the predicted annulus environment and accounted for in the pipe design. Corrosion fatigue tests could be necessary for the armor wires. Other potential failure modes, including SSC, HIC, erosion, and hydrogen embrittlement, should be accounted for by material selection, with reference to the requirements of API 17J and API 17K.

Wear and fatigue in the metallic layers is discussed in 5.7.11.2. Polymer/elastomer layer degradation and wear/abrasion of polymers/elastomer is accounted for by material selection and layer design for the specified application and by ageing analysis/testing. The end fitting should be designed to conform with the requirements of API 17J and API 17K, with particular emphasis being placed on material selection, tensile armor anchoring, pressure armor structural capacity at the transition to the end-fitting body, seal integrity, and fatigue analysis considering stress concentrations.

Fatigue damage should be calculated at all critical locations along the riser arc length. Proper consideration should be given to the determination of riser damping. The critical locations are defined at the structural, boundary, and geometrical discontinuities of the riser configuration in the bend stiffener, touchdown, sag bend, and hog bend areas. At each critical location, the following sources of fatigue damage should be evaluated:

a) wave frequency induced motions for all wave systems defined in the metocean criteria,

b) slow drift (second-order) vessel motions,

c) VIV frequencies of riser under steady current conditions,

d) VIV motions of the riser tower that supports the flexible riser in a hybrid riser system and/or the vessel hull if applicable,

e) oscillations during installation and handling,

f) slugging.

#### 5.7.11.2 Fatigue and Wear Analysis

Fatigue and wear of structural and sheath layers are critical aspects that should be evaluated in conducting the service life analysis, particularly for riser applications. Fatigue calculations for flexible risers involve substantial uncertainties because of simplifications in the long-term load data and mathematical models and complexities in the wear and fatigue processes. An in-service condition and integrity monitoring program should be implemented (see Section 11) if appropriate.

Potential failure mechanisms for the tensile armor wires include the following:

a) wear between layers and wires of individual cables,

b) fatigue of armor wires in dry annulus conditions and in corrosive annulus environment,

c) fretting fatigue of individual wires—unbonded pipe,

d) wear or fretting between wires within cables,

e) corrosion of armor wires.

In bending of an unbonded flexible pipe, the armor layers will slide over each other, with a resulting potential for wear. The wear rate is a function of the contact pressure, wear coefficients, and degree of slippage (bending related). Models have been developed using experimentally derived data to simulate this failure mode. However, this problem has generally been overcome in current designs by the use of polymeric antiwear layers between the armor layers. The service life analysis should confirm the functional performance of the antiwear layer for the specified design life, particularly for high temperature applications. Similar sliding occurs between the individual wires in reinforcing cables.

The annulus conditions of the pipe should be taken into account when performing fatigue calculations. Section 5.3.4.1 of API 17J states that for a seawater flooded annulus the effect of permanent contact with water (or appropriate salinity) and corrosive gases ($H_2S$, $CO_2$, etc.) should be accounted for. This is applicable for static and dynamic pipe applications.

For dynamic pipe applications, Section 5.3.4.2 c) of API 17J states that the calculation of service life shall consider an annulus environment representative of the permanent operating conditions. The definition of the "permanent operating" conditions (i.e. whether or not it is to be deaerated seawater flooded) is to be agreed upon by the purchaser and supplier of the pipe, in accordance with the requirements of Section 5.1.4 of API 17J; Section 5.1.4 also requires that intact annulus conditions be considered in the design load case matrix. The aerated seawater flooded annulus condition should be checked by the manufacturer—upon the operator request—for the remaining service life even if it is not the permanent operating condition (abnormal operating event).

Fresh seawater (aerated) that is being flushed through the annulus will cause higher corrosion rates then seawater contained inside a sealed annulus. Thus, if integrity of the outer sheath is compromised and aerated fresh seawater is being introduced to the annulus, efforts should be made to evaluate the degree of corrosion in the outer tensile armor and potential impact on remaining service life and to seal the leak as soon as possible.

Sections 5.3.1 and 5.3.3 of API 17J state that the predicted fatigue life should be 10 times the service life [i.e. a factor of safety (FOS) of 10 should be used]. However, API 17J also states that a lower safety factor may be used for the deaerated seawater flooded annulus condition based on expected operating conditions.

The fatigue analysis should show that the extreme stresses in the tensile armors of unbonded and reinforcement layers of bonded pipe are below the material endurance limit (e.g. Goodman line), otherwise fatigue damage calculations should be performed. Before an endurance limit can be used, API 17J requires that it be a documented and verifiable quantity that has been established by testing and approved by purchaser. The Haigh diagram should be based on relevant test data and should account for material properties, wire sizes and shapes, and service environment.

Fatigue damage calculations may be based on a limited number of seastate classes, provided selection of such classes is based on conservative criteria. See Annex G for guidelines on selection of load cases for fatigue analysis. Cases with significant dynamic tension in combination with possible metal to metal contact need particular attention.

Fatigue life may be calculated based on the S-N fatigue approach under the assumption of linear cumulative damage. The S-N data should be derived based on the requirements of API 17J and API 17K. Calculations should be performed for all critical locations in the riser, such as at connection points and in the sag bend region based on combinations of mean and alternating stresses.

Conditions leading to fretting fatigue can cause a large reduction in fatigue strength of individual armor wires or cables, particularly in the low stress/long life region. The Goodman line under fretting conditions would be considerably lowered in the Haigh diagram for armor wires. The potential for fretting fatigue should therefore be the subject of close scrutiny.

Fretting fatigue cracks are nucleated at the stick/slip interface, primarily by the oscillating tangential (friction) force transmitted in the stick region. Important parameters include surface reactions (oxidation and other environmental interactions), water ingress (a result of damage to the outer sheath), and lubrication. The crack driving force of the tangential stresses has decayed when cracks reach a length of about 1 mm (0.04 in.). The cracks can become arrested at that point in the absence of normal stresses in the wire. The cracks may continue to grow with oscillating normal stresses, and the net result is a significant reduction in fatigue life, particularly in the low stress/long life region. This emphasizes the requirement for dynamic axial stresses in prototype fatigue tests.

Interlocked pressure armor can also fail from fatigue, fretting fatigue, or wear, and therefore this potential failure mode should also be addressed in the service life analysis. A single fracture of the pressure armor wire can be critical for the whole pipe. Theoretical models can be used to predict the service life of the interlocking profile. These models should be validated by experimental test results. The primary loading parameters to be considered for the pressure armor are as follows:

a) static stress and contact pressure from internal pressure and axial tension;

b) dynamic stresses, sliding, and friction forces as a result of bending;

c) combined effect of fatigue and corrosion.

A critical parameter in pressure armor fatigue calculations is the residual stress in the wires after preforming, though this will depend on the design used for the pressure armor. The residual stress should be assessed, for example, by local finite element analysis, after accounting for residual stress redistribution across the wire cross section due to FAT.

Interlocked carcass can also fail from fatigue, and therefore this potential failure mode should also be addressed in the service life analysis. Theoretical models should be used to predict the service life of the interlocking profile. These models should be validated by experimental test results, considering the relevant manufacturing tolerances of the layer pitch and carcass profile geometry. The primary loading parameters to be considered for the carcass are as follows:

a) contact pressure from axial tension;

b) dynamic stresses, sliding, and friction forces as a result of bending;

c) combined effect of fatigue and corrosion.

Fatigue analysis of end fittings and connectors, in addition to the armor layers, should be performed where relevant. The analysis should be based on validated design methodologies and account for all relevant fatigue loads (the load cases from the fatigue analysis of the armor layers may be used). Fatigue analysis of the tensile wires inside the end fitting (i.e. in the anchoring system) should be also carried out for riser top end fittings (or riser intermediate end fittings, where relevant). This analysis should be conducted with design tools validated in full-scale prototype tests. Fatigue analysis of the armor wires in the end fitting shall be performed for intact annulus and annulus flooded with deaerated seawater environments.

### 5.7.12 Component Analysis

All ancillary components of the flexible pipe system should be included in the global analysis at the detailed design stage. This includes buoyancy modules, subsea arch/buoy systems, tethers, and bend limiters. In addition, local analysis of the individual components could be necessary.

Ancillary components are to be designed with regard to the same design parameters as the flexible pipe system, including load cases (global loads and service conditions) and service life. Components should be designed and manufactured in accordance with recognized codes and standards.

Component interference, which refers to the clashing of system components, should also be included in component analysis. Interaction between pipes in a bundle and possible impact between system components, such as between buoys or chains and risers, should be addressed in the design. See 5.5.6 for guidelines on interference issues.

Possible "weathervaning" of the subsea buoy/arch system is a critical aspect for certain flexible riser configurations. Generally, care should be taken to ensure that unsymmetrical hydrodynamic loads do not cause the buoy/arch system to weathervane and twist the riser beyond acceptable levels. The riser configuration and buoy/arch system should be designed to avoid this problem.

### 5.7.13 Temperature and Pressure Loads

Temperature and pressure induced elongation are generally only a concern in trenched flowlines where there is a possibility of upheaval buckling. In addition, short unbonded jumper flowlines may experience significant compression loads from temperature and pressure effects, in which case the pipe may need to be reinforced with additional antibuckling and/or polymer layers to prevent birdcaging.

### 5.7.14 External Vortex-induced Loads

The sensitivity of flexible risers to vortex shedding under current loading has been the subject of a number of experimental investigations, which have shown that though VIV occurred in the modelled risers, the vibration amplitudes were insufficient to cause fatigue damage. This can be attributed to the following:

a) relatively low vibration amplitudes, probably a result of the inherent structural damping;

b) the complexity of flow incident to typical flexible riser systems and difficulty in obtaining coherence of vortices in a heaving inclined riser;

c) hydrodynamic damping.

Many of the contributory factors to VIV are difficult to model accurately in small-scale tests. In full scale, especially with deepwater risers, the effects of VIV may become more significant due to the following:

a) increased tension-reducing influence of structural damping,

b) increase in hydrodynamic drag coefficients from VIV,

c) strong currents present in some deepwater regions.

As a result of the above, the effects of VIV on both the loads on the structural layers and ancillary components and on riser global behavior, particularly with respect to the potential for interference, should be reviewed on a case-by-case basis. Current practice to account for vortex-induced loading for interference checks is to conduct analysis with amplification factors applied to the hydrodynamic drag coefficients.

Due to the highly complex nature of VIV, the industry standard VIV analysis tools tend to rely on simplified or semiempirical methods of calculating fatigue damage due to VIV.

If VIV analysis of a flexible riser is to be carried out the geometry of the riser configuration should be accounted for. Some of the industry standard VIV software packages are limited to modelling risers as vertical top-tensioned structures and as such can only account for the component of velocity normal to the riser axis. In these cases, the components of current velocity normal to the riser catenary or hog bend(s) should be applied in the VIV software.

### 5.7.15 Internal Vortex-induced Loads

Vortex-induced vibrations inside the pipe (also known as flow-induced pulsations) due to flow of conveyed gases at high velocities should be evaluated against possible consequences to the connected floating unit piping (e.g. pipe rupture and gas leakage).

# 6 Materials

## 6.1 Scope

Section 6 provides support for the material requirements specified in API 17J and API 17K and gives general guidance on material selection for flexible pipe applications. Commonly used flexible pipe materials are identified and their performance characteristics are given. Recommendations are given for fluid compatibility and ageing resistance testing of polymer/elastomer and metallic materials. For composite armor materials, refer to Annex H.

## 6.2 Materials—Unbonded Pipe

### 6.2.1 General

Section 6.2 identifies the commonly used materials in the unbonded flexible pipe industry and presents in general terms the performance characteristics of these materials, such as allowable temperature ranges and fluid compatibility.

Flexible pipe materials have to be properly selected and comprehensively qualified, because the suitability of a particular material is based on several factors including transported fluid components, temperature, pressure, and parameter variations over the service life (see API 17J, Annex B for a detailed listing of relevant parameters). The purchaser should therefore specify to the manufacturer the design and operating values of all relevant parameters, including variations over the service life, with reference to the requirements of API 17J.

The materials and their properties should be reviewed against potential failure modes so as to identify the critical requirements of the materials in each layer of the pipe. A detailed list of potential failure modes is given in Section 11.

### 6.2.2 Polymer Materials

#### 6.2.2.1 General

Table 13 lists the polymer materials typically used in unbonded flexible pipes. Typical thermoplastics used in pressure sheaths are high density polyethylene (HDPE), crosslinked polyethylene (XLPE), polyamide (PA), and PVDF. Other polymers such as thermoplastic elastomer (TPE) have also been used. While individual grades of particular materials will have similarities, each grade should be qualified separately and completely.

API 17J requires that each material have its relevant properties documented. In addition, major aspects of the performance of the material within a pipe structure should be verified. The detailed property requirements for polymer materials are outlined in Table 12 of API 17J. Data should be available to verify that the required performance is maintained over the design life of the flexible pipe.

Because no small-scale test of material sample can simulate the strain/stress conditions of the internal pressure sheath in the pipe (including the interface with adjacent layers/termination), full-scale pipe fatigue tests should be carried out in representative scenarios of bending, internal pressure, and temperature, in order to qualify the polymer. The layer configuration (monolayer or multilayer) and thickness should represent the actual range of the risers for field application.

In addition, the first use of a new material should also trigger a requirement for relevant prototype tests, based on the requirements of Section 7 and as agreed between manufacturer and purchaser. The performance of the internal pressure sheath interface with the end-fitting sealing system should be documented against thermal cycles as per Annex A or Annex C of this document.

**Table 13—Typical Polymer Materials for Unbonded Flexible Pipe Applications**

| Layer | Material Type |
|---|---|
| Internal pressure sheath | High density polyethylene (HDPE), crosslinked polyethylene (XLPE), polyamide (PA), polyvinylidene fluoride (PVDF) |
| Intermediate (anticollapse) sheaths | HDPE, XLPE, PA, PVDF, TPE |
| Antiwear Layers | PA, PVDF, HDPE |
| Outer sheath | HDPE, PA, TPE |
| Insulation | Polypropylene, polyvinyl chloride, polyurethane |
| NOTE 1 The insulation may be solid material, foam, or syntactic foam.<br>NOTE 2 Medium density polyethylene may be used instead of HDPE.<br>NOTE 3 Designation systems for PA-11, PA-12, and PVDF are shown in DIN 73378, ISO 1874-1, ISO 12086-1, and ISO 10931-1. | |

#### 6.2.2.2 General Capabilities and Uses of Sheath Polymers

##### 6.2.2.2.1 General

Each of the polymers has limitations in terms of operating temperature range, fluid compatibility, and blistering characteristics.

Use of qualified polymers at temperatures outside the recommended operating ranges is possible in some circumstances, particularly for short periods of time, subject to a comprehensive engineering review of potential failure modes and validation of performance by a combination of analysis and test, where required.

Assessment of polymer service life requires manufacturers to develop validated ageing models for each grade of material as required by Section 5.3.4.5 in API 17J. For some polymers, it may be necessary to carry out testing on the basis of chemical compatibility.

Values given for the materials are for information only and should not be taken as proof that the materials are qualified to these conditions. The materials should be qualified in accordance with the requirements and procedures in Section 6 of API 17J.

##### 6.2.2.2.2 Polyethylene (PE)

HDPE [or medium density polyethylene (MDPE)] is predominately used for internal pressure sheathes in water handling duty, typically in the temperature range −50 °C to +65 °C, and for outer sheathes on static pipes. XLPE is a form of PE manufactured using one of several proprietary cross-linking methods to produce polymers with improved temperature capability up to 90 °C at moderate pressures—typically 90 °C/1500 psi and 70 °C/3000 psi for gas, oil, and water.

##### 6.2.2.2.3 PA

PA nylons are predominately used for internal pressure sheathes in hydrocarbon duty, typically in the temperature range −20 °C to +80 °C, and for outer sheathes on dynamic pipes, as a result of better abrasion and fatigue resistance than HDPE. It is typically used in a plasticized form. While historical use of polyamides has predominately involved PA-11 materials, at least one PA-12 grade is now fully qualified and in use. It should be noted that for conveyed fluids that are water saturated the pipe service life can be drastically reduced for operating temperatures much below +80 °C if pH is less than 7; see API 17TR2 [14] for further guidance.

#### 6.2.2.2.4 PVDF

PVDF is predominately used for internal pressure sheathes in hydrocarbon duty, typically in the temperature range −20 °C to +130 °C. PVDF typically needs to have its flexibility and elasticity optimized for pressure sheath applications by the addition of plasticizer, the addition of a PVDF copolymer, the use of copolymer, or a combination of any of these. The specific issues related to loss of plasticizer leading to lower flexibility and to dimensional changes need to be taken into account in the pipe and end-fitting design, in particular with regard to thermal cycling between operating and shut-in conditions and the interface of the internal pressure sheath and the end-fitting sealing system.

#### 6.2.2.3 Fluid Compatibility

One important aspect of pressure sheath performance is chemical compatibility with the bore fluids. Compatibility with produced and injected fluids as well as production chemicals should be assessed. Table 14 lists typical fluid compatibility characteristics for the main flexible pipe polymer materials. Note that fluid compatibility is highly dependent on temperature and exposure time and concentration. Applied stress may also be important in determining material performance.

In accordance with the requirements of API 17J, the compatibility of any particular combination of polymer and production chemical should be verified by testing. Typically, this will involve testing under higher concentrations and at higher temperature than would be experienced in service, with retention of relevant mechanical properties used to judge acceptability.

#### 6.2.2.4 Gas Exposure

Gas in the transported fluid is an important consideration in material selection for the polymer layers. The main issues relate to the blistering resistance of the internal pressure sheath and to the permeation characteristics of the inner and outer sheathes, which determine the pipe wall condition (see 5.6.3).

Table 14 lists typical blistering resistance characteristics for the internal pressure sheath polymer materials. It should be noted that the performance of certain materials in blistering tests, particularly certain PVDF grades, has been shown to be dependent on the degree of mechanical constraint that is applied (i.e. material samples perform differently to the same material constrained as a pressure sheath within a rough bore pipe structure). This may be taken into account when qualifying materials for gas service, through decompression testing of partial or complete pipe structures.

Gas permeation rates depend on many factors (see 5.6.3). The main issues to be considered in relation to gas permeation are the effect of the transported fluid components to be evaluated (the main components being $CH_4$, $CO_2$, $H_2S$, and water vapor), their effect on the steel layers in the annulus (see 6.6), and the design of the gas-venting system.

### 6.2.3 Metallic Materials

#### 6.2.3.1 General

Property requirements for metallic materials are listed in API 17J. These properties should be compared with the requirements of each application, with reference to the critical failure modes identified in 11.3.

#### 6.2.3.2 Carcass

Materials typically used for the carcass layer are as follows:

a) carbon steel;

b) ferritic stainless steel (AISI 409 and AISI 430);

c) austenitic stainless steel (AISI 304, AISI 304L, AISI 316 and AISI 316L);

d) high-alloyed stainless steel (Duplex UNS S31803);

e) nickel-based alloys (such as N08825).

**Table 14—Typical Fluid Compatibility and Blistering Characteristics for Flexible Thermoplastic Pipe Polymer Materials**

| Polymer Material | General Compatibility Characteristics (1) | Blistering Characteristics (2) (3) |
|---|---|---|
| High density polyethylene (HDPE) | Good ageing behavior and resistance to water-based fluids.<br>Some grades are susceptible to environmental stress cracking in alcohols, liquid hydrocarbons, and surfactants so resistance should be verified. | Good blistering resistance at low temperatures and pressures only. |
| Crosslinked polyethylene | Good ageing behavior and resistance to water-based fluids, weak acids, and produced fluids with high water cuts.<br>Less susceptible to environmental stress cracking than HDPE (environments include alcohols and liquid hydrocarbons). | Better blistering resistance than HDPE, but traditionally limited to relatively low temperature and pressure [e.g. 20.68 MPa (3000 psi) and 60 °C].<br>Recent developments have produced grades of crosslinked polyethylene that can withstand temperatures/pressures of up to 90 °C/1500 psi and 70 °C/3,000 psi for gas, oil, and water |
| Polyamide | Good ageing behavior and resistance to hydrocarbons.<br>Good resistance to environmental stress cracking.<br>Limited resistance to acids, including heavy bromide brines, at high temperatures, methanol, high TAN crudes and traces of oxygen—see 6.5.3 for further details. Limited resistance to bromides.<br>Weak resistance to high temperatures when any liquid water is present. See API 17TR2. [14] | Good blistering resistance up to 68.95 MPa (10,000 psi) and 100 °C (212 °F). |
| Polyvinylidene fluoride | High resistance to ageing and environmental stress cracking.<br>Compatible with most produced or injected well fluids at high temperatures including alcohols, acids, chloride solvents, aliphatic and aromatic hydrocarbons, and crude oil.<br>Weak resistance to strong amines, concentrated sulphuric and nitric acids and alkaline fluids (recommend pH < 8.5). | Good blistering resistance up to 68.95 MPa (10,000 psi) and 130 °C (266 °F). |

NOTE 1 The suitability of a material for a particular application should be verified by the manufacturer and the independent verification agent.

NOTE 2 Blistering characteristics are a function of transported fluid, pressure, depressurization rate, temperature, and material grade. Generally, lower pressure values allow higher temperature values and vice versa.

NOTE 3 Quoted values (temperatures, pressures, etc.) are provided for informational use only. All polymer properties should be confirmed by testing in accordance with the requirements and procedures given in Section 6 in API 17J.

Material selection for the carcass is based on the internal fluid components and expected use of the flexible pipe. Important parameters to be considered are identified in API 17J.

As the severity of the internal fluid environment increases, the material selected for the carcass will move from Items a) to e), that is, carbon steel will be used for noncorrosive environments while high-alloyed stainless steels will be used for corrosive applications. The most commonly used materials are 304L and 316L austenitic stainless steel. A high molybdenum content (2.7 % to 3.0 %) can be specified for AISI 316L material to improve its corrosion resistance characteristics.

The main parameters to be considered in the material selection for the carcass are fluid temperature, $CO_2$, $H_2S$, chloride, and oxygen content. Other parameters that should be considered include pH, water, free sulphur, and mercury content of internal fluid. The carcass material in sour service environments should be resistant to HIC and SSC with reference to NACE MR0175 as applicable. Testing against SCC for fluids with high-chloride content should also be carried out.

#### 6.2.3.3 Pressure and Tensile Armor Layers

Typically, the material used for the pressure and tensile armor layers is carbon steel, with carbon content dependent on the design requirements. High carbon content steel is used where the design requires very high strength and where the environment permits. Low or medium carbon content steels are used for sour service environments. Not all wires, however, meet NACE MR0175 sour service requirements. For sour service environments, the steels may also be heat treated (quenched and tempered).

Chemical composition of the steel material for both the pressure and tensile armors should be reviewed to confirm suitability for the specified application. Other important issues are manufacturability, weldability, sour service requirements, conformance to specified structural capacity, and compliance with API 17J requirements. Important components to be specified and controlled include carbon, manganese, phosphorus, sulphur, silicon, and copper. The manufacturer’s material specifications should define content limits for these components and distinguish between sweet and sour service applications. For some applications, consideration should also be given to minimizing the manganese content and performing calcium treatment of the melt.

Qualification of the steels for sour service should account for the thickness and cross-section profile of the wire.

Wire weldability should be verified by conducting tests with defined and documented acceptance criteria. For evaluation of material weldability, the maximum carbon equivalent content should be specified when no postweld heat treatments are performed. The maximum carbon equivalent may be defined by formulas similar to the following:

$$CE = C + \frac{Mn}{6} + \left(\frac{Cr + Mo + V}{5}\right) + \left(\frac{Ni + Cu}{15}\right)$$

where

| | |
|---|---|
| $CE$ | is the maximum carbon equivalent; |
| $C, Mn, Cr, Mo, V, Ni, Cu$ | are standard notation from the Periodic Table of Elements. |

### 6.2.4 Textile Materials

The materials used for the holding bandages wrapped around the armor layer to prevent birdcaging are generally either an aramid fiber or glass fiber weave. The manufacturer should demonstrate that the selected materials have the sufficient long-term mechanical capability to perform the required function, in accordance with Section 5.3.2.7.4 of API 17J.

#### 6.2.5 End Fittings

The materials typically used for the primary metallic end-fitting components are AISI 4130 steel or alloyed stainless steel (duplex or 6Mo). The corrosion-resistant coatings typically used for the end fittings include the following:

a) electroless nickel plating,

b) Inconel 625 inlay,

c) epoxy coating systems,

d) fluoropolymer coatings.

The material and corrosion coating selection for the end fitting is a function of the application, particularly the internal and external environmental conditions. End-fitting materials and coatings should meet the requirements of API 17J.

### 6.3 Materials—Bonded Pipe

#### 6.3.1 General

Section 6.3 identifies the commonly used materials in the bonded flexible pipe industry and presents, in general terms, the performance characteristics of these materials, such as allowable temperature range and fluid permeability. The elastomer materials are identified by their primary elastomeric component, for example, nitrile butadiene rubber (NBR). While the primary component is given, the recipe or mix used is, in general, specific to each company and not usually released to second parties.

The characteristics identified for the various materials for specific applications are perhaps not appropriate, because the suitability of a particular material is dependent on a large number of factors including transported fluid components, temperature, pressure, compound mix, and parameter variations over the service life (see API 17K, Annex A). The purchaser should therefore specify to the manufacturer the design and operating values of all relevant parameters including variations over the service life, with reference to the requirements of API 17K.

The materials and their properties should be reviewed against potential failure modes so as to identify the critical requirements of the materials in each layer of the pipe. A detailed list of failure modes is given in Section 11.

#### 6.3.2 Elastomer Materials

##### 6.3.2.1 General

Table 15 lists the elastomer materials typically used in bonded flexible pipes. These elastomer materials constitute approximately 40 % to 65 % of the final compound mix, with carbon black, antioxidants, activators, plasticizers, and curing agents making up the remainder amongst other ingredients. The final properties of the rubber compound are dependent on the final mix of all ingredients. For example, the higher the carbon black content in a compound mix the lower the electrical resistance will be in addition to a generally higher tensile strength (although the structure and size of the carbon black particles play a significant role also). NBR is extensively used as a liner material because of its low permeability to gas, such as $N_2$ and $O_2$. However, NBR is itself dependent on the percentage of acrylonitrile in the elastomer. This is usually 17 % to 50 %. The higher the acrylonitrile content in the NBR, the higher the heat and oil resistance and the lower the elasticity of the material at low temperature.

**Table 15—Typical Elastomer Materials for Bonded Flexible Pipe Applications**

| Application | Material |
|---|---|
| Liner | Nitrile butadiene rubber, hydrogenated nitrile rubber, polychloroprene, natural rubber, ethylene propylene diene monomer rubber |
| Cover | Polychloroprene, chlorinated polyethylene |
| Filler | Various |
| Insulation | Polyvinyl chloride, polyethylene, closed cell foam, glass fiber |

Chlorinated polyethylene is a typical elastomer used for bonded pipe covers. Its characteristics make it suitable for a relatively high abrasive environment where it can be exposed to both seawater and ozone.

Typical properties (operating temperature range, fluid compatibility, and fluid permeability) for the main elastomer materials are found in 6.3.2.2 to 6.3.2.4. As each rubber compound material is made up of an elastomer material and several other materials the properties will therefore vary with mix type. In addition, for most applications the elastomer material properties/characteristics are interdependent. For example, the allowable maximum operating temperature may be a function of the transported fluid.

API 17TR1 [13] describes development of test plans to evaluate the suitability of candidate polymers for high temperature service. Also defined are a set of evaluation criteria for material qualification.

#### 6.3.2.2 Temperature

Table 16 contains guidelines for selection of elastomers for bonded flexible pipe applications. These guidelines consider a relatively benign transported fluid.

A validated ageing model is required to confirm the elastomer service life requirements for detailed engineering (see 6.5.3 and API 17K).

Table 16 shows only general limits and may not apply for specific applications. The temperature ranges for each of the materials also depend on the components of the conveyed fluid. For example, the maximum operating temperature for NBR may be reduced by as much as 20 °C (68 °F) if the transported fluid contains a relatively large percentage of aromatics. Temperature excursions above the maximum stated values may also be acceptable for relatively short durations with manufacturer acceptance.

#### 6.3.2.3 Fluid Compatibility

Table 16 lists typical fluid compatibility characteristics for bonded flexible pipe elastomer materials. Note that fluid compatibility characteristics are highly dependent on temperature.

#### 6.3.2.4 Gas Exposure

Gas exposure will have to be taken into consideration in material selection for the elastomer layers if bonded flexible pipe is to be used for service in which the transported fluid contains gas. The main issues relate to the blistering resistance and continuing curing of both the pipe liner and the remainder of the pipe body. In general, elastomer materials are more susceptible to blistering than thermoplastic materials used in flexible pipe applications. This is attributed to the relatively higher permeability to gas and lower tearing resistance of elastomer materials over thermoplastic materials. A mitigating factor used by the industry is that the bonded flexible pipe, made up of elastomeric materials, is supported by an internal steel stripwound carcass and so the liner is not quite as susceptible to blistering as small-scale test results on elastomer alone would suggest. Bonded pipe bodies exposed to $H_2S$ can experience continuing curing in field applications, because sulphur is a cross-linking agent for many elastomers. Rubber compounds usually contain ZnO, which acts as $H_2S$ scavenger. Nevertheless, the presence of $H_2S$ can result in reduced local flexibility and increased global riser stiffness.

**Table 16—Temperature Limits for Thermosetting Elastomers in a Bonded Flexible Pipe Liner Application**

| | **Brittleness Temperature** °C (°F) | **Maximum Continuous Operating Temperature** °C (°F) | **Comments** |
|---|---|---|---|
| Nitrile butadiene rubber | −20 to 40 (−4 to 104) | 125 (257) | Properties dependent on acrylonitrile content. Excellent resistance to hydrocarbons. Very good tensile strength and dynamic properties. Good impermeability and heat resistance. Poor resistance to weather and ozone. |
| Hydrogenated nitrile rubber | −40 to 50 (−40 to 122) | 150 (302) | Good resistance to hydrocarbons. Very good tensile strength and dynamic properties. Good impermeability and very good resistance to weather and ozone. |
| Polychloroprene | −30 to 40 (−22 to 104) | 100 (212) | Reasonable resistance to hydrocarbons. Good tensile strength and reasonable dynamic properties. Good impermeability and heat resistance. Very good resistance to weather and ozone. |

The gas permeation rate through the elastomer material is dependent on many factors including internal and external pressure, surface area, liner thickness and permeability coefficient. The main issues to be considered in relation to gas permeation are the propensity for blistering to occur under rapid decompression, the likelihood of transported fluid components to permeate through the body of the pipe, and their effect on the elastomer and steel reinforcing layers.

### 6.3.3 Metallic Materials

#### 6.3.3.1 General

Property requirements for metallic materials are listed in API 17K. These properties should be compared with the requirements of each application, with reference to the critical failure modes identified in 11.3.

#### 6.3.3.2 Carcass

Materials typically used for the carcass layer are as follows:

a) carbon steel;

b) ferritic stainless steel (AISI 409 and AISI 430);

c) austenitic stainless steel (AISI 304, AISI 304L, AISI 316, AISI 316L);

d) high alloyed stainless steel (such as Duplex UNS S31803);

e) nickel-based alloys (such as N08825).

The selection of the material for the carcass is dependent on the internal fluid components and expected use of the flexible pipe. Important parameters to be considered are identified in API 17K.

As the severity of the internal fluid environment increases, the material selected for the carcass will move from Items a) to e), that is, carbon steel will be used for noncorrosive environments while high alloyed stainless steels will be used for corrosive applications. The most commonly used materials are AISI 304L and AISI 316L austenitic stainless steel. A high molybdenum content (2.7 % to 3.0 %) may be specified for AISI 316L material to improve its corrosion resistance characteristics.

The main parameters to be considered in the selection of the carcass material are fluid temperature and $CO_2$, $H_2S$, chloride, and oxygen content. Other parameters that should be considered include pH, water, free sulphur, and mercury content of internal fluid. In sour service environments, the carcass material should meet the requirements of NACE MR0175.

If the transported fluid is oxygenated (aerated), for example, by seawater injection, and a carcass is required, consideration can be given to using nonmetallic material (such as polymers or composites) for the carcass. However, this is unproven technology and would require validation by testing.

The hydrotest fluid should be benign to the carcass material. Consideration may be given to the use of biocide and, for particularly aggressive cases, corrosion inhibitor.

#### 6.3.3.3 Reinforcing Layers

The typical material used for the cables of the primary reinforcing layers is carbon steel. High carbon content steel is used to give a high-strength cable.

Chemical composition of the steel material for the reinforcing layers should be reviewed to confirm suitability for the specified environment. Other important issues are sour service requirements, conformance to specified structural capacity, and compliance to API 17K requirements. The effect of the enclosing rubber should be considered in determining suitability.

Important components to be specified and controlled include carbon, manganese, phosphorus, sulphur, silicon, and copper. The manufacturers' material specifications should define content limits for these components. Consideration to minimizing the manganese content and performing calcium treatment of the melt is recommended for some applications.

### 6.3.4 End Fittings

The materials typically used for the primary metallic end-fitting components are AISI 4130 steel or alloyed stainless steel (such as duplex, 6Mo). The corrosion-resistant coatings typically used for the end fittings include the following:

a) electroless nickel plating, thickness at least 75 μm (0.00029 in.);

b) Inconel 625 inlay, thickness at least 3 mm (0.12 in.);

c) epoxy coating systems;

d) fluoropolymer coatings;

e) zinc coating.

The material and corrosion coating selection for the end fitting is a function of the application, in particular, the internal and external environmental conditions. End-fitting materials and coatings should meet the requirements API 17K.

## 6.4 Alternative Materials

### 6.4.1 Aluminum

Aluminum material may be used to replace steel in any of the structural layers of the flexible pipe, including carcass, pressure armor, and tensile armor layers. Aluminum's main advantage is that, compared to steel, it gives a weight saving of between 30 % and 60 % for the same strength characteristics. When substituting steel with aluminum in any structural layer, the manufacturer should conduct a similar qualification program to the qualification program specified in API 17J and API 17K and the program should be agreed with the purchaser or IVA.

The corrosion behavior of aluminum should be evaluated carefully prior to its use for flexible pipe applications. Other important issues to be addressed include abrasion and wear resistance, SSC and HIC resistance, fatigue, and welding.

### 6.4.2 Composite Materials

Refer to Annex H of this document for guidance relating to composite materials.

## 6.5 Polymer/Elastomer Test Procedures

### 6.5.1 Scope

API 17J and API 17K specify material property requirements and test procedures. Standard procedures are unavailable for polymer/elastomer fluid compatibility and ageing resistance tests. Therefore, procedures are not given in API 17J and API 17K. This section gives guidelines and recommendations for performing these tests.

### 6.5.2 Fluid Compatibility

#### 6.5.2.1 General

API 17J and API 17K contain general requirements for the performance of fluid compatibility tests and identify critical parameters for evaluating compatibility. This section gives recommendations on the test procedures.

#### 6.5.2.2 Test Procedures

Laboratory tests with extruded samples of the polymer or calenderized or extruded samples of the elastomer can be used to determine gross incompatibility. Tests should be based on the design conditions, subject to the following recommendations:

— test fluid contains components of design internal fluid that possibly have adverse effects on the polymer, particularly seawater, production fluid, $H_2S$, $CO_2$ and injection chemicals, and fluid pH level to be controlled to design conditions;

— maximum operating temperature as a minimum;

— ambient pressure for liquids and design pressure or greater for gases;

— stress conditions zero, and if there is potential for stress cracking, also test at maximum design strain;

— a minimum exposure time of 300 h for accelerated tests (increased temperature);

— sample thickness should be 3 mm (0.12 in.) unless thinner samples are shown to be more sensitive to fluid compatibility when deterioration is diffusion controlled, sample length should be based on the test equipment, and sample should be immersed in all phases if test fluid is multiphase;

— critical parameters and acceptance criteria should be established based on the polymer/elastomer being evaluated and the particular application; tensile strength, elongation, visual appearance, and fluid absorption (weight gain) and desorption (weight loss) parameters should be considered for evaluation/measurement

A 2000-h test at operating temperature can be used to evaluate whether there are any crucial incompatibility issues but may not be sufficient for a qualification of a thermoplastic material with a required lifetime of 20 years or more.

#### 6.5.2.3 Other Considerations

Sulphur can be liberated from $H_2S$ reacting with steel components or the elastomer compounds in the bonded pipe to cause cross-linking and hardening. The effects of released sulphur on either metallic or elastomeric components should be evaluated.

### 6.5.3 Ageing Test

#### 6.5.3.1 General

The chemical ageing of elastomer/polymer materials is for design purposes normally regarded as an irreversible process that occurs when the material is exposed to particular environmental conditions. Recent research has indicated that hydrolysis of PA-11 is reversible to some degree if the temperature is reduced. Physical ageing such as swelling may be reversible. Polymer ageing is dependent on the fluid transported in flexible pipes, temperature, pressure, and external conditions, such as ultraviolet (UV) radiation. The ageing process is characterized by change in properties, such as reduction in strength or ductility, and embrittlement or softening. In addition, the physical properties of the polymer/elastomer can be significantly altered by migration of plasticizers.

#### 6.5.3.2 Test Procedures

API 17J, API 17K, API 17TR1 [13] , and API 17TR2 [14] contain general requirements for the performance of ageing tests and identifies critical parameters for the most commonly used polymers. The objective in performing ageing tests is to develop satisfactory ageing prediction and monitoring models, which may include Arrhenius plots. This gives the material service life as a function of the inverse of temperature, plotted to a log-linear scale. Some materials (such as PA-11 and PA-12) have been found to be more amenable to the development of Arrhenius plots than other materials (such as PVDF). Arrhenius plots are useful to extrapolate accelerated high temperature ageing tests to lower temperatures and longer times. This is particularly true when there is no change in ageing mechanism or any kind of phase transition over the temperature range considered.

The ageing criteria should be established prior to test start-up. The ageing criteria should be based on measurable performance properties at the end of the pipe's service life.

#### 6.5.3.3 Other Ageing Considerations

The ageing of PA materials (including both PA-11 and PA-12) has been a particular concern to manufacturers and users, and is discussed in detail in API 17TR2 for PA-11. The capability of other PA materials should be assessed using the same methodology.

The mechanical properties of PA materials are determined by the molecular weight of the material. The standard method of molecular weight measurement adopted for PA in flexible pipe applications is the corrected intrinsic viscosity (CIV) measured according to Appendix D of API 17TR2. Other methods of molecular weight determination may be used in support of this technique.

In order to maintain highly ductile mechanical behavior, the molecular weight of PA has to be higher than a critical range. For new PA extrusions, CIV is typically above 1.8 dl/g and falls as the material ages. If and when the CIV of a PA material reaches 1.2 dl/g, it is said to have reached the initial acceptance criterion. This level of CIV does not represent the end of the useful life of the pipe. It does, however, indicate that the material has aged significantly and the integrity management of the pipe should then require additional assurance of the state of the pressure sheath to take account of this heightened risk.

While API 17TR2 primarily identifies the potential impact of temperature, water, acid gases ($CO_2$ and $H_2S$), and methanol on PA materials, other environmental factors are now known to be important. Prolonged exposure to large amounts of methanol, for example during batch treatment, is now thought to have a large effect on the long-term performance of PA, possibly as a result of dissolved oxygen in the methanol. Oil with TAN > 1.0 mgKOH/g also appears to decrease the life of PA significantly. The impact of just water and $CO_2$ is currently thought to be less than first envisaged.

### 6.5.4 Epoxy Shear Strength Test

The epoxy shear strength test is intended as an alternative to the ASTM D695 (ISO 604) compressive strength test in determining the shear capacity of the epoxy resin used for anchoring the reinforcing cables in some bonded pipe end fittings.

API 17K contains general requirements for the performance of epoxy shear strength tests. This section provides recommendations on the test procedures.

The epoxy shear strength test involves testing cured epoxy samples by shearing the sample at different temperatures, thereby obtaining the temperature-dependent shear capacity of the material. Tests should be based on operating conditions, subject to the following recommendations:

a) sample size should be based on the test equipment, and a minimum of 3 samples per temperature should be tested;

b) sample should be tested at both minimum and maximum operating temperature and at sufficient temperature intervals in between to satisfactorily define the shear strength/temperature relationship of the material;

c) samples should be molded and cured under the same temperature and humidity conditions as prevailing when filling the end fitting;

d) the epoxy resin should be mixed according to the manufacturer's specification and poured slowly into the prepared mold to ensure no air bubbles are entrapped;

e) the epoxy samples should be taken from the batch used to fill the end fitting if the shear strength test is required as part of the pipe manufacture quality process.

## 6.6 Metallic Material Test Requirements

### 6.6.1 General

Section 6 discusses the qualification test requirements for flexible pipe metallic materials and gives recommendations on the performance of the tests and interpretation of results. API 17J specifies qualification of materials for the carcass, pressure armor (unbonded pipe), and tensile armor layers (unbonded pipe), and API 17K specifies test requirements for reinforcing layers (bonded pipe). The following tests are required:

a) SSC and HIC resistance;

b) corrosion resistance (fluids, chemicals);

c) erosion resistance;

d) fatigue resistance;

e) hydrogen embrittlement resistance;

f) chemical resistance.

These tests are discussed in detail below and also supplement requirements in API 17J and API 17K.

### 6.6.2 SSC and HIC Resistance

Hydrogen enters steel components at the corroding surface in wet $H_2S$ environments. Depending on the type of steel, its microstructure, and the inclusion distribution, the hydrogen may give rise to internal decohesion resulting in HIC or brittle fracture, termed SSC. API 17J and API 17K specify SSC and HIC test procedures for steel wire and cables materials used in flexible pipe applications.

The following two types of SSC tests are required by API 17J and API 17K.

a) NACE TM01-77 test. The threshold level for the occurrence of SSC and HIC should be determined by testing multiple specimens to various levels of $H_2S$ and pH. Tensile load tests or four-point bend tests shall be used. SSC threshold levels shall also be demonstrated for each weld procedure. Specimens shall be loaded to at least 90 % of the structural capacity. For welds, the test shall assure that that the welded joint is subjected to at least the same deformation that the welded wire experiences when the structure is exposed to its maximum load.

b) SSC test with actual service conditions, comprising the calculated annulus partial pressure of $H_2S$ and the calculated pH in the annulus, in aqueous solution (3 % NaCl minimum) at ambient pressure and temperature, with the samples stressed to 0.9 times the actual yield stress of the sample, as defined in API 17J or design stress levels as defined in API 17K. For welds, the test shall assure that that the welded joint is subjected to at least the same deformation the welded wire experiences when the structure is exposed to its maximum load. If the manufacturer does not have a verified model for calculating annulus conditions, then pipe bore partial pressures shall be used.

Results from both of these tests are used to determine suitability of the steel material for the proposed application. Important considerations in the performance of these tests include the following:

a) the recommended test procedures for both SSC tests described above, are as follows:

    1) for pressure armor wires of unbonded pipe (including interlock and backup flat wires), ring tests should be used where practical for pipe diameters less than 15.24 cm (6 in.). Otherwise, four-point bend tests from ring samples should be used. Four-point bend tests from ring samples should be used only as an alternative for larger pipe diameters where the ring test would not be practical;

    2) for tensile armor wires of unbonded pipe, depending on the wire size, Method A of ASTM A370 [16] or four-point bend tests should be used;

    3) for reinforcing layer cables, a coating of embedding compound should be applied, the maximum thickness of which should not be greater than the minimum design thickness of the embedding compound in the pipe construction;

b) HIC to be checked for following completion of the NACE TM01-77 SSC tests;

c) all samples should represent, as closely as possible, the as-manufactured wires and cables and should be tested on a statistical basis to verify resistance;

d) welded samples should be tested to qualify welding procedures for wires used in unbonded pipe;

e) each wire size/grade or origin (steel mill and the whole material processing) combination should be individually qualified;

f) test procedures should ensure that the important test parameters are kept largely constant, including stress and strain levels, pH, temperature, and $H_2S$ partial pressure;

g) the material is considered to have failed the test if there is evidence of cracking from visual, microscopic, or magnetic particle inspection, other than surface blisters;

h) a 20 °C (±3 °C) [68 °F (±5.4 °F)] test temperature is recommended, because this is considered the worst temperature for hydrogen effects;

i) NACE TM0284 [53] testing may be used as a quality control test on the wire material.

The specified tests apply to pipes for both static and dynamic applications. In addition, for DAs, fatigue and corrosion fatigue tests will be required, as discussed in 6.6.5.

### 6.6.3 Corrosion

This section addresses uniform or pitting corrosion. This is particularly relevant for unbonded pipe armor wire corrosion. Corrosion problems in the carcass are generally avoided by proper material selection, as discussed in 6.2.3. Though the pressure and tensile armors are not directly in contact with the transported fluid, they will be exposed to permeated fluids, such as $CO_2$ and $H_2S$ gas, and seawater if there is a breach in the integrity of the outer sheath.

Uniform corrosion will be caused by $CO_2$ in the presence of deoxygenated seawater and may be assessed by modelling. This uniform corrosion should be accounted for in the selection of the armor wire thickness. Corrosion from oxygenated water, in the immediate vicinity of tears in the outer sheath, should be controlled by appropriate design of the cathodic protection system. No pitting corrosion should occur under design environmental and stress conditions that could cause utilization factors to exceed design criteria or affect the service life requirements.

### 6.6.4 Erosion

The production of reservoir sand may cause erosion in the carcass layer of flexible pipes. In addition, the sand can remove any protective films on the carcass, thereby increasing corrosion. Therefore, the erosion and corrosion rates should be calculated based on test data or validated models. Calculations should confirm the following:

a) the hydrostatic collapse resistance of the eroded and corroded carcass is not lower than the design requirements for the specified service life,

b) the tensile load capacity with the eroded and corroded carcass is not less than the design requirements.

Erosion rates will be most severe at high curvature areas. Important parameters that influence erosion rates include fluid velocity, amount and size of produced sand, carcass geometry, and steel material. The partial pressure of $CO_2$ and the fluid temperature have a significant effect on the erosion/corrosion characteristics of the carcass. The type of sand has an impact on the wear due to the difference in grain shape (e.g. quartz vs clay type sands). Fine particles should be considered for the permanent operating conditions and bigger particles should be considered for short-term events (e.g. well cleanup).

### 6.6.5 Fatigue Resistance

#### 6.6.5.1 General

Adequate fatigue resistance of steel wire materials for DAs is required. A fatigue analysis should show that all stresses are below the material endurance limit. Otherwise, fatigue damage calculations should be performed, such as with Miner's method using design S-N curves and accounting for damage due to cycles with stresses below the endurance limit. The determination of the S-N curves is critical for the fatigue analysis. API 17J and API 17K specify relevant test requirements, namely that S-N data are to be developed based on the actual annulus conditions and the design basis for the annulus (such as exposure to air, seawater), or design annulus environment for unbonded pipes, and based on rubberized cables and pipe bore conditions for bonded pipe.

#### 6.6.5.2 Test Procedures

The objective of a fatigue test is to identify the fatigue performance of the material, accounting for the specific environment in which the fatigue takes place. Data from previous testing in more severe conditions may be used. Note that a reduction in the fatigue life is expected for sour service applications.

Tests should consider variations in the material strength and hardness. Softer material generally gives a lower fatigue limit in air, but this can change for corrosive environments.

The standard S-N tests for wires of unbonded pipe are based on un-notched specimens. Consideration may also be given to performing tests with notched specimens or to use the results of full-scale tests for validation when pitting, wear, corrosion, or other sources of notches are likely to occur. This would give a lower-bound S-N curve for pitted or worn wires, or wires scratched during manufacture.

The number of samples and stress levels for development of S-N data should be in accordance with ASTM E739 [22]. Strain gauges should generally be used for stress measurements where appropriate. A recommended test frequency is 0.5 Hz, unless other higher test frequencies have been shown to provide equivalent results in testing with the same setup and in similar environmental conditions.

Sufficient S-N data should be available to confidently extrapolate the S-N curve to stress ranges below those at which it is possible to test. The S-N curve may introduce a reduced slope at longer lives/lower stress ranges if this is supported by the test data. Results should be presented in accordance with ASTM E468 [21].

In the case of welds on the pressure and tensile armor wire located in fatigue-critical areas (e.g. hangoff and touchdown areas), then Section 5.3.4.2 of API 17J requires that these welds shall be qualified for the fatigue loads expected at the locations of the welds. Weld fatigue qualification can be achieved by testing of welded wire samples to confirm the fatigue performance assumed in the design or by developing S-N curves for welded armor wires for the appropriate annulus conditions.

For additional information on test procedures reference should made to the Test Protocol Report from the MARINTEK JIP [49].

#### 6.6.5.3 Other Considerations

The endurance limit should be the stress level at which specimens exceed $1 \times 10^7$ cycles with no evidence of fatigue cracks. The endurance limit stress is only relevant for fatigue life analyses that do not include any cycles with stresses above the endurance limit. An endurance limit is normally only found in air; corrosion fatigue environments do not show such limits.

Unbonded flexible risers may be designed on the basis that the outer sheath will never be breached (no flooding of the annulus with seawater); however, service life is usually limited by the length of time to failure of tensile and pressure armors when the annulus is flooded with aerated seawater from a rupture of the outer sheath, and conservatively this should be calculated assuming a breach during pipe installation (although this is an accidental situation) with the calculated service life determining the length of time before the pipe should be replaced. The replacement time should be included in the operation manual. Risers may also be designed on the basis of a deaerated seawater flooded annulus, where small leakages from the vent valves, sheath breach, outer sheath sealing system, etc., which are not detectable by visual in situ inspections, might occur during the pipe installation.

The factors of safety applicable to the remaining life (accidental situation) or to the whole life (normal operation conditions) calculations should be in accordance with the recommendations given in 5.7.11.2; that is in the case of a flooded annulus the standard FOS applicable to the calculated fatigue life (i.e. 10) may be reduced in accordance with the requirements of API 17J if agreed between the purchaser and the pipe manufacturer.

#### 6.6.6 Hydrogen Embrittlement

Cathodically protected, high tensile strength steels can be vulnerable to hydrogen embrittlement. API 17J specifies required testing to confirm satisfactory performance of high strength wires of unbonded flexible pipes subject to cathodic protection.

# 7 Prototype Testing

## 7.1 General

This section gives guidelines on prototype testing of flexible pipe. The guidelines include a list and classification of different tests, and present procedures for performing the most frequently conducted tests. Prototype qualification will normally include material and FAT tests, as specified in API 17J and API 17K.

Prototype test documentation is intended to be reviewed by the IVA as part of the pipe design methodology verification (see API 17J and API 17K).

The requirements for prototype testing are subject to agreement between the manufacturer and the purchaser and can be based on the recommendations given in this section. As an alternative to prototype testing, the manufacturer may provide objective evidence that the product satisfies the design requirements. Objective evidence is defined as documented field experience, test data, technical publications, finite element analysis, or calculations that verify the performance requirements.

The number and range of prototype tests that can be performed on flexible pipe is extensive. Cost and/or time implications may make it impractical to perform a full range of prototype tests for each pipe design. The need for a test can be determined from a risk assessment specific to the target application, based on assessing the manufacturer’s ability to predict the pipe behavior correctly and on assessing the consequence of potential unconservative predictions leading to pipe failure.

## 7.2 Objectives of Prototype Testing

### 7.2.1 General

There are two objectives of prototype testing:

a) evaluate the performance (i.e. structural, functional, fabrication) of a new or established pipe design; and

b) qualification of an established pipe design for use outside its previously qualified envelope.

### 7.2.2 Evaluating Pipe Structural Performance

Evaluating the pipe structural performance can include:

a) establishing physical limits by testing to failure (e.g. burst, collapse, fatigue);

b) establishing pipe characteristics (e.g. axial and bending stiffnesses) needed for riser system design; or

c) verifying that the pipe has the capacity to withstand prescribed loads by nondestructive testing.

### 7.2.3 Evaluating Pipe Functional Performance

Evaluating the pipe functional performance can include:

a) leak testing, or

b) annulus vacuum or pressure testing.

Hydrostatic and gauge tests can be used for example to evaluate the pipe fabrication performance.

Some tests (e.g. burst, fatigue) can be used to evaluate structural, functional, and fabrication performance when systematic observations are made at predefined load levels.

Any test can be used for verification, validation, or qualification.

### 7.2.4 Qualification Tests

Qualification tests can be carried out by testing on both preproduction and postproduction pipe lengths. The ability to fulfill the requirements for a specific application can also be demonstrated by the manufacturer showing the envelope of previously qualified pipes (e.g. pressure vs diameter graphs for burst or collapse destructive tests) and analysis that bridges the differences between the new pipe design and the pipes tested previously based on using manufacturer’s design methodology and predictive tools.

### 7.2.5 Verification and Validation Tests

Verification and validation tests are typically done on postproduction pipe lengths. Examples of verification tests are tests that confirm assumed pipe performance characteristics. Examples of validation tests are tests of stock pipe designed for one application, to the requirements specific to a different pipe application. The application-specific requirements include testing to the design parameters, such as pipe pressure and collapse pressure proportional to the water depth, and testing to pipe strength and fatigue response parameters determined from dynamic simulation and analyses.

### 7.2.6 Structural Performance Testing

Structural performance testing can be carried out to a number of different test levels.

For example strength testing can be done to five different test levels:

a) to failure of pipe body or end-fitting termination,

b) to ultimate tensile strength (UTS) value of the critical strength component,

c) to specified minimum yield strength (SMYS) value of the critical strength component,

d) to the design acceptance criterion (DAC) of the critical strength component (usually a fraction of SMYS), or

e) to the maximum load in terms of stress utilization of the critical layer or of the critical strength component.

For example fatigue testing can also be done to five different test levels:

a) to failure,

b) to a target S-N curve (e.g. mean S-N curve plus one standard deviation) of the fatigue critical component,

c) to damage ratio of 1.0 determined from the design S-N curve of the fatigue critical component,

d) to the maximum allowable damage ratio in a service life (e.g. 0.1) determined from the fatigue critical component, or

e) to the maximum damage ratio accumulated in the fatigue critical component in a service life.

Successful testing to a greater load or damage ratio level is preferable as it automatically validates the pipe suitability to the lower load or damage ratio levels; however, it is generally more time consuming and more expensive. For example, a successful strength test to SMYS of the critical strength component would demonstrate that the pipe strength design includes the safety margin associated with the DAC. Successful testing to the DAC level would demonstrate that the pipe can withstand the maximum load, which should be less than the DAC. The maximum load should be determined from extreme statistics after bounding all uncertainties.

### 7.2.7 Design Verification

Any test can be used for verification of the manufacturer's design methodology and validation of manufacturer's software tools (see 5.6.1). If a design methodology builds a model of the pipe, then a design tool is used to predict the pipe response to loads triggering one or more specific pipe failure modes. Pipe design is based on making predictions of pipe response to loads triggering known failure modes and mechanisms by using different tools. Ensuring that those predictions are conservative approximations of actual pipe responses is the main objective of the design methodology verification and software tool validation tests. All tests are designed on checking the pipe resistance to specific failure modes and mechanisms. Testing to pipe failure and showing that the load level predicted to cause failure does not exceed the load level that caused the actual failure, and that the predicted failure mechanism corresponds to the actual failure mechanism, validates design methodology and software tool predictions. Software tool validation is based on demonstrating consistent conservative failure predictions for a series of failure tests. If the series of failure tests reveal the pipe component that fails first, then tool validation testing can be done to load levels lower than the failure load as long as the critical component is instrumented, its response measured for comparison with the predicted response. For example, if a series of pull-out tests reveal that tensile wires are failing by overstress then instrumenting the tensile wires with strain gauges and showing that the predicted wire stresses exceed the measured stresses can be used for tool validation without resorting to destructive testing.

### 7.2.8 Prototype Tests

Fundamental to reducing the number of prototype tests is the necessity to increase the level of confidence in the predictive capability of the design methodology and tools. Prediction of pipe response to loads triggering a selected failure mode is based on using a deterministic method (e.g. a limit state equation) and a number of load and resistance variables specific to the failure mode. Building a good model and calibrating a tool to confidently and conservatively predict pipe behavior requires bounding the uncertainties associated with all variables and a number of tests to measure pipe hysteretic behavior or component stresses, strains, and displacements. All prototype tests performed should be used to verify the design methodology and validate the design tools and so minimize future requirements for prototype testing.

In order to allow the verification of the design methodology, prototype tests may require additional instrumentation than is required for the prototype tests discussed hereafter. For instance, stress and strain measuring of the pipe layers/components may be necessary. Furthermore, pipe or layer hysteretic behavior might not be captured by the test procedures discussed hereafter. Additional tests or variations to the ones discussed hereafter may be necessary in order to allow the proper verification of the design methodology.

## 7.3 Classification of Prototype Tests

Prototype tests can be full-scale tests (a full pipe construction) or medium-scale tests (a pipe construction comprising only the layers required for the test, with or without end fittings).

There are different ways to classify the prototype tests: by use (qualification, verification, validation), by failure mode (burst, collapse, etc.), by timeline of product evolution (manufacturing, load out, installation, operation), by number of load applications (static, dynamic), by outcome (destructive, nondestructive), or by frequency of conducting similar tests. In this section, prototype tests are classified into three classes as follows.

a) Class I: Standard prototype tests, as most commonly used.

b) Class II: Special prototype tests, used regularly to verify specific aspects of performance, such as installation or operating conditions.

c) Class III: Tests used only for characterization of the pipe properties.

Table 17 lists tests that come under these classifications.

Procedures for Class I and II tests are given in 7.6 and 7.7, respectively. Procedures for Class III tests should be per the specifications of the purchaser or manufacturer.

## 7.4 Test Requirements

### 7.4.1 General

The requirements for prototype tests should consider the characterization of the new pipe design and what are the critical failures modes and consequences. In addition, scaling limitations and applicable tests should be addressed. These are discussed in the following subsections.

### 7.4.2 Recommendation for New Tests

Table 18 and Table 19, respectively, identify critical issues related to pipe structure and application, as well as recommendations on prototype test requirements. The requirements for prototype testing of a new pipe design are very dependent on the application and this should be considered. For example, a large difference exists between a low-pressure static flowline and a high-pressure riser application.

### 7.4.3 Failure Modes

The requirements for prototype tests should consider the criticality and consequences of pipe failure. In particular, potential failure modes and causes should be identified. Table 20 identifies critical prototype tests that can be used to verify the pipe design for some of these failure modes. This table should be referred to when determining prototype test requirements. Note that in the event that new failure modes are identified, it may be necessary to develop additional prototype tests.

### 7.4.4 Qualification by Similarity Assessment

A new pipe design may be accepted, by the purchaser, as qualified without the requirement of prototype testing. Acceptance requires that the new pipe design be compared to one or more previously qualified pipe designs and/or pipe designs that are in the process of being qualified by means of a similarity assessment. The similarity assessment should be submitted for purchaser approval.

For similarity assessment to be valid:

a) pipe design principles and functional operation should be similar;

b) design stress levels in relation to material mechanical properties should be based on the same criteria, that is, equivalency in utilization or accumulated fatigue damage;

c) sufficient technical evidence, based on available data and representative test results, should be provided.

Scaling typically within ±2 in. internal diameter is allowed for new pipe designs if they have the same or lower pressure times inside diameter ($P \times \mathrm{ID}$) as a previously tested pipe and provided that a risk assessment is performed for application specific failure modes and mechanisms.

A representative test is one in which all the following conditions apply.

a) The sample for the reference test has a similar design to the new pipe design.

b) The test sample is produced by the manufacturing process (machinery, procedures, and workmanship) used to manufacture qualified pipes and was manufactured with a qualified and controlled process.

c) The test conditions for the reference test are equal to or more severe than those required for the qualification of the new pipe design for all applicable failure modes and mechanisms.

d) Key parameters are properly measured and controlled during the test, as per test specification or other normative test procedure.

If required by the purchaser, the manufacturer should also submit the similarity assessment for IVA review.

### 7.4.5 Applicable Prototype Tests

This section describes the prototype tests that are applicable to the design modifications and application changes listed in 7.4.2. Table 21 and Table 22 list the requirements for Class I and Class II prototype tests, respectively, as defined by Table 17.

Changes to transported fluid, service life, or external environment do not require Class I tests but may require materials testing as in API 17J and API 17K.

## Table 17—Classification of Prototype Tests

| Class | Type | Description | Test Condition/Comment |
|---|---|---|---|
| I | Standard prototype tests | a) Burst pressure test | Typically in straight line |
| | | b) Axial tension test | At ambient pressure |
| | | c) Collapse test | With outer sheath perforated or omitted |
| | | d) Temperature test | High and low temperature cycling; applicable to polyvinylidene fluoride only |
| II | Special prototype tests | a) Dynamic fatigue test | Bending, tension, torsional, cyclic pressure, rotational bending, or combined bending and tension fatigue tests |
| | | b) Crush strength test | Installation test |
| | | c) Combined bending and tensile test | Installation test |
| | | d) Sour service test | To examine degradation of steel wires |
| | | e) Fire test | |
| | | f) Erosion test | To examine degradation of carcass |
| | | g) Through flowline test | Also includes pigging test |
| | | h) Vacuum test | Bond strength in test for bonded pipes |
| | | i) Kerosene test | Detect permeation or leakage of hydrocarbon through liner of bonded pipe |
| | | j) Adhesion test | Verify bond strength of bonded pipe |
| | | k) Full-scale blistering test | Determine suitability of bonded pipe to gas service |
| | | l) Combined pressure and tensile test | A test for riser applications only. To verify that the pipe has sufficient capacity to withstand max loading and conform with design criteria |
| | | m) Outer sheath holding system test | A test for deepwater riser applications only. To check the outer sheath/end-fitting interface under high tension load |
| | | n) External sealing system test | To verify the adequacy of the external sealing system of the flexible pipe end fitting |
| | | o) Dynamic tension-tension test | Fatigue test to verify performance of tensile armor anchoring in the end fitting |
| | | p) Curved collapse test | To check the influence of curvature; for deepwater applications only |
| | | q) Vent valve test | To confirm the short- and long-term performance of vent valves |
| III | Characterization and other tests | a) Bending stiffness test | Up to a given curvature |
| | | b) Torsional stiffness test | To given torque (nondestructive) |
| | | c) Abrasion test | Test for external abrasion |
| | | d) Rapid decompression test | |
| | | e) Axial compression test | To determine compression stiffness capacity or verify prediction of birdcaging |
| | | f) Thermal characteristics/TEC test | Dry and/or flooded conditions |
| | | g) Arctic test | Low temperature test |
| | | h) Weathering test | Ultraviolet resistance |
| | | i) Structural damping test | |
| | | j) Internal pressure cycling | Check the internal sealing system of the internal pressure sheath under cyclic pressure loading |
| | | k) Lateral buckling test (unbonded pipe only) | To check the buckling resistance of tensile armors under compression and bending |
| | | l) Impact test | |

**Table 18—Recommendations for Prototype Tests—Modifications to Pipe Structure Design**

| No. | Design Modification | Recommendation on Requirement for Prototype Tests |
|---|---|---|
| 1 | Internal/external diameter | For changes in diameter not justifiable by similarity analysis per 7.4.4. |
| 2 | Number and order of layers | Required for substantive change to structural layers only. |
| 3 | Carcass or armor layer construction | Required if cross-sectional shape or material type is substantially changed.<br>Material qualification required. |
| 4 | Polymer layer | Where polymer material properties, application or imposed loading regime vary significantly from field proven designs, there should be consideration for full-scale qualification testing. |
| 5 | Spiralling angle (2) | Only required for angle ($\theta$) changes outside the following, where $\theta$ is measured relative to longitudinal axis:<br>— carcass or pressure armor (unbonded) layers: $\theta > 80°$;<br>— tensile armor (unbonded) and reinforcement (bonded) layers: $20° < \theta < 60°$. |
| 6 | Antibuckling tapes material change | Required for substantive change to material properties, and end-fitting termination design. Material qualification is required. |
| 7 | End fitting | Required for substantive change to the end-fitting design, in particular:<br>— change in armor/reinforcing layer anchoring system,<br>— change in epoxy material,<br>— change in internal/external fluid integrity systems (sheath/liner anchoring). |
| 8 | Lubricant (unbonded) | Performance should be evaluated if used to prevent wear in service. |

NOTE 1 The above recommendations may vary for different applications, such as flowlines and risers.

NOTE 2 Lay angle criteria may not be sufficient for deepwater pipes, for which additional parameters and tests need to be established to address tensile armor buckling.

**Table 19—Recommendations for Prototype Testing—Changes in Pipe Application**

| No. | Change in Pipe Application | Requirement for Prototype Testing |
|---|---|---|
| 1 | Transported fluid | If required performance is beyond the envelope of the validated design methodology or performance limits established by previous prototype tests |
| 2 | Service life | |
| 3 | External environment | |
| 4 | Combination of all of the above | |

**Table 20—Potential Flexible Pipe Failure Modes and Associated Critical Prototype Tests**

| Pipe Component | Failure Mode | Prototype Test |
|---|---|---|
| Carcass layer | 1) Collapse failure modes: | |
| | — due to external pressure | Collapse test |
| | — due to armor layer pressure | Tensile test |
| | — due to installation loads | Combined bending and tensile test, crush strength test |
| | — due to rapid decompression (multilayer liner) | Rapid decompression test |
| | 2) Wear | Erosion test |
| | 3) Material failure | |
| Internal pressure sheath or bonded pipe liner | 1) Rupture due to pressure | Burst test |
| | 2) Creep extrusion | |
| | 3) Material failure | |
| | 4) Wear | Erosion test, if applicable |
| | 5) Fatigue | Dynamic fatigue test |
| Structural layers | 1) Structural failure due to loading: | |
| | — tension | Tensile test |
| | — compression | Axial compression test |
| | — pressure | Burst test |
| | — bending | Bending test |
| | 2) Wear and fatigue | Dynamic fatigue test |
| | 3) Radial buckling/birdcaging | Axial compression test, external hydrostatic pressure bird-cage test (flooded annulus) |
| | 4) Lateral buckling | Combined cyclic bending and axial compression test |
| | 5) Adhesion/delamination for elastomers | Adhesion test |
| | 6) Material failure | |
| | 7) Collapse due to ovalization during Installation | Combined bending and tensile test |
| Antibuckling tapes | 1) Structural failure due to loading: — compression | Axial compression test |
| | 2) Wear | Dynamic fatigue test |
| | 3) Material failure | |
| Insulation layers | 1) Loss of insulating capacity due to flooding | Material and thermal insulation tests |
| | 2) Thickness reduction or deformation under crushing loads | Crush strength test |
| End fitting | 1) Pressure sheath/liner pull-out | Temperature test |
| | 2) Tensile armor wire pull-out/rupture | Dynamic test, tension test, combined pressure and tensile test, and dynamic tension-tension test |
| | 3) Epoxy failure | Temperature test |
| NOTE Detailed lists of potential pipe failure modes and mechanisms are given in 11.3. | | |

## 7.5 Test Protocol

### 7.5.1 Test Sample

Prototype testing should be conducted on full-size products that represent the specified dimensions for the relevant components of the end product being verified. This does not apply to the length of the flexible pipe, excluding end fittings. The minimum length excluding end fittings should be the greater of 3 m (9.84 ft) or $10 \times \mathrm{ID}$, unless specified in the test procedures in 7.6 and 7.7. The test samples should have been subjected to FAT testing where applicable.

The dimensions of the prototype pipe shall be within the allowable dimensional tolerance range for the normal production pipe. If applicable, the sample should include welds or repaired sections or process variations.

Test samples should represent the actual product to be supplied, considering both the design and manufacturing procedures. Consideration should be given to potential differences between sample and production pipe if samples are made up using semimanual procedures (e.g. not from a production run). It may be necessary to consider repeating some of the critical tests on production samples to verify the manufacturing equipment and procedures.

All full-scale prototype proof tests should be carried out with end fittings mounted that are structurally identical to those to be used on the product to be qualified, except where allowed or recommended by this part of API 17J.

**Table 21—Recommendations for Class I Prototype Tests**

| Design Modification or Change in Application | Recommended Class I Prototype Tests | | | |
|---|---|---|---|---|
| | Burst | Tension | Collapse | Thermal Cycling (Temperature Test) |
| Internal/external diameter (carcass/pressure armor layer diameter) | X | X | X | |
| Number or order of layers | X | X | X | |
| Internal carcass | | | X | |
| Internal pressure sheath | | | | X applicable for polyvinylidene fluoride and new polymers |
| Pressure armor layer | X | | X | |
| Tensile armor layer | X | X | | |
| Significant variance in spiraling angle | X | X | X | |
| End-fitting design | X | X | | X |

**Table 22—Recommendations for Class II Prototype Tests**

| Design Modification or Change in Application | Recommended Class II Prototype Tests |
|---|---|
| New design | Dynamic fatigue test<br>Combined pressure and tension test (risers only)<br>Dynamic tension-tension test (for new end-fitting design)<br>Sour service test |
| New installation system or more severe installation conditions | Crush strength test, combined bending and tensile test (if applicable) |
| Installation of new design or more severe installation conditions using horizontal laying spread | Combined bending and tension test, crush strength test |
| Critical fire protection requirements and untested design | Fire test or fire survival time conservatively calculated by a method validated by previous fire test results |
| Severe sand production and severe consequences of failure | Erosion test |
| Deepwater Application | Combined cyclic bending and axial compression test<br>Curved collapse test<br>Dynamic tension-tension test (risers only)<br>Outer sheath holding system test<br>External sealing system test |

### 7.5.2 Test Equipment

All test equipment and instrumentation shall be calibrated in accordance with the manufacturer quality system or external test facility quality system. Current certification and calibration certificates for all test equipment should be referenced in the test report and shall be made available to the purchaser or the IVA when applicable.

### 7.5.3 Test Procedures

If tests require variables (such as temperature or pressure) to be constant, the particular variable should be stabilized prior to commencement of the test. Stabilization shall be defined in the test procedure.

The necessity for pressure cycling the sample prior to test start-up should be evaluated by the manufacturer when structure accommodation (bedding-in) can affect the results. For example, in a burst test where deformation measurements are required, a minimum of three cycles (from zero to operating/design pressure as required) shall be performed as follows:

a) first cycle for structure accommodations (bedding-in);

b) second cycle for accurate measurements;

c) third cycle to verify measurements from second cycle;

d) the same could similarly apply for a tensile or a compression test.

The load application requirements are different for each test type and are discussed in the individual test descriptions. The load applications rate should be representative of the load application rate applied under factory and field acceptance testing, installation, and service conditions.

The number of tests should be agreed between the manufacturer and the purchaser, or the IVA when applicable, as part of the approval of the test protocol.

### 7.5.4 Accelerated Tests

Accelerated tests may be performed by increasing the following:

a) cyclic frequency,

b) internal pressure,

c) magnitude of movement,

d) temperature.

The manufacturer should provide documented evidence for accelerated tests that the variation in test parameter does not significantly affect the results or change the mode of failure and that the test period is satisfactory.

### 7.5.5 Multiple Tests

Single samples can be subjected to multiple tests, with nondestructive tests performed prior to a destructive test. The test sequence needs to be carefully evaluated to ensure that earlier tests do not affect the results of subsequent tests.

### 7.5.6 Posttest Examination

Posttest examination, which may include dissection, should be performed whenever a sample fails outside the acceptance criteria. Failure evaluations and abnormalities should be reported. All relevant items should be photographed. The examination document should include a written statement describing any failure mechanisms that were found in the test sample. Dissection may be required by purchaser in order to allow the investigation of unpredicted failure modes or mechanisms. If agreed with the purchaser, further investigation such as microscopy examination may be carried out in order to conclude on the failure mechanism and the root cause, as applicable.

### 7.5.7 Test Results

#### 7.5.7.1 Applicability of Results

Tests should as much as possible be carried out in a consistent manner, such that the results will be applicable to future designs. All test results should be available for verification of future designs. Tests should be conducted, where practical, such that the results and records could be accepted in lieu of repeated testing for other applications.

If possible, results at intermediate stages can also be used to define pipe properties, such as axial and bending stiffness, to avoid multiple tests.

#### 7.5.7.2 Comparison with Calculation Methodology

When possible, results of all tests, including results at intermediate stages, should be compared with the calculation methodology of the manufacturer. Discrepancies should be investigated and reported to the purchaser or the IVA when applicable.

#### 7.5.7.3 Validity of Test Results

Test results are valid unless a substantial change to the process (test procedure, design, or manufacturing process) invalidates the use of the results.

#### 7.5.7.4 Repeatability of Results

The design parameters and manufacturing tolerance parameters that affect the performance should define the bounds for the qualification achieved and should be accounted for in the definition of the acceptable application envelope when a single sample is tested. Application of the test results in design and analysis should use the critical parameters in a conservative manner.

### 7.5.8 Documentation

#### 7.5.8.1 Test Procedure

Before testing, the manufacturer should issue a detailed test procedure and/or specifications that should include the following items as a minimum:

a) type of tests to be performed;

b) schedule and duration of tests;

c) test descriptions (including sketches and equipment setup);

d) type and size of samples to be tested;

e) equipment descriptions (including accuracy, calibration, and sensitivity);

f) data forms to be filled during the tests; optional datalogger may negate the need to fill forms;

g) acceptance criteria;

h) predicted results and failure modes and mechanisms, where applicable;

i) references to applicable quality control procedures, codes, standards, etc.;

j) documentation of as-built dimensions and material strength, and traceability of used materials and welds, if available. If not they should be included in the test report;

k) a risk assessment and safety measures for each phase of the test

#### 7.5.8.2 Test Report

After testing, the manufacturer should issue a number of detailed test reports. These test reports should contain the following as a minimum:

a) final results and traceability to gathered data;

b) report on posttest examination or dissection, if applicable;

c) comparisons between predicted and observed values;

d) conclusions.

## 7.6 Procedures—Standard Prototype Tests

### 7.6.1 General

This subsection contains procedures for the standard Class I prototype tests, namely burst, axial tension, collapse, and temperature tests.

For high temperature applications, the design of the end-fitting sealing mechanism for unbonded pipe is critical. The test procedures are given in Annex A and Annex C for both static and dynamic applications.

### 7.6.2 Burst Test

#### 7.6.2.1 Purpose

The main purpose of a burst test is to determine the burst resistance of the flexible pipe.

A burst test can be used to achieve one or more of the following objectives:

a) qualify a flexible pipe for use up to a specified design pressure,

b) verify manufacturer stated burst resistance,

c) validate burst pressure design methodology and calculation tools, and

d) verify the pipe pressure deformation (axial and/or radial) and twist against design methodology and calculation tools.

These objectives can be achieved using a nondestructive test, provided that the internal pressure can be increased up to the specified pressure.

The burst pressure shall be calculated for both the pipe body and the end fitting. It is usually calculated based on nominal pipe dimensions and minimum guaranteed materials properties.

NOTE 1 A flexible pipe design may have its burst pressure deriving from pipe body or end-fitting resistance.

NOTE 2 A specific end fitting with a burst pressure higher than the pipe body can be used if the test is to validate the pipe body design methodology and tools.

NOTE 3 The burst pressure is not a design parameter (refer to API 17J, Section 5); however, a burst test is an appropriate way of demonstrating the structural capacity of a flexible pipe.

NOTE 4 Burst pressure is defined as the maximum pressure seen during the test.

#### 7.6.2.2 Procedure

The burst test should be performed with the specimen in a straight configuration. The minimum length of the test sample, excluding end fittings, should be either two times the pitch length of the outer armor wires/reinforcing cables for a straight configuration or three times the pitch length of the outer wires for a bent pipe. The test fluid is generally water.

The requirement for pressure cycling (see 7.5.3) should be considered prior to commencement of the burst test. It is recommended not to exceed 1 % air content

The first 50 % of the target load should be applied at a maximum rate of 1 %/s with no holding period prior to applying the balance of the load at a maximum rate of 5 %/min without holds as shown in Figure 12. Failure is defined by a sudden loss in pressure. The burst pressure, mode, and location of failure shall be noted. Internal pressure, pipe twist, and pipe elongation should be continuously monitored during the test.

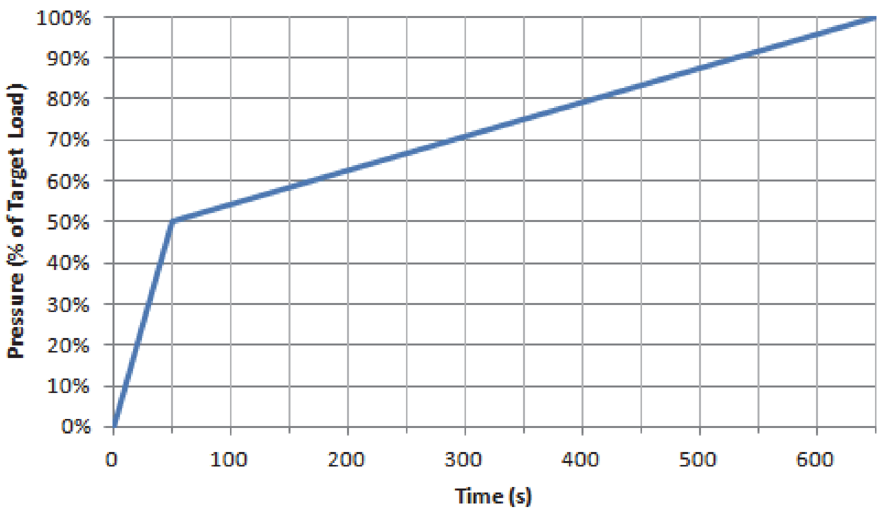



**Figure 12—Burst Test Allowable Pressure Rate**

#### 7.6.2.3 Acceptance Criteria

For a nondestructive test:

a) if the purpose of the test is to qualify a flexible pipe up to a specified design pressure, the maximum pressure seen during the test should be greater than 1.5 times the design pressure;

b) if the purpose of the test is to verify the manufacturer's stated burst pressure, the maximum pressure seen during the test should be greater than the stated burst pressure.

For a destructive test or for validation of design methodology or calculation tools the acceptance criteria are summarized in Table 23.

#### 7.6.2.4 Analytical Requirements

The effect of tension and bending on burst pressure should be analyzed.

#### 7.6.2.5 Alternatives

The burst test may be performed with the sample bent.

### 7.6.3 Axial Tension Test

#### 7.6.3.1 Purpose

The purpose of this test is to determine the damaging pull of a flexible pipe.

An axial tension test can be used to achieve one or more of the following objectives:

a) to qualify a flexible pipe for use up to a specified axial pull;

b) to verify manufacturer's stated flexible pipe tensile capacity and end-fitting anchoring system capacity;

c) to verify the pipe elongation, diametric deformation, and twist against design methodology and calculation tools; and

d) validate failure tension design methodology and calculation tools.

**Table 23—Design Acceptance for Calculated vs Measured Burst Pressure**

| Pipe Body Calculated Burst Pressure | End-fitting Calculated Burst Pressure | Design Acceptance |
|---|---|---|
| Burst pressure is above | Burst pressure is above | Accept both pipe body and end fitting |
| Burst pressure is above | Burst pressure is below | Accept pipe body<br>Change the end-fitting design or derate the pressure capacity<br>Investigate end-fitting failure mechanism and take corrective action |
| Burst pressure is below | Burst pressure is above | Accept end fitting<br>Change the pipe design or derate the pressure capacity<br>Investigate pipe failure mechanism and take corrective action |
| Burst pressure is below | Burst pressure is below | Neither pipe body or end fitting is accepted<br>Investigate failure mechanism and take corrective action |
| Does not burst or failure not due to burst, and is above | Does not burst or failure not due to burst, and is above | Accept both pipe body and end fitting |

These objectives can be achieved using a nondestructive test, provided that the axial tension can be increased up to the specified tension.

The tensile and anchoring system capacities shall be calculated for both the pipe body and the end fitting, respectively. It is usually calculated based on nominal pipe dimensions and minimum guaranteed materials properties.

A flexible pipe design may have its overall tensile capacity deriving from pipe body or end-fitting anchoring system. The pipe body tensile capacity may be derived from carcass/pressure armor collapse under tensile armors squeezing pressure or from tensile armors capacity.

#### 7.6.3.2 Procedure

The axial tension test should be performed with the specimen empty and free to twist. The minimum length of the test sample, excluding end fittings, should be two times the pitch length of the outer armoring wires/reinforcing cables. Pigs or other measurement devices can be used to check the change in diameter during or after the test.

One end of the sample is fixed and an axial load applied to the other end.

The load should be increased at a rate sufficiently low in order not to introduce shock load. Consideration should be given to load cycling and structural accommodation (bedding in) prior to testing. Guidance is given in 7.5.3.

The failure tension, mode, and location of failure should be noted. In addition, applied load, elongation, and twist of the sample should be continuously recorded. Failure tension is the maximum tensile load achieved during this test.

#### 7.6.3.3 Acceptance Criteria

For a nondestructive test:

a) if the purpose of the test is to qualify a pipe for use up to a specific axial pull, then no failure should occur below the specified axial pull;

b) if the purpose of the test is to verify manufacturer's stated flexible pipe tensile capacity and end-fitting anchoring system capacity, then no failure should occur before the stated capacity.

For a destructive test or for validation of design methodology or calculation tools, the acceptance criteria are summarized in Table 24.

**Table 24—Design Acceptance for Calculated vs Measured Failure Tension**

| Pipe Body Calculated Failure Tension | End-fitting Calculated Failure Tension | Design Acceptance |
|---|---|---|
| Failure tension is above | Failure tension is above | Accept both pipe body and end fitting |
| Failure tension is above | Failure tension is below | Accept pipe body<br>Change the end-fitting design or derate the tension capacity<br>End-fitting design methodology is invalidated |
| Failure tension is below | Failure tension is above | Accept end fitting<br>Change the pipe design or derate the tension capacity<br>Pipe design methodology is invalidated |
| Failure tension is below | Failure tension is below | Neither pipe body or end fitting is accepted<br>Design methodologies are invalidated |
| Does not fail or failure not due to tension, and is above | Does not fail or failure not due to tension, and is above | Accept both pipe body and end fitting |

#### 7.6.3.4 Analytical Requirements

The effect of internal pressure and fixing the ends from rotating on the failure tension should be analyzed.

#### 7.6.3.5 Alternatives

The axial tension test may be performed with the pipe full of water at design or a lower internal pressure. The internal pressure in this case should be continuously monitored during the test with sudden pressure drop (indicating an internal sealing failure) or reduction in tensile load taken as failure of the sample. The test may also be performed with the ends of the pipe fixed in rotation.

### 7.6.4 Collapse Test

#### 7.6.4.1 Purpose

The main purpose of this test is to determine the pipe collapse resistance to external pressure.

A collapse test can be used to achieve one or more of the following objectives:

a) qualify a flexible pipe for use up to a specified design water depth,

b) verify manufacturer stated collapse resistance, and

c) validate collapse pressure design methodology and calculation tools.

These objectives can be achieved using a nondestructive test, provided that the external pressure can be increased up to the specified pressure.

A hydrostatic pressure test can also be used to verify the adequacy of the end-fitting inner sealing system(s), for the external pressure.

#### 7.6.4.2 Procedure

The test setup should be such that the end fittings (or sealed simple end caps) are not exposed to external pressure or, if exposed, a rigid bar should be installed between the two ends to eliminate end-cap loads. The rigid bar may be omitted if the manufacturer wishes to demonstrate that the pipe design is suitable for compression loads. The minimum length of the sample, excluding end fittings, should be $5 \times \mathrm{ID}$.

For straight and bent collapse test, the outer sheath should be removed or perforated such that water ingress into the annulus of the pipe occurs prior to the test. Intermediate sheaths should also be removed or perforated, unless the pipe design is based on an impervious intermediate sheath. The sample should be at ambient internal pressure and may be empty or filled (partially or completely) with water. In general, water is used as the test fluid. For a straight collapse test, it is not necessary to include the tensile armor layers or the outer sheath in the sample.

For a bent collapse test, the tensile armor layers should be included if the complete pipe structure and end fitting is immersed inside a pressure vessel. The antibuckling tape layer and outer sheath may also be included. The sample should be bent to a specified radius and held in this configuration.

The external pressure may be applied at a maximum rate of 10.34 MPa/min (103.42 bar/min or 1500 psi/min) until failure occurs in the pipe.

Pressure holding periods may be included during the test, preferably at a pressure lower than the pipe water depth capacity.

Failure is defined as a sudden variation of the volumetric measurement or, depending on the test equipment, a sudden pressure loss.

The collapse pressure, mode, and location of failure should be noted.

#### 7.6.4.3 Acceptance Criteria

For a nondestructive test:

a) if the purpose of the test is to qualify a pipe for use up to a specific water depth, then no failure should occur below the specified design water depth divided by the allowable utilization factor used for the cross-section design;

b) if the purpose of the test is to verify manufacturer's stated collapse resistance, then no failure should occur before the stated resistance.

For a destructive test:

a) the collapse pressure should not be less than the design requirements specified in API 17J and API 17K;

b) if the purpose is validation of design methodology or calculation tools, the collapse pressure should not be less than the predicted collapse pressure.

A pipe design is also acceptable if it does not collapse or if failure is not by collapse at a pressure above the design requirement.

#### 7.6.4.4 Analytical Requirements

The effects of bending and ovalization on the collapse pressure shall be analyzed. A comparison of the predicted and test results shall be provided.

#### 7.6.4.5 Alternatives

The sample may include end fittings. The test may be performed with a leak-proof outer sheath or with support to prevent axial compression of the pipe. The test may also be performed with an axial tension load applied.

The collapse test can also be performed after nondestructive crush test and a bending and tension test which may ovalize pipe the cross-section. This determines the collapse resistance of the pipe post installation.

### 7.6.5 Temperature Test

Refer to Annex A and Annex C for thermal cycling test requirements.

## 7.7 Procedures—Special Prototype Tests

### 7.7.1 General

This subsection lists recommended procedures for Class II prototype tests, namely dynamic fatigue, crush strength, combined bending and tensile, sour service, fire, erosion, TFL, vacuum, kerosene, adhesion, and full-scale blistering tests.

### 7.7.2 Dynamic Fatigue Test

#### 7.7.2.1 Purpose

The main purpose of the dynamic fatigue test is to evaluate the structural fatigue performance of a flexible pipe.

A fatigue test can be used to achieve one or more of the following objectives:

a) qualify a flexible pipe for dynamic service,

b) verify manufacturer stated fatigue performance, and

c) validate service life design methodology and tools.

Each objective can be achieved with either destructive or nondestructive testing. Destructive testing provides data for validating service life design methodology and tools by comparing predictions of failure location, pipe layer, and fatigue damage to those of the actual failure. Nondestructive testing can also be used to validate manufacturer's design methodology and tools provided that: component stresses/strains are measured and component fatigue resistance is bounded by using a proved S-N curve with known and acceptable probability of failure. Once a flexible pipe is instrumented, series of measurements can be obtained for validating the tool predictions with confidence by demonstrating that the predicted stresses exceed the measured ones.

Nondestructive service simulation testing is based on:

1) calculated fatigue damage of the critical component at the critical pipe location,

2) bounded fatigue resistance (S-N curve) of the critical component, and

3) a target test fatigue damage of the critical component agreed upon between manufacturer and purchaser.

The target fatigue damage can be determined for either a specific or generic target application. Testing to the target fatigue damage without failure would either qualify the flexible pipe or verify manufacturer's stated performance.

#### 7.7.2.2 Procedure

The test sample comprises the assembly of pipe body, end fittings, fasteners, and all devices and components that simulate the riser top connection, and a bend stiffener/bellmouth if the pipe is subjected to cyclic bending.

A typical test setup consists of a pressurized pipe sample tensioned vertically or horizontally and force or displacement actuators to apply curvature and or tension variations at either end of the pipe sample (Figure 13). The horizontal setup would cause sagging between the pipe supports due to the dead weight of the sample, regardless of the tension level. The impact of sagging on pipe component stresses/strains needs to be accounted for. When sagging deflection is prevented by midspan pipe supports, care should be taken to avoid outer sheath wear and additional interlayer friction.

Different test load methods can be used: in-plane cyclic bending, resonant bending, or tension-tension. Maintaining constant pressure inside the pipe is recommended for all test methods, in order to capture the friction stress contribution to wire fatigue damage. In-plane bending would cause the maximum stress ranges in diametrically opposed wires in the bending plane. In in-plane bending, the curvature variations are imposed by a rocker arm at one of the sample ends, while applying constant or varying tension at the other end of the test sample. Resonant bending would cause the same maximum stress range on every wire around pipe layer circumference, while maintaining constant pressure in the test sample. Tensile-tensile or cyclic tension loading applied on straight test samples would cause the same maximum stress range on every wire around the pipe layer circumference.

The minimum length of the test sample, excluding end fittings, should be as follows:

1) the length between the lower end fitting and the bottom of the bend protection device should be at least three times the pitch of the outer armor wires/reinforcing cables;

2) the length between the top end fitting and the top of the bend protection device should be at least one pitch of the outer armor wires, unless the end fitting is attached to a bend stiffener.

The test sample should be subjected to maximum operating internal pressure for some period during the test. However, depending on the test load matrix, the pressure may be changed to simulate periods of normal operation (possibly several pressures), shutdown, or other relevant conditions.

In in-plane bending, bend stiffeners can be attached to one of the sample end fittings, provided that the end fitting has similar to or more conservative fatigue design than the pipe body. Bend stiffeners different from the ones used in service may be used to shorten the test duration by simulating curvature ranges exceeding those expected in operation. As an alternative, a pipe without a bend stiffener may be tested if the setup includes a suitable bellmouth.

The cyclic loading of the test sample should be divided into a number of blocks each with specified loading amplitude, frequency, and number of cycles. The frequency for each load case should be specified by the manufacturer. Typically, the frequency increases as the loading amplitude is reduced. A higher frequency and amplitude can reduce the test duration but may generate an unacceptable temperature increase in the flexible pipe because of friction between the layers, or in the bend stiffener. Local test site conditions, including temperature, machinery, and cooling requirements, will influence the cycling rate. Monitoring of the temperature at critical locations during the test is recommended to determine the cycling rate. Typical considerations in selection of the test parameters are given in Table 25.

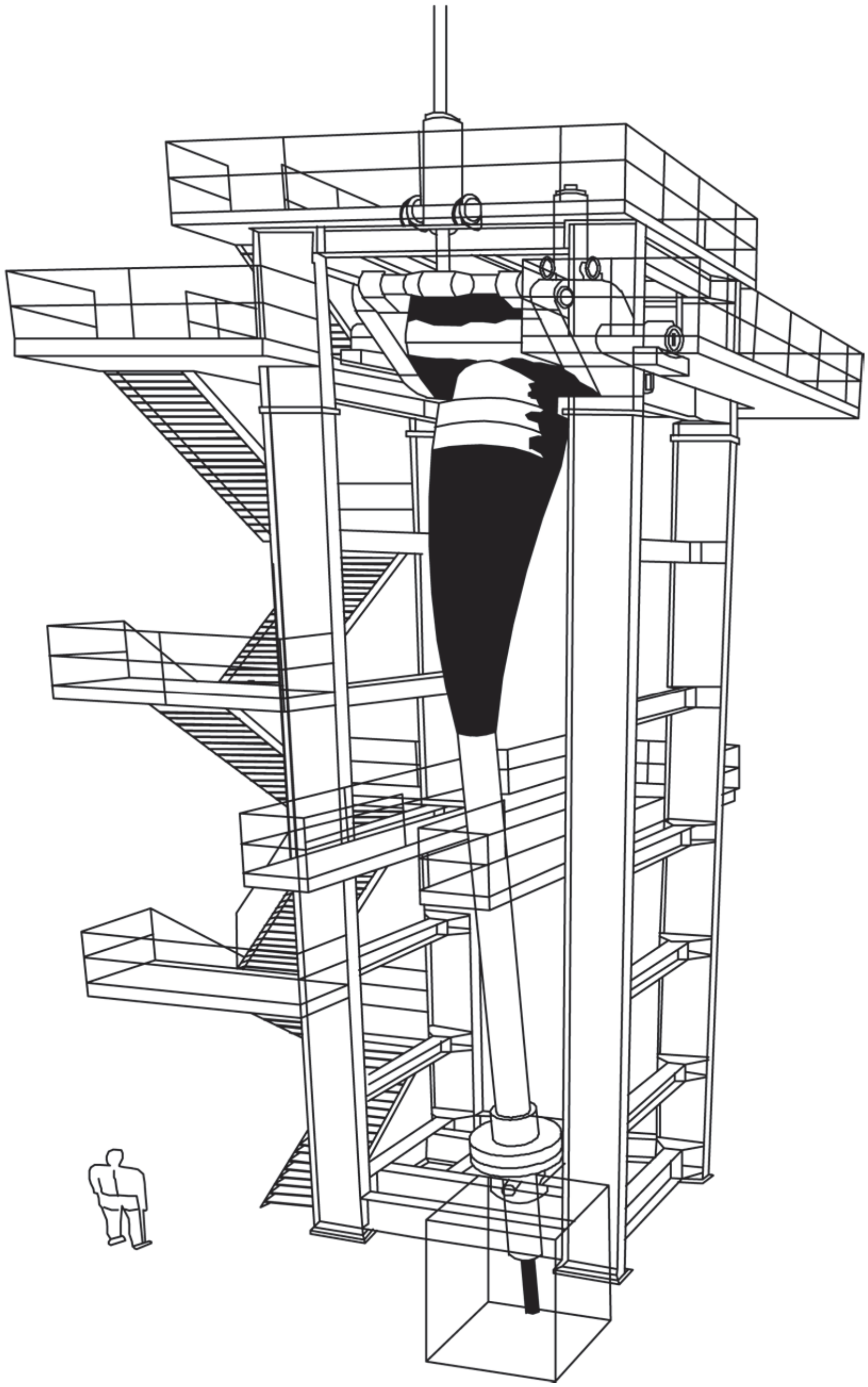


**Figure 13—Typical Setup for a Dynamic Fatigue Test**

**Table 25—Dynamic Fatigue Test Parameters**

| Parameter | Comment |
|---|---|
| Mean angle | Representative of flexible pipe static vessel hangoff angle |
| Cyclic angle amplitude | Selected to achieve desired curvature ranges |
| Tension amplitude | Selected to achieve desired tension ranges |
| No. of cycles | Representative of no of cycles of a given fatigue scatter diagram |
| Cycle frequency | Ideally, frequency of incident seastate. However, it may be accelerated to reduce the test duration |

Typically, 1 million cycles is needed to achieve the cumulative fatigue damage of 0.1. The test load matrix needs to be based on the load levels expected during the service life. The difference in annulus environment between test and field conditions should be considered in comparing the test damage with the field damage. The loading should be applied either randomly or in groups of a specified percentage of all of the load blocks.

Typically, for a nondestructive test the cumulative number of cycles in all blocks is up to 2 million. For a destructive test, the damage phase of the test may require up to 400,000 cycles, although for the damage phase other issues should be considered such as the level of stresses (should not exceed the material yield point) or the level of loading (should not exceed the pipe design methodology envelope).

The target test fatigue damage can be achieved by varying wire mean stress, stress range, and number of cycles of each test block. Variation of mean wire stress can be achieved by varying the mean tensile load and the test pressure. Variation of wire stress range can be achieved by varying curvature range and/or tension range. Test acceleration would require selection of test load blocks that impose wire mean stress and/or stress ranges exceeding those expected in operation. Consideration should be given to layer wear and pressure armor fretting.

Nondestructive inspection (typically, X-ray) may be conducted periodically to check for damage to the structural layers in the critical zones. Strain gauges, acoustic emission, and accelerometers may be used to detect tensile armor initial ruptures so as to ensure recording of data that may otherwise be lost should destruction of the sample occur. Strain gauge readings can be taken for validation of fatigue design methodology and tools, or to indicate proximity to the target test fatigue damage ratio.

The following variables should be continuously recorded:

a) number of cycles,

b) internal temperature,

c) external ambient temperature,

d) internal pressure,

e) applied tension load,

f) cyclic loading range,

g) pipe deflection angle.

The end of the service simulation dynamic fatigue test program is defined as failure of the pipe (either loss of pressure containment, or structural component failure) or, alternatively, successful completion of all cycles. The sample should be subsequently pressure tested at a minimum of 1.25 times the design pressure if fatigue failure of the pipe does not occur. Then the pipe should be inspected to verify the condition of the pipe or the structural layers. The service simulation test can then be followed by a verification test.

After the test, the sample shall be inspected for armor rupture or disorganization in the pipe body and/or pull-out or displacement inside the end fitting. In order to allow comparisons, the sample should be inspected before starting the test.

A layer-by-layer dissection of the test sample should be conducted to record the condition and evidence of degradation of the armor wires in the pipe body or end fitting. Layers that show signs of damage should be subjected to detailed examination.

#### 7.7.2.3 Acceptance Criteria

The target test fatigue damage should be determined from the design S-N curve of the fatigue critical component that provides a 97.5 % probability of survival. For dynamic service, API 17J requires that pipes are designed with a FOS of 10 against fatigue over the service life. Thus, the minimum target test fatigue damage ratio should be determined after ensuring that:

1) service life load uncertainties have been adequately bounded, and

2) the FOS is applied on the loads predicted during the service life.

Testing to the target test fatigue damage ratio of 1.0 is recommended, as it is the only way to ascertain the flexible pipe was designed with a FOS of 10 without taking any measurements. The alternative way to ascertain the flexible pipe was designed with a FOS of 10 is to take stress measurements on the critical fatigue component to ensure that the actual test stresses achieved are equal to or exceed the stresses from which the minimum target fatigue damage ratio is calculated. Consideration should be given to avoid unwanted stress raisers when attaching strain gauges or other stress/strain measuring devices.

No loss of pressure containment should normally occur before reaching the target test fatigue damage ratio. Note however that the design S-N curve is based on fatigue test data with statistically significant lower bound design curve that provides a 97.5 % probability of survival. Consequently, some armor wire failures may occur due to the statistical spread of material properties before reaching the damage ratio of 1.0.

A statistical criterion based on allowable number of broken wires may be mutually agreed between the manufacturer and the purchaser.

The pipe should have passed the test sequence without leakage or failure of the pipe structural layers as defined in Table 26. See 11.3 for other failure mechanisms that may be considered to affect the integrity of the pipe structure. A test pipe that has been through a service simulation test is expected to suffer some layer degradation from the as-built condition. The acceptance criteria for each layer should be clearly agreed between the purchaser and manufacturer prior to the start of the initial dynamic test.

The acceptance criteria for destructive testing are: pipe leakage, failure of the pipe structural layers as defined Table 26, or other criteria agreed upon between manufacturer and purchaser.

#### 7.7.2.4 Analytical Requirements

The results of this test indicate the number of cycles per class without failure of the pipe structure, end fitting, or bend stiffener and documentation of the dissection. A comparison of the predicted and actual results based on the service life analysis should also be provided. This information can be used to estimate the lifetime of a particular riser design for the expected history of floater motion and environmental conditions.

**Table 26—Layer Failure Definition**

| Layer | Failure Definition |
|---|---|
| Internal carcass | Throughwall crack or loss of interlock that would cause pipe collapse or damage to the pressure sheath if the pipe was bent to the storage bend radius (SBR) in any plane. |
| Pressure sheath | Through thickness crack. |
| Pressure armor | Through-wall crack or loss of interlock that would cause failure of the internal pressure sheath if the pipe was bent to the SBR in any plane. |
| Tensile armor | Torsion imbalance greater than 1 °/m in the field hydrotest (one end free to rotate).<br>Presence of armor wire broken or cracked, inside or outside the end fitting, which is demonstrated, by inspection, not to be due to the presence of a local wire defect. |
| High strength tape | Excessive wear leading to significant strength reduction and potential radial wire buckling, where applicable. |

#### 7.7.2.5 Alternatives

The procedure described in 7.7.2.2 focuses on fatigue at a riser top connection. Alternative test setups may be required if other sections of the riser are considered critical, such as riser sag bend or seabed touchdown region for catenary risers. In this particular test configuration, the following parameters may be altered:

a) internal pressure,

b) internal temperature,

c) mean curvature and/or tension,

d) cyclic loading amplitude,

e) number of cycles.

In addition, strain in the outer tensile wires/reinforcing cables may be recorded.

### 7.7.3 Crush Strength Test

#### 7.7.3.1 Purpose

The purpose of the crush strength test is to determine the crush resistance of a flexible pipe.

A crush strength test can be used to achieve one or more of the following objectives:

1) qualify a flexible pipe for use with a specified installation spread,
2) verify manufacturer stated crush strength, and
3) validate crush design methodology and calculation tools.

There are two parameters of interest (i.e. tensile load and crushing force).

#### 7.7.3.2 Procedure

The test setup should represent the tensioner system on the particular installation vessel. In particular, the number of belts and geometry of shoes should be comparable. The minimum length of the sample should be two times the pitch length of the outer armoring wire when tensile loads are applied.

The flexible pipe sample should be positioned, empty without internal pressure, on the test device. The crushing load is increased from zero up to required clamping load determined by the manufacturer at a rate not greater than 1 % of the maximum load per second (1 %/s). The clamping load should be kept constant (within ±2 %) for a period of at least 1 h. The ovalization of the pipe (based on variation of ID) should be measured before loading, at maximum loading and after unloading (the third measurement as applicable for a proof test only).

#### 7.7.3.3 Acceptance Criteria

If the objective of the test is to qualify a flexible pipe for use with a specified installation spread, the measured ovalization after unloading shall meet the permissible utilizations in API 17J and API 17K, considering the maximum specified water depth. See 5.4.1.8 for guidance on the maximum permissible ovalization.

If the objective of the test is to validate the manufacturer’s design methodology, the max crushing load should be greater than that predicted by design methodology.

If the objective of the test is to verify the manufacturer’s stated crush strength, the calculated collapse resistance, for the measured ovalization after unloading shall meet the permissible utilizations in API 17J and API 17K, considering the maximum specified water depth.

A crush strength test may be followed by a collapse test, as per 7.6.4.

#### 7.7.3.4 Analytical Requirements

The effect of tensile load on the crush strength of the flexible pipe should be analyzed.

#### 7.7.3.5 Alternatives

The crush strength test may be performed with a tensile load applied. It is recommended that the tensile load be at least the design installation tension and be applied prior to the compression load at a rate not to exceed 1 % of the load per second. Also, the crushing load could be increased in steps until the acceptance criteria are exceeded, so as to determine the maximum crushing capacity of the pipe.

### 7.7.4 Combined Bending and Tension Test

#### 7.7.4.1 Purpose

The purpose of a combined bending and tension test is to verify the installation of a particular flexible pipe design with a horizontal or a reel tensioned installation spread.

This test simulates the passage of the pipe over the sheave or chute of an installation vessel. It is not necessary in this test for the sample to include production type end fittings. The terminations need only be capable of transferring tensile load to the flexible pipe.

#### 7.7.4.2 Procedure

The test sample should be positioned, empty, at ambient internal pressure, on an arch that simulates the radius of curvature and cross section of the pipe laying sheave or chute of the installation vessel. The sample should also be connected to a suitable tensile load machine. The straight section of pipe connected to the tensile load machine should be at least the length of the pipe bent over the sheave or chute.

The axial load is applied at a rate not greater than 1 % of the design installation tension per second up to 110 % of the design tension (up to max installation tension for a proof test). The allowable variation in the design tension should be ±2 %. This load is held for a minimum period of 1 h.

The diameter of the pipe is measured at two locations on the pipe circumference in the curved section of the pipe, with one measurement location being perpendicular to the contact face of the pipe where the minimum diameter is expected, and the other being parallel to the contact face of the pipe where the maximum diameter is expected. The selected measurement locations should be based on the sheave and chute type (i.e. “V” or “U”). The tensile load is released, and the diameter measurements retaken.

#### 7.7.4.3 Acceptance Criteria

The variations in the external diameter shall be within allowable values agreed between purchaser and manufacturer based on manufacturers design predictions.

a) The ovality criteria can also be based on internal diameter, which can be measured postdissection.

b) A higher ovality can be acceptable, provided it is accounted for in the design calculations such as collapse.

#### 7.7.4.4 Analytical Requirements

The effect of different sheave bend radii and tensile loads on the pipe deformation should be analyzed.

#### 7.7.4.5 Alternatives

After completion of the above test, the tensile load may be increased in steps not greater than 1 % of the design installation tension per second until the acceptance criteria above are exceeded. This is defined as the failure installation tension.

A collapse test may be performed after this test.

### 7.7.5 Sour Service Test

#### 7.7.5.1 Purpose

The purpose of a sour service test is to verify the performance of a full-scale pipe in sour service conditions representative of the operational conditions.

This test comes in addition to bench tests of the steel wire/cable materials and is used to generate a realistic sour service environment in the pipe annulus (unbonded) containing the steel wires and at the cable surface (bonded), and in addition simulate wire loading conditions by flexing the pipe.

#### 7.7.5.2 Procedure

The test sample should include end fittings identical to those proposed for the application.

For a dynamic service simulation the pipe can be installed in a horizontal flexing frame, producing known alternating stresses. One or both pipe ends could require bend stiffeners installed to control curvature. The pipe to be tested has to be sited in a facility suitable for large-scale sour service testing. This normally comprises a concrete bunker or an enclosed space with extraction ventilation in accordance with local health and safety regulations.

The tests will normally be carried out while simulating a wet annulus for unbonded pipe, either with salt water to test the failure condition or with fresh water to simulate normal operating conditions assuming shutdowns have caused condensation. Rubberized cables will normally be used for bonded pipe tests.

Exposure of the flexible pipe armor wires/reinforcing cables to $H_2S$ and $CO_2$ can be achieved by two approaches as follows:

1) injection of a known concentration of $H_2S/CO_2$ into the wet annulus directly, at a predetermined rate;

2) injection of the known $H_2S/CO_2$ concentration into the pipe bore at a predetermined rate and allowing the annulus/cable surface to reach an equilibrium state from permeation through the internal pressure sheath.

In either case it is necessary to carry out a prediction of the steady state annulus/cable surface conditions based upon a diffusion/corrosion model agreed upon with the flexible pipe manufacturer.

NOTE 1 Only Approach 2) is relevant to bonded flexible pipe.

NOTE 2 Tests based on injection into the pipe bore are preferred, because the diffusion of $H_2S$ and $CO_2$ correctly models pipes in service.

NOTE 3 The test fluid characteristics may simulate service conditions for the pipe product, or be in accordance with NACE TM 01-77 if a general qualification is sought. The test should be designed to obtain saturation of the steel components in the annulus of the pipe or at the surface of the cable to a level at least equal to the design partial pressure [in the annulus/pipe bore (bonded)] of $H_2S$ and $CO_2$. The internal fluid in the pipe should be at design pressure.

NOTE 4 The fluid temperature is recommended to be approximately 25 °C (77 °F), unless operational temperature is expected to be considerably less, in which case the operating temperature should be used.

NOTE 5 It is likely that to achieve steady state in a reasonable period of time (2 months to 3 months), an artificially high concentration will be necessary for an initial period to accelerate stabilization, unless the concentration of $H_2S$ is high. Prediction of the stabilization process should also be made using a consistent diffusion/corrosion model agreed upon with the manufacturer. The duration of the static test shall be determined from small-scale wire tests. The duration of the fatigue test shall be determined by accounting for the effect of the testing frequency on the wires corrosion processes.

Sampling of fluid from the pipe outlet (annulus/bore) is required to determine the consumption of $H_2S$ and $CO_2$. Where injection is into the bore, sampling of the annulus is also required.

The test solution will then be continuously injected for a given period of time after equilibrium is reached to determine either the corrosion rate (static pipes) or fatigue performance (dynamic pipes).

For dynamic service pipe the test is typically carried out in two stages:

1) injection of $H_2S/CO_2$ while the pipe is static;

2) then once the desired equilibrium is reached, flexure of the pipe, producing known alternating stresses; the alternating stresses should be representative of the stress range blocks modelled in a dynamic fatigue program, adjusted so as to generate a known level of fatigue damage in the wires/cables.

The pipe should be pressure-tested to 1.25 times design pressure and then dissected at the end of the exposure test.

The test pressure depends on whether burst test data is required, which may be most appropriate for static flowlines, or if remaining fatigue life data is required. In the latter case, appropriate to dynamic risers, a pressure test is not required and the pipe should be dissected and wire samples bench tested for remaining fatigue life compared to new unexposed formed wires.

A burst pressure test should be carried out in stages, raising the pressure by 20 % of design (or lesser steps if desired) from the exposure test pressure, with a hold time of at least 3 h between each step. The fluid in the pipe should be clean of $H_2S$, while precautions should still be maintained for $H_2S$ due to release of the gas when burst occurs.

#### 7.7.5.3 Acceptance Criteria

For static pipe tests, the predicted burst pressure over the service life based on the decay of the burst pressure over time because of corrosion shall not be less than the design pressure divided by the allowable utilization factor that was used for the cross-section design.

For dynamic pipe tests, the predicted armor wire fatigue life shall meet the acceptance criteria of 7.7.2.3.

#### 7.7.5.4 Analytical Requirements

An analytical model should be available for the corrosion rate and the loading conditions (including annulus environment and the service life assessment) that has been accepted by both manufacturer and user prior to the tests.

### 7.7.6 Fire Test

#### 7.7.6.1 Purpose

The objective of the fire test is to determine the time to loss of containment for the flexible pipe in a particular fire situation. The fire resistance can be designed into the pipe structure or may be achieved by nonintegral passive fire protection.

#### 7.7.6.2 Procedure

The fire test may be carried out to the conditions defined in Lloyd's Register Recommended Test, 00/OSG 1000/499 Rev.1 [50]. These can be summarized as a fire temperature of 700 °C (1292 °F) and a fire duration of 30 min. Generally, a fire resistant blanket is needed for an unbonded flexible pipe to pass this test. The fire resistant blanket should be installed identically to the field installation prior to conducting the test.

The pipe should be tested at the design pressure. The pipe internal fluid may be water or another agreed fluid. The fluid should be stationary to simulate worst-case loading conditions. The end-fitting design to be used in the application should be used in the test sample.

The pipe is pressurized to the design pressure. The fire test should commence once pressure stabilization occurs. Both the flexible pipe body and end fitting should be subjected to the required test conditions. Pressure in excess of the design pressure may be relieved.

Pipe failure should be considered to have occurred if the pressure in the pipe drops below 90 % of the test pressure. The survival time is then defined by the time from fire start-up to pipe failure.

#### 7.7.6.3 Acceptance Criteria

The survival time should exceed the design requirements.

#### 7.7.6.4 Analytical Requirements

There are no analytical requirements for this test.

#### 7.7.6.5 Alternatives

Alternatively, the test setup may be in accordance with DNV GL IMO Resolution A 753 (18) (furnace or propane burners). The flame temperature should be based on the worst-case likely fire loading condition. Typical flame temperatures for a jet fire are approximately 1100 °C (2012 °F) and for a pool fire are approximately 1000 °C (1832 °F), specifically for a pipe engulfed by flames. Flame temperatures of 400 °C to 600 °C (752 °F to 1112 °F) can be appropriate if the pipe is not engulfed.

### 7.7.7 Erosion Test

#### 7.7.7.1 Purpose

The purpose of the erosion test is to determine the erosion rate of the innermost flexible pipe layer under flow conditions representative of (or conservative with respect to) design conditions.

#### 7.7.7.2 Procedure

A typical test setup for an erosion test is shown in Figure 14. The test sample should be fixed at its MBR in a 90° angle. Erosion rates can be determined by thickness reduction (localized erosion rate) or by weight loss (average erosion rate) in the internal carcass or internal pressure sheath for smooth bore pipes.

The internal fluid composition should represent design conditions or be conservative. Consideration should be given to the following:

a) flow rate,

b) sand content,

c) particle size,

d) temperature,

e) pressure,

f) corrosive gas content.

The test fluid should be circulated through the flexible pipe for a minimum of 7 days. Erosion measurements should, as a minimum, be made at five points around the bend (0°, 15°, 30°, 45°, and 90° measurement points are recommended) after completion of the test.

#### 7.7.7.3 Acceptance Criteria

The erosion rate should be such that the collapse pressure is not reduced below the design value for the specified service life. In addition, for a smooth bore pipe the liner thickness is not reduced below the design value for the specified service life.

#### 7.7.7.4 Analytical Requirements

The effect of variations in the test fluid composition, flow rate, and pipe bend radius should be analyzed.

#### 7.7.7.5 Alternatives

The effect of corrosive fluids on the erosion rate may be tested to determine corrosion-enhanced erosion rates.

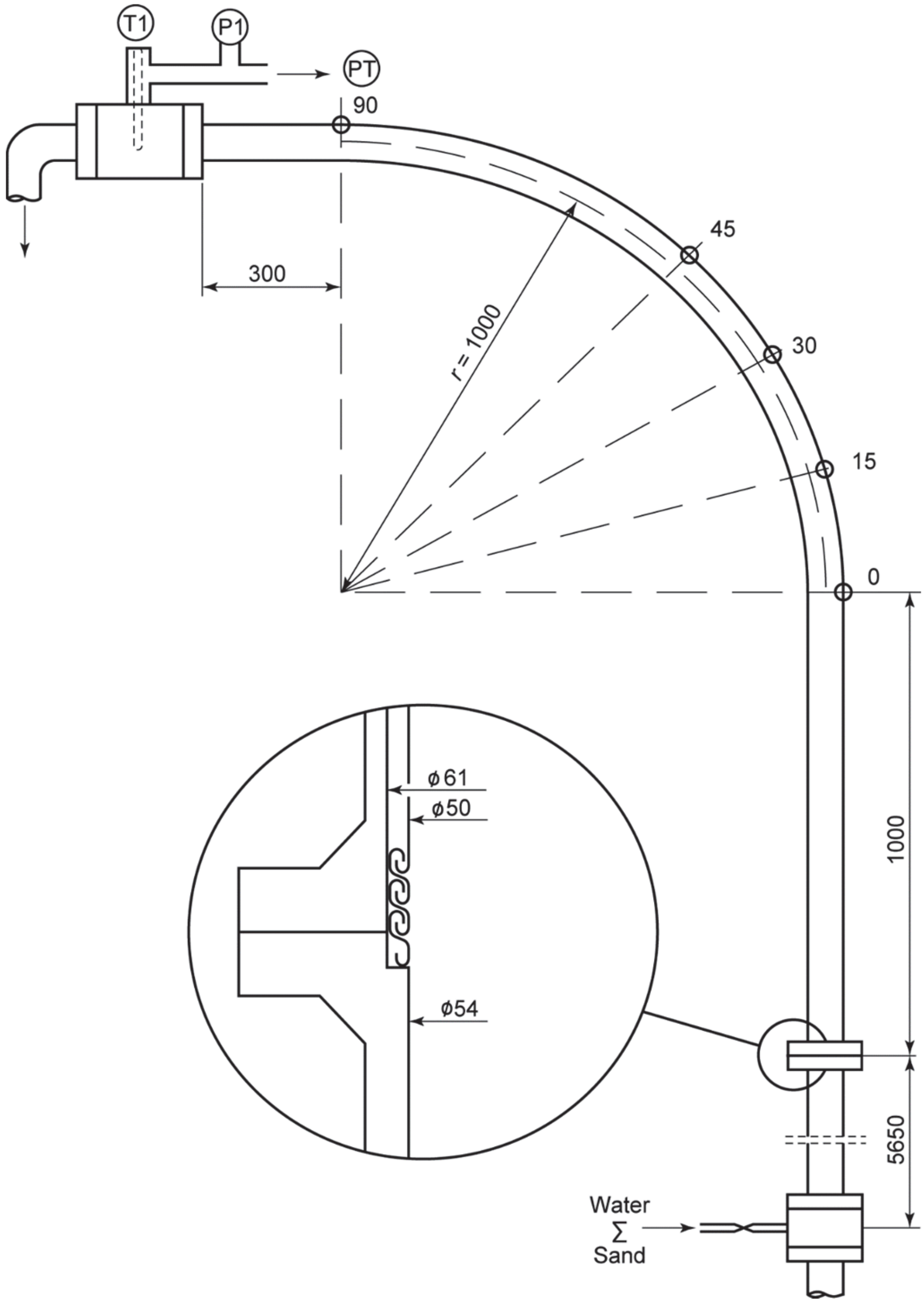



**Figure 14—Schematic of Setup for the Erosion Test [12]**

### 7.7.8 TFL Test

#### 7.7.8.1 Purpose

The purposes of the TFL test are to verify that TFL pumpdown tools adequately drift through the flexible pipe and to determine flexible pipe wear rates because of repeated tool travel. The test unit simulates a TFL pipe run using a flexible pipe that is 45.72 m (150 ft) long.

#### 7.7.8.2 Procedure

The pipe is attached to both ends of a pump and manifold unit that provides measurable hydraulic fluid power and a means for reversing the fluid direction inside the pipe. The flexible pipe is laid out in two configurations corresponding to the minimum storage bend radius (SBR) and minimum operating bend radius.

A TFL pumpdown tool string is inserted in the pipe prior to hookup. The TFL tool string should consist of four “up” locomotives, four “down” locomotives, and a running tool. The running tool can be either a TFL drift mandrel or two “sharp shouldered” drift mandrels, in which the first drift’s spring-loaded keys are oriented 90° out from behind the second drift’s keys. Both running tools should be run through both test configurations and cycled through the pipe several times.

If specialized running tools for an application are known (such as paraffin scraper, sand wash wand, or “kick-over” tool), then it is recommended to run these tools in the test loop as well.

#### 7.7.8.3 Acceptance Criteria

In general, the TFL drift mandrel tool string should be able to pass freely through the pipe in either direction (see API 17C for drift mandrel dimensions, forces, and pressures). The tool strings and the pipe interior should be inspected for adverse wear or damage after the tests are completed.

### 7.7.9 Vacuum Test

#### 7.7.9.1 Purpose

The vacuum test is intended for bonded flexible pipes only. The objective of the vacuum test is to indicate the adequacy of the bond strength of the liner to other pipe layers.

The vacuum test is not applicable to pipes in which an internal steel interlocked carcass is used. In addition, the vacuum test is possibly not practical for long length [>11 m (36 ft)] or small diameter pipes.

#### 7.7.9.2 Procedure

The pipe should be vacuum tested to a pressure of 85 kPa (0.85 bar) gauge and held for a 10 min period.

A clear plastic window should be fitted at either end of the test sample so that visual inspection of the interior can be made by an adequate light source in one end with its beam directed to the other.

#### 7.7.9.3 Acceptance Criteria

Collapse of the pipe liner, failure of adhesion between layers within the pipe body, blisters, and other deformities should not occur.

The pipe should be examined outside as well as inside for any possible deformities.

#### 7.7.9.4 Analytical Requirements

There are no analytical requirements for this test.

#### 7.7.9.5 Alternatives

This test can be carried out within 24 h of the kerosene test to determine the resistance of the pipe to permeation or migration of fluids or gases. The vacuum test “pulls” the kerosene out of the pipe body if significant permeation or migration has occurred.

### 7.7.10 Kerosene Test

#### 7.7.10.1 Purpose

The prototype test is intended for bonded flexible pipes only. The objective of the kerosene test is to detect any permeation or leakage of a hydrocarbon liquid through the pipe liner.

This test is primarily for bonded flexible pipe with no internal interlocked steel carcass.

#### 7.7.10.2 Procedure

The pipe should be laid out straight and filled with kerosene venting all air. The pipe should then be pressurized to the design pressure and held at this pressure for 24 h.

Consideration should be given to cycling the pressure, prior to initiating the test, to help stabilize the pressure over the 24 h period.

This test may be followed immediately by a vacuum test to further detect any residual kerosene that may have migrated into the pipe body.

#### 7.7.10.3 Acceptance Criteria

After 24 h, the pipe should be depressurized, drained, dried, and observed for any blistering, leakage, or separation of the liner from the carcass or from the end fitting.

#### 7.7.10.4 Analytical Requirements

An analytical model for the permeation of fluids or gases should be available and accepted by both manufacturer and purchaser prior to the tests.

#### 7.7.10.5 Alternatives

A vacuum test should be performed after completion of the kerosene test to further detect the permeation or migration of fluids or gases into the pipe body.

### 7.7.11 Adhesion Test

#### 7.7.11.1 Purpose

This prototype test is intended for bonded flexible pipe only. The adhesion test is used to verify the bond strength of the manufactured pipe.

#### 7.7.11.2 Procedure

Adhesion tests should be performed on samples made from materials taken from current manufacture and on samples representative of every tenth hose thereafter (in the case of specific lengths).

Samples should be built with the same cross-section makeup as the production pipe and should be built at the same time as the production pipe or as agreed on by the purchaser and manufacturer. The sample piece may be built with the cables at the reinforcing layer wound in the radial direction (i.e. a lay angle of 90° to pipe longitudinal axis) to facilitate this test. Vulcanization should occur under the same conditions as the production pipe.

Adhesion tests should be carried out according to either ASTM D413 Machine Method [17] or BS 903, Part A12 [25] using strip pieces.

#### 7.7.11.3 Acceptance

The measured adhesion strength should not be less than 6 N/mm.

### 7.7.12 Full-scale Blistering Test

#### 7.7.12.1 Purpose

This prototype test is intended for bonded flexible pipe only. The full-scale blistering test is performed to determine the suitability of a particular pipe design for service in a gas-containing environment and hence qualify the materials used for service.

#### 7.7.12.2 Procedure

The pressure, depressurization rate, temperature, and fluid type should, as a minimum, be consistent with conditions the pipe is expected to be subjected to during a typical application. It is preferable to use an inert gas of similar molecular structure as the gas expected to be conveyed and with a minimum $CO_2$ content of 5 %.

The test pipe should be at least 3 m (9.84 ft) long including end fittings or sufficiently long as to ensure that any beneficial effects the end fittings have on influencing the outcome are eliminated.

The manufacturer should have documented procedures to ensure that the test gas occupies 100 % of the internal pipe volume. Once the pipe is filled with the test gas, the pressure should be gradually increased at a rate not greater than the manufacturer’s test procedure, to the design pressure, and held for a period of at least 2 h to allow for stabilization. If necessary, the pressure shall be considered stabilized when the pressure drop is less than 1 % in a 1 h period. The pressure should be cycled to this pressure until stabilization is achieved. The pipe should then be held at this pressure to ensure saturation of the pipe body with gas for a length of time not shorter than that of the manufacturer’s test procedure.

Once saturation of the pipe body is achieved, the pipe should be depressurized at a rate equal to the expected depressurization rate or else a minimum of 7 MPa/min (70 bar/min). A lower depressurization rate is acceptable for pressure values below 10 % of the starting pressure.

The procedures set out above should be repeated for the expected number of cycles or a minimum of 60 cycles.

Once the test is complete, the end fittings should be cut off the test pipe, the pipe body should be cut in half lengthwise, and the half shells cut radially into three approximately equal lengths. The carcass layer should be removed to expose the elastomer surface beneath it.

#### 7.7.12.3 Acceptance Criteria

When the sample pieces are inspected on all surfaces at 1x magnification, there should be no evidence of delamination, blistering, or voids in the elastomer layers.

#### 7.7.12.4 Analytical Requirements

The soak time should be computed based on the measured permeability and solubility of the elastomer to the gas under consideration.

#### 7.7.12.5 Alternatives

Small-scale blistering resistance tests that reflect the design requirements, relating in particular to fluid conditions, pressure, temperature, number of depressurizations, and depressurization rate, may be performed (see API 17K) as an alternative to this test.

In addition, the full-scale prototype test piece can be used to measure adhesion of the elastomer to the end fitting once the blistering test is completed. The full-scale blistering test can also be carried out on the pipe after it has been used in a full-scale fatigue test program.

### 7.7.13 Combined Pressure and Tensile Test

#### 7.7.13.1 Purpose

A test for riser applications only. The purpose of the test is to verify, for a specified application, that the pipe has sufficient capacity to withstand max loading and conform with design criteria.

#### 7.7.13.2 Procedure

One end of the sample is fixed and the other end is free to rotate. A straight sample shall be mounted full of water (no internal pressure), in a suitable test device.

Internal pressure is then set to the maximum operating pressure (pressurization rate not exceeding 10 MPa/min) and kept constant during the test within the range (−0/+20 %). Internal pressure and temperatures shall be continuously monitored and recorded during the whole test period.

The sample is axially loaded in steps, at a rate not exceeding 300 kN/min, until the design tension (calculated from the global analysis, for normal operation conditions) is achieved.

During loading and after unloading, the following parameters shall be recorded:

a) sample longitudinal elongation;

b) sample twist.

After removing the outer sheath at the middle of the sample, the external diameter and perimeter is measured over the outermost tensile armor or holding bandage. As an alternative, after the measurements are taken, sample is tensioned up to failure.

#### 7.7.13.3 Acceptance Criteria

Measured longitudinal elongation, horizontal and vertical diametric deformations, and twist, for loaded (design tension) and unloaded conditions, shall be in accordance with manufacturer predictions.

No structural damage of the end fitting itself (e.g. cracking or rupture of its structure) or of pipe layers (e.g. wire rupture) shall be observed before the test maximum tension load is achieved [i.e. up to the design tension divided by the utilization factor (refer to Table 8 of API 17J)].

### 7.7.14 Outer Sheath Holding System Test

#### 7.7.14.1 Purpose

A test for deepwater unbonded flexible pipe riser applications only, to check the outer sheath/end-fitting interface under high tension load.

#### 7.7.14.2 Procedure

The test sample, including end fittings, shall have its outer sheath pulled out in its longitudinal direction by means of a traction system. This system shall not compress the outer sheath against the sample internal layers, allowing free sliding of this layer when it is under tension load.

The load shall be increased gradually up until outer sheath rupture occurs. The load shall be increased at a rate no greater than 300 kN/min.

During the test, the following parameters shall be monitored and recorded:

a) outer sheath elongation,

b) tension load,

c) ambient temperature.

#### 7.7.14.3 Acceptance Criteria

Outer sheath shall tear. Brittle failure or slippage from the end fitting is not acceptable.

### 7.7.15 External Sealing System Test

#### 7.7.15.1 Purpose

The purpose of this test is to verify the adequacy of the external sealing system of the unbonded flexible pipe end fitting after a pipe sample is subjected to a tension representative of a typical pipe installation load.

#### 7.7.15.2 Procedure

The test is performed in two stages as follows.

1) The test sample with end fittings assembled in both extremities shall have one end fitting fixed at the test bench while the other is pulled out in its longitudinal direction by means of a traction system. When representative of the installation simulation, the test bench should have a curved structure so to impose a curvature to the sample, thus subjecting the outer sheath to a maximum strain at its interface with the end-fitting sealing system.

   The sample is tensioned gradually at a maximum rate 100 kN/min, step by step, until a representative installation tension load on the sample is achieved.

2) With the sample inside the hyperbaric chamber, the external pressure is increased at a maximum rate of 10 MPa/min until a value between 1.0 times and 1.2 times the design external pressure. The pressure is kept within this range during a minimum 24-h period, after confirmed stabilization.

During both stages, ambient temperature and loading shall be continuously monitored and registered.

#### 7.7.15.3 Acceptance Criteria

There shall be no leakage detected during the 24-h period. No water ingress shall be detected after sample dissection.

### 7.7.16 Vent Valve Test

#### 7.7.16.1 Purpose

The purpose of the test is to confirm the long-term performance of the valves.

#### 7.7.16.2 General

Representative samples of each type of vent valve shall be subjected to a qualification test program comprising the tests specified below. The manufacturer shall determine the sampling of each test in order to assure that test results are consistent. As a minimum, at least 3 samples of each type of valve shall be subjected to each test specified hereafter.

#### 7.7.16.3 Immersion Test at High Temperature

##### 7.7.16.3.1 Purpose

The purpose of this test is to verify the performance of the valve after long-term exposure to high temperature.

##### 7.7.16.3.2 Procedure

Submerge valve samples in a water bath, for a 30-day period, and measure the crack and reseat pressures.

Water shall be kept at a temperature equal or higher than the maximum design temperature of the pipe (end fitting) in which the valve shall be installed.

##### 7.7.16.3.3 Acceptance Criteria

Crack and reseat pressure shall exceed the design requirements.

#### 7.7.16.4 Cyclic Test

##### 7.7.16.4.1 Purpose

The purpose of this test is to verify the reproducibility of the crack and reseat pressures of the valve after cycling the inlet pressure while keeping the external environment (valve outlet) at a pressure equal to the hydrostatic head of the specified water depth for the pipe.

##### 7.7.16.4.2 Procedure

Samples of the valve shall be subjected to 5000 cycles, with each cycle defined as 1 valve opening + 1 valve reseat.

Pressurized air is used in the valve inlet while the valve outlet is pressurized to the hydrostatic head equivalent to the specified water depth for the pipe.

Inlet pressure ($P_{in}$) shall vary from a pressure 20 % below the valve reseat pressure to 20 % above the valve crack pressure.

Test is performed at the ambient temperature.

#### 7.7.16.4.3 Acceptance Criteria

Crack and reseat pressure shall exceed the design requirements.

### 7.7.16.5 Seawater Long-term Immersion Test

#### 7.7.16.5.1 Purpose

The purpose of this test is to verify the performance of the valve after long-term exposure to seawater.

#### 7.7.16.5.2 Procedure

Immerse valve samples into a 10-m deep seawater bath, for a period of 6 months.

After that, measure the crack and reseat pressures.

#### 7.7.16.5.3 Acceptance criteria

Crack and reseat pressure shall exceed the design requirements.

### 7.7.16.6 Test of Simulated Immersion at Seabed

#### 7.7.16.6.1 Purpose

The purpose of this test is to verify the reproducibility of the crack and reseat pressures of the valve samples after subjecting them to degradation caused by seawater and sand.

#### 7.7.16.6.2 Procedure

Immerse valve samples into salt water bath (at the ambient temperature) and cover them with a 50-mm thick layer of sand.

The sand grains shall have outside diameter between 0.074 mm and 0.250 mm, with the addition in weight of 30 % of silt with OD < 0.074 mm.

Samples shall be kept in the bath for a period of 1 month with daily cycling of valve opening and close.

Crack and reseat pressures are measured.

Upon completion of the test, valves are inspected against internal and external corrosion and internal abrasion.

#### 7.7.16.6.3 Acceptance Criteria

Crack and reseat pressure shall exceed the design requirements.

### 7.7.16.7 External Sealing Pressure Test

#### 7.7.16.7.1 Purpose

The purpose of this test is to verify the valve external sealing system against seawater ingress.

#### 7.7.16.7.2 Procedure

Valve samples coming from the above test shall have their outlet hydrostatically pressurized, at the ambient temperature, up to the hydrostatic pressure of the specified water depth.

Samples shall be kept in the bath for a period of one month with a daily cycle of valve opening and closure.

#### 7.7.16.7.3 Acceptance criteria

There shall be no water ingress after 10 cycles of valve opening/closing. Additionally, valves shall be externally/internally inspected.

No corrosion and abrasion is allowed.

Crack and reseat pressure shall exceed the design requirements.

### 7.7.16.8 Flow Test

#### 7.7.16.8.1 Purpose

The purpose of this test is to obtain the characteristic curve of the valve (i.e. flow rate vs inlet pressure) and verify that it corresponds to the design premise.

#### 7.7.16.8.2 Procedure

Valve outlet shall be connected to the bottom of a 100-mm water column, open to the atmosphere.

Using pressurized air the valve inlet pressure is varied in the full valve design range.

Pressurized air is used to confirm that the measured flow rate meets the design requirements.

#### 7.7.16.8.3 Acceptance Criteria

The flow rate specified in the valve design shall exhaust the gas trapped in the pipe annulus without permanent deformation of the pipe outer sheath.

The measured flow rate shall match the design premise to within ±5 $m^3.h^{-1}$.

## 7.7.17 TEC Test

### 7.7.17.1 Purpose

A test to verify the design tool/methodology for the prediction of the heat transfer characteristics of the flexible pipe.

### 7.7.17.2 Procedure

The minimum pipe sample length shall be such that:

a) the heat flux at the extremities must be lower than 15 % of the total internal transferred heat,

b) the sample length with end fittings assembled shall be approximately 10 times or more the external diameter of the pipeline.

A test sample is placed in a hydrostatic pressure vessel. The sample is filled with water and its extremities are sealed and thermally insulated. The pressure inside the sample is kept constant during test. The chamber is filled with water and pressurized.

The sample is instrumented with at least 16 temperature transducers installed, which are distributed along the sample (8 placed internally in contact with the carcass and 8 placed externally in contact with the outer sheath). An additional 4 temperature sensors are installed in contact with each end-fitting flange (2 located inside and 2 outside). The heat source should be equally distributed along the sample or circulation should be ensured.

The test is carried out in two phases as follows:

1) dry annulus condition,

2) annulus fully flooded with water.

For both phases the test procedure is as follows.

1) Carry out controlled internal heat generation and measure the internal and external temperatures, or carry out controlled internal and external heat generation of the pipe and measuring of the heat flux at the external pipe wall.

2) A numerical thermal simulation shall be carried out taking into account the heat flux transferred through the sample extremities and through all flexible pipe layers. In order to assure that test uncertainties are properly determined, materials used in the flexible pipe structure and at the test system (e.g. thermal insulation of the end fittings/flanges) shall have, as applicable, known thermal properties. For this simulation, manufacturer test procedure shall define all details such as:

    a) internal heat power source,

    b) testing temperatures,

    c) expected distribution of temperature,

    d) heat flux sensors and temperature sensor locations,

    e) method for uncertainty analysis.

3) The TEC shall be evaluated for at least two external pressures, with the final pressure being equivalent to the specified maximum water depth. For the test with annulus fully flooded with seawater, the final external pressure is 10 % above that corresponding to the specified maximum water depth. Also, this pressure is kept for a 72-h period (soaking time for insulation water absorption), before data for TEC evaluation is gathered.

4) Pressures and temperatures inside and outside the sample, as well as the heat flux, shall be automatically monitored and recorded during test.

5) Test duration shall be in such a way that adequate temperature stabilization is assured.

6) The internal and external fluctuation of the temperature in the final 24 h of the test must be considered in the test uncertainty analysis.

7) Small-scale saturation and aging tests should be done per Table 12 of API 17J to determine the thermal performance of the insulation and to calculate the long-term performance of the pipe

#### 7.7.17.3 Acceptance Criteria

The TEC shall be equal or less than the value predicted by the manufacturer. Prediction accuracy/error shall be bounded for applications where low insulation is preferable (e.g. maximum temperature inside a bending stiffener).

# 8 Manufacturing

## 8.1 General

API 17J and API 17K specify manufacturing requirements for unbonded and bonded flexible pipes. Section 8 describes the processes involved in the manufacture of the pipe. In addition, guidelines on selection of manufacturing tolerances are given. Guidelines on assembly of end fittings are also included.

Furthermore, Section 8 provides guidelines on marking and storage of flexible pipes. The marking guidelines supplement the minimum requirements for marking shown in API 17J and API 17K.

## 8.2 Manufacturing—Unbonded pipe

### 8.2.1 General

The manufacturing of unbonded flexible pipe is composed of two main stages, as follows:

a) fabrication of the flexible pipe body,

b) assembly and mounting of the end fittings.

### 8.2.2 Manufacturing Processes

#### 8.2.2.1 General

The main processes in the fabrication of the flexible pipe body are as follows:

a) carcass forming,

b) polymer extrusion,

c) pressure armor winding,

d) tensile armor winding,

e) tape winding.

Depending on the pipe design, Processes a) and c) may not be required.

#### 8.2.2.2 Carcass Forming

In the carcass forming process, flat metallic strips are pulled into a forming head in which they are shaped into an interlocking helical tube (see Figure 7).

#### 8.2.2.3 Polymer Extrusion

Extruded components in a flexible pipe include polymer sheaths (internal pressure, anticollapse, or outer) and solid antiwear layers. The stations and equipment in the polymer extrusion line are typically as follows (for a rough bore structure):

a) payoff reel (or basket) with the inner carcass layer,

b) caterpillar (pre-extrusion),

c) extruder,

d) quench tanks (hot and cold water),

e) caterpillar (postextrusion),

f) take-up reel (or basket).

The control of the extrusion process is important for quality of finished product, and a feedback control system is recommended.

#### 8.2.2.4 Pressure Armor Winding

For interlocking pressure armors the pressure armor winding machine preforms, interlocks, and winds the wires circumferentially around the internal pressure sheath using shaped wires (see Figure 7). Payout/take-up reels or (baskets) and caterpillars are used to control the feed of the pipe through the winding machine.

The interlocking pressure armor is laid as one or two wires at a lay angle of close to 90°. A flat backup layer can also be wound on top of the interlocked layer using the same process.

#### 8.2.2.5 Tensile Armor Winding

The tensile armor winding machine takes flat, round, or shaped wires and preforms and winds the wires onto the surface of the pipe. The number of wires wound in one layer is typically between 30 and 80. The wires are generally laid with an angle range between 20° and 60°. The wires are stored in individual drums connected to the winding machine. The drums rotate with the winding machine while feeding it with wire.

Two machines in sequence or one machine used twice can be used to apply the double cross wound tensile armor layers used in most applications. These machines can be subject to regular stoppages for reloading of drums and welding of new wires.

#### 8.2.2.6 Tape Winding

Tape winding machines are used to apply both high strength tapes on armors and antiwear tapes, manufacturing aid, or insulation layers. These machines are typically used in sequence with one of the other processes. The main aim in the winding process is to apply the tape with uniform gap or overlap in accordance with the fabrication specification.

### 8.2.3 End Fittings

The end fitting is a critical part of the flexible pipe. A well-designed transition zone is required for all the pipe wall components to converge into one flange or connector piece that carries all the pipe wall forces.

The pressure and tensile armor layers are locked to the end termination body to anchor the layers in both radial and axial directions. The pressure integrity of the external and internal sealing layers (polymer sheaths) is provided by a seal arrangement that also ensures radial and axial attachment. The zone near the end fitting does not have the same flexibility as the rest of the pipe. This zone corresponds to approximately two pitch lengths of the tensile armor.

Figure 8 illustrates a typical unbonded pipe end fitting. Most of the components in the end fitting are applied manually with special tools and fixtures. Quality control of all processes in the fabrication and assembly of the end fitting is critical to assuring structural and fluid tight integrity over the service life of the flexible pipe.

An example of the main steps in the end-fitting mounting process is as follows.

a) Cut back individual layers of pipe.

b) Bend tensile armor away from pipe body. Care should be taken at this step to control the MBR of the tensile armor to minimize reduction of fatigue life of the tensile armor in the bending region, particularly in DAs. The MBR should be verified by fatigue testing.

c) Mount inner seal assembly and main end-fitting body.

d) Clamp pressure armor layer.

e) Secure tensile armors around body.

f) Mount external jacket.

g) Mount outer locking assembly (sealing of outer sheath).

h) Fill voids in end fitting with epoxy resin and allow to set.

The end-fitting mounting processes should be qualified by prototype testing in accordance with Section 7.

Bend stiffeners, when required at the end of the flexible pipe, are usually mounted on the pipe prior to the end fitting and subsequently pulled up and attached to the end fitting once it is mounted.

#### 8.2.4 Tolerances

##### 8.2.4.1 General

This section provides guidelines on the selection of manufacturing tolerances (see API 17J). The tolerances specified are defined in terms of percentage of nominal values.

##### 8.2.4.2 Tolerances for Pipe Length

For unbonded flexible pipes the length tolerance for lengths up to 100 m should typically be 0 m and +1 m. For unbonded lengths greater than 100 m, the length tolerance may be increased to 0 % and +1 %. The tolerance can typically be ±1 % for bonded pipes. For certain projects there can be additional requirements on the length tolerance to be considered, including those described in this section. Global analyses should conservatively account for length tolerances. For example, a far configuration analysis should use the minimum length tolerance and a near configuration analysis should use the maximum length tolerance.

The tolerances for certain applications (such as jumpers) could need to be reduced. Some applications can have problems if the length is too long, for example, for long flowlines a maximum tolerance of +1 %

can be too large because of insufficient space at the end connection to accommodate excess length. This may be more critical for trenched pipe.

Consideration should be given to possible problems caused by the individual risers having different lengths if two or more risers are clamped together (such as with umbilicals in some applications).

The calculation of the required flowline length should accurately account for all parameters, including undulations in the route, accuracy of end point locations, installation tolerances, manufacturing tolerance, and orientation of the flowline to the component (e.g. the pipe can be laid in a loop around the component, such as at a wellhead, and connected at a 90° orientation to the main flowline direction).

#### 8.2.4.3 Layer Tolerances

Tolerances should be established and controlled by the manufacturer for each layer of the pipe. Table 27 lists recommendations on critical aspects of dimensional tolerances for the flexible pipe layers.

## 8.3 Manufacturing—Bonded Pipe

### 8.3.1 General

The manufacture of bonded flexible pipe comprises the following three main stages:

a) fabrication of the flexible pipe body,

b) assembly and mounting of the end fittings,

c) curing of flexible pipe.

Note that Stages b) and c) are interchangeable in sequence for some pipes.

### 8.3.2 Manufacturing Processes

#### 8.3.2.1 General

The main processes in the fabrication of the flexible pipe body are as follows:

a) carcass forming,

b) preparation of compound and calendering

c) elastomer winding,

d) reinforcement armor winding.

Process a) may not be required, depending on the pipe design and application.

#### 8.3.2.2 Carcass Forming

Flat metallic strips are pulled into a forming head in which they are shaped into an interlocked helical tube (see Figure 7 for an illustration). Some bonded flexible pipe manufacturers do not carry out this task, preferring instead to obtain premanufactured carcasses.

## Table 27—Critical Aspects for Selecting of Unbonded Flexible Pipe Manufacturing Tolerances

| | Recommendations on | | |
|---|---|---|---|
| **Layer** | **Thickness** | **Layer Diameter (Inner and Outer)** | **Other Parameters** |
| Internal carcass | The minimum value should meet the design requirements, considering the potential for erosion/corrosion over the service life. The strip thickness should be controlled by the manufacturer's material specification. | The minimum inside diameter (ID) should ensure clear passage for equipment such as gauging pigs. The maximum outer diameter (OD) should consider the effect on collapse resistance and tolerance of the other layers. | The maximum ovality should be less than that used in the calculation of collapse resistance.<br>Carcass pitch control (or check through computation) should be implemented during (or after) the internal pressure sheath extrusion in order to avoid carcass fatigue or reduced collapse resistance |
| Internal pressure sheath | The minimum thickness should be determined based on API 17J. | The maximum OD should consider the effect on hoop strength of the pressure armor layer in accordance with API 17J. | Surface finish and texture to be controlled such that potential defects that could propagate through the layer thickness do not occur. |
| Pressure armor layer | Thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop strength in accordance in with API 17J. | The maximum OD should consider the effect on hoop strength in accordance with API 17J. Variations in OD with length should consider the load sharing along the length in a tensioner installation. | The OD should be controlled such that gaps between the pressure armor layer and the internal pressure sheath do not affect the load sharing between the carcass and pressure armor layer under external radial compression and hydrostatic loading. The maximum gap should assure utilization is as specified in API 17J.<br>Pitch control should be implemented in order to avoid fatigue issues in the pressure armor.<br>The manufacturer should check pressure armor layer tolerances for the allowable gap between adjacent wires and the allowable average gap over a group of wires against manufacturer specifications. The gap between the wires is checked to ensure that the sheath thickness is sufficient to overcome creep issues. |
| Intermediate (anticollapse) sheath/antiwear layers | In dynamic applications, the minimum thickness should ensure that the sheath does not wear through over the service life. Where the intermediate (anticollapse) sheath is to bear hydrostatic loading, the minimum thickness should ensure that the layer is not breached (lose pressure integrity) over the service life. | The maximum value should consider the effect of tolerance buildup on subsequent layers. | |
| Tensile armor layer | The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop and axial strength in accordance with API 17J. | The maximum diameter should consider the effect of tolerance buildup on subsequent layers, and ensure that the tensile wires lay flat against the pipe. | Variations in lay angle should assure that allowable utilization is in accordance with API 17J.<br>The maximum gap between wires should be determined considering the effect of circumferential stress concentration in the pressure armor (local bending of the pressure armors within the gaps). Where no pressure armor is present, the maximum gap should be determined based on API 17J. |

| Recommendations on | | | |
|---|---|---|---|
| **Layer** | **Thickness** | **Layer Diameter (Inner and Outer)** | **Other Parameters** |
| Insulation layer | The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should give an overall heat transfer coefficient for the pipe, smaller than the specified maximum. | The maximum OD should consider the effect of tolerance buildup on subsequent layers and ensure that the insulation lays flat against the pipe. | |
| Outer sheath | The minimum thickness should assure watertight integrity over the service life, including at the end fittings. Shear transfer to the underlying layers during installation with a tensioner should also be considered. The variation in thickness along the length of a pipe should consider the effect of stress concentration and possible thinning during installation. | The maximum OD should consider the effect on packaging, installation loading, hydrodynamic loading, and attachment of ancillary equipment such as buoyancy clamps. | |
| External carcass | The minimum thickness should consider the requirement for abrasion and impact protection in the specific application. | The maximum OD should consider the effect on packaging, installation and hydrodynamic loading. | |

#### 8.3.2.3 Preparation of Compound and Calendering

The process by which the compound is prepared involves accurately weighing out each ingredient of the compound, mixing the ingredients in the specified order and at specified temperatures in a large "Banbury" type mixer until a homogenous consistent compound is formed.

The calendering process involves passing the prepared compound between rollers repeatedly until the compound takes on the form of a smooth, even sheet with no flaws or blisters. This sheet can be subdivided into smaller strips and subsequently wound onto reels for storage or cut and stored as smaller flat sheets. The friction caused by forcing the compound through the calendering rollers causes an increase in the temperature. This temperature should be controlled so as to ensure that overcuring does not occur during calendering. The compound is generally passed through a bath containing an antiadhesion substance prior to storage. Alternatively, the compound material may be stored with plastic sheets between each layer.

The steel cables of the reinforcing layer may be incorporated into a sheet of compound during the calendering process or by an extrusion process. This facilitates winding of the reinforcing layer onto the pipe and speeds up the fabrication stage. These sheets are generally stored on reels for ease of use.

#### 8.3.2.4 Elastomer Winding

The production pipe is generally built up by winding sheets of calendered elastomer onto a mandrel or interlocked steel carcass. The winding process continues with different compounds per the cross-sectional specification, including calendered reinforcing cables, until the pipe is fully built up.

The control of the winding process is important for the quality of the finished product as irregular overlaps and gaps in the winding process may cause unevenness in the pipe cross section (see API 17K).

The elastomer can also be extruded to build up the pipe cross section although winding is more common (see 8.3.2).

#### 8.3.2.5 Reinforcement Armor Winding

The cables that make up the reinforcement can be wound onto the pipe body in two formats. The first format is simply by an armor winding machine where the cables are stored in individual drums connected to the winding machine. The drums rotate with the winding machine while feeding it with cable as the pipe advances through the machine. In some cases, the pipe rotates while the winding machine traverses horizontally. The second format is identical to the way in which the elastomer sheets are wound. The cables are precalenderized and stored on reels in long narrow strips. These strips are then wound onto the pipe body by rotating the pipe body and advancing either the pipe or winding machine at a predefined rate.

Two machines (or more) in sequence or one machine (or more) used twice can be used to apply the double cross wound armor cables.

The control of the winding process is important to maintain the quality of the finished product (see API 17K).

### 8.3.3 End Fittings

The end fitting is a critical part of the flexible pipe. A well-designed transition zone is required for all the pipe wall components to converge into a flange or connector piece that carries all the pipe wall forces. Bend stiffeners can be integrated in bonded hose ends.

The cables of the reinforcement armor layer are locked to the end termination body to ensure reliable attachment in both radial and axial directions. The pressure integrity of the external and internal sealing layers (elastomer cover and liner) is provided by curing the layer onto the end fitting, which also ensures radial and axial attachment.

The end fitting can be swaged onto the pipe body in some cases. This involves an internal and external steel end-fitting piece that encapsulates the pipe body and, when swaged, compresses the pipe body sufficiently to ensure both fixity and sealing of the liner, cover, and cables of the reinforcement layer. The end-fitting face in contact with the pipe body may be smooth or toothed. The toothed end fitting is designed to contact the cables of reinforcement layer and so provide a stronger mechanical grip.

The zone near the end fitting does not necessarily have the same flexibility as the rest of the pipe. This zone, corresponding to the length of a couple of turns of the reinforcing cables, therefore does not have the same curvature capacity (flexibility) as the main pipe section. Care should be taken to avoid high local strain in this zone due to bending, tension, and pressure.

Bend stiffeners, when required at the end of the flexible pipe, are usually mounted onto the pipe prior to the end fitting and subsequently pulled up and attached to the end fitting once it is mounted. Alternatively, inherent stiffness may be introduced into the pipe during the manufacturing process by winding on additional elastomer layers.

The flexible pipe can be cured fully or partially cured prior to mounting the end fitting. Alternatively, the end fitting can be mounted prior to cure and cured with the pipe. The difference in procedures is partially due to the differing temperature and time required to cure elastomer compound and epoxy resin.

### 8.3.4 Curing Process

Curing of the elastomer of bonded flexible pipes is generally accomplished by applying heat and pressure in the presence of curing agents to the pipe. Heat can be applied by a steam oven or by electrical inductance. Pressure is generally applied by wrapping the pipe tightly with nylon prior to cure.

The elastomer compound will change properties irreversibly during the curing process, and the elastomer material making up the pipe cross section will initially flow and subsequently form one composite cross section.

A composite cross section with minimal flaws will be formed once proper manufacturing procedures are adhered to, followed by the manufacturer's documented curing procedures. However, a sample piece identical in construction to the pipe should be constructed with the pipe, dissected, and inspected for voids in accordance with manufacturer's procedures. The acceptance criterion should be that no visible voids are observed.

### 8.3.5 Tolerances

This section provides guidelines on the selection of manufacturing tolerances (see API 17K). The tolerances specified in this section are defined in terms of percentage of nominal values.

The length tolerance for bonded flexible pipe should typically be 0 % and +1 %. Additional requirements on the length tolerance that can be considered for certain projects, include the following:

a) the tolerances can require reduction for certain applications, such as jumpers;

b) some applications can have problems if the length is too long. This can be more critical for trenched pipe;

   EXAMPLE A maximum tolerance of +1 % can be too large for long flowlines, because of insufficient space at the end connection to accommodate excess length.

c) consideration should be given to possible problems caused by the individual risers having different lengths if two or more risers are clamped together (such as with umbilical in some applications);

d) the calculation of the required flowline length should accurately account for all parameters, including undulations in the route, accuracy of end point locations, installation tolerances, manufacturing tolerance, and orientation of the flowline to the component.

   EXAMPLE The pipe can be laid in a loop around the component (such as at a wellhead) and connected at a 90° orientation to the main flowline direction.

The recommended tolerance on the flexible pipe overall OD is ±3 %.The tolerance on internal diameter should be 0 % and +2 % for carcass layers that are not manufactured on a mandrel. The recommended tolerance on the internal diameter is between 0 % and +2 % for liners that are not built on an inner carcass.

Tolerances should be established and controlled by the manufacturer for each pipe layer. Table 28 lists recommendations on critical aspects of dimensional tolerances for the flexible pipe layers.

The manufacturer should check reinforcement armor layer tolerances for the allowable gap between adjacent wires or the allowable average gap over a group of wires against manufacturer specifications.

## 8.4 Marking

### 8.4.1 General

API 17J and API 17K specify minimum requirements for marking of flexible pipes. The objective of this section is to provide recommendations on additional markings that may be applied to the pipe. These additional markings will be useful for particular applications and can make the pipe and its intended use more identifiable during its service life.

**Table 28—Critical Aspects in Selection of Bonded Flexible Pipe Manufacturing Tolerances**

| Recommendations on | | | |
|---|---|---|---|
| **Layer** | **Thickness** | **Layer Diameter (Inner and Outer)** | **Other Parameters** |
| Internal carcass | The minimum value should meet the design requirements of API 17K, considering the potential for erosion/corrosion over the service life. The strip thickness should be controlled by the manufacturer's material specification. | The minimum inside diameter (ID) should ensure clear passage for equipment such as gauging pigs. The maximum outer diameter (OD) should consider the effect on collapse resistance and tolerance buildup of the other layers. | The maximum ovality should be less than that used in the calculation of collapse resistance. |
| Liner | The minimum thickness should be determined based on the requirements of API 17K. | The maximum OD should consider the effect of tolerance buildup on subsequent layers. | Surface finish and texture to be controlled such that potential defects that could propagate through the pipe body do not occur. |
| Reinforcement armor layer | The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should consider the effect on hoop and axial strength in accordance with API 17K. | The maximum diameter should consider the effect of tolerance buildup on subsequent layers. | Variations in lay angle should assure that allowable utilization is in accordance with API 17K. |
| Insulation layer | The minimum thickness should be controlled by the manufacturer's material specification. The minimum thickness should give an overall heat transfer coefficient for the pipe smaller than the specified maximum. | The maximum OD should consider the effect of tolerance buildup on subsequent layers, and ensure that the insulation lays flat against the pipe. | |
| Cover | The minimum thickness should assure watertight integrity over the service life, including at the end fittings. Shear transfer to the underlying layers during installation with a tensioner should also be considered. The variation in thickness along the length of a pipe should consider the effect of stress concentration and possible thinning during installation. | The maximum OD should consider the effect on packaging, installation loading, hydrodynamic loading, and attachment of ancillary equipment, such as buoyancy clamps. | |
| External carcass | The minimum thickness should consider the requirement for abrasion and impact protection in the specific application. | The maximum OD should consider the effect on packaging, installation, and hydrodynamic loading. | |

The marking system should be sufficient to resist installation and operational abrasions, with letters and numbers at least 10 mm (0.39 in.) high. All markings should be sufficiently clear to be read and/or recognized, in situ, by a remotely operated vehicle (ROV), and be suitable for the required service life in the design environment. This does not apply to markings that are only required for installation purposes (e.g. circumferential bands for length measurement or for clamp or buoyancy locations) and therefore only need to be sufficient to accommodate the installation procedures.

#### 8.4.2 Flexible Pipe

Nameplates (AISI 316 material is recommended) should be securely attached to both ends of the pipe. The nameplate should not be covered by any ancillary component, such as bend stiffeners or bend restrictors. Consideration is recommended for including the markings listed in Table 29, in addition to the requirements of API 17J and API 17K.

The length markings are to be done by rings 25 mm wide: 1 ring every 10 m, 2 rings every 50 m, and 3 rings every 100 m (the spacing between rings to be 25 mm). Every 300 m, a single 100-mm ring is painted. The length markings should indicate the direction of the length measurement.

A longitudinal marking should be included along the pipe (flowline, riser, or jumper) so that its behavior during installation and operation can be monitored.

The following marking requirements can also be considered for riser applications:

a) unique and logical markings applied to identify different risers or the locations for the attachment of any ancillary items, such as clamps or buoyancy modules;

b) the location of the seabed touchdown point should be marked, if applicable.

#### 8.4.3 End Fittings

In general, the nameplate with the pipe markings is attached to the end fitting and applies to both pipe and end fittings. Separate markings are therefore not generally required for the pipe and end fitting. Consideration should be given to the markings listed in Table 29 for the end fitting. Special care should be taken to ensure that identification markings do not damage any surface anticorrosion treatment on the end fitting.

#### 8.4.4 Connectors and Flanges

Marking requirements for connectors, flanges, and associated components should be as specified in API 6A [5] or other applicable standard for the specified connector.

#### 8.4.5 Reels

Reels should be marked clearly with the following:

— gross weight,

— direction of reeling,

— respective packing drawing number,

— pipe identification (i.e. structure number and section number).

### 8.5 Storage

#### 8.5.1 General

Flexible pipe can be stored in a number of ways, with the most common being reels, baskets and crates, or pallets. Reels and baskets in particular should be marked such that the manufacturer, serial number, flange and drum diameters, width, empty weight, and weight capacity are identified.

**Table 29—Marking Recommendations for Flexible Pipe Products**

| Mark (2) | Flexible Pipe | End Fitting | Comments |
|---|---|---|---|
| API 17J and API 17K designation | X | X | Required by API 17J and API 17K. |
| Serial number | X | X | Required by API 17J and API 17K. Should ensure full traceability of all materials, processes and tests during manufacture. |
| Company name | X | X | |
| Project reference name | X | X | |
| Item of subcontract—contract award reference number | X | X | |
| Manufacturing test pressure | X | X | Expressed in MPa. |
| Flow direction | X | X | Shown with an arrow. |
| Fluid being conveyed | X | X | |
| Line identification (tag number) | X | X | |
| Longitudinal marking | X | NA | A longitudinal line along the pipe to assess twist. |
| Manufacturer name or mark | X | X | Required by API 17J and API 17K. |
| Date of manufacture | X | X | Required by API 17J and API 17K. Month and year. |
| API license number | X | X | Required by API 17J and API 17K. API licensees only. |
| API monogram | X | X | Required by API 17J and API 17K. API licensees only. |
| Design pressure | X | X | Required by API 17J and API 17K. In MPa units. Specify differential pressure. |
| Storage MBR | X | NA | Required by API 17J and API 17K. |
| Sweet or sour service applications | X | X | Designated by letters SW (sweet) or SO (sour). |
| Static or dynamic application | X | X | Designated by letters S (static flowline, riser, or jumper) or D (dynamic riser or jumper). |
| Internal diameter | X | X | Expressed in millimeters. |
| External diameter | X | NA | Expressed in millimeters. |
| Design temperatures | X | X | Minimum and maximum design temperatures expressed in degrees Celsius. |
| Length | X | X | Length of flexible including end fittings. Expressed in meters. |
| End-fitting condition | NA | X | Designated by letters OEF (original end fitting) or REF (replaced end fitting). |

NOTE 1 Imperial units (inches, psi, and °F) can be given in brackets after the SI units.

NOTE 2 The marking for the pipe and end fitting may be covered by a single template attached to the end fitting.

The flexible pipe should be stored under environmental conditions that do not affect its performance characteristics. In particular, the following are recommended.

a) Blind flanges, temporary caps or hubs should be installed to seal the pipe bore or any access to the annulus. Gas-relief valves should be protected from damage.

b) The storage temperature should be within the acceptable limits of the flexible pipe structure and its end fittings.

c) The end fitting connections should be protected by watertight blank end caps that shall be secured to prevent damage of the seal area, threads, and other areas susceptible to damage:

    1) the securement of the end fitting should ensure that it cannot become loose and possibly damage the pipe,

    2) securing of the end fitting should not damage the pipe by overbending the section adjacent to the fitting.

d) The flexible pipe should be covered to prevent degradation by ultraviolet radiation, for materials sensitive to sunlight.

e) If stored outdoors, end cuts of flexible pipe should be covered for long-term storage.

f) The possible effect of the test fluid on the flexible pipe materials should be taken into consideration if flexible pipe is stored for a long period of time after having been pressure tested.

g) Long-term pipe storage can cause a curvature set of the pipe, because of the polymer layers and could require consideration in installation planning.

h) Packaging material should assure that the radiant heating of the flexible pipes does not result in exceeding allowable design temperature.

Product handling during shipping and while in storage should be documented. A full and thorough inspection program for the flexible pipe while in storage should be performed periodically. Inspection reports should be provided to the purchaser.

Repairs carried out while in storage should be performed under permanent or temporary cover along with the environmental control facilities normally provided during manufacture. Work carried out in the storage area should be strictly controlled and performed in such a manner as to cause no damage or contamination to stored products. The storage area should be subject to purchaser acceptance and should be in a location where the pipe will not be susceptible to damage.

#### 8.5.2 Reels

Reels rotated around a horizontal axis are the support most commonly used for storage of flexible pipe in long lengths. Reels, when driven by a winch system, can also be used to maintain the flexible pipe’s tension during installation and recovery. The tension applied to the pipe during reeling should be sufficient to prevent the pipe being stored slack, which can damage the pipe during subsequent unreeling. The parameters to be considered in selecting storage reels for flexible pipe include the following:

a) the drum radius should meet or exceed the storage MBR requirements of the flexible pipe;

b) the size of the reel should accommodate the length of flexible pipe, including end fittings and accessories;

c) the structure of the reel should be capable of safely supporting the weight of the flexible pipe and its contents;

d) reel dimensions, structural design, and construction should account for the loads induced during loading, transportation, and offloading the reel full of pipe;

e) reel dimensions, structural design, and construction should account for the loads induced by the vessel motions and the flexible pipe tension during installation and recovery, if the reel is to be used for offshore shipping or installation.

Reels should be designed and manufactured in compliance with DNV 2.22 [38]. In the fabrication of reels, all surfaces in contact with the flexible pipe should be free of any surface condition or point loading that could that can damage the flexible pipe. This also applies to partitions when used to subdivide reels into separate sections.

#### 8.5.3 Baskets or Carousels

Baskets or carousels rotated around a vertical axis are frequently used for the storage of flexible pipe in very long lengths. Baskets are normally used only for storage and are not capable of supporting any significant tension in the flexible pipe. Therefore, a tensioning system is generally required for installation of flexible pipe from a basket. Design parameters and fabrication requirements are otherwise similar to those of reels.

#### 8.5.4 Crates/Pallets

Crates or pallets are commonly used for storage of flexible pipes in short lengths, either straight or coiled. If stored in coil, the storage MBR criteria for the flexible pipe should be met. The flexible pipe should be tightly secured to the crate or pallet to prevent damage due to abrasion. The crate or pallet should contain no surface condition or point loading that would damage the pipe.

# 9 Handling, Transportation, and Installation

## 9.1 General

Section 9 provides guidelines and recommendations for handling, transportation, and installation of flexible pipe systems. The installation section addresses general considerations and describes sample installation procedures and final commissioning.

## 9.2 Handling

### 9.2.1 General

The precautions listed in this section should be taken during handling and transportation of flexible pipe to prevent damage.

Precautions should be taken to ensure that flexible pipe will not be damaged by dragging on the floor or against sharp edges of handling equipment or by unacceptable torsional/bending loading as a result of improper procedures when it is to be transferred from reel (or basket) to reel (or basket).

The flexible pipe should be securely fastened to its supporting reel, basket, or crate. The end fittings will usually require additional fastening by means of wire ropes, fiber slings, bands, adjustable lever hoists, or clamps, as well as protection with a soft packaging material, in order to protect adjacent pipe layers and to take up any creep or subsequent motion.

Handling and lifting appliances used for flexible pipes both onshore and offshore, whether temporary or permanent, include items such as the following:

a) cranes and A-frames;

b) reels, carousels, baskets, and strip-out pallets;

c) lifting frames and cradles;

d) caterpillars/tensioners;

e) pulling heads;

f) winches;

g) load cells;

h) chutes and bend limiters;

i) spreader beams and bars;

j) Portable manual hoists and “come-alongs;”

k) lifting ropes, slings, and webbing straps;

l) Chinese fingers;

m) control lines;

n) shackles;

o) sheaves;

p) carabiner hooks;

q) lifting eyes.

All handling equipment should meet the following requirements and additional best offshore working practices:

— used in accordance with the rules and regulations of relevant international or national standards;

NOTE Certification requirements could apply.

— protected from damage and deterioration while not in use;

— inspected for signs of damage and deterioration prior to use;

— designed and specified for DAs when intended for offshore use.

#### 9.2.2 Steel Pipelay Tensioners and Equipment

If steel pipelay tensioning or other type of equipment that is not specifically designed to handle flexible pipe is to be used for the installation of flexible pipes, it should be documented by detailed calculation that the crushing loads on the pipe do not exceed the design requirements of API 17J and API 17K. The tensioner compression force should also be shown to be sufficient to resist the tension in the pipe.

As a principle, the calculations should be verified by trials of either the actual equipment or a shoe and loading configuration that consistently simulates the actual equipment used, and it should be verified that the relevant installation loads are simulated or validated by representative test or use of the equipment.

#### 9.2.3 Reels, Carousels, Baskets, and Strip-out Pallets

Support and drive frames, shoes, cradles, and bobbins forming a part of an assembly should be designed and certified for offshore DAs, including lifting both individually and as an assembly, if appropriate. Potential damage or collapse of pipes on reels and carousels because of excess overlying weight should be assessed where relevant. The drive facility should be fitted with the following facilities when used for installation reels and carousels:

a) fully controllable braking,

b) manual override for automatic tensioning devices,

c) back-tensioning facility (e.g. for re-reeling).

#### 9.2.4 Overboarding Chutes—Rotating and Fixed

Fixed or rotating bend limiters (such as sheaves, arches, and chutes) to be employed as installation or handling aids should be designed as recommended by the flexible pipe manufacturer in accordance with relevant international or national standards. All such equipment should be maintained in good condition. Surfaces that will come into contact with the flexible pipe should not be corroded or abrasive and should be free from sharp edges. Wetting of the chute may be used in some cases to reduce the friction with the pipe.

A larger diameter roller or conveyor, sheave, or other type of equipment should be used in place of an overboarding chute when tensions or other installation parameters are such that an overboarding chute can damage any structural or component part of a flexible pipe. Alternatively, the vertical lay system can be employed. A stinger constituting a number of small rollers is generally not acceptable.

#### 9.2.5 Chinese Fingers

Chinese fingers, if used, should be selected with due consideration for the flexible pipe materials, and acceptance for the selected design should be obtained from the flexible pipe manufacturer. Chinese fingers should have a suitable finish to prevent pipe cover damage when used for flexible pipe installations.

### 9.3 Transportation

#### 9.3.1 General

Section 9.3 includes any movement of a partially or fully manufactured product that is not a normal part of the manufacturing procedure. The transportation facility should be selected to minimize handling and opportunity for damage. Use of cranes, if required, should be certified fully and rated in accordance with the lift requirements.

The manufacturer and purchaser should satisfy themselves of the validity of travel authorization prior to transportation. Due regard should be given to all rules and regulations imposed by relevant countries en route if transportation involves international travel.

Procedures for the load-out, seafastening, and transportation should be submitted to purchaser for approval at a time period to be agreed between the manufacturer and purchaser prior to load-out date.

#### 9.3.2 Load-out

Load-out covers the period from immediately prior to lifting or transferring flexible pipes onboard a vessel up to and immediately after the vessel leaves the quay side. All flexible pipes should be visually inspected prior to and during load-out. Such inspection should be carried out by the manufacturer, purchaser, and installation or transport representatives, where employed. The inspection should be documented fully and signed off by the above parties.

All flexible pipes should be packed and handled in accordance with the requirements of API 17J and API 17K and further protected against deck activities where necessary. Such protection and packaging should remain in place during load-out. The transportation vessel should not be permitted to leave the quay-side until the purchaser has issued a load-out acceptance certificate, unless otherwise agreed by the manufacturer and purchaser.

#### 9.3.3 Seafastenings

Seafastenings should be designed for the final transported weight in a dynamic environment appropriate for the transportation vessel and the sailing route. All seafastenings should be fully certified in accordance with the appropriate design code prior to sail-away. All designs should be approved by purchaser prior to load-out.

#### 9.3.4 Reeled Flexible Pipe

Reeled flexible pipe in this context covers flexible pipe that is on a reel, carrousel, or basket. Flexible pipes should not be placed on a reel so that end fittings or other attachments induce unacceptable local loading in the pipe structure. End fittings or attachments that are not wrapped and packed should not be overwrapped with unprotected pipe.

Weights should be accurately monitored and recorded during lifting, either with load cells certified in accordance with established practice, or crane gauges, where such gauges have been individually certified. The reel should be fixed to prevent rotation prior to lifting in a drive or support frame. The reel should clearly identify that the pipe is full of fluid and the effect of the fluid weight on the total weight, if relevant.

#### 9.3.5 Coiled Flexible Pipe

Coiled flexible pipe covers all pipes loaded out and secured on deck in coiled condition, either packaged or unpackaged. The flexible pipes should be coiled so that removal of storage straps will not result in uncontrolled release. Coiled flexible pipes should be suitably seafastened prior to sail away. Deck location should be such that potential hazards are minimized during overboarding.

#### 9.3.6 Uncoiled Flexible Pipe

Uncoiled flexible pipe covers all flexible pipes secured on deck but neither reeled nor coiled. The flexible pipes should be provided with suitable protection from dragging over dockside surfaces.

The flexible pipes should be located on deck within reach of the deck crane, or lifting facility, so that dragging across the deck and lifting around objects during subsequent installation is minimized. The flexible pipes should be suitably seafastened and provided with protection from normal deck activities prior to sail-away.

## 9.4 Installation

### 9.4.1 Installation Analysis

#### 9.4.1.1 Maximum Seastates

The installation analysis should take into account contingency scenarios. Dynamic installation analyses should be used to define the maximum seastate and current profile suitable for deck and installation activities on the particular vessel. The loads applied in the analyses should be for the maximum defined seastate for the planned activities.

#### 9.4.1.2 Installation Lay Tables

The installation analysis is typically performed in a series of static steps. Each static step is summarized in an installation lay table, which is used onboard the installation vessel during the operation. Parameters that can be directly monitored on the vessel are provided in the lay table as well as results from the analysis. The lay tables should include:

a) layback distance,

b) top tension,

c) top angle,

d) cable payout (for each step and cumulative),

e) vessel movement (for each step and cumulative),

f) water depth,

g) bend radius,

h) bottom tension,

i) bending moment in bend stiffener/restrictor,

j) depth of ancillary equipment.

#### 9.4.1.3 Key Flexible Pipe Installation Parameters

##### 9.4.1.3.1 General

A number of issues with regard to the flexible pipe need to be considered when specifying the requirements of the installation system. These issues relate to pipe diameter, pipe MBR, tensions required at hangoff, and minimum squeeze forces to prevent slippage of the pipe without exceeding the maximum squeeze force to prevent crushing of the pipe.

##### 9.4.1.3.2 Flexible Pipe MBR

The flexible pipe MBR is a critical parameter to consider when specifying the requirements of the installation system. The chute radius should always be greater than the flexible pipe MBR in order to avoid damaging the pipe. The definition of the acceptable MBR for dynamic and static flexible pipe is specified in Table 9 of API 17J and API 17K.

#### 9.4.1.3.3 Installation Tension

The maximum installation tension will be used to determine the tensioner capacity. Even though most flexible pipes are installed empty, it is recommended to be able to retrieve these lines when flooded with seawater (i.e. in case of any accidental events whereby the bore could flood).

The installation load cases should check that minimum and maximum tensioner loads do not violate the pipe design criteria if tensioners are used. The maximum load (with pipe hangoff tension) should be checked for potential collapse of the pipe.

The minimum required squeeze force to hold the flexible pipe in the tensioner during the installation procedure will be largely dependent on the friction forces present. For a bonded flexible pipe, the load is transferred directly to the pipe through the tensioner pad to the outer surface of the pipe. Thus, the only friction to be considered is between the surface of the tensioner pads and the outer sheath of the flexible. For an unbonded flexible pipe, the load transfer is more complex as the design consists of a number of unbonded layers that can move relative to one another. Thus, the squeeze force applied to the flexible pipe must be sufficient to prevent slip between the tensioner pads and outer sheath and between the layers. For a noninsulated unbonded flexible pipe, the critical contact internal surface is between the tensile armors and the outer sheath, whilst for an insulated unbonded flexible pipe the critical contact surface is between the insulating material and the tensile armors.

Another issue that must be considered when determining the minimum required squeeze force to prevent slippage is the collapse capacity of the pipe. The crush capacity of the flexible pipe can be provided by the manufacturer and should be checked against the calculated squeeze loads to ensure it is not exceeded.

The minimum squeeze load is calculated according to the following relation:

$$F_{\text{min}}^{\text{squeeze}} = \frac{F_{\text{tension}}}{l \times n \times \dfrac{\min(\mu_1, \mu_2)}{\text{SF}}}$$

where

$F_{\text{min}}^{\text{squeeze}}$ is the minimum radial force to prevent slippage (kN/m/track);

$F_{\text{tension}}$ is the tensile force required to hold pipe (kN);

$l$ is the active length of tensioner (m);

$n$ is the number of tensioner tracks;

$\mu_1$ is the friction coefficient between pipe outer sheath and tensioner pads;

$\mu_2$ is the friction coefficient between pipe outer sheath and underlying armor layer.

$\text{SF}$ is the safety factor.

#### 9.4.1.3.4 Flexible Pipe Crushing Loads

When flexible pipe is being laid or recovered care should be taken to assure that the pipe is not damaged due to crushing loads. These crushing loads are induced by:

a) the caterpillar tensioners that control the lay of the pipe from the laying vessel,

b) the gutter over which the pipe passes before entering the tensioners (vertical lay),

c) the radius controller below the tensioners (vertical lay),

d) or when overboarding the risers (horizontal lay).

Typical values for maximum ovalization of an unbonded flexible pipe are in the range of [1.5 %, 3 %] in the loaded condition, and [0.2 %, 0.5 %] in the unloaded condition. Bonded and unbonded pipe manufacturers can advise project-specific ovalizations based on testing or by using predictive methodology and tools validated by prior testing. The crushing capacity of the pipe is usually calculated by means of an finite element analysis or by empirical/analytical calculations. The crush capacities are dependent on factors of safety defined in API 17J and API 17K.

#### 9.4.1.3.5 Gutter Crushing Loads

The crushing load on the flexible pipe as it passes over a gutter or chute will be dependent on the tension in the pipe and the profile or radius of the gutter. Thus the allowable crush loads will determine the allowable tension in the pipe during installation using an overboarding chute. The parameter used to determine this allowable tension is the two-point crushing strength. This value can be provided by the flexible pipe manufacturer. The maximum allowable pull over a structure like a gutter can be calculated by the following equation:

$$F = f_{\text{2-track}} \times R$$

where

$f_{\text{2-track}}$ is the two track crushing capacity of the pipe;

$R$ is the radius of curvature of the gutter.

Note that this calculation is based on crushing loads and does not consider the MBR criteria.

#### 9.4.1.3.6 Pipe Buckling

Buckling of the flexible pipe armor wires during installation should be taken into consideration when determining the installation parameters. Two general types of buckling can occur—radial and lateral buckling. Radial buckling is also referred to as “birdcaging,” and lateral buckling is also referred to as “z-buckling.” Buckling can occur as a result of improper installation procedures or as a result of axial compression loads on a pipe in deepwater conditions. If correct procedures are not followed during procedures such as pipe transpooling, loading, and installation, torsional forces can accumulate in the pipe, which can cause localized buckling, yielding, or ovalization of the armor wires. Compressive loads on a pipe due to hydrostatic loads during immersion in deepwater can cause the armor wires to buckle radially or laterally due to the end-cap pressure effect.

The risk of both radial and lateral buckling can be avoided if the pipe is installed with the bore flooded with water or another suitable fluid. Depending on the pipe structure, the risk of tensile armor buckling can be minimized if damage to the outer sheath is avoided during installation. However, the tensions and corresponding squeeze loads required to install the risers in the flooded condition may be prohibitive for large water depths, thus necessitating the riser to be installed empty. In this case, care must be taken so that the curvatures experienced by the riser at the touchdown point are kept as low as possible.

The risk of birdcaging can also be reduced if the flexible pipe design utilizes a layer of antibuckling tape to contribute to additional radial constraint to the tensile armors.

#### 9.4.1.4 Interference

After the installation laying tables have been completed, the installation procedure should be checked for any possible interference during the procedure. Possible cases of interference are as follows.

a) Each stage of the flexible installation should be checked for clashing with other risers, mooring lines, and nearby structures. The abandonment, recovery, and the transfer to the production vessel of the flexible may have possible cases of interference. An installation sequence may be necessary to avoid interference. Installations of flexibles on a turret-moored vessel are particularly susceptible to clashing.

b) The flexible pipe should not clash with the seabed during installation. If it is necessary to lay a section of pipe temporarily on the seabed, then a seabed survey should be carried out before the installation.

c) Wet stored risers should be adequately spaced so that the buoyancy sections do not clash due to current loading. Wet stored risers may also interfere with the installation of other risers.

d) Interference between mooring lines and flexibles should be analyzed, particularly if the flexible passes over or underneath the mooring line during installation. The installation offset, installation tolerance, and draft of the moored vessel should be taken into account in this type of analysis.

e) The hangoff angles of the installation cables and the flexible should be checked to identify interference with the moonpool or the hull of the installation vessel. Clashing between the hull of the production vessel and the installation cables is also possible. The possibility of clashing during cross-haul or hand-off to the production vessel is increased if the separation distance between the vessels is large or if the transfer is performed below the keel of either vessel.

f) It is recommended to define an exclusion zone around the production vessel that the installation vessel will not enter during the operation. A larger safety zone can also be defined where the installation vessel will only enter during specific monitored conditions, when close proximity to the production vessel is necessary. The safety zone should include the installation tolerance, installation offset as well as the exclusion zone. As the installation vessel will usually be in close proximity to the production vessel, interference with the mooring lines should be analyzed.

g) Complex installations involving multiple cranes should be checked for interference on the deck of the installation vessel.

### 9.4.2 Wet Storage

If the production vessel is not installed on-site before the installation of the risers, the risers may be wet stored on the seabed. A bathymetric seabed survey should be performed and any debris removed before the risers are laid on the seabed. Wet stored risers are usually installed free flooded as this improves the seabed stability of the riser. The installation analysis includes abandonment and recovery of the risers. Free-flooding of the riser with fresh seawater may cause corrosion depending on the storage time; therefore, commissioning of the pipe may be performed and seawater replaced by treated water.

After the production vessel has been installed, the risers can be recovered and connected to the vessel. Issues associated with wet storage are as follows.

a) In deepwater fields, there may be limited space to wet store the risers.

b) There should be adequate space between risers to avoid clashing of the buoyancy sections. Also, the buoyancy sections will deflect due to current and should be spaced so as not to pass over adjacent risers or any subsea structure.

c) Risers should be wet stored within their design depths.

d) The accuracy of the lay usually depends on the water depth. The laying tolerance plus at least an additional 5 m clearance should be accounted for.

e) If the risers are laid in curves, the stability of the curve should be ensured. The laying tension should not overcome the friction force of the straight section of riser laid on the seabed.

f) It is feasible to cross risers in wet storage if they are suitably protected from damage.

g) An interference analysis may be necessary, particularly for the recovery phase.

h) Risers may be difficult to recover after the production vessel is installed, if they are laid under or near the production vessel. Additional installation vessels may be required or it may be necessary to cross-haul the riser under the production vessel.

i) If it is necessary to drag the risers on the seabed during recovery, a seabed survey should be carried out to ensure the integrity of the risers. However, it is preferable to avoid dragging where possible to avoid damage to the outer sheath, if it is feasible to use alternative methods.

j) Risers should not be laid over clump weights or other subsea structures with sharp edges.

k) Risers should be wet stored away from the vicinity of mooring lines as far as possible. This will avoid interference with the mooring lines during recovery and eliminate the possibility of a mooring line being dropped on a riser during installation of the production vessel. The riser should be checked for self-burial prior to recovery. If self-burial has occurred, the impact on loads and potential MBR violation during recovery should be checked.

l) It may be necessary to abandon or recover the risers in a particular sequence to avoid interference with other risers, mooring lines, and the production vessel.

m) Bend stiffeners may need to be protected from abrasion damage from the seabed. To prevent the pipe and end fitting sinking into mud and to allow recovery later, it may be appropriate to lay the riser on a mudmat.

n) Current densities are reduced if anodes or protected structures are submerged in mud. Also, items such as connectors may need their own anodes if not in electrical continuity with the flexible pipe cathodic protection system.

### 9.4.3 Monitoring

The subsea activities should be constantly monitored using diver and/or ROV mounted cameras as approved by the client and installation contractor. The monitor recordings should be stored for review of subsea activities after installation has finished. The recordings should identify all visible markings and confirm lay patterns and configurations as well as the status of bolted flanges, connectors, bend restrictors, bend stiffeners, and buoyancy modules. All recordings should be stored with a log and uniquely marked for storage and retrieval.

### 9.4.4 Installation of Reeled Flexible Pipes

Deployment reels should be placed directly in line with overboard chutes whenever possible. The use of rollers, single point attachments, or sheaves should not induce unacceptable loads on the flexible pipe structure. Pipe deflection units may be used provided the MBR criterion is met. Single-point contacts should be avoided. Detailed calculations should be carried out to ensure that no unacceptable loads are induced at any contact point.

### 9.4.5 Installation of Flexible Pipes from a Carousel

The recommendations in 9.4.4 also apply to flexible pipes on carousels.

### 9.4.6 Installation of Coiled Flexible Pipes

Storage straps should be replaced by temporary deployment rigging prior to deployment of coils overboard unless the storage straps can be used for installation. The flexible pipe should be coiled on a rotating pallet and the strip-out rigging should have a suitable swivel, when possible. The crane should slowly raise the pipe to a vertical position, allowing it to release any inherent twist through the swivel. Divers should not use sharp tools for removal of temporary deployment rigging.

### 9.4.7 Installation of Uncoiled Flexible Pipes

Uncoiled flexible pipes should be lifted overboard with a crane using a multiple point lift. Care should be taken to ensure that no damage is caused to the flexible pipe or end fittings if overboarding chutes and winches are used. The pipe can also be laid out straight on the deck and picked up by one end. The installation procedures should ensure that the MBR criteria are not exceeded in this case.

### 9.4.8 Deployment and Tie-in

Loads and deformations during deployment should be within allowable limits. Bend radii should be monitored during installation or the installation method and laying parameters defined to ensure the MBR criterion is not exceeded, for example, by monitoring the seabed touchdown point with an ROV and using a transponder to maintain a minimum layback distance, thereby ensuring the configuration does not exceed the MBR criteria. Pull-in wires (or weak links if used) should be such that they break before damage is sustained to the flexible pipe as a result of excessive tension, if feasible. Flexible pipes should not be overtensioned during deployment through a steel pipe or J-tube, while accounting for the maximum friction force from the pull-in. Back tension will be required during these operations.

The tie-in sequence should be arranged such that minimal inhibited fluid is lost after blind flanges are removed, unless flooding with inhibited water is carried out immediately after tie-in. In general, flexible pipes should not be laid around obstacles such that natural movement is restricted. This can be acceptable, however, if the procedures, equipment, and flexible pipe are designed for the application. The use of scour mats should be considered in preference to physical restriction if scour is considered a problem.

It is recommended that flowlines be connected to their termination points (wellhead, manifold) at right angles to, or offset from, the main lay direction. This allows excess lengths and expansions of the line to be absorbed in a final S-shaped section at the connection point. This final S-shaped section may also be used if there is an underestimation of the flowline length.

### 9.4.9 Trenching and Burial

A pipe tracking facility should be incorporated to facilitate route confirmation at a later date if an installed flexible pipe is expected to become buried in soft seabed conditions. Suitable sand bagging or some such method should be provided to support a flexible pipe over sharp edges or corners in the event the MBR criteria could be violated or if the outer sheath cover could be damaged if the pipe enters a trench in hard seabed conditions or passes over a boulder within the trench.

### 9.4.10 Vessel and Equipment

The vessel and equipment should be in good condition and working order and be checked prior to vessel mobilization. All measurement equipment, particularly for measuring load, should be calibrated. All lifting equipment should have suitable certification. It is recommended to use color coded tags on equipment in relation to its usage.

The installation procedures and control systems should be sufficient to ensure control of the tension in the pipe if pipe tension is to be distributed among tensioners, reel drives, and carousel drives.

Typically, the vessel spread should include the following equipment for monitoring the flexible pipe during installation:

a) ROV for subsea observation,

b) tension measuring equipment for maximum top tension,

c) departure angle measuring equipment,

d) compression load measurement for caterpillar tensioners.

#### 9.4.11 Vessel Selection

In the first phase of the installation analysis, the methods of installation are defined and an installation vessel is selected. The three alternatives for installation of flexible pipes are vertical lay, horizontal lay, or reel lay. The method selected is dependent on water depth, due to increased laying tension in deepwater. The final choice of vessel is heavily dependent on cost and vessel availability in the region.

The capacity of the installation vessel may affect the method of installation. Installation vessel limitations include:

a) equipment onboard,

b) deck load and available space,

c) length of installation cable,

d) reel/carousel capacity,

e) allowable cable declination angle and azimuth of cable at hangoff,

f) maximum laying tension,

g) engine thrust and positioning capabilities,

h) angle range of cranes,

i) lifting capacity of cranes,

j) ROV tether length.

#### 9.4.12 Installation Procedures

##### 9.4.12.1 General

The installation procedure employed for each flexible pipe is dependent on the system configuration and the particularities of the system components. Horizontal installation using an overboarding chute is shown in the sample installation procedures in this section.

The flexible pipes can be installed either flooded, free-flooding, or empty. The manufacturer and installation contractor should determine the installation conditions. Some pipes can require flooded or free-flooding installation to prevent collapse of the pipe or to ensure the stability of the installed line. The suitability of the carcass material (for rough bore structures) should be confirmed with the manufacturer in this case.

In determining the installation strategy to be used, some of the issues that need to be addressed and can influence schedule and risks include the following:

a) preinstallation of risers prior to hookup;

b) number and size of ancillary components, including buoyancy, to be installed;

c) type of bases, if any, to be used and anchoring system (gravity, pile, or suction);

d) tension in line;

e) tie-in systems, such as riser/flowline connections;

f) maximum environmental conditions (installation window);

g) interfaces with installation of other systems, such as mooring lines;

h) diver-assisted or diverless operations;

i) installation vessel requirements, including number, size, and mobilization or demobilization costs;

j) trenching or protection requirements;

k) installation of bundles or multiple lines;

l) subsea versus topside operations;

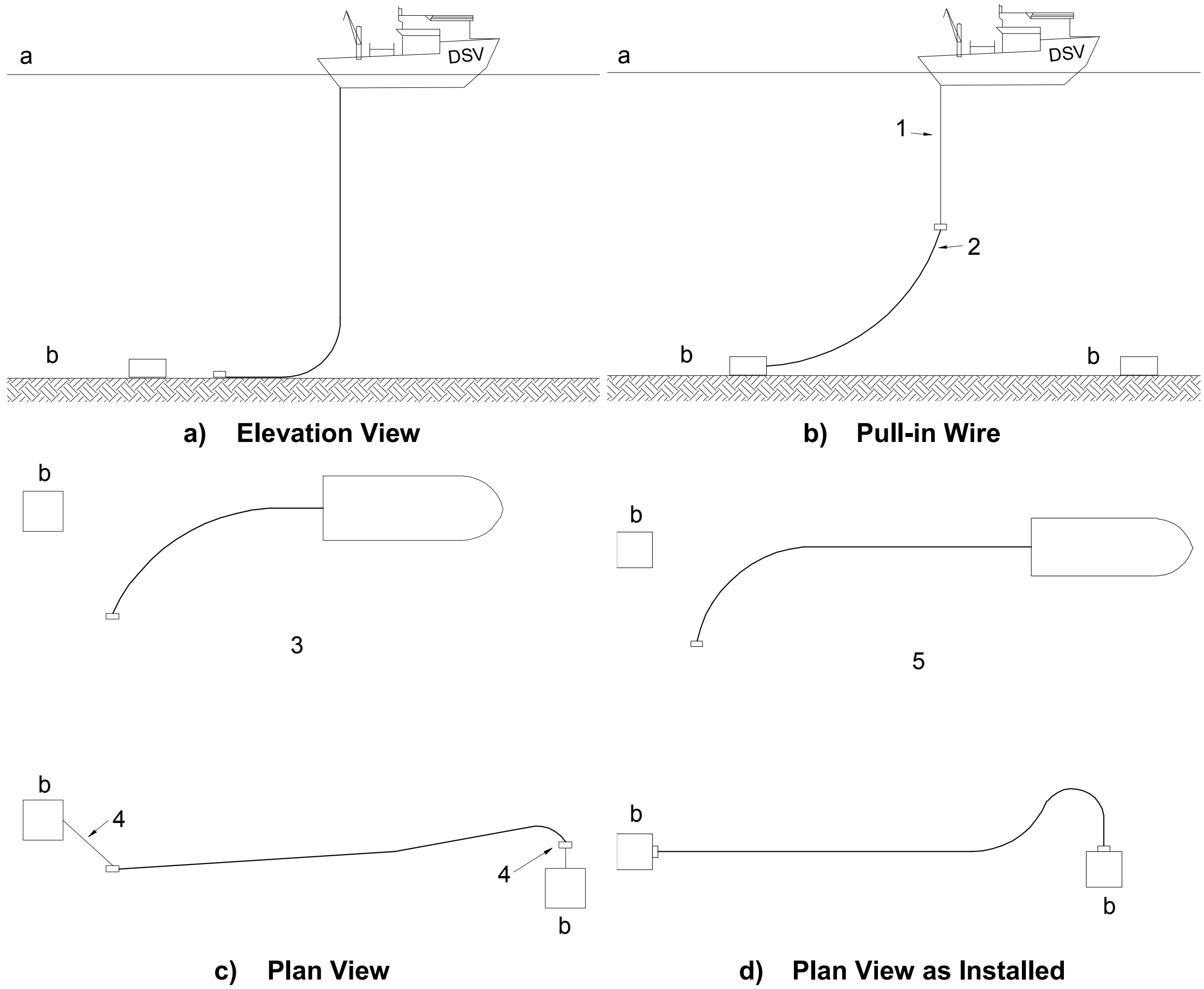
m) identification of components or equipment to be installed onshore to minimize offshore operations;

n) ROV operations (see API 17H [11]).

#### 9.4.12.2 Flowlines

Figure 15 shows a typical installation procedure for a flexible flowline. The flowline is attached to a pile or clump weight in the vicinity of the start flowline base and is laid out along the seabed towards the end flowline base. The final portion of the flowline is laid out in an overlength shape. Inflatable buoyancy units may then be attached to the flowline ends, which are then winched into the flowline bases for connection.

Figure 16 illustrates an example installation of a flexible flowline through a J-tube. For a J-tube pull-in, a preinstalled sealing plug can be used to seal the J-tube at the lower bellmouth to prevent loss of corrosion inhibitors.




**Key**

1 Pull-in wire

2 Flexible pipe

3 Overboard first flange to seabed

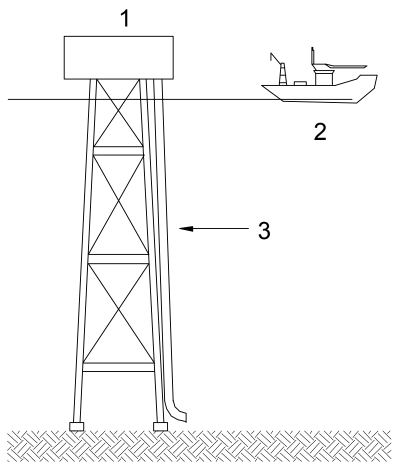
4 Pull-in wire

5 Layout pipe

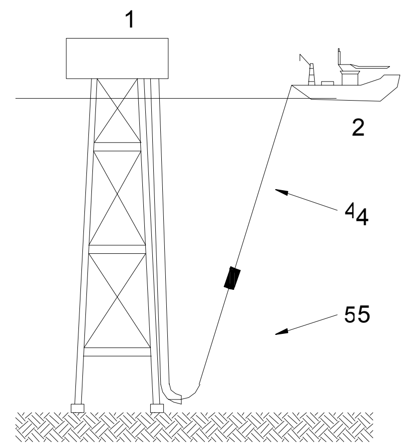
a Mean water line

b Flowline base

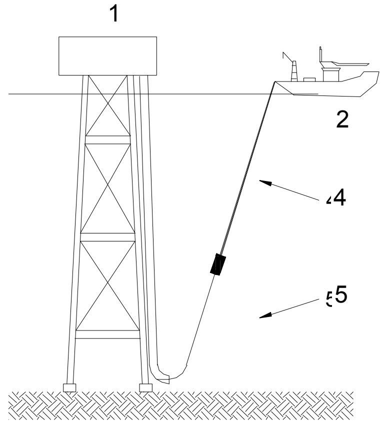
**Figure 15—Typical Flowline Installation Procedure**



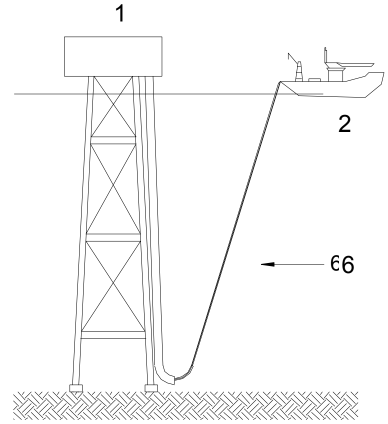

a) **The Installation Vessel Moves up to the Platform**



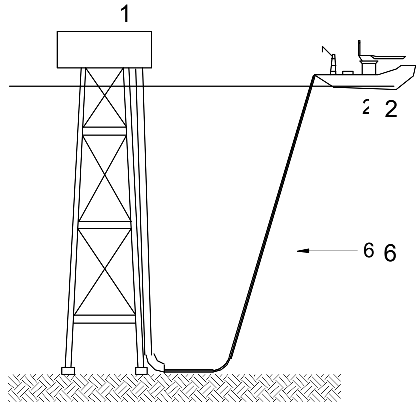

b) **The Preinstalled Messenger Line, Followed by a Pull-in Wire, is Transferred to the Vessel from the Platform**




c) **The Pull-in wire is Attached to the End of Flexible Pipe, and Pull-in Operation Begins**




d) **When the End of the Flexible Pipe Reaches the Top of the J-tube, the End Fittings are Attached to a Hangoff Structure**




e) **The Installation of the Flexible Pipe is Then Continued in a Layaway Operation**

**Key**

| | | | | | |
|---|---|---|---|---|---|
| 1 | Platform | 3 | J-tube | 5 | Pull-in wire |
| 2 | Installation vessel | 4 | Messenger line | 6 | Flexible pipe |

**Figure 16—Schematic of J-tube Pull-in Operation**

#### 9.4.12.3 Risers

The initiation phase of the installation operation is where the flexible pipe is landed on the seabed or connected to a production vessel. Initiation can consist of connecting the flexible pipe to a flowline or manifold, direct handover to a production vessel, or landing a clump weight to start laying the flexible without a permanent connection, depending on the application.

The normal-lay phase occurs when there is a full catenary of flexible with no structures in the catenary, and when no specific changes occur, such as water depth or weight. Tension and MBR criteria define a range of acceptable normal lay configurations. A range of acceptable layback distances are governed by these parameters. A long layback will induce large tension while a short lay back will induce low MBR in the sag bend.

Where buoyancy modules are being deployed, it may be necessary to increase the layback to ensure the MBR of the flexible is not violated. Temporary clump weights may be required to aid installation during buoyancy module deployment. Temporary buoyancy modules may also be used in certain applications to ensure clearance with the seabed or other structures.

Clump weights can be used to aid tether installation if the riser connection point is not close enough to the seabed connection point during the installation of the flexible. After the tether has been connected, the clump weight is released and recovered. It is necessary to analyze the release and recovery of the clump weight in order to ensure the integrity of the riser and the tether.

The flexible may be directly handed over to the production vessel at the start of the installation or cross hauled at the end of the operation. When cross hauling from the installation vessel to the production vessel, increasing the transfer depth will reduce the horizontal loads on both vessels. The transfer depth may be limited by other factors such as seabed interference or cable length. An interference analysis should be performed on the cross-haul operation, particularly on a turret-moored vessel where the risers are in close proximity.

When the riser is stored in the installation vessel carousel, it is necessary to do a transpooling analysis. The transpooling analysis consists of the loading of the flexible from the quay into the carousel on the installation vessel. The purpose of the analysis is to avoid compression and overbending during the operation. The contact forces of the flexible on the chutes, deflectors, and spooler have to be determined. The required tension to be applied at the tensioners must also be applied. The radii of the chutes and deflectors must be greater than the allowable bending radius of the flexible.

#### 9.4.12.4 Riser Configurations

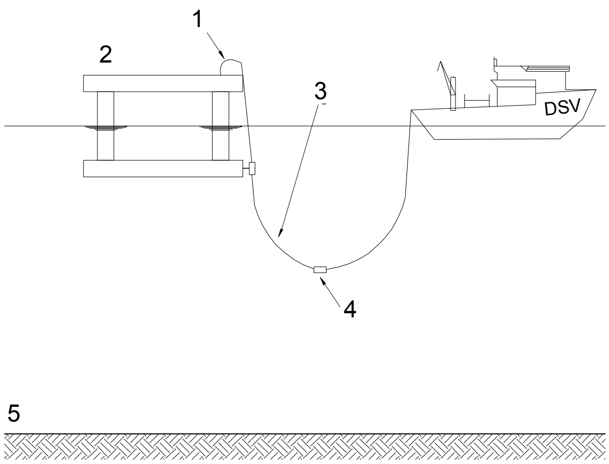
Figure 17 to Figure 21 illustrate typical lay systems and installation procedures for flexible riser configurations for lazy-S, steep-S, lazy wave, steep wave, and free-hanging catenary configurations. These figures show the flexible pipe being installed with the first end connected to the vessel. This method does not necessarily suit all applications and can be reversed.

The vessel is represented schematically as a semisubmersible, but this is of no consequence with regard to the actual installation. Note that many installers prefer to handle flexibles, buoys, and clump weights separately.

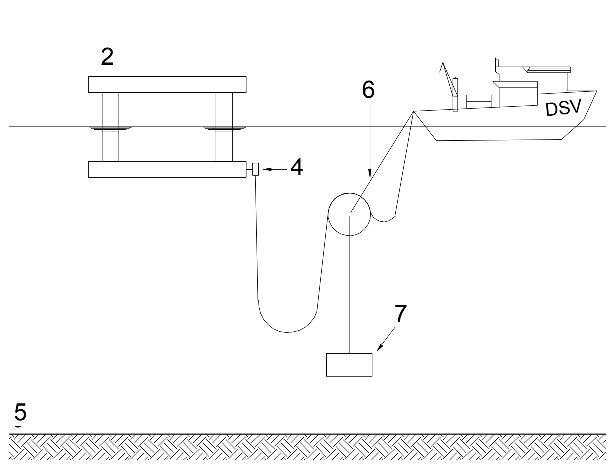
### 9.4.13 Installation Methods

#### 9.4.13.1 General

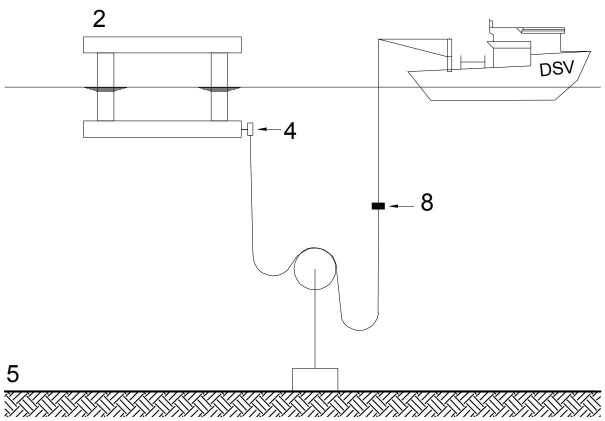
There are three types of installation systems, which are described in the following sections.



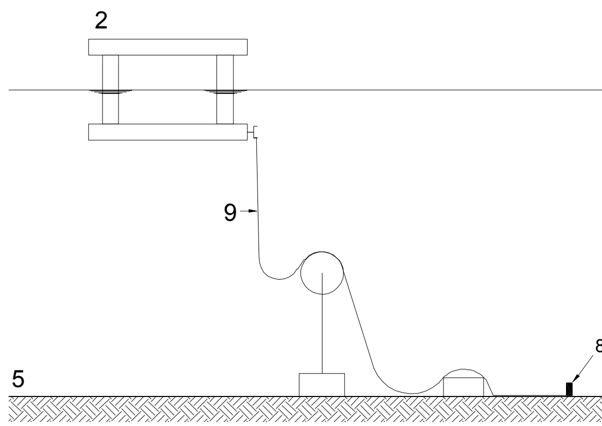

**a) Pull-in Riser End Fitting**




**b) Overboard Subsea Buoy/Arch System**




**c) Overboard Riser Lower-end Flange**




**d) System as Installed**

**Key**

1 Pull-in winch

2 Floating production system

3 Pull-in wire

4 Riser end fitting

5 Seabed

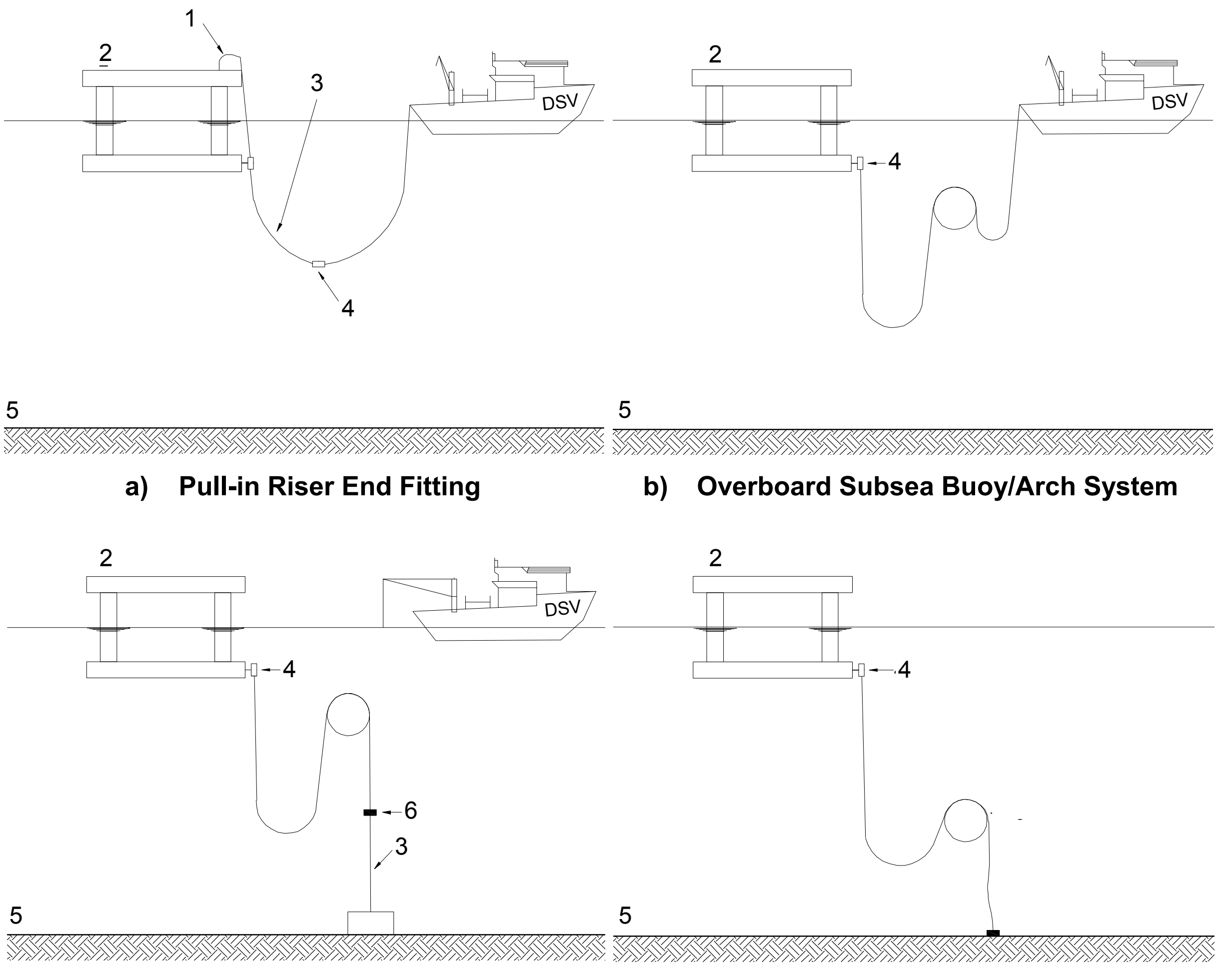
6 Layout wire

7 Clump weight

8 Riser flange

9 Flexible riser

**Figure 17—Typical Lazy-S Riser Installation Procedure**




**a) Pull-in Riser End Fitting**

**b) Overboard Subsea Buoy/Arch System**

**c) Overboard Riser Lower End Flange**

**d) System as Installed**

**Key**

1 Pull-in winch

2 Floating production system

3 Pull-in wire

4 Riser end fitting

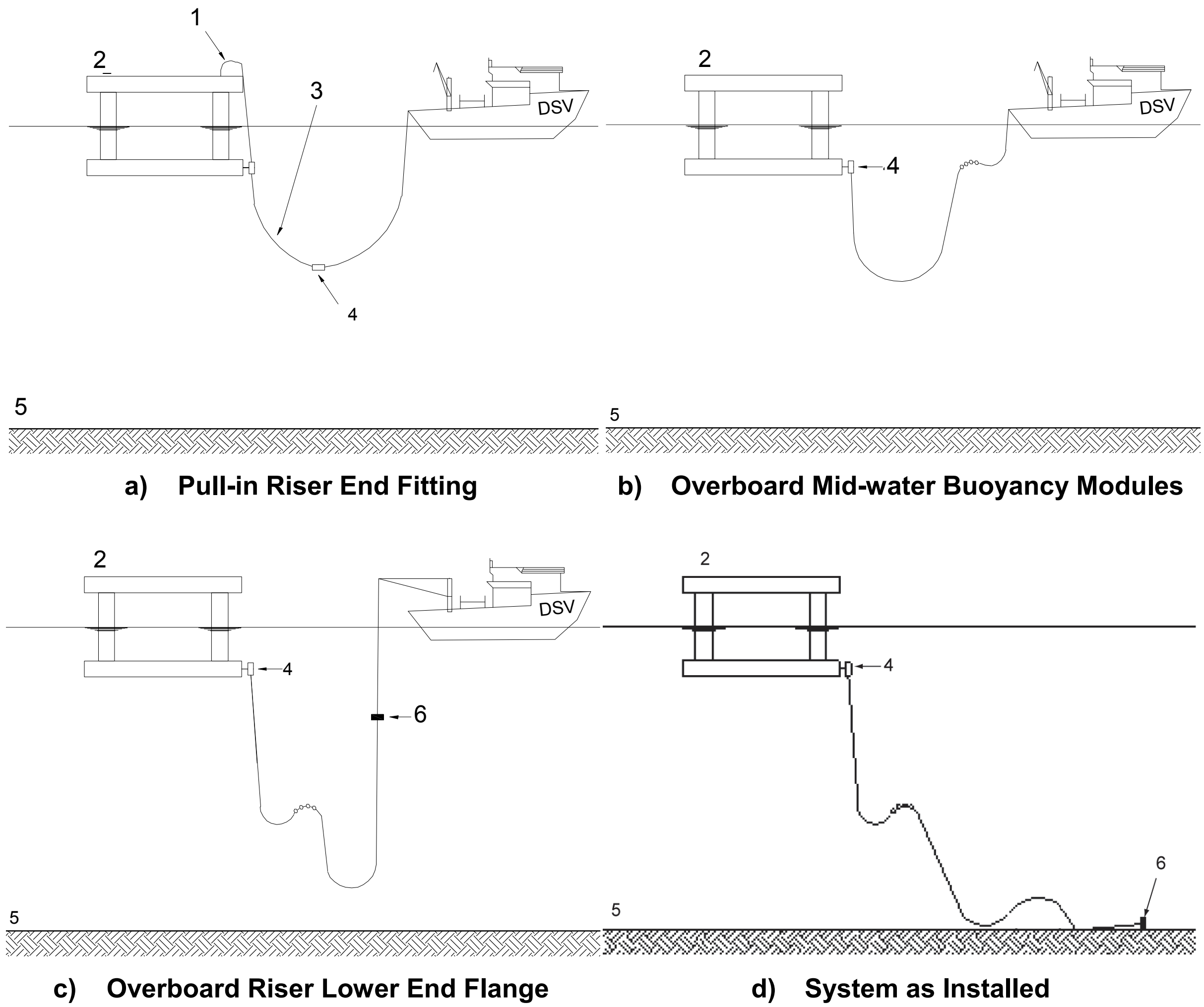
5 Seabed

6 Riser flange

NOTE 1 This procedure is based on connecting to the floating production system first, then laying away from the floating production system. The procedure may be reversed.

NOTE 2 The horizontal lay procedure may be replaced with a vertical lay procedure.

**Figure 18—Typical Steep-S Riser Installation Procedure**




**Key**

1 Pull-in winch

2 Floating production system

3 Pull-in wire

4 Riser end fitting

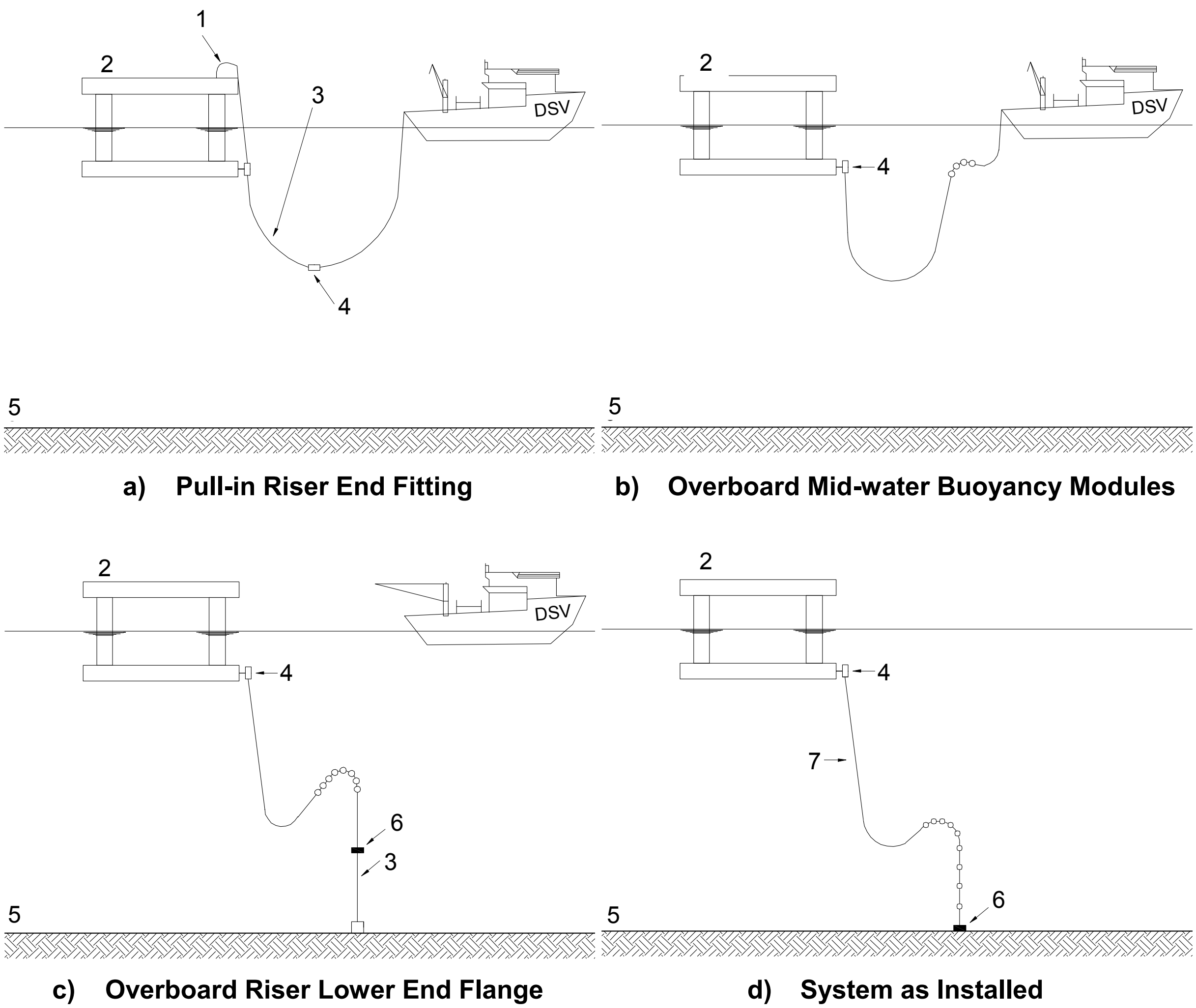
5 Seabed

6 Riser flange

NOTE 1 This procedure is based on connecting to the floating production system first, then laying away from the floating production system. The procedure may be reversed.

NOTE 2 The horizontal lay procedure may be replaced with a vertical lay procedure.

**Figure 19—Typical Lazy Wave Riser Installation Procedure**




**Key**

1 Pull-in winch

2 Floating production system

3 Pull-in wire

4 Riser end fitting

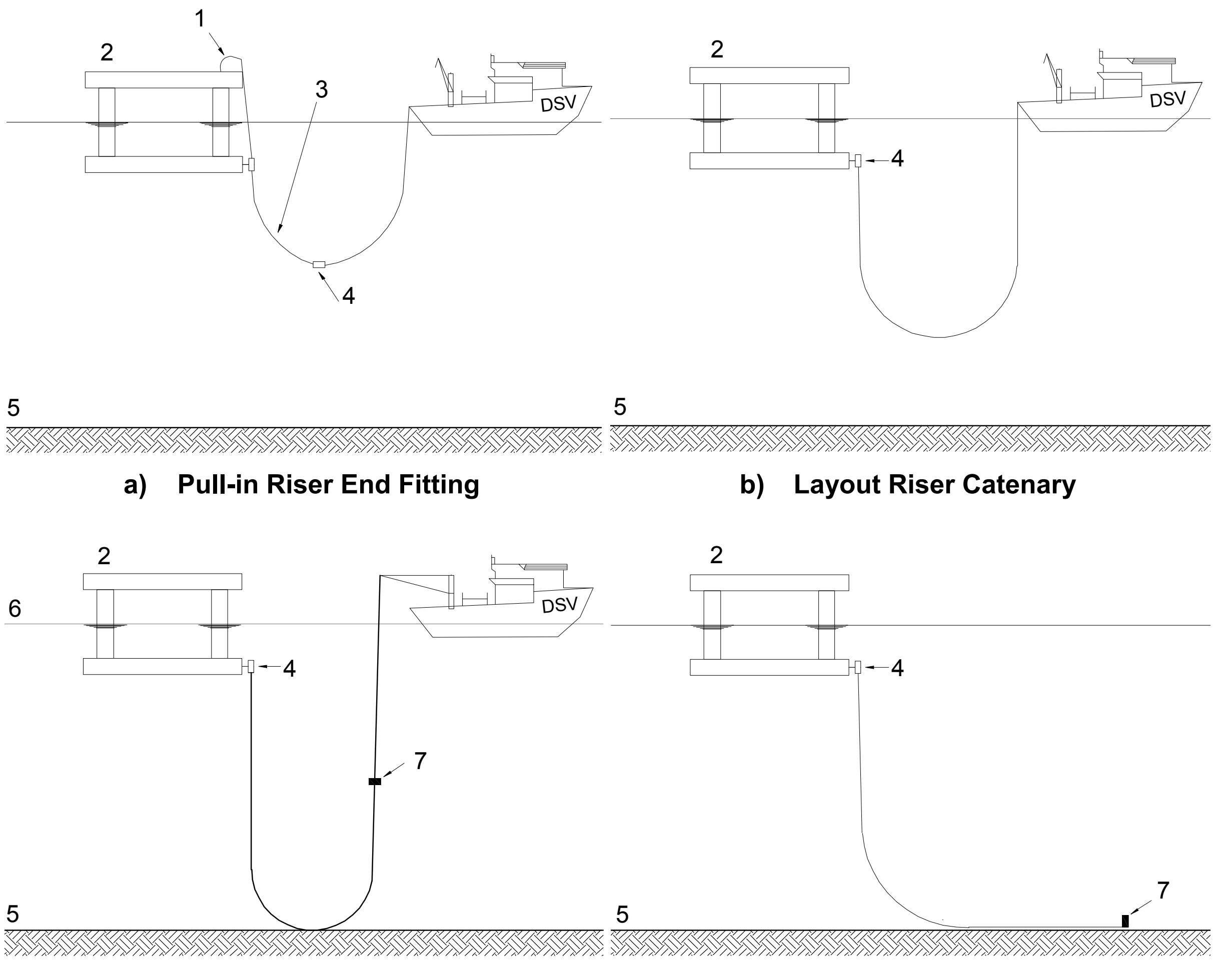
5 Seabed

6 Riser flange

NOTE 1 This procedure is based on connecting to the floating production system first, then laying away from the floating production system. The procedure may be reversed.

NOTE 2 The horizontal lay procedure may be replaced with a vertical lay procedure.

**Figure 20—Typical Steep Wave Riser Installation Procedure**




**a) Pull-in Riser End Fitting**

**b) Layout Riser Catenary**

**c) Overboard Riser Lower End Flange**

**d) System as Installed**

**Key**

1 Pull-in winch

2 Floating production system

3 Pull-in wire

4 Riser end fitting

5 Seabed

6 MSL

7 Riser flange

NOTE 1 This procedure is based on connecting to the floating production system first, then laying away from the floating production system. The procedure may be reversed.

NOTE 2 The horizontal lay procedure may be replaced with a vertical lay procedure.

**Figure 21—Typical Free-hanging Catenary Installation Procedure**

#### 9.4.13.2 Tensioned Reel Lay System

The tensioned reel lay system consists of a motorized laying reel that controls both the tension in the riser and the rate of lay. An under roller or reel hub drive system is used and the flexible pipe is overboarded by means of a laying chute or gutter.

The bend radius of the pipe must be greater than the radius of curvature of the overboarding chute to avoid overbending of the riser. The tension in the riser at the overboarding chute must also be monitored to avoid excessive crushing loads at the chute. This is less critical as this method is usually utilized for low tension applications although this will depend on the pipe crushing capacity.

This method of installation has a maximum approximate laying tension of 30 Te although this will depend on the size of the reel. This means that the tension reel lay method is only suitable for shallow water systems with small diameter pipe. A typical lay speed is 1 km/hr. This, however, will be affected by ancillary equipment requirements, such as buoyancy modules. A schematic of a tensioned reel lay system is shown in Figure 22 a).

#### 9.4.13.3 Horizontal Lay System

The horizontal lay system is similar in principal to the tension reel lay system described above. The same principal is applied in conjunction with horizontal caterpillar tension systems to increase the maximum lay tension capacity. As with the tensioned reel lay method, the pipe is overboarded by means of a laying chute or gutter usually located at the stern of the vessel.

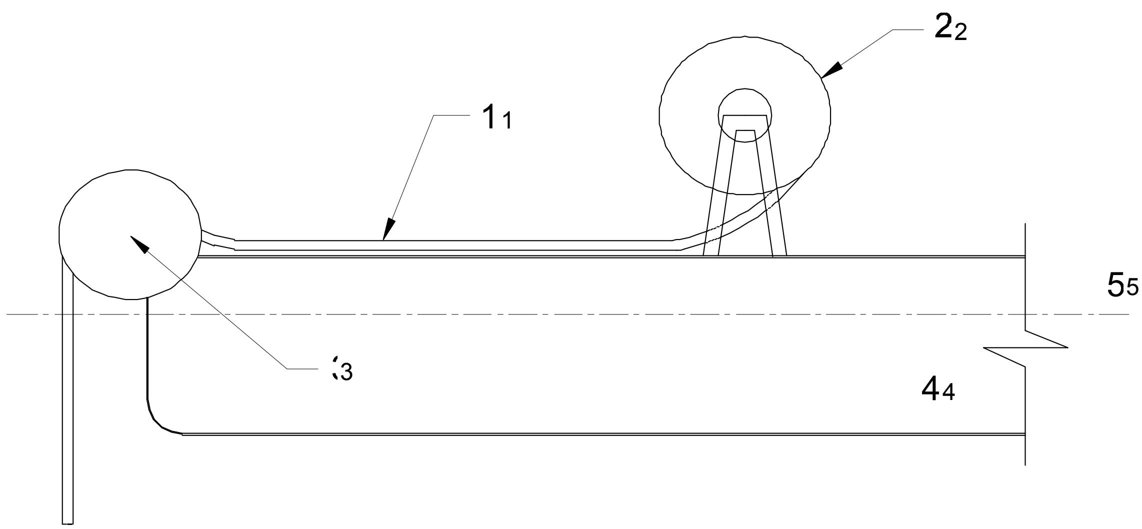
Critical issues associated with this method include crushing of the pipe at the tensioners, overbending of the pipe at the chute, and crushing loads at the chute due to the combination of tension and bending.

The horizontal tensioners can be bi, tri, or quad track systems. Depending on the available work space, several caterpillar tensioners can be placed in line to provide the tension capacity needed. A typical lay speed is 1 km/hr. This, however, will be affected by ancillary equipment requirements. A schematic of a horizontal lay system is shown in Figure 22 b).

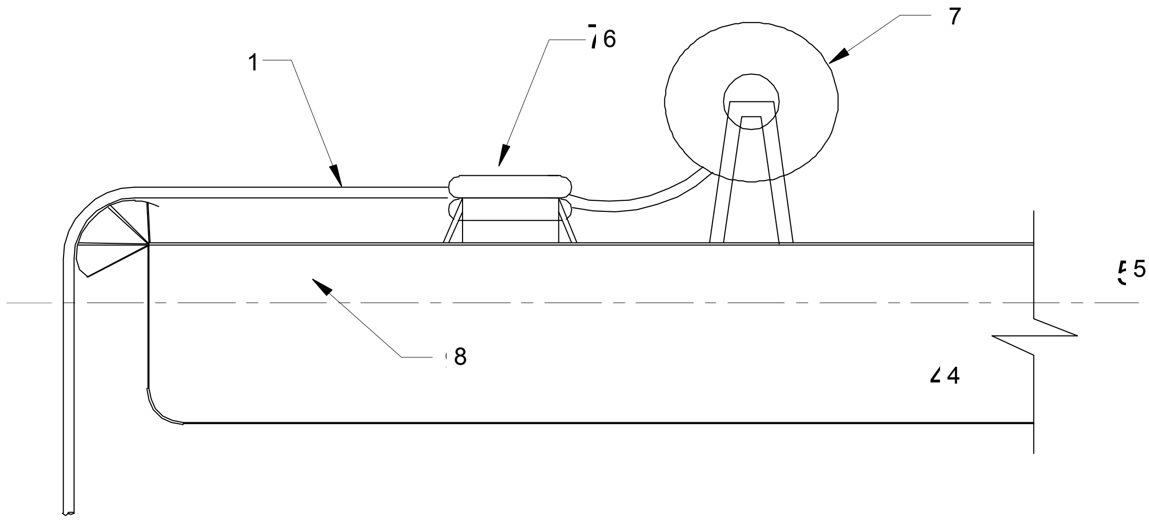
#### 9.4.13.4 Vertical Lay System

A schematic of a vertical lay system through a moonpool is shown in Figure 23. The vertical lay system involves the flexible pipe being fed from a reel or carousel onboard the vessel and down through the installation tower in a near vertical configuration. As the riser is fed into the installation tower, it passes over a gutter that acts as both a guide and prevents overbending of the riser. The installation tension is then taken by a caterpillar tension system. The riser is typically fed down through a moonpool beneath the installation tower although the tower can be located at the stern of the vessel or on the side of the vessel.

A critical issue to be considered for the vertical installation method is crushing of the flexible pipe. In order to maintain the required tension and prevent the riser from slipping during installation, the caterpillar tensioners exert a clamping or crushing load on the outer surface of the riser. Care must be taken to ensure that the required clamping force to prevent slippage is not greater than the crush capacity of the pipe. Flexible pipe manufacturers can supply crush resistance loads for various tensioner types if requested. Another issue is overbending of the pipe at the gutter at the top of the installation tower. The radius of curvature of this gutter must be greater than the allowable bend radius of the pipe. Combined bending and tension over this gutter is usually not an issue as the pipe is under low tension at this location.




**a) Low Tension ($T$ < 20 tonnes)**




**b) High Tension ($T$ > 20 tonnes)**

**Key**

1 Flexible pipe

2 Installation reel

3 Laying chute

4 Installation vessel

5 Mean water level

6 Tensioners

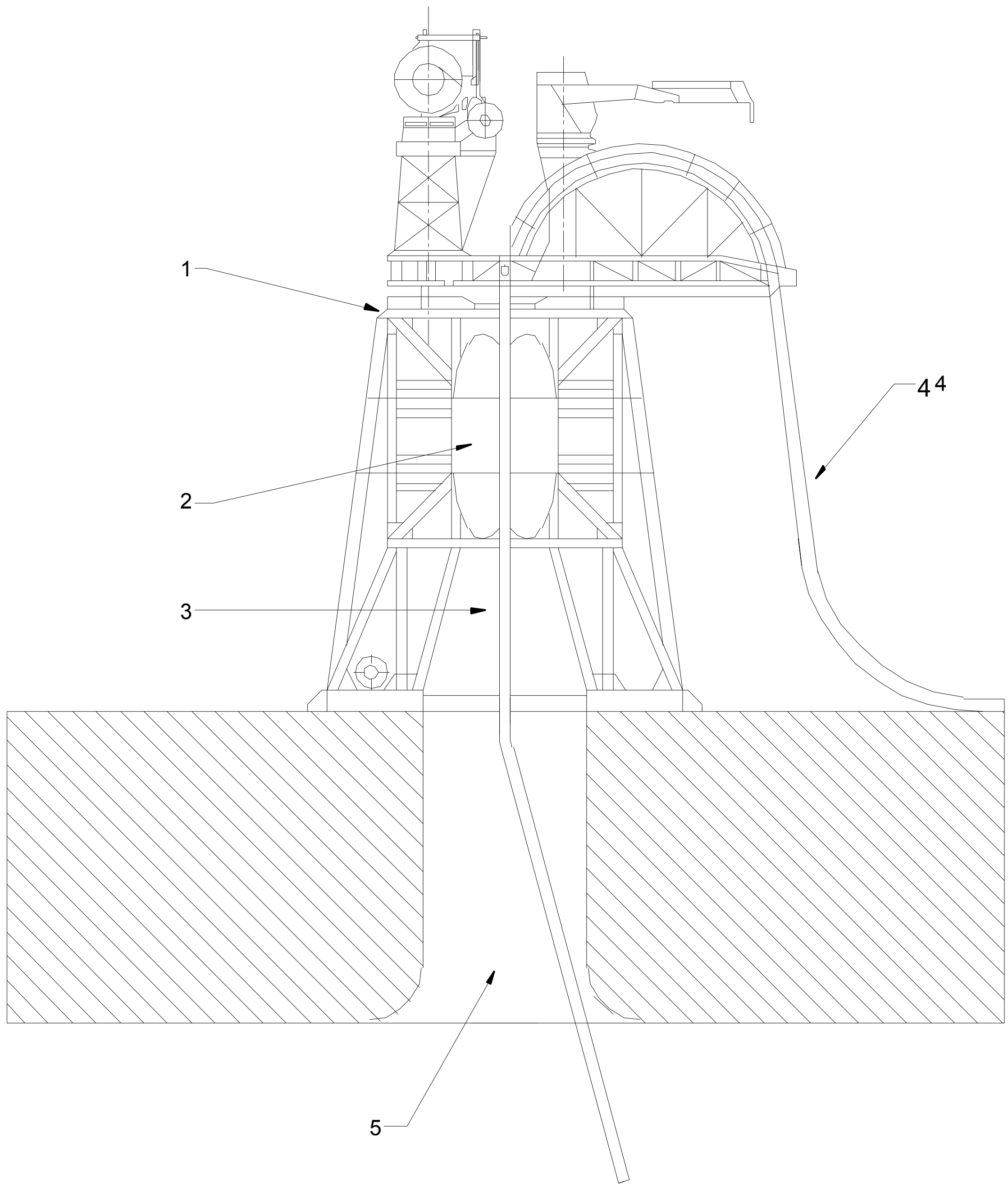
7 Installation reel

8 Installation vessel

NOTE 1 For low tension systems, holdback tension is provided by the installation reel or a winch.

NOTE 2 For high tension systems, the pipe is kept slack behind the tensioners.

**Figure 22—Schematic of Horizontal Lay Installation**




**Key**

1 Installation derrick

2 Caterpillar tensioners

3 Working table; buoyancy modules, anodes, etc. fitted at this point

4 Flexible pipe

5 Vessel moonpool

**Figure 23—Schematic of Vertical Lay Installation**

The vertical lay system is the optimum solution for deepwater installation of flexible pipe. This is due to the large tension requirements involved in deepwater installation. In addition to the increased tension capacity, the vertical lay system also has other advantages over the tensioned reel and horizontal systems in relation to working space as it requires less deck space. The location of the working table just below the tensioner system allows easy access for addition of buoyancy modules or making intermediate connections and thus eliminates the requirement of an overboarding spread as is required by the other installation methods. The vertical lay is typically a modular system that can be easily removed from one vessel and set up on another vessel. This can be carried out quickly with the installation of the lay tower on a vessel taking approximately 24 h. Due to the modular nature of the tower, modifications to increase tension capacity can be made quite easily. Another advantage of the vertical lay system is that as the pipe is laid vertically through a moonpool or off the stern there is no overboarding chute required and thus the crushing issue at this location is eliminated.

A typical vertical lay system utilizes a quad track caterpillar tensioner system. A single vertical tensioner system has an average tension capacity of approximately 125 Te. Some designs have capability of 270 Te. A typical vertical lay system has a speed of up to 900 m/hr. This, however, will be affected by ancillary equipment requirements.

#### 9.4.14 Diverless and Diver-assisted Installation

The selection of diver-assisted or diverless installation will depend on a number of factors, including the following:

a) safety aspects;

b) water depth;

c) regulatory requirements or guidelines;

d) available space for tie-in operations (if a large number of risers are to be connected to a turret, there may be insufficient space for divers);

e) economic factors (diverless tie-in equipment may have significant costs);

f) environmental conditions;

g) equipment reliability (technical risks);

h) schedule requirements (e.g. diverless operations may be much quicker).

## 9.5 Precommissioning and Commissioning

### 9.5.1 Introduction

This process involves the testing and monitoring of flexible pipes after tie-in and completion of the full system, of which the flexible riser and/or flexible flowlines are an integral part. Damage should be repaired and the commissioning should be restarted if the flexible pipe incurs damage during the commissioning period. The pipe manufacturer and the purchaser should decide, through consultation, if the pipe is repairable.

The purchaser should provide the test specification. The manufacturer’s recommendations on testing should be taken into account, and the testing should be carried out prior to any backfilling.

### 9.5.2 Pigging

The guidelines in this section should be implemented if commissioning requires pigging of the flexible pipe. Metallic brushes should not be used in flexible pipes without a metallic carcass layer. Metallic brushes may be used if the internal liner comprises a steel carcass, provided the materials are compatible and the brush does not damage the carcass. Metallic scrapers should not be used.

Gauges may be used, provided the discs are designed such that any obstruction protruding within the gauged diameter will be indicated by a permanent deformation. The gauge plate should be approved by the flexible pipe manufacturer (see API 17J and API 17K).

Articulated pigs should only be used if the natural weight of the pipe or installed imposed bend radius is sufficiently large to accommodate the segment lengths in the pig assembly. Foam pigs should be used for pipes without a metallic carcass layer if possible, but other types of pig may be used, subject to acceptance by the flexible pipe manufacturer.

### 9.5.3 Hydrostatic Pressure Test

#### 9.5.3.1 General

The hydrostatic test may be performed separately on the flexible pipe or as a system test if the flexible pipe is part of the total system. The pipe system may include manifolds, trees, valve assemblies, couplings, seals, etc. All components in the system should be verified as being capable of withstanding the maximum test pressure. The installation test procedure should be in accordance with API 17J and API 17K (hydrostatic pressure test), where relevant.

The hydrostatic test should be in accordance with the following recommendations:

a) only a leak test (with pressure recommended at 1.1 times the design pressure) is necessary if the flexible pipe is installed without the occurrence of any suspected damage, because a FAT hydrotest will have already been performed;

b) a structural integrity test (with pressure recommended at 1.25 times the design pressure) can be required if the pipe has sustained structural damage, been repaired, end fittings replaced, retrieved, and reinstalled without a FAT hydrotest, or other such occurrence that may be considered relevant;

c) the hold period for the test should be 24 h, unless otherwise recommended (see 9.5.3.5);

d) regulatory authority requirements can exceed the recommended test pressures in Items a) and b) and should be checked with the relevant authorities;

e) the flexible pipe design should be checked against allowable criteria for the pressure test load case, including loads from maximum test pressure (which will be between 1.04 and 1.1 times nominal as specified in 9.5.3.3), functional loads (including weight and buoyancy of pipe, contents, and attachments), relevant environmental loads, and any appropriate accidental loads.

The hydrostatic test procedure should identify the following, as and where applicable:

a) pretest and posttest pigging requirements;

b) fill medium details;

c) pressurization and depressurization rates;

d) stabilization criteria;

e) pressure isolation details;

f) entrapped air assessment;

g) permissible unidentifiable pressure loss, and pressure variation calculation method;

h) instrumentation requirements;

i) visual inspection details;

j) data recording details;

k) inspection requirements

l) acceptance criteria.

All annulus vents in unbonded pipes should be opened in end fittings that are not immersed in seawater during the test. The hydrostatic pressure test comprises the following main tasks:

a) test of instrumentation and connections,

b) pressurization of the line,

c) stabilization period,

d) hold period,

e) depressurization.

Recommendations for these tasks, and acceptance criteria, measuring equipment, and test records are given in the following sections.

#### 9.5.3.2 Test of Instrumentation and Connections

A pressure test should be performed on the test equipment and connections at a pressure not less than 104 % of the nominal test pressure of the flexible pipe. The duration of this test is half an hour.

#### 9.5.3.3 Pressurization

Pressurization of the pipe should be carried out at a steady and controlled rate to be specified by the manufacturer. Too high a rate can lead to excess stabilization periods. The pressure should be raised to a value no greater than 110 % of the nominal test pressure.

Different manufacturers specify factors between 104 % and 110 % of the nominal test pressure; any factor within this range is suitable, so long as it is documented and used consistently throughout design and test activities.

The air content should not exceed 0.5 % for smooth bore pipes and 1.0 % for rough bore pipes. Venting at the pipe ends should be performed and pressurization recommenced if the air content exceeds the above values.

#### 9.5.3.4 Stabilization

The stabilization period may last for about 10 h after the end of pressurization. This stabilization period may be extended if significant pressure drops are still occurring after the first 10 h, because of the dimensional or thermal stabilization in the flexible pipe. The period may also be reduced if the line is stabilized. Stabilization is defined as a pressure change over 1 h of less than 1 % of the test pressure. During stabilization, the pressure should be recorded and a log of pressure, and subsea and test fluid temperatures should be maintained (every half hour for pressure readings and every 2 h for temperature readings).

#### 9.5.3.5 Hold Period

The 24-h hold period may start when the stabilization period is completed. A log of pressure and subsea and test fluid temperature readings should be taken at half hour intervals during the hold period. The pressure should be greater than or equal to the nominal test pressure for the hold period. There should be no unaccountable pressure drop during the test. The maximum pressure drop during the hold period should not exceed 4 % of the nominal test pressure.

The hold period for a leak test may be reduced to 6 h if all of the flexible pipe, including both end fittings, can be visually inspected for leakage during the test.

The line should be depressurized if the pressure falls below the test pressure once the test has commenced. In such a case, the hold period is considered as recommencing from this point.

#### 9.5.3.6 Depressurization

The depressurization of the pipe should be performed at a steady and controlled rate as pipe failure can be caused by depressurization at too high a rate. The maximum rate will be a function of the material used for the internal pressure sheath and whether it is built from a single or multiple sublayers.

The maximum depressurization rate for the pipe should be defined by the manufacturer.

#### 9.5.3.7 Qualitative Acceptance Criteria

The following acceptance criteria are recommended, as a minimum:

a) the test pressure is maintained for the period specified above,

b) the test pipe does not undergo unintended or major changes in shape or configuration under pressure,

c) the pipe does not leak.

Leaks through all components in the pipe system should be evaluated if the pressure loss is such that a leak is suspected, because the leak can be from valves, seals, etc., rather than the pipe itself.

#### 9.5.3.8 Measurement Equipment

Measurement equipment used for pressure testing should be calibrated at least every 6 months. Equipment should be maintained in good order and used only for the purpose for which each item has been designed and intended. Equipment used should be listed with all relevant details in the test documentation and should be calibrated to within the following levels of accuracy:

a) hydrostatic pressure gauges: 0.0 % to 0.5 %,

b) dead weight testers: 0.0 % to 0.1 %,

c) pressure chart recorders: ±0.5 %,

d) all other measurement equipment: ±1.0 %.

#### 9.5.3.9 Test Records

It is recommended that the following test records be maintained:

a) date and time;

b) location, condition, and situation details;

c) test and safety personnel;

d) pigging and fill medium details;

e) all equipment and certification details;

f) pressure recorder charts showing continuous recordings;

g) periodic pressure readings, every 30 min as a minimum;

h) periodic ambient temperature readings, every 30 min as a minimum;

i) periodic fill medium temperature readings, every 30 min as a minimum;

j) visual observations.

The test records should be signed by the appropriate personnel and filed for reference.

A postcommissioning survey should be carried out and recorded to verify that the flexible pipe system is installed as designed.

#### 9.5.4 Offshore Repair of Unbonded Flexible Pipe

Offshore outer-sheath weld repair procedures shall be qualified on material exposed to an environment similar to the environment of the damaged outer sheath and cyclic loading characteristics similar to the installation/operation, as applicable, with the same equipment, drying processes, and sheltering as those at the repair site.

#### 9.5.5 Drying of Pipe

There can be stringent requirements on the amount of water that may be left in a flexible pipe after the hydrostatic pressure test in some cases. An example of this is gas export flexible risers tied-in to major export lines, which have stringent requirements on the dryness of the gas. In a rough bore pipe, the interlocking carcass layer forms a large trap for water that, subsequent to a hydrotest, could violate the gas dryness requirements. Vacuum drying of the flexible riser is potentially a very costly and time-consuming operation on the critical path of a project.

A special valve skid could be developed for the seabed end to allow dry installation and tie-in. In addition, the factory hydrotest of the riser could be performed with glycol instead of water, and the riser pressurized with nitrogen during transportation and installation, to ensure dryness.

## 10 Retrieval and Reuse

### 10.1 General

Section 10 addresses the retrieval of flexible pipe and reuse at an alternative location. Recommendations are provided on the inspection and test requirements for the pipe prior to reuse. Note that the retrieval recommendations for when the pipe is to be reused also apply where the pipe is to be retrieved and scrapped.

Consideration should also be given to the recommendations in this section for a pipe that is to be retrieved for repair purposes and reinstalled after repair.

## 10.2 Retrieval

### 10.2.1 General (Bonded and Unbonded Pipe)

A flexible pipe can be retrieved because of the cessation of its usefulness at a particular location or because of damage to the pipe. The retrieval operation is essentially the reverse of installation. A presurvey to assess the condition of the pipe should be carried out to highlight any potential problems, such as the following:

a) pipe burial—jetting could be necessary to unbury the pipe to avoid kinking the pipe during recovery;

b) pipe crossings and adjacent lines—to ensure these are not damaged by retrieval operations;

c) hard marine growth—this can cut through the outer sheath as the pipe comes in contact with layover arches, bending shoes, tensioners, etc.;

d) The riser should be checked for radioactive scale.

A procedure for pipe retrieval should be prepared to preserve the pipe integrity during the operation. The same conditions considered in the global and local analysis of the original installation should be used for the pipe retrieval operation (such as pipe flooded or empty, restrictions because of environmental conditions, equipment imposed loads and configurations considered), as applicable.

Issues with polymer layers cracking due to embrittlement can be encountered during retrieval, especially considering the lines would be recovered at a relatively low temperature where polymer material tends to be more brittle. Attached equipment (anodes, strapped equipment, etc.) could also fall off the pipe during recovery due to abrasion/corrosion of straps/fasteners.

Local environmental laws and regulations should also be considered. Special care regarding pipe fluid spillages should be taken to avoid pollution. The potential for hazardous elements in the pipe, such as radioactive materials, mercuric compounds, etc., should be evaluated and appropriate safety procedures and equipment specified. Pipe flushing with inhibited seawater and cleaning may be necessary prior to disconnection and retrieval.

Risks involving personnel should be a subject of special review. A hazard identification and operability type study should be performed for all operations. Paraffin plugging is a major safety and environmental hazard. Pipe recovery is possibly not safe if there is a possibility of paraffin plugging occurring.

Procedures for pipe retrieval should foresee how the pipe will be identified. Proper visual identification (e.g. through ROV) should be used for this purpose. Buried pipe requires special procedures to avoid possible damage to the pipe or other subsea equipment from trawler equipment used for unburying the pipe.

All limitations of the pipe during installation and handling (such as MBR, maximum allowable torsion, maximum crushing load and tension, and winding/unwinding and storage recommendations) should be included in the retrieval procedure to avoid damage or failure of the pipe. Consideration should be given to the pipe’s aged condition (reduced structural capacity) when specifying retrieval criteria.

The tensions experienced by the pipe are greater during retrieval than installation because of friction on the overboarding chute. Voiding the pipe could be necessary prior to retrieval, depending on the tension and riser configuration.

The recovery operation may be simulated using suitable software. The simulation should take into account relevant factors (such as seastate, current profile, vessel motions) and possible restrictions to recovery, including burial material (soil, clay, or rocks), protection mats, and structures.

Loads, deformations, and abrasions of the pipe should be monitored at all times during pipe retrieval. The pipe should be inspected during recovery. Any damage should be identified clearly on the pipe outer sheath by means of suitable markings. The manufacturer should be consulted for acceptance criteria for damage and cleaning and storage procedures.

### 10.2.2 Unbonded Pipe

The potential for corrosive or toxic fluids or gases in the pipe annulus should be evaluated. Any vent ports or valves containing such fluids in the end fittings should be immediately plugged on retrieval of the pipe until these fluids can be safely discharged. One possibility for discharging the fluids is to pump air or nitrogen into one end fitting and allow release at the other end fitting.

Special care should be taken during retrieval to avoid bursting the outer sheath because of excessive differential pressure between the annulus and exterior of the pipe. A gas pocket accumulated at a low point of the pipe prior to retrieval can propagate upwards in the annulus during retrieval and cause such excessive differential pressure at a point of the pipe closer to the free water surface. Excessive differential pressure can also cause loosening of the outer sheath and may result in problems (including damage to the sheath) if the pipe is retrieved using tensioners or if Chinese fingers are used (compression created may not be sufficient to take tension load through friction). The retrieval rate should be controlled to allow such excess pressure to be bled off at the end-fitting vent valve during retrieval. The pressure release system should be controlled to ensure the safety of personnel and the environment if the annulus contains toxic fluids.

The allowable retrieval rate should be calculated based on the condition of the gas-relief system. Gas-relief valves that have not been operational for a substantial period could become stuck because of scale deposition, marine growth, corrosion, etc. Clogged valves should be safely opened prior to recovery of the pipe, if feasible. Consideration can be given to drilling burst discs in the outer sheath prior to recovery to safeguard the integrity of the outer sheath. Where corrosive or toxic fluids or gases may have accumulated at a low point of the pipe, consideration should be given to a safe penetration of the external sheath (around 50 mm or 2 in. in diameter) prior to retrieval. Gas/liquid exiting from this penetration should be safely collected and discarded. After recovery the penetration of the external sheath may be sealed for further reuse or investigation of the pipe.

### 10.2.3 Bonded Pipe

For float/sink type bonded pipes that float when empty (are full of air), the pipeline should be retrieved by floating it to the surface and then heaving it onto a reel from the surface of the water. The manufacturer should be consulted for dewatering and pigging procedures and limitations.

Care should be taken during reeling of bonded pipelines that consist of multiple lengths to protect the adjacent pipe layers from damage due to contact with an end fitting. The manufacturer should be consulted for packing recommendations related to his/her particular end fitting.

Care should be taken during retrieval of smooth bore (collapsible) bonded pipes to avoid capturing excessive twist on the reel. Consideration should be given to maintaining a nominal pressure in the pipe bore during retrieval to control twist. Full twists captured on the reel should be relieved by transpooling the pipe under internal pressure. The twist can also be relieved by pulling the pipe off the retrieval reel onto the water, pressurizing it with air, then heaving it back on to the reel off the surface of the water if the pipe floats when full of air. The pipe should not be stored or reused in the twisted condition.

Smooth bore bonded pipe can exhibit high elongation due to tension, particularly when the pipe is unpressurized. Care should be taken during retrieval to minimize the amount of elongation that is captured on the reel. The pipe should be transpooled, under internal pressure, to relieve the elongation before the pipe is stored or reused if excessive elongation is captured on the reel. Alternatively, the pipe can be pulled off the retrieval reel onto the water, pressurized with air, then heaved back on to the reel off the surface of the water if the pipe floats when full of air.

## 10.3 Reuse

### 10.3.1 General

As a minimum, the following stages are recommended in the process to reuse a flexible pipe in a new application:

a) documentation,

b) pipe evaluation,

c) pipe retrieval,

d) inspection and repair,

e) test requirements,

f) installation.

Section 9 presents guidelines on pipe installation and 10.2 presents guidelines on pipe retrieval. The remaining stages in the process are addressed in 10.3.2 to 10.3.5. A retrieved pipe designed for SAs should not be reused for a DA. Stages a) and b) above should be performed prior to pipe retrieval to determine if it will be feasible to reuse the pipe.

### 10.3.2 Documentation

The user should maintain a detailed record of previous use so that it will be possible to accurately evaluate the feasibility of reusing the pipe. The record should specify water depth, production fluid characteristics, installation date, length in service, operating pressure and temperature, and any unanticipated events that might affect the pipe function.

Any events that can have damaged the pipe and any previous repairs to the pipe should also be documented and held as evidence of the pipe's service history. In addition, records of all previous inspections and monitoring operations relating to the pipe should be maintained.

### 10.3.3 Pipe Evaluation

#### 10.3.3.1 General

When a pipe is under evaluation for reuse, the new design conditions should be defined using the purchasing guidelines in API 17J and API 17K. The flexible pipe to be reused should conform with the pipe structure design criteria specified in API 17J and API 17K for the new design conditions.

A general review should be carried out, prior to the pipe reuse, considering the pipe design characteristics, the new conditions of use, the remaining pipe service life, and all previous conditions that may have affected its characteristics. The evaluation should also address any accidental damage found from the pipe inspection after retrieval. The effect of corrosive fluids on the structural layers of the pipe should be evaluated in the calculation of the remaining service life. In addition, the aged state and remaining life of the liner or internal pressure sheath/liner polymer/elastomer material should be evaluated.

Pipe verification and assessment for reuse are addressed in the subsequent sections for the following reuse conditions:

a) similar use,

b) new conditions,

c) special cases.

#### 10.3.3.2 Evaluation for Similar Use

The pipe is intended to be reused in conditions similar to the original application in this case. This does not include situations in which the pipe was subjected to abnormal occurrences, damage, or other events that could have significantly reduced the service life. The information to be determined for the evaluation is as follows:

a) the new conditions of use (see API 17J and API 17K), including identification of any major changes in the application ($H_2S$ or $CO_2$ levels) as well as environmental conditions and interfaces to other systems or structures;

b) the remaining service life;

c) the original data specified by the manufacturer, including pipe capacity (datasheet and design report);

d) the availability of additional test and measurement data, or updated design and analysis methodology, that were not available during pipe manufacturing.

An inspection of the pipe for damage should be sufficient to approve the pipe for reuse if the new conditions of use (including installation and retrieval equipment and procedure, and environmental and operational conditions) are easily identified as equivalent or less critical than the original conditions or original design criteria and if the remaining service life is greater than the life required for the new location.

Attention should be given to the procedures and equipment used for installation and retrieval, particularly for deepwater applications where installation conditions can be critical. The installation loads should be confirmed to be less than the original installation, or alternatively a new analysis should be performed to confirm that the pipe meets the design requirements specified in API 17J, API 17K, and guidelines in Section 5.

#### 10.3.3.3 Evaluation for New Conditions of Use

The following information should be assessed if the new conditions of use are not similar to the original ones or if the evaluation carried out according to 10.3.3.2 is inconclusive:

a) new global and cross-section analyses (considering new installation equipment, new operational conditions, new application, etc.);

b) the results of prototype tests, as available (short- and long-term tests).

The liner or internal pressure sheath of flexible pipe to be reused should be suitable for the new transported fluid conditions, considering aspects such as chemical compatibility, temperature, gas permeation, and ageing. Ageing models and methods for determination of elastomer or polymer residual life should be used in the analysis with appropriate safety margins, where available.

The metallic materials should be qualified for SSC and HIC resistance in the new design conditions if sour conditions are foreseen. Elastomer, polymer, and metallic layer thickness reduction as a result of fretting or abrasion, which may have occurred during previous use, should be properly evaluated.

#### 10.3.3.4 Evaluation of Special Cases

Additional analysis could be necessary if the pipe was subjected to abnormal occurrences, damage, critical stresses, or other events that could have significantly reduced the service life of the pipe. In such situations, the following could be required:

a) special local analyses;

b) new prototype tests;

c) records of abnormal operation, such as occurrences where the pipe was submitted to conditions beyond those considered by the original design (extreme loads or temperatures);

d) records of defects or condition detected from inspection during operation or after retrieval (such as damage, corrosion, or ageing);

e) records of former conditions of long-term pipe storage;

f) tests for material qualification (ageing tests, compatibility tests, SSC/HIC NACE qualification tests).

Special local analyses can be useful for evaluation of damage, such as wire rupture, corrosion, wear, etc. New prototype tests may be performed to confirm some specific characteristic required for reuse of the pipe in new conditions (if new installation equipment applies high stress to the pipe).

Results of qualification tests on materials (see API 17J and API 17K) can be useful for evaluation of their remaining life when exposed to operational fluid or to environmental conditions. New tests could be necessary if data is not available. See API 17J and API 17K for test procedures and criteria.

Qualified methods for the pipe and system design should be available to carry out the global and local analysis. Operators can use their own methods or those of a manufacturer or a third party to carry out the pipe assessment. In all cases, the programs and methods used should be validated as required by API 17J and API 17K.

Special attention should be given to calculating the pipe remaining life. Safety margins should be the same as specified in API 17J and API 17K. Information concerning long-term performance of materials under the original use conditions is essential for taking any decision about pipe reuse. Sources of data that can be useful for this purpose include operational experience with materials and pipes, results of long-term tests performed for material qualification, prototype testing (destructive testing of sample from retrieved pipe), inspection of retrieved pipes, suitably qualified nondestructive testing monitoring techniques, and calibrated models for calculating service life, both theoretically and with tests.

### 10.3.4 Inspection and Repair

#### 10.3.4.1 General

Qualified technical personnel should be involved in any inspection and/or repair operation. Manufacturer should be consulted for repairs (e.g. retermination).

#### 10.3.4.2 Unbonded Pipe

Rapid corrosion of exposed pipe metallic armor can occur when it is subjected to the atmosphere as a result of damage (caused, for instance, during the pipe retrieval). It is therefore recommended that such areas be immediately protected by using special anticorrosion products and by covering with tape or bandage if they cannot be immediately repaired. Anticorrosion products used for repair should be checked for compatibility with the polymer materials, including the tapes.

An inspection should assess the degree of corrosion that has taken place and evaluate the corrosion that may be present in areas with an intact outer sheath as a result of damage to the outer sheath that allows the ingress of water. Corrosion can both reduce the armor load capacity and adversely affect its wear characteristics. Areas of the pipe where burst discs opened during the pipe’s previous operation are an example of a pipe section where significant corrosive damage can occur. Acceptance tests (see 10.3.5) and local analysis should be performed to evaluate if the damage is critical.

It could be convenient to cut out critical damage in a localized area and install end fittings on the extremities of remaining sections to make their reuse feasible. Special attention should be given to the interface between the pipe and the bend stiffener/restrictor, where damage and corrosion are likely to appear.

Qualified procedures and personnel should be used for outer sheath repair. The procedures should guarantee the minimum required pipe performance properties. The qualification of repair procedures should include tests that confirm pipe characteristics. The long-term degradation of the repaired area should also be considered. As an alternative to outer sheath repair, it could be more convenient to strip off the whole layer and re-extrude a new outer sheath.

End fittings should be subjected to detailed inspection. The corrosion protection system should be evaluated for all components (end-fitting body, bolts, nuts). The gasket seat should be checked against the design standard for the required surface finish. It should be decided whether regrooving by machining will be feasible or whether the flange should be replaced if the face does not meet the requirements. Replacing the flange can possibly require replacement of the end fitting, as it may not be possible to weld on a new flange. Relief valves should be tested and recalibrated or replaced.

The long-term degradation of plastic components of end fittings should be evaluated. Service life of resins and gaskets should be obtained from the pipe manufacturer.

The new end fittings should be assembled using personnel and procedures approved by the pipe manufacturer if the end fittings are removed.

Internal video inspection is recommended to check for carcass layer anomalies.

#### 10.3.4.3 Bonded Pipe

The exterior surface of the pipe should be thoroughly cleaned and inspected during or after retrieval.

Rapid corrosion of exposed reinforcing plies can occur if the cover layer of a bonded flexible pipe is damaged (caused, for instance, during pipe retrieval). It is therefore recommended that the area be immediately protected by applying anticorrosion product(s) and covering with a temporary, impermeable layer.

All areas of cover damage should be inspected for corrosion. Corrosion can produce rapid degradation in the filament-wire cables typically used in bonded flexible pipe. Acceptance tests and local analysis should be performed to determine if the corrosion damage is critical.

Cutting out the damage and installing new end fittings at the cut ends of the remaining sections could be possible if the damage in a localized area is determined to be critical. New end fittings should be installed by qualified personnel using qualified procedures. Bonded flexible pipes with built-in end fittings may use temporary repair fittings, but in general, this type pipe cannot be permanently reterminated.

Qualified procedures and personnel should be used for all cover repairs. The repair procedure qualification should include tests that confirm pipe characteristics. Long-term degradation of the repaired area should also be considered.

End fittings should be subjected to detailed inspection. The corrosion protection system should be evaluated for all components (end-fitting body, bolts, nuts). The gasket seat should be checked against the design standard for the required surface finish. The decision should be made whether regrooving by machining will be feasible or whether the flange should be replaced if the face does not meet the requirements. Replacing the flange could require replacement of the end fitting, as it may not be possible to weld on a new flange.

The long-term degradation of plastic components of end fittings should be evaluated. Service life of resins and gaskets should be obtained from the pipe manufacturer.

The interface between the built-in nipple and the liner layer should be visually inspected using a mirror or borescope for bonded pipes with built-in end fittings. Any evidence of delamination of the liner layer, linear movement (slippage) between the nipple and liner, or seepage of oil into the nipple-liner interface should be thoroughly evaluated to determine if it is critical.

#### 10.3.5 Test Requirements

After a pipe is prepared for reuse, it should be subjected to the factory tests specified in API 17J or API 17K or as required by the user (such as a hydrostatic test, gauge test, or electric continuity test). The hydrostatic test pressure should be in accordance with FAT requirements in API 17J. The design pressure should be reduced to 0.67 times the test pressure if the test pressure is reduced.

Pipe flushing and corrosion protection for storage can be necessary after the pressure test. Other tests or inspection methods (see 11.4) can be used to check for defects in the pipe, such as material loss by corrosion or cracks or flaws in the structural layers. The pipe should be subjected to further analysis, as recommended in 10.3.3.4, if abnormalities are identified.

Reinstallation and commissioning of the pipe should be in accordance with the recommendations of 9.4 and 9.5.

# 11 Integrity Management

## 11.1 General

Section 11 provides guidelines and recommendations on integrity management and the associated potential inspection/condition monitoring measures, including potential pipe failure mechanisms and defects, for unbonded flexible pipes. In general, Section 11 does not apply to bonded flexible pipes.

## 11.2 General Philosophy

### 11.2.1 Integrity Management and Inspection/Monitoring Philosophy

A detailed integrity management strategy and condition monitoring or inspection program should be established, based on an evaluation of the failure modes to which the flexible pipe is exposed and the risk attributed to failure from each source. See API 580 [15] for guidelines on risk-based inspection.

The integrity management strategy should include a feedback element so that lessons learnt from the inspection and condition monitoring can be captured and used to modify the risk assessment and inspection/condition monitoring strategy in the future, for example, identifying new failure modes and/or modifying inspection and monitoring intervals. A schematic of a typical integrity management strategy is shown in Figure 24.

A broad and thorough approach to collection, analysis, and assessment of measurements, tests, and monitoring data is recommended. A monitoring system designed to operate throughout the field design life, or for a reduced period, on one or more dynamic risers or flowlines for research or operational use may be proposed by manufacturer or required by purchaser. These issues should be resolved fully and a field philosophy completed concurrent with the design phase. The monitoring and inspection philosophy should be identified in the project design premise.

### 11.2.2 Scope

The inspection and condition monitoring program should typically include all applications of flexible pipe and their ancillary components.

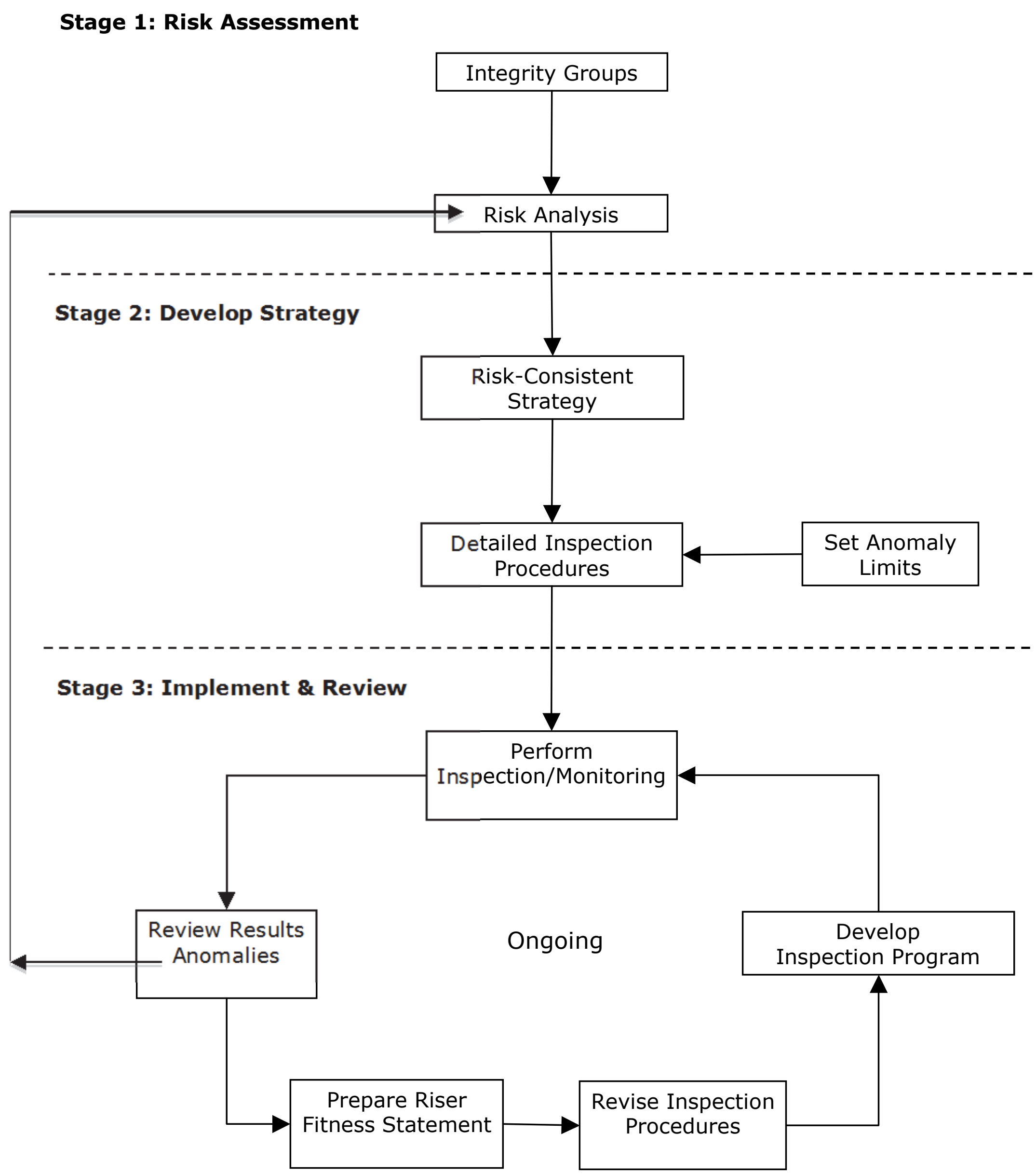



**Figure 24—Flowchart of Typical Integrity Management Strategy**

### 11.2.3 Objectives

The objectives of an in-service integrity management and inspection or condition monitoring program should include the following:

a) detection of possible degradation at a sufficiently early stage to allow for remedial action and thereby:

   1) protect against accidents or loss of life,

   2) protect against environmental pollution,

   3) avoid downtime,

   4) minimize the risk of economic loss arising from pipe system degradation or damage to field equipment;

b) a means to generate a targeted inspection program with a view to reducing inspection costs;

c) compliance with all relevant statutory and regulatory requirements;

d) provision of a record of service data that will be required when considering future reuse and future life extension;

e) input to a spares retention program;

f) detection of abnormal conditions or parameters outside of design envelopes. An example could be detection of marine growth when no marine growth had been considered in the design.

### 11.2.4 Establishment of Inspection/Monitoring Program

Potential failure modes and mechanisms should be identified for the specific design and application of the flexible pipe. The pipe system's functional and operational requirements should be taken into account when assessing potential failure modes.

A risk analysis should seek to quantify the risk attributed to each failure mode, typically as a function of the probability of occurrence and consequence of failure. The establishment of an inspection and monitoring strategy should relate the degree of required monitoring or an inspection to the calculated level of risk.

Available direct or indirect methods to inspect/access the pipe should be evaluated for their suitability for the intended flowline or riser application. Furthermore, adequate provision for facilitating pipe monitoring should be made in the design of the pipe system and associated topside and subsea facilities. In this respect, topside piping should be designed to allow access for internal inspection tools. Equally, should annulus testing or coupon sampling be required, these items will need consideration at the design of the associated topside pipework. Consider saving and storing a piece of unused pipe for consequent inspection/monitoring evaluations of the impact of operational history incidents and accidents on pipe remnant life.

A baseline survey should be implemented for each of the methods that are selected as part of the integrity and condition monitoring program. Provision should be made for any such baseline survey before the pipe is brought into service, and records should be held for the full life of the flexible pipe system. In case an annulus is partly filled during installation, a volume check should be performed after installation and compared with the theoretical and FAT measured volumes.

Integrity monitoring should begin at the factory with thorough inspection, quality control, and documentation of the manufacturing process. The FAT are an essential part of this process; API 17J provides details of the requirements for this. FAT of dynamic risers fitted with vent ports should include vacuum or pressure testing of the annulus to determine free volume and check for outer sheath damage to ensure they are leak proof prior to shipping and commissioning. Note that the reference volume for operational purposes should be that measured offshore after installation and not that measured during FAT. Dynamic risers should have an end-fitting seal integrity test of the outer sheath, smooth bore pipes with an anticollapse sheath should have the same seal integrity test for the anticollapse sheath, and insulated pipes should have a seal integrity test of the seawater barrier (intermediate sheath, or external sheath).

Installation operations need thorough planning to avoid damage caused by handling equipment. Where installation is considered likely to cause outer sheath damage (e.g. I-tube deployment), consideration should be given to the use of an additional protective outer sheath or alternative means of protecting the pipe locally or wholly. Continuous pressure monitoring of the annulus during installation operation may be considered to detect leakage of seawater into the annulus. Consideration should be given to independent review of the installation procedures.

Special care should be taken with the first baseline visual inspection after installation to document minor anomalies or damage that may indicate undetected problems and the need for more frequent monitoring. This first inspection is very important as it should become the benchmark for all future inspections.

It is recommended that an annulus integrity (vacuum or pressure in accordance with Annex E or Annex F) test be carried out immediately after flexible risers have been installed. The volume determined from this first vacuum test in the field (the reference volume) should be used in comparison to volumes determined in subsequent vacuum tests. The results of the test should be verified by other methods such as an inspection of the flexible pipe outer sheath to see if a damaged area can be found. Vacuum testing of unbonded flexible pipe annuli is discussed in Annex F.

Any anomalies and nonconformancies recorded during Installation should be added to the design and fabrication documentation (see Section 7 of API 17J). Where a flexible has been kept in storage prior to installation, consideration should be given to inspecting the asset for damage.

Detailed inspection procedures should be developed for each inspection/condition monitoring method. These should enable subsea contractors to identify anomalies, document and record the required data, and where relevant carry out secondary inspections to further investigate the issue.

The risk assessment and integrity management strategy should define clear operating envelopes for each flexible asset. Should it be necessary to operate outside these envelopes, then the new conditions should be fully assessed.

An integrity envelopes document should be provided to operations to allow monitoring of the system within its allowable limits.

The manufacturer supplied operating manual should specify a preliminary inspection/monitoring program, based on failure modes identified by the manufacturer and based on its knowledge of flexible pipe design criteria and experience of flexible pipe in service in similar operating conditions. For this, manufacturer should consider the uncertainties of its design tools and the uncertainties in material/component test data. This program should include, at least, the following:

a) locations of the pipe/end fitting, ancillary equipment, and accessories to be inspected/monitored;

b) specification of the inspection and monitoring methods (including those for the vent system, annulus and outer sheath integrity, internal fluid, internal pressure sheath degradation, ancillary equipment, and corrosion), equipment, and criteria;

c) specification of criteria for inspection/monitoring;

d) recommended inspection/monitoring frequency;

e) description of the recommended maintenance actions, equipment, facilities, and logistics;

f) special access requirements for inspection, maintenance, and replacement;

g) loads imposed on product by the suggested inspection, monitoring, and maintenance tools.

#### 11.2.5 Inspection and Monitoring Program Review

The inspection and monitoring program should be subjected to regular documented review throughout the service life of the flexible pipe field system. This review should reconsider the methods and frequency of review based on the results of inspection or monitoring, experience of this or similar systems, or additional knowledge of flexible pipe behavior. Documented records of the review process should be retained for the service life of the field system or the service life of each flexible pipe in the field system if any pipes are reused.

Equally, this data is essential should life extension of the pipe be required at the end of the design life of the asset.

Effective integrity management of the subsea system requires critical issues to be identified, addressed, and closed out with minimum delay. A periodic review activity in which operational data is reviewed on a regular predetermined basis also facilitates this process.

Topics of an urgent nature should be focused on by identifying the issues to be addressed and developing a path to a satisfactory resolution.

Procedures should be developed for recording and closing out any anomalies identified during the periodic review.

#### 11.2.6 Anomalies and Repair

Should damage occur to a flexible pipe then advice should be sought relating to:

— implications for ongoing safe operation,

— repair requirements,

— system improvements to avoid occurrence of damage to other lines.

Typically, a team including manufacturer representative, installation and pipe subject matter experts, and purchaser representatives (as required) should be formed to assess the damage and identify remedial actions. The key to preventing further damage occurring due to a primary source of damage is the remedial actions as soon as damage is identified. For example, the impact of secondary damage due to corrosion from initial damage to the outer sheath can be managed through flushing procedures and repair clamps.

### 11.3 Failure Modes and Potential Pipe Defects

A flexible pipe failure mode describes one possible process by which a flexible pipe system could fail. A single failure mode typically represents a succession of pipe/ancillary equipment defects that have the potential to culminate in pipe failure. The identification of relevant failure modes should be based on a detailed knowledge of flexible pipe behavior.

Table 30 to Table 31 identify potential defects or failure mechanisms that apply to the integrity of flexible pipe systems. Each defect/failure mechanism is numbered, and the likely cause and consequence of the defect has been identified.

Table 30 and Table 31 relate to static and dynamic applications, respectively, individually classifying defects/failure mechanisms in each layer of pipe. Table 32 applies to defects/failure mechanisms associated with system components and pipe attachments and damage that can affect the condition or integrity of the flexible pipe itself.

These tables should be reviewed during the selection of the integrity and condition monitoring program. The review will allow identification of critical components in the pipe system and potentially critical defects/failure mechanisms, thereby facilitating a better definition of the requirement and relevancy of available monitoring methods.

For a detailed summary of historical failures refer to the Sureflex JIP state-of-the-art report [55] or visit http://www.ptil.no/getfile.php/Roerledningsskader.3.mars2012.pdf.

### 11.4 Monitoring Methods

Table 33 lists current methods available for the monitoring of flexible pipes in service. Visual inspection and bore pressure, bore temperature, bore fluid sampling, and annulus pressure testing have been, to date, the most common forms of in-service condition monitoring used for the demonstration of continued fitness for purpose. Monitoring methods should only be used if they have been qualified for the particular application and/or have had successful track record on previous field developments.

For a detailed discussion on the methods currently in use and new methods being developed to monitor flexible pipe failure modes refer to the Sureflex JIP guidance note [59].

## 11.5 Recommendations

### 11.5.1 Scope of Recommendations

Although the methods and frequency of required condition monitoring and inspection are recommended to be determined based on the results of a documented risk analysis, some general comments are provided on available inspection and monitoring measures.

### 11.5.2 General Recommendations

Subsea visual inspection can be performed using divers or ROVs. Subsea and topside visual inspection should be used periodically to provide evidence of observable damage to flexibles from accidents, degradation during service, or damage during installation. Risers and flowlines should be inspected following potentially damaging incidents, where possible. The pipe system should be reinspected after repair work to confirm that any pipe or component repairs or replacements have been properly performed. Visual inspection should also occur after reconnection following an emergency or routine pipe disconnection. Visual inspection should seek to identify the following potential problems:

a) extent and type of marine growth;

b) pipe general integrity and condition, including leaks;

c) pipe outer sheath or external carcass integrity and condition;

d) debris and dropped objects;

e) evidence of scour and estimated length of free spans;

f) condition of end fittings;

g) condition of cathodic protection system;

h) any identifiable damage, distortion, or degradation;

i) any identifiable disarrangement of pipe and disarrangement or loss of pipe ancillary components;

j) interference with other subsea hardware;

k) loops and kinks;

l) movement or displacement from “as installed” conditions;

m) corrosion of and accumulation of marine growth in vent valves.

Defects should be documented in terms of type, size, location (pipe identification and Northing and Easting coordinates), depth, and time of observation. The influence of defects on structural or pressure integrity should be assessed. An acoustic survey can also be performed to identify the location of buried pipes and depth of cover.

The outer surface of the pipe should be examined for cuts, gouges, abrasion, bulges, soft spots, loose outer sheath, pigtailing/corkscrewing of armor wires visible by the outer sheath profile, or any sign of separation of the flexible pipe from end fittings. Any tendency for a suspended line to form a loop should also be noted, since these could form kinks under tension. Exposed surfaces of end fittings should be examined for cracks or excessive corrosion.

Slow permeation of a chemical or product through the internal pressure sheath can first become evident when product migrates along the line and is discharged through vent valves at the end fitting.

The pipe locations selected for physical measurement should be chosen to reflect the severity of service conditions in terms of loading, deformation, and internal or external environmental conditions where direct measurement of a section of pipe is possible, either through external or internal nondestructive test methods. Areas of critical design loading may include one or more of the following for flexible risers:

a) top end bend stiffener location connection for tension, bending, and deflection monitoring;

b) pre- and post-mid-water support buoy for bending and torsion measurement;

c) riser base connection for temperature, bending, and pressure monitoring;

d) buoyancy modules for slippage;

e) riser touchdown point for compressive forces/abrasion and bend radius;

f) riser tethers for tensions;

g) buoyancy and anchor clamps and hold-backs.

Test pipes should be exposed to the same pressures, stresses, and diffusion transport conditions as those existing in the flexible pipe, if practicable. The test pipe or sample trap, for polymer monitoring of production fluid, should be located at the end of the flexible pipe nearest the wellhead or else the temperature at the test pipe should be controlled to a temperature at least as high as that in the flexible pipe section closest to the wellhead. Alternatively, although less ideal, sample traps can be put at topsides. Then the samples can be analyzed knowing their conditions (pressure, temperature) with the ageing model and the ageing associated with the wellhead conditions may be extrapolated. The bend radius at the test pipe should be designed to be less than the MBR of the flexible in service for erosion monitoring.

Annulus monitoring methods should be demonstrated to be practical, and quantitative criteria should be developed for their implementation. If the requirement for monitoring of dynamic risers or flowlines has been specified, suitable methods of measurement should be proposed for the relevant areas. The Sureflex JIP report [60] provides guidance on the methodologies for annulus monitoring by gas sampling and analysis.

### 11.5.3 Inspection Intervals

Inspection intervals should be devised from a consideration of pipe failure modes. The following factors should be considered when determining inspection intervals:

a) consequences of failure to human life, property, or the environment;

b) operational criticality;

c) degree of innovation or lack of service experience under similar conditions;

d) pipe product and service conditions, for example, sour service, high pressure, high temperature, large and frequent variations over short time (large gradients);

e) present condition and inspection and service history of the pipe;

f) predicted time to failure, for example, remaining service life based on PA degradation calculations;

g) fatigue life for flooded annulus condition;

h) cost/ease of inspection and condition monitoring activity;

i) risk associated with undertaking the inspection and monitoring activity.

With regard to Item g) above, the predicted fatigue life for the flooded annulus condition may prompt increased frequency of annulus vacuum or low pressure testing to ensure that in the event of a flooded annulus being discovered there is sufficient time to source a replacement flexible pipe before the fatigue life for the flooded annulus condition is used up.

In addition, an external visual inspection interval for a flexible pipe should be carried out immediately after suspected damage, severe storms, reconnection, or installation, and prior to any trench backfilling or rock dumping.

The need for inspection and condition monitoring should also be assessed following an excursion from normal operating limits that the asset has been exposed to (e.g. bore fluid temperature, pressure, extended change of service, etc.).

**Table 30—Potential Pipe Defects/Failure Mechanisms for Static Applications**

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Carcass | 1.1 | Hole, crevice, pitting, or thinning. | Reduced collapse resistance and reduced tension capacity. | a) Sand erosion;<br>b) crevice, pitting, or uniform corrosion [and sulphide stress cracking/hydrogen-induced cracking (SSC/HIC)];<br>c) excessively sour service;<br>d) pigging damage;<br>e) hydrate formation (caused by excessive pressure drop and wet gas) causing pipe blockage and excessive pressure buildup in pipe bore. |
| | 1.2 | Unlocking deformation. | Locally reduced collapse resistance and tension capacity. | a) Overbending;<br>b) excess tension with bending;<br>c) pigging damage;<br>d) hydrate formation (caused by excessive pressure drop and wet gas) causing pipe blockage and excessive pressure buildup in pipe bore. |
| | 1.3 | Collapse or ovalization. | Blocked or reduced bore. | a) Excess tension;<br>b) overpressure built between the different layers in a multilayer pressure sheath design, when the pipe bore is unpressurized;<br>c) rapid gas decompression;<br>d) high initial ovality (manufacturing defect);<br>e) excess loading or deformation during installation;<br>f) high radial gap between pressure armor and internal pressure sheath (manufacturing defect);<br>g) side impact or point contact. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Internal pressure sheath | 2.1 | Crack or hole. | Leak of medium into annulus and/or rupture of outer sheath and/or pipe rupture/leakage. | a) Hole, bubble, or inclusion during fabrication;<br>b) pressure armor rupture;<br>c) pressure armor unlocking;<br>d) ageing (embrittlement);<br>e) temperature above design levels;<br>f) carcass defect;<br>g) pressure above design levels;<br>h) pigging damage;<br>i) environment assisted cracking;<br>j) erosion (smooth bore pipes);<br>k) product composition outside design limits;<br>l) inadequate material finishing;<br>m) fatigue related failure due to thermal and pressure load cycling. |
| | 2.2 | Rupture. | Failure of pipe. | a) Pipe bending (tension side);<br>b) collapse (outer sheath leak, low internal pressure, collapsed carcass);<br>c) ageing and embrittlement;<br>d) failure of pressure armor;<br>e) fatigue failure due to multiple shutdowns associated with vacuum conditions (smooth bore pipe only). |
| | 2.3 | Collapse. | Recoverable, but plastic straining. | Excessive reduction in product pressure or excessive external relative to internal pressure (no carcass or collapsing carcass). |
| | 2.4 | Ageing embrittlement/chemical degradation. | Reduced elasticity and greater susceptibility to cracking; material properties degradation. | Exposure to production fluids (temperature, pH, water/methanol content), chemical injection, drilling fluid etc. |
| | 2.5 | Excess creep (extrusion) of polymer into metallic layer. | Possible hole or crack rupture. | a) Operation at pressures and/or temperatures outside limits;<br>b) inadequate material selection;<br>c) inadequate wall thickness. |
| | 2.6 | Blistering. | Possible hole or crack rupture. | a) Rapid decomposition due to operation at pressures and/or temperatures outside limits;<br>b) rapid decomposition under inadequate material selection. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Pressure armor layer | 3.1 | Individual or multiple wire rupture. | Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath. | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) excess internal pressure;<br>e) failure of tensile/backup pressure armor (excess tension/pressure);<br>f) unlocking;<br>g) manufacturing (welding) defect. |
| | 3.2 | Unlocking. | Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath. | a) Overbending;<br>b) excess tension;<br>c) impact;<br>d) failure of tensile or backup pressure armor;<br>e) radial compression at installation;<br>f) excess torsion during installation;<br>g) manufacturing defect (fishscaling, uncontrolled outer diameter/pitch). |
| | 3.3 | Collapse or ovalization. | Reduced bore.<br>Reduced structural capacity and collapse resistance. | a) Side impact;<br>b) point contact;<br>c) excess tension (in service);<br>d) radial compression at installation. |
| | 3.4 | Corrosion. | Pressure armor tensile failure. | a) Sour service/corrosive annulus;<br>b) ingress of seawater into annulus. |
| Backup pressure armor layer | 4.1 | Rupture (single or all wires). | Reduced structural capacity or pipe rupture (burst). | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) excess internal pressure;<br>e) failure of tensile/pressure armors;<br>f) manufacturing (welding) defect. |
| | 4.2 | Ovality. | Reduced bore.<br>Reduced structural capacity and collapse resistance. | a) Side impact;<br>b) point contact;<br>c) excess tension. |
| | 4.3 | Clustering. | Uneven support of pressure armor layer, failure. | a) Manufacturing defect;<br>b) overbending. |
| | 4.4 | Corrosion. | Pressure armor tensile failure. | a) Sour service/corrosive annulus;<br>b) ingress of seawater into annulus. |
| Tensile armor layers | 5.1 | Multiple wire rupture. | Reduced structural capacity or pipe rupture (burst). | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) excess tension or internal pressure;<br>e) manufacturing (welding) defect;<br>f) accidental impact. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Tensile armor layers (cont.) | 5.2 | Radial buckling or clustering. | Reduced tension capacity. | a) Overtwist;<br>b) compression;<br>c) internal pressure below minimum design value;<br>d) damaged, aged, or inadequately designed holding bandages;<br>e) overbending. |
| | 5.3 | Kinking of pipe. | Reduced tension capacity. | a) Side impact;<br>b) point contact;<br>c) loop in line due to design, manufacturing defect, or installation error;<br>d) overbending. |
| | 5.4 | Corrosion. | Tensile armor rupture. | a) Sour service/corrosive annulus;<br>b) ingress of seawater into annulus. |
| | 5.5 | Individual wire rupture. | Tensile armor reduced structural capacity, rupture if structural capacity exceeded. | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) overstressed armors (excess tension or internal pressure);<br>e) improper clamp design or fit;<br>f) manufacturing (welding) defect;<br>g) accidental impact;<br>h) torsion imbalance (generally more than one wire). |
| Insulation layer | 7.1 | Crushed layer. | Inadequate insulation. | a) Crushing during installation;<br>b) external overpressure. |
| | 7.2 | Pipe clogging. | Wax deposit. | a) Lower waxing temperature than predicted;<br>b) inadequate insulation. |
| Outer sheath | 8.1 | Hole, tear, rupture, or crack. | Ingress of seawater (if through wall). | a) Manufacturing defect;<br>b) tear during installation;<br>c) point contact, impact, or shearing;<br>d) improper clamp design or fit;<br>e) pressure buildup in annulus;<br>f) blocked vent valve;<br>g) internal pressure sheath leak/hole;<br>h) overbending + existing defect;<br>i) ageing, weathering (ultraviolet radiation). |
| | 8.2 | Ingress of seawater. | Tensile or pressure armor wire corrosion (especially splash zone) vent valve blocked open or flooded insulation layer. | a) Hole, tear, rupture, crack in outer sheath;<br>b) defective seal in the end fitting. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| End fitting | 9.1 | Internal pressure sheath pull-out. | Leak of medium into annulus, failure. | a) Loss of friction (carcass deformation etc.);<br>b) tear;<br>c) sheath shrinkage due to temperature cycling or loss of plasticizer;<br>d) creep. |
| | 9.2 | Tensile armor pull-out (all wires). | Failure, burst. | a) Wire break within end fitting;<br>b) epoxy failure (sour service);<br>c) epoxy failure (high temperature ageing);<br>d) loss of friction;<br>e) excess tension. |
| | 9.3 | Outer sheath pull-out. | Ingress of seawater (hydrostatic pressure). | a) Excess annulus pressure;<br>b) creep. |
| | 9.4 | Vent valve blockage. | Outer sheath burst (if it occurs to all vent valves). | a) Debris;<br>b) marine growth;<br>c) mechanism failure (corrosion etc.);<br>d) fabrication errors;<br>e) installation/operation error. |
| | 9.5 | Vent valve leakage. | Possible seawater ingress into annulus. | a) Corrosion;<br>b) failure of mechanism (seal failure etc.). |
| | 9.6 | Individual tensile armor pull-out. | Reduced structural capacity. | a) Wire break within end fitting;<br>b) epoxy failure (sour service);<br>c) epoxy failure (high temperature ageing);<br>d) loss of friction;<br>e) excess tension. |
| | 9.7 | Failure of sealing system (sealing rings, etc.). | Leak of medium into annulus, possible vent valve blockage, possible outer sheath burst and pipe leakage (failure), possible flooding of insulation layer, and possible wax/hydrate formation in flexible pipe bore. | a) Fabrication errors—ineffective seal of internal pressure sheath;<br>b) excess internal pressure;<br>c) excess tension or torsion;<br>d) inadequate installation;<br>e) excessively low production temperature. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| End fitting (cont.) | 9.8 | Crack or rupture of pressure armor or backup pressure armor. | Possible pipe burst or reduced pressure capacity. | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) excess internal pressure;<br>e) failure of tensile armor layer (excess tension or internal pressure);<br>f) inadequate material qualification. |
| | 9.9 | Crack or rupture of tensile armor. | Possible progressive pull-out and pipe failure or reduced structural capacity. | a) Corrosion;<br>b) SSC;<br>c) HIC;<br>d) excess internal pressure;<br>e) failure of tensile armor layer (excess tension or internal pressure);<br>f) failure due to manufacturing defect. |
| | 9.10 | Structural failure of end-fitting body or flange. | Pipe burst/catastrophic failure. | a) Excess internal pressure;<br>b) excess tension or torsion loads;<br>c) hydrostatic collapse;<br>d) corrosion/chemical degradation;<br>e) brittle fracture;<br>f) fatigue. |
| | 9.11 | Cracking of pressure sheath. | Pipe burst/catastrophic failure. | Fatigue due to thermal stress cycling or pressure cycling. |
| Holding bandages | 10.1 | Rupture. | Possible lateral buckling of tensile armors. | a) Pipe bending;<br>b) flooded annulus;<br>c) operation in annulus at pressures, temperatures, and/or pH outside limits;<br>d) damage during manufacture/installation;<br>e) ageing;<br>f) manufacturing defect (loose holding bandage). |
| | 10.2 | Ageing. | Reduced structural capacity of holding bandage. | Material property changes (degradation) arising from ageing. |
| | 10.2 | Excess creep (extrusion) of polymer/composite. | Loosening or failure of holding bandage, loss of or reduced support to tensile armors and possible lateral buckling of tensile armors. | a) Operation at pressures and/or temperatures outside limits;<br>b) inadequate material selection;<br>c) inadequate thickness. |

**Table 31—Potential Pipe Defects/Failure Mechanisms for Dynamic Applications**

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Carcass | 1.1 to 1.3 | As Table 30 for static applications. | As Table 30 for static applications and reduced bending fatigue. | As Table 30 for static applications. |
| | 1.4 | Unsupported carcass/full extension of carcass under its own weight. | Pipe collapse. | Loss of carcass support from overlaying polymeric layer. |
| | 1.5 | Cracking/wear. | Reduced collapse resistance and reduced tension and bending fatigue capacity or pressure sheath rupture. | a) Fatigue + crevice, pitting or uniform corrosion;<br>b) carcass-to-carcass wear or friction;<br>c) inadequate manufacturing tolerances and controls;<br>d) excessive curvature of pipe. |
| Internal pressure sheath | 2.1 | Crack or hole. | Leak of medium into annulus and/or rupture of outer sheath and/or pipe rupture/leakage. | a) to m) As for Table 30 static applications;<br>n) fatigue related failure due to bending load cycling. |
| | 2.2 to 2.6 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| | 2.7 | Rupture. | Failure of pipe. | Fatigue cracking. |
| | 2.8 | Wear/nibbling. | No adverse consequence if thickness is maintained above minimum value to prevent blow through or internal pressure sheath crack or hole. | a) Abrasion between internal pressure sheath and carcass;<br>b) abrasion between internal pressure sheath and pressure armor. |
| Pressure armor layer | 3.1 to 3.4 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| | 3.5 | Individual or multiple wire rupture. | Reduced structural capacity or pipe rupture (burst) or extrusion/leakage of internal pressure sheath. | a) Wear at inter-wire contact;<br>b) wear from contact with backup pressure layer;<br>c) cracking along wire;<br>d) fatigue failure;<br>e) welding defect. |
| | 3.6 | Longitudinal wire crack. | Potential elongation to critical defect size. | Inter-wire contact and local stress concentration. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Backup pressure armor layer | 4.1 to 4.4 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| | 4.5 | Individual or multiple wire rupture. | Reduced structural capacity or pipe rupture (burst). | a) Wear from contact with pressure armor layer;<br>b) fatigue failure. |
| Tensile armor layers | 5.1 to 5.5 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| | 5.6 | Multiple wire rupture. | Reduced structural capacity or pipe rupture (burst).<br>Torsion imbalance. | a) Wear between armor layers (gap in antiwear layer, loss of lubricating oil);<br>b) fretting fatigue;<br>c) notch or crack fatigue failure;<br>d) fatigue failure;<br>e) corrosion or corrosion combined with fatigue. |
| | 5.7 | Individual wire rupture. | Reduced structural capacity or pipe rupture (burst). | a) Wear between armor layers (gap in antiwear layer, loss of lubricating oil);<br>b) fretting fatigue;<br>c) notch or crack fatigue failure;<br>d) fatigue failure. |
| | 5.8 | Tensile armor lateral or radial buckling under compression. | Disorganization of armor wires and tensile armor rupture. | a) Axial compression and cyclic bending;<br>b) manufacturing defect; tension on holding bandages lost. |
| Antiwear layer | 6.1 | Wear, cracking. | Radial contact of armor layers, wear. | a) Relative movement between layers;<br>b) temperature;<br>c) manufacturing defect. |
| | 6.2 | Clustering. | Radial contact of armor layers, wear. | Manufacturing defect. |
| Insulation layer | 7.1 to 7.3 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| Outer sheath | 8.1 | As items 8.1 and 8.2 in Table 30 for static applications. | As items 8.1 and 8.2 in Table 30 for static applications. | As items 8.1 and 8.2 in Table 30 for static applications. |
| | 8.2 | Wear, tear. | Possible rupture due to annulus pressure or possible hole due to wear or accelerated corrosion of metallic armor layers. | Abrasive contact with seabed, other lines or other surfaces. |
| | 8.3 | Aging, fatigue. | Accelerated corrosion of steel armor wires. | Temperature exceeding allowable, particularly when thermally insulated by ancillary components such as bend stiffener. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| End fitting | 9.1 to 9.10 | As Table 30 for static applications. | As Table 30 for static applications. | As Table 30 for static applications. |
| | 9.11 | Cracking of pressure sheath. | Pipe burst/catastrophic failure. | a) As 9.11 of Table 30 for static applications;<br>b) fatigue due to bending load cycling. |
| | 9.12 | Crack or rupture of tensile armor. | Possible progressive pull-out and pipe failure or reduced structural capacity. | a) Fatigue failure due to nonuniform stress distribution in end fitting;<br>b) fatigue failure due to manufacturing defect (inadequate surface roughness, surface cracking in wire bending process, weakening of wire mechanical properties due to bending/heating processes). |
| | 9.13 | Rupture. | Possible lateral buckling of tensile armors. | a) Fatigue failure. |

**Table 32—Potential Pipe Defects/Failure Mechanisms for Pipe System Components**

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Bend limiters (stiffeners and bellmouths) | 10.1 | Stiffener crack. | Possible pipe overbending. | a) Stiffener fatigue;<br>b) excessive bending at stiffener;<br>c) material degradation;<br>d) manufacturing defect (inadequate material finishing, inadequate internal steelwork finishing, inadequate polymer/steelwork bonding)/installation damage. |
| | 10.2 | Stiffener rupture. | Possible pipe overbending or possible tear of outer sheath. | a) Stiffener fatigue;<br>b) excessive bending at stiffener;<br>c) abrasion or impact damage;<br>d) material degradation;<br>e) manufacturing defect (inadequate material finishing, inadequate internal steelwork finishing, inadequate polymer/steelwork bonding). |
| | 10.3 | Stiffener support structure failure. | Possible pipe overbending or possible tear of outer sheath. | a) Excessive bending at stiffener and overloading of bindings or support;<br>b) impact damage;<br>c) structural fatigue of bindings or support structure. |
| | 10.4 | Bellmouth deformation or inadequate size. | Pipe overbending. | a) Bellmouth design or manufacturing fault;<br>b) excessive pipe bending around bellmouth;<br>c) impact damage to bellmouth;<br>d) “pig tailing” of pipe. |
| | 10.5 | Stiffener malperformance. | Pipe overbending. | a) Design uncertainty (stiffness vs temp);<br>b) improper polyurethane (PU) pour or curing, PU cracking, PU ageing. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Bend restrictors | 11.1 | Unlocking disarrangement. | Possible pipe overbending. | a) Excessive bending in pipe;<br>b) defective or damaged restrictor. |
| | 11.2 | Position disarrangement. | Possible pipe overbending. | a) Inadequate clamping of bend restrictor(s);<br>b) impact or abrasion. |
| | 11.3 | Loss of bend restrictor(s). | Possible pipe overbending. | a) Inadequate or damaged clamp(s);<br>b) abrasion or impact damage. |
| Buoyancy modules | 12.1 | Position disarrangement. | Possible pipe overbending or excess tension or tear of outer sheath, riser configuration disarrangement, sag bend clash with seabed, hog bend reaching surface or clashing with vessel, damage to other equipment (end fittings, subsea connections, etc.). | a) Defective buoyancy modules;<br>b) abrasion or impact damage;<br>c) inadequate or damaged clamp(s). |
| | 12.2 | Loss or failure of buoyancy module(s). | Possible pipe overbending or excess tension or tear of outer sheath, riser configuration disarrangement, sag bend clash with seabed, hog bend reaching surface or clashing with vessel, damage to other equipment (end fittings, subsea connections, etc.). | a) Inadequate or damaged clamp(s);<br>b) abrasion or impact damage. |
| | 12.3 | Reduced buoyancy. | Possible pipe overbending or excess tension or seabed contact (abrasion, compression, overbending or impact) in sag bend area. | a) Defective buoyancy modules;<br>b) abrasion or impact damage;<br>c) hydrostatic compression, water absorption, or creep. |
| Subsea buoys | 13.1 | Position disarrangement. | Possible pipe overbending or excess tension, failure of pressure or tensile armors, riser configuration disarrangement, sag bend clash with seabed, hog bend/buoyancy tank reaching surface or clashing with vessel, damage to other equipment (end fittings, subsea connections etc.). | a) Defective buoy;<br>b) abrasion, dropped object, collision or trawl-board impact damage;<br>c) inadequate or damaged clamp(s);<br>d) tether failure (excessive corrosion). |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Subsea buoys (cont.) | 13.2 | Loss of buoy. | Likely pipe overbending or excess tension, failure of pressure or tensile armors, riser configuration disarrangement, sag bend clash with seabed, hog bend/buoyancy tank reaching surface or clashing with vessel, damage to other equipment (end fittings, subsea connections etc.). | a) Under design of bindings and anchors;<br>b) dropped object, collision or trawl-board damage to tethers or buoy;<br>c) fatigue of tethers and bindings;<br>d) flooding of buoy;<br>e) degradation of buoy material. |
| | 13.3 | Reduced buoyancy. | Possible pipe overbending or excess tension, failure of pressure or tensile armors, riser configuration disarrangement, sag bend clash with seabed, sag bend and touchdown point (TDP) area clash with mid water arch tethers or gravity base, damage to other equipment (end fittings, subsea connections etc.). | a) Defective buoy;<br>b) abrasion or impact damage;<br>c) inadequate or damaged clamps;<br>d) flooding of buoy;<br>e) degradation of buoy material;<br>f) hydrostatic compression, water absorption, or creep. |
| Clamps | 14.1 | Rupture. | Loss of buoyancy module or bend restrictor or other equipment connected by clamps. | a) Defective clamp;<br>b) abrasion or impact damage;<br>c) hydrogen embrittlement of bolts protected by anodes;<br>d) not fully seawater resistant materials used when not protected by anodes. |
| | 14.2 | Damage. | Reduced clamping capacity. | Abrasion or impact damage. |
| | 14.3 | Degradation. | Possible rupture. | Ageing or creep of plastic or corrosion of metallic clamp. |
| Riser bases | 15.1 | Damage to riser connection. | Possible end-fitting damage or leakage at connection. | Dropped object, anchor drag or trawl-board impact damage. |
| | 15.2 | Displacement. | Possible pipe overbending or possible excess tension. | a) Dropped object, anchor drag or trawl-board impact damage, scouring, soil settlement;<br>b) lack of stability on seabed. |
| | 15.3 | Flow induced pulsations (generated by dry gas flow in flexible pipe and acoustic amplification). | Fatigue failure of topside or subsea piping. | Fatigue due to dynamic stress cycles. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Riser support structures | 16.1 | Disarrangement of risers. | Possible pipe overbending or possible excess tension or tear of outer sheath. | Inadequate or damaged clamp(s). |
| | 16.2 | Structural failure or displacement of support structure itself. | Possible pipe overbending and possible excess tension or tear of outer sheath. | a) Loads in excess of design values;<br>b) manufacturing error;<br>c) dropped object, collision or trawl-board impact damage. |
| Cathodic protection | 17.1 | Disarrangement. | Inoperative cathodic protection with risk of excessive corrosion. | a) Dropped object, collision or trawl-board impact damage;<br>b) clamping failure. |
| | 17.2 | Electrical discontinuity. | Inoperative cathodic protection with risk of excessive corrosion. | a) Inadequate manufacturing QA;<br>b) dropped object, collision or trawl-board impact damage. |
| | 17.3 | Anode exhaustion. | Inoperative cathodic protection with risk of excessive corrosion. | Anode depletion in excess of design assumptions, cathodic protection drawn by adjacent equipment, damaged area to outer sheath or end-fitting coating greater than design allowance. |
| Mattresses or sand bags | 18.1 | Disarrangement. | Free spans or possible overbending or interference or abrasion. | a) Excessive uplift due to riser motion;<br>b) excessive uplift or horizontal motion due to accidental loading;<br>c) scouring/soil settlement. |
| Dumped rock or trench backfill | 19.1 | Loss of cover. | Possible pipe free spans and overbending, exposure to trawl board or other impact damage. | Gradual upward motion of pipe towards surface, trawl board impact. |
| Flexible pipe layout | 20.1 | Upheaval buckling or upheaval creep of buried pipe. | Possible overbending and local unlocking of pressure armor, exposure to trawl board or other impact damage. | a) Axial compression (temperature and/or pressure induced elongation);<br>b) inadequate installation for buried pipe. |
| | 20.2 | Pipe loop. | Possible overbending pipe excess torsion. | a) Excess torsion during installation;<br>b) excess pipe length at installation. |

| Pipe Layer | Defect Ref. | Defect | Consequence | Possible Cause |
|---|---|---|---|---|
| Flexible pipe layout (cont.) | 20.3 | Pipe disarrangement (compared to designed or as-built layout). | Possible overbending or possible excess tension or possible ovalization or possible tear of outer sheath, clashing with neighboring lines or other equipment. | a) Anchor dragging;<br>b) floating production system or floating production storage and offloading excursion outside design limits;<br>c) trawl board or other side impact;<br>d) point contact;<br>e) environmental loading in excess of design data.<br>For tear to outer sheath, see Table 30 and Table 31. |
| | 20.4 | Pipe free spans. | Possible overbending. | a) Routing over sharp seabed feature;<br>b) loss of cover of trenched or rock-dumped pipe. |
| | 20.5 | Riser interference. | Possible damage to buoyancy devices, clamps or bend restrictors or possible overbending or possible impact damage or wear/abrasion of pipe outer sheath. | a) Extreme environmental conditions in excess of design values;<br>b) inadequate clearance;<br>c) loss of buoyancy modules or clamping devices maintaining pipe separation;<br>d) anchor dragging;<br>e) excessive vessel excursion. |
| Adjacent Pipework | 21.1 | Flow induced pulsations generated by dry gas flow and acoustic amplification. | Small bore pipework failure. | Fatigue due to dynamic stress cycles. |

**Table 33—Current Integrity and Condition Monitoring Methods**

| Method No. | Monitoring Method | Description | Purpose |
|---|---|---|---|
| 1. | Visual inspection:<br>(i) external; | By remotely operated vehicle (ROV) or manually to assess leakage or visible deformation or damage to pipe or outer sheath. | To establish the overall integrity of visible sections of the pipe and the general arrangement of the pipe system. To establish the amount of burial of sections of the pipe and compare this to the design. |
| | (ii) internal. | By camera device inserted into the pipe bore. | To check the condition of the internal carcass or internal pressure sheath. |
| 2. | Pressure test [hydrotest]. | Pressure applied to pipe and decay measured as a function of time. Leakages or anomalies identified. | To establish the ability of the pipe to withstand pressure loads, typically in excess of max. allowable operating pressure, at a given time. |
| 3. | Destructive analysis of removed samples. | Generally applied to coupon testing for ageing of internal pressure sheath whereby ageing coupons of polymer are exposed to flow environment in a spool piece sample trap and removed periodically for destructive testing. | To predict the state of ageing or degradation of the internal pressure sheath by extrapolation from tensile or other testing of thermoplastic material samples removed from actual flow conditions. |
| 4. | Load, deformation and environment (metocean data) monitoring. | Measured parameters include wind, wave or current environment (including wave heights and periods, current and wind speeds, and associated directions), vessel motions, vessel heading, product temperature, pressure and composition, depressurization rates and structural (or flexible pipe) loads and deformations. | Used for design verification or remaining life assessment.<br>Actual loads and environmental conditions may be compared with those predicted during design, thereby establishing the degree of conservatism in the design.<br>Service life calculations may also predict remaining life based on measured environment or loads, to predict actual fatigue cycles used during operation to date.<br>Product composition can help to determine the potential for hydrate buildup and or blockage due to deposits/wax.<br>Some flexible pipe cross-section designs may be restricted to a maximum depressurization rate as advised by the manufacturer. |
| 5. | Nondestructive testing of pipes in service. | These may include radiography, acoustics, or eddy current measurement of steel layers.<br>X-ray tomography has been used previously on end fittings and can identify very small cracks. May not, however, be suitable for use onboard a vessel/platform. | To establish the condition of steel tensile armor and pressure armor layers in service. |
| 6. | Gauging operations. | Gauging pigs to determine pipe ovality or check for obstructions. | To check for damage to the internal pipe profile. |

| Method No. | Monitoring Method | Description | Purpose |
|---|---|---|---|
| 7. | Spool piece/test pipes:<br>(i) di-electric sensing or ultrasonic condition monitoring; | Options:<br>Applied to online ageing analysis of internal pressure sheath coupon inserted into a rigid test spool that is designed to emulate flow conditions. The test pipe is likely to be in series with the flow. | To predict the state of ageing or degradation of the internal pressure sheath by extrapolation from online measurement of a material sample exposed to actual flow conditions. |
| | (ii) test pipe. | Use of a flexible (or rigid with mock-up internal) test pipe in series or in parallel with the flow that is periodically removed for destructive or nondestructive testing.<br>Test method has not been widely adopted. | To examine the state of ageing or degradation of the internal carcass, internal pressure sheath and/or pressure and tensile armor layers of the flexible pipe. |
| 8. | Annulus monitoring:<br>(i) gas diffusion monitoring. | Measurement of annulus fluid (pH, $CO_2$, $H_2S$, chemical composition, volume). | To predict degradation of the steel pressure armor or tensile armor layers or the aged condition of the internal pressure sheath or susceptibility of annulus materials to degradation. |
| 9. | Cathodic protection tests. | Measurement of potential and current density. | To predict the effectiveness of the subsea cathodic protection system at reducing corrosion. |
| 10. | Annulus vacuum or low pressure tests. | Measure the free volume of gas in the flexible riser annulus. | To determine the free volume of the annulus and determine whether the annulus is flooded and therefore subject to increased corrosion. |
| 11. | Flooded member testing. | Examination using ultrasonics of large buoyancy tanks such as those used on mid water arches. | To determine whether buoyancy tanks are flooded/partially flooded with seawater. |
| 12. | Laser leak detection. | Fluorescent dyes are injected topside and detected by ROV subsea. Note that the use of dye may be subject to local rules and regulations. | To identify small leaks and areas of damage of a flexible risers external sheath. |
| 13. | Tether monitoring. | Measurement of strain levels. | To monitor the dynamic and static stress levels in the tether/riser system. To calculate excessive riser motion and use to predict actual fatigue cycles used during operation to date. |
| 14. | Bend stiffener strain measurement. | Use of strain gauges attached to riser bend stiffeners. | To measure the dynamic stress levels in the bend stiffeners and to predict actual fatigue cycles used during operation to date. |
| 15 | Bend stiffener location curvature and tension monitoring. | Monitoring of riser curvature and tension at bend stiffener location. | To check that the riser is being properly protected from overbending by the bend stiffener. |
| 16. | Subsea annulus vent monitoring. | Monitor subsea annulus vents with ROV inspection cameras. | To check that the valves are still operational and that permeated gas is not escaping through a damaged external sheath. |

| Method No. | Monitoring Method | Description | Purpose |
|---|---|---|---|
| 17. | Bend stiffener sonar measurement (experimental technique). | Use of sonar to check the location of the bend stiffeners from the topside. | Check that the bend stiffeners have not slipped and are protecting the flexible riser. |
| 18. | I-tube camera. | Use of a small bullet camera deployed down the riser I-tube. | Check the riser external sheath for damage and/or location of the bend stiffeners below. |
| 19. | Vibration monitoring. | Use of subsea (ROV deployed) accelerometers and topside vibration equipment to measure pipework operational response. | To identify the presence of flow induced pulsation in gas export pipework and determine the subsequent potential for fatigue related failure of the rigid small bore connection pipework. |
| 20. | Polymer degradation. | Use of predictive techniques using bore pressure, temperature and pH data. | To predict the ageing of the polymer layer due to material degradation. |
| 21. | Produced sand monitoring. | Measurement of production sand levels and fluid velocity. | To review levels against design criteria and assess the potential for increased erosion rates. |
| 22. | Riser flushing checks. | Monitor the volume of flushing fluids injected through the riser annulus. | To see if quantities of flushing fluid increase, which may indicate new external damage to the riser. |
| 23. | Vessel transit. | Monitor and record unauthorized vessels entering exclusion zones around the flexible risers. | To identify the potential for damage (e.g. through trawling). |
| 24. | Dropped object reporting. | Record all overboard dropped objects around the flexible assets. | To determine the potential for external damage to the flexible riser. |
| 25. | Fiber optic monitoring. | Fiber optics are embedded into the riser or fitted externally. | To monitor strain levels and temperature in the flexible asset during operation. |
| 26. | Operating condition monitoring. | Monitoring of the operating characteristics of the riser. | To monitor pressure, fluid conditions etc. and compare against the integrity envelopes for the equipment. |

# Annex A
(normative)

# Flexible Pipe High Temperature End-fitting Qualification Test Protocol: Volatile Content Polymers

## A.1 General

This procedure is a synthesis of the various requirements and objectives of many flexible pipe operators and manufacturers. It is primarily intended to qualify end fittings generically, rather than for specific project requirements. Section A.7 provides discussion of topics that can be appropriate to tests conducted for specific projects and for interpreting the results of tests conducted under this procedure for specific projects. The procedure can also be used together with Annex B to evaluate end-fitting performance when subjected to specific crude oil environments. In addition to the mechanical behavior tested by this procedure, appropriate testing is required to qualify the chemical and physical suitability of the end fitting and pressure sheath materials. The procedure does not qualify the strength or stiffness of the end fittings. See A.7 for other qualification topics.

Pairs of identical samples will be tested to identical conditions. Four end fittings are required to meet the acceptance criteria to achieve unrestricted qualification for the envelope of service covered by the test conditions.

The procedure can be used to qualify static or dynamic end fittings and is recommended for qualification of the end-fitting termination for new volatile content polymer materials. The procedure is applicable for plasticized polymer fluid barriers. Its development was based on the behavior of PVDF plasticized with dibutyl sebacate (DBS). The procedure, however, is not restricted to this material and is applicable to any new volatile content polymer.

## A.2 Test Objective

The procedure defined below provides an industry-acceptable methodology to qualify the mechanical performance of both existing and newly developed end-fitting designs for flexible pipes made with high temperature polymer internal pressure sheaths for a representative service life of 20 years.

The procedure is applicable to plasticized polymer fluid barriers used for flexible pipes in oil service, gas service, and water injection service.

## A.3 Initial Data

Prior to the start of testing, the manufacturer is to specify:

a) the rated service temperature, $T_{\mathrm{hi}}$, and the minimum service temperature, $T_{\mathrm{lo}}$, for which the end-fitting design is being qualified;

b) the “initial movement” because of “bedding-in” or “compliance take-up” that is predicted to occur in the early stages of the testing;

c) an objective weight percent, $W$, that is equal to or greater than the plasticizer loss expected under the seal grip ring during 20 years of production at the upper test temperature;

d) specify the following deplasticizing times:

$T_1$ = the time at the upper test temperature $T_{hi}$ required to reduce by one-third of $W$, the average weight percent of plasticizer below the seal grip ring;

$T_2$ = the incremental time at the upper test temperature, beyond $T_1$, required to reduce the average weight percent of plasticizer below the seal grip ring by an additional one-third of $W$ for a total of two-thirds of $W$;

$T_3$ = the incremental time at the upper test temperature, beyond $T_2$, required to reduce the average weight percent or plasticizer below the seal grip ring by an additional one-third of $W$ for a total of $W$.

The full-scale or midscale test simulates field performance of the end-fitting design for project-specific crude oil applications if the percent volume change correlating with the percent weight change achieved under the seal ring in the full-scale test is greater than the equilibrium percent volume change expected under the seal ring in the service conditions during 20 years or during a shorter service life based on tests as outlined in Annex B.

NOTE The final weight percent plasticizer present in the polymer is dependent on the service use of the pipe. Oil service can result in final plasticizer content between 3.5 % and 6 %, while high temperature gas service can result in complete removal of plasticizer.

## A.4 Test Samples

Two test samples are required. The test samples shall be complete production flexible pipes with all layers and features. All end fittings shall be of the same design and assembled to the same procedure and dimensional tolerance specification. Pipe length shall be 10 m (32.8 ft) or more. The pipe annulus should be vented. The pipe should be manufactured according to normal procedures; in particular, the hydrostatic test shall be at ambient temperature and shall not exceed 1.5 times the rated design pressure.

Alternatively, two midscale test samples can be used. A midscale test sample shall include the following:

a) all layers of the full-sized flexible pipe through the pressure armor; thermal mass or insulation external to the pressure armor should be applied to represent the remaining flexible pipe layers;

b) midscale end fittings that include identical design, dimensions, and tolerancing attributes for the following functions:

   1) anchoring of the internal carcass;

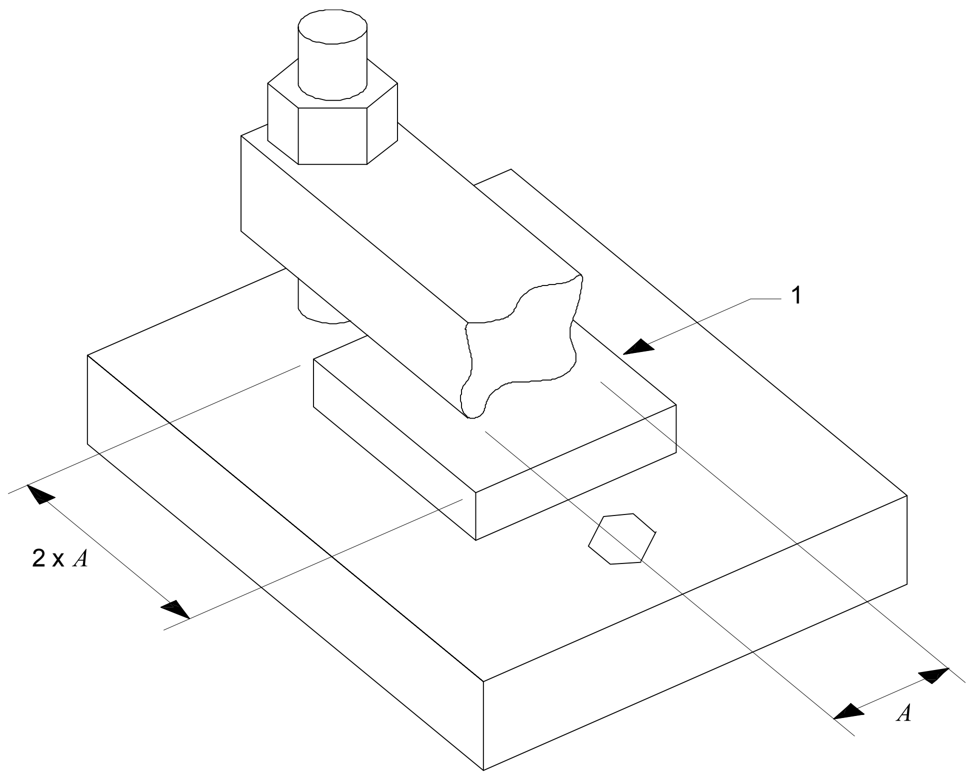
   2) anchoring and sealing of the internal pressure sheath and any sacrificial or tape layers adjacent to the internal pressure sheath;

   3) thermal mass and insulation, which is representative of a full end fitting.

The length of a midscale sample is typically 1 m to 2 m (3.28 ft to 6.56 ft). It shall be demonstrated that the tension force applied to a pressure sheath seal during thermal cycling of a midscale sample is equal to or greater than that in the full-scale sample. This is accomplished by fixed restraints applied to both end fittings. The restraints prevent the midscale sample from changing length during thermal cycling.

The manufacturer shall have available, for review by any interested parties, detailed records of the as-built material, dimensions, fits, and clearances of all pieces of the end fitting and pipe body that may affect the performance of the end fitting during testing. The records shall include the dimensioned and toleranced manufacturing drawings for the pipe and end fittings and all manufacturing and procurement procedures and standards. In addition, the records shall include the calculations associated with the initial data (initial movement, $\Delta W$, $T_1$, $T_2$, $T_3$, etc.)

Four monitoring assemblies shall be placed inside each test pipe (see Figure A.1). Each assembly can consist of a square pressure barrier material sample with edge dimensions at least twice the width of the seal grip ring. The barrier material shall be compressed between a rigid plate that is larger than the material sample and a rigid bar that is at least as wide as the seal/grip ring and longer than the material sample width. The percent compression of the material sample shall be equal (±5 %) to the compression achieved under the seal/grip ring.




**Key**

1 Material sample

$A$ Seal/grip ring width

**Figure A.1—Monitoring Assembly**

Alternative monitoring assembly configurations may be accepted, by agreement. The purpose is to identify plasticizer content and hydrocarbon uptake in the seal ring area. This is based on the assumption that a validated analytical or empirical model exists for the relationship between plasticizer in the main body of the pipe and the plasticizer condition at the seal grip ring. Development and validation of this model is a necessary part of prequalification testing. Validation will include survey of the barrier condition in the seal area from a dissected end fitting after a documented deplastification process.

## A.5 Test Procedures

### A.5.1 Test Setup

The test pieces shall be set up initially for static temperature cycling and subsequently in a dynamic test bench or alternative test structure to allow flexing of the upper end of the test riser. The static phases

(Procedure 1 through Procedure 4, see below) may be carried out with the sample on a workshop floor. The dynamic test procedures shall be carried out with the test sample(s) mounted in a testing apparatus suitable to flex the riser upper end sufficiently to ensure any effects of inter-layer friction are removed from the temperature cycling. Dynamic flexing is not required in the midscale test samples as the axial stiffness of the hoop strength layer alone is negligible. Therefore, the inter-layer friction between the internal pressure sheath and the hoop strength layer will not affect the load on the internal pressure sheath anchoring.

Thermocouples shall be installed on the inside and outside of each end fitting approximately in the plane of the seal grip ring. Additional thermocouples may be applied for data taking at the manufacturer's discretion.

The test pipes shall be filled with nonhazardous oil that facilitates deplasticizing of the inner polymer sheath(s).

Load cells shall be installed between the fixed restraints and the test samples so that axial loads generated during thermal cycling may be measured.

### A.5.2 Test Temperatures and Pressures

An upper and lower test temperature shall be specified by the manufacturer ($T_{hi}$ and $T_{lo}$).

This procedure may be used for qualification without the application of design margins. The maximum service temperature for which the pipe becomes qualified shall be the average of $T_{hi}$ achieved during the test program. The minimum service temperature for which the pipe becomes qualified shall be the average of $T_{lo}$.

An industry target for $T_{hi}$ is 130 °C (266 °F). Target for $T_{lo}$ is –25 °C (–13 °F) but no higher than 0 °C (32 °F). An acceptable value for $T_{lo}$, excluding blowdown, may be –5 °C to –8 °C (–23 °F to –17.6 °F).

The internal pressure shall vary with the temperature such that no less than atmospheric pressure is induced at ambient temperature, and a maximum pressure of approximately 7 MPa (70 bar) is induced at the top flange at maximum test temperature. Relief valves shall be provided so that the internal pressure does not fall below ambient at any time (no vacuum).

Cooling rates should be no slower than those predicted for typical field applications. Cooling shall be controlled so as to simulate these typical operating conditions. Heating at a slower rate than predicted for typical field applications is acceptable but will increase the time required to complete the temperature cycling process.

NOTE An industry basis for cooling rate has been agreed as a riser termination at the deck level of an FPSO turret or a semisubmersible, in air. See A.7.12 for discussion of "hangoff" and "insulation" effects.

### A.5.3 Thermal Cycling Procedure

#### A.5.3.1 Full-scale Test

Each thermal cycle shall consist of the five steps described as follows.

a) The pipe internal temperature ($T_{hi}$) shall be raised to the upper test temperature.

b) The test temperature shall be maintained for an additional 24 h after internal and external thermocouples on the pipe reach a stable temperature.

NOTE The soaking period is related to the creep and relaxation behavior of the polymer that is considered. The 24-h period is valid for PVDF; other polymers can require different values.

c) The test pipe shall be cooled until the internal and external thermocouples stabilize at ambient temperature. Dynamic pipes shall be flexed at least two times while at this step. Cooling shall be at a rate equivalent to natural convection, with representative temperature gradient within the end fittings.

d) The temperature shall be reduced to the lower test temperature ($T_{lo}$) by controlled cooling until the internal and external thermocouples stabilize.

e) The temperature shall be maintained at the lower temperature for a minimum of 1 h.

#### A.5.3.2 Midscale Test

Each thermal cycle shall consist of the five steps described as follows.

a) At installation, the restraints shall be adjusted so that the axial force is within 500 N of zero while the sample is at ambient temperature.

b) The pipe internal temperature $T_{hi}$ shall be raised to the test temperature.

c) The pipe internal temperature shall be maintained at $T_{hi}$ until 24 h from the start of the heating cycle.

d) The pipe internal temperature shall be reduced to the lower test temperature by controlled cooling, until the pipe internal temperature reaches $T_{lo}$.

e) The pipe internal temperature shall be maintained at $T_{lo}$ until 24 h from the start of the cooling cycle. The cycle is repeated at Step b).

### A.5.4 Test Procedures

#### A.5.4.1 Descriptions

#### A.5.4.1.1 Procedure 1

Procedure 1 consists of 10 cycles of static thermal cycling. The bore of each end fitting shall be inspected after 5 (±1) and 10 (±1) cycles.

The pipes should be essentially horizontal during Procedure 1 thermal cycling, and fittings may be raised for convenience in filling, inspecting, etc., with the pipes free to expand and distort as a result of heating and induced loads.

#### A.5.4.1.2 Procedure 2

Procedure 2 consists of deplasticizing at the test temperature for no less a period of time than $T_1$. At the end of the procedure a pressure test shall be conducted, one of the monitoring assemblies shall be removed from the test pipe, and the degree of deplasticizing in the center of the material sample shall be compared with the manufacturer's predictions. If the predicted extent of deplasticizing has not been achieved, the deplasticizing times for all procedures shall be recalculated to achieve the removal of the objective fractions of $W$ and the current procedure shall be continued to achieve the recalculated time. If the intended deplasticizing has been exceeded, the future deplasticizing times shall be recalculated and reduced accordingly.

#### A.5.4.1.3 Procedure 3

Procedure 3 consists of a repeat of Procedure 2 for no less than duration $T_2$, including any necessary adjustment of $T_2$ to achieve the intended level of deplasticizing.

#### A.5.4.1.4 Procedure 4

Procedure 4 consists of a repeat of Procedure 2 for no less than duration $T_3$. Achievement of the objective weight percent of deplasticizing $W$ in test samples is to be confirmed before proceeding to Procedure 5.

#### A.5.4.1.5 Procedure 5

##### A.5.4.1.5.1 Static Flexible Pipes

Procedure 5 consists of at least 40 cycles of thermal cycling.

If any apparent movement is recorded by changes in dimensions during the first 40 cycles, the thermal cycling shall be continued until 20 cycles without any dimensional changes occurring or until a steady rate of change is achieved.

Each end fitting shall be inspected after 10 (±1) cycles and thereafter every 10 (±1) cycles if no changes occur or every 5 (±1) cycles if apparent movement occurs.

##### A.5.4.1.5.2 Dynamic Flexible Pipes

Procedure 5 consists of at least 40 cycles of thermal cycling while flexing the pipe through an angle. Flexing is not required on the midscale tests.

During Procedure 5, flexing of at least one end of the test pipe shall be carried out by lifting or flexing in a hinged frame to a radius of curvature equal to the design minimum for the pipe structure. The flexure shall be repeated at least two times in each temperature cycle, while the pipe is at ambient temperature.

The thermal cycling shall be continued until 20 cycles without any dimensional changes occurring, or until a steady rate of change is achieved, if any apparent movement is recorded by changes in dimensions during the first 40 cycles.

Each end fitting shall be inspected after 10 (±1) cycles and thereafter every 10 (±1) cycles if no changes occur or every 5 (±1) cycles if apparent movement occurs.

#### A.5.4.1.6 Procedure 6

Procedure 6 consists of dissecting the end fittings and measuring the plasticizer content under the seal/grip ring and at $2t$ and $4t$ ($t$ is the uncompressed sheath thickness) on either side of the seal grip ring center to confirm that the acceptance criteria have been met. If the objective weight percent of deplasticizing $W$ is not achieved under the seal/grip ring in the first pipe end fittings, the second pipe shall not be dissected until it has been subjected to a $T_3$ duration recalculated to achieve the objective.

### A.5.4.2 General

The second test pipe shall not be subjected to Procedure 4 testing until the first test pipe has completed Procedure 6 and the deplasticizing time $T_2$ has been confirmed or corrected. Thereafter, the second test pipe's deplasticizing times ($T_2$ and $T_3$) shall be adjusted according to the test results for the first pipe.

To facilitate testing, deplasticizing in Procedures 2, 3, and 4 can be continued while the monitoring assemblies are evaluated and deplasticizing times ($T_1$, $T_2$, $T_3$) are adjusted.

## A.5.5 Inspection and Test Activities

### A.5.5.1 Inspection

The bore areas of each end fitting shall be inspected for movement of the layers. The position of the fluid barrier and any sacrificial or metallic layers adjacent to the fluid barrier that are retained in the end fitting by the seal/grip ring, relative to a fixed reference location, shall be measured and recorded. Special "ports" or "windows" may need to be cut in the carcass or other layers, or through the end-fitting body, to facilitate such measurements.

### A.5.5.2 Pressure Testing

Each pipe shall be subjected to a 2-h leak test at design pressure (or a value agreed by the parties) and room temperature at the end of each test procedure. For the midscale test samples, the test pressure should be sufficiently high to achieve axial extension equal to or greater than that which would be experienced in the full-scale test.

# A.6 Acceptance Criteria

The objective weight percent $W$ of plasticizer shall have been removed under the seal/grip ring in at least two end fittings and achieved within 0.5 weight percent in the others.

There shall be no leakage, cracking, or blistering.

There shall be no evidence of movement under the seal/grip ring, or the movement shall be steady, predictable, and progressing at a rate that would not cause failure within 20 years.

# A.7 Technical Issues—Discussion of Parameters

## A.7.1 General

The following sections are a commentary. The procedure includes these sections as advice upon qualification, criteria, or interpretation of results from the testing. Although the procedure is aimed to be material independent, the technical issues discussed below are somewhat more specific to PVDF, for historical reasons.

## A.7.2 Volumetric Stability

Plasticizer content will decline to zero, following the laws of diffusion. If the transported medium is gas or water, this will be the final condition. If the transported medium is crude oil, absorption of some of the crude components will occur, dependent on the crude and the operational temperature. For PVDF, the equilibrium is expected somewhere between 2 % to 4 % DBS by weight for temperatures between 110 °C and 130 °C (230 °F and 266 °F), with higher levels or replasticizing at lower temperatures. This has to be verified by small-scale testing. The differences between crudes (condensate, light, heavy, aromatics or not) are being investigated, the other main parameter being temperature. Tests with a number of crudes are required to build an empirical model of behavior.

Qualification for crude oil service may be achieved by means of assessment against predicted equilibrium for the specific field conditions. Basically, the qualification testing has to show stability in conditions of greater effective deplastification than the predicted final in-service conditions.

An assessment for crude oil service may be carried out as in A.7.10 following acceptance of crude oil replastification test results determined according to the procedure in Annex B.

### A.7.3 Number of Temperature Cycles for Qualification

For PVDF, it is agreed that 10 (static) cycles are sufficient to “precondition” a test pipe (generate the predicted tensile load in the barrier when cooled to the lowest test temperature and reduce the hysteresis in the response to a stable level).

Based on the rate of decay to “failure” of previous design end fittings in service, and an empirical relationship of 1:2 between cycles in the field versus cycles in test pipes, it is proposed that a further 40 cycles (static or dynamic, depending on the pipe application) after completing the specified deplastification process are sufficient to demonstrate fitness for purpose. Alternatively, if temperature cycling is carried out in stages during the deplastification, the final temperature cycling series may be reduced to 20 cycles, subject to the minimum total being 50 cycles.

Zero movement can be interpreted as permanently stable. If steady movement is identified, this may be projected linearly, based on the progression of the early test specimens (field monitoring is recommended to confirm the projections are accurate).

Simulation of field applications where the service life is 20 years and operations involve frequent temperature cycles might require several additional years of continuous cycling. In practice, therefore, the most practical approach may be to accept qualification for the service period simulated by the testing, introduce markers in the PVDF barrier, and set up a monitoring program to calibrate against the full-scale test data.

### A.7.4 Number and Nature of Dynamic Flexures for Qualification of Dynamic Pipe

It is necessary to flex at least one end of the test pipe sufficiently that any interlayer friction between the PVDF layers and the carcass/PVDF/pressure armor is released. This will then ensure that the tension generated in the critical PVDF layers will be delivered to the crimped seal. Flexing is not required on the midscale tests.

It is unnecessary to apply a program of flexures as for a riser mechanical fatigue test because the bend stiffener will reduce the loading at the end fitting to varying tension load, which is considerably smaller than the temperature-induced loading.

### A.7.5 Diameter Scaling

The key parameters to PVDF barrier behavior in the seal ring area are percentage indentation and the related stresses in the crimp zone. If test results are to be used for other diameters, then the indentation of the sheath in radial direction as percentage of the barrier thickness should be constant. The following elements shall be evaluated in calculating the percentage indentation or crimp:

a) crimp geometry (generally scaled to ensure similar stress distribution);

b) deflection of any underlying steel supporting inserts;

c) manufacturing and assembly tolerances: these should be adjusted so that the designs being compared have the same minimum barrier compression under the crimp ring.

### A.7.6 Number of End Fittings and Alternative Methods of Interpretation

While one pipe (two end fittings) can be sufficient to identify mechanisms and provide a preliminary basis for qualification, a second test (one pipe, two end fittings) is required to verify repeatability of results and interpret variability of manufacturing tolerances.

It may be possible to use test pipes with end-fitting designs that are sufficiently similar rather than identical. The criteria for acceptance of marginally different end fittings are to be established (see below).

### A.7.7 Carcass Weight

The inner layer of PVDF (for risers) intrudes into the spiral spaces in the carcass. The carcass weight is transferred to this PVDF layer through these protrusions. If the PVDF is a single layer construction, it also protrudes into the spiral spaces of the pressure armor. By this means, for a static line, any weight loads are distributed along the suspended pipe length.

Multiple layer risers have a smooth surface between the PVDF layers. Unless the internal pressure is able to transfer the weight loading (plus the temperature cycling induced tensile loads), the weight and temperature-induced load (proportional to barrier thickness) is transferred directly to the upper end fitting. Based on typical examples of in-service conditions, it is likely that the barrier weight loading would increase the total loading by 10 % to 15 %.

### A.7.8 Dimensional Tolerances

The effect of dimensional tolerances on performance is specific to the manufacturer's end-fitting design. No general guidance can be given with the exception that production end fittings shall be able to be verified to have assembly tolerances equal to or better than the tolerances achieved for the test pipe end fittings. Minimum barrier indentation percentage shall be greater than or equal to the indentation percentage of the qualification samples.

The manufacturer-detailed design, design basis, and tolerances shall have documentation, with the tests as a benchmark, to provide this verification.

### A.7.9 Predeplastification

Predeplastification of the PVDF sheath prior to assembly can be used as a means to document a minimum service life for pipes that transport hot gas or condensate. The deplastification required is related to the status achieved by suitable test pipes. As an example, consider the case that the pipe qualification tests have successfully reached 5 % plasticizer, from 12 % (including temperature cycling to prove end-fitting stability), and the predicted equilibrium for a condensate line to be qualified is 2 %. In this case, a plasticizer loss of 7 % has been proven and the end fittings should be predeplastified to less than 9 % [7 % (+2 %)] (a predeplastification of more than 3 % to verify long-term stability).

### A.7.10 Assessment of Service Life for Pipes in Crude Oil Service

To qualify for long-term service, the percent volume change $V$ corresponding to the weight percent change $W$ achieved in the test pipe shall be greater than that determined by exposure testing as in Annex B for the maximum operating temperature of the pipe in the given crude, or equivalent. The service life shall be determined by the creep rate based on temperature cycles over the service life if there is evidence of movement of the barrier in the end fitting. The pipe shall be considered qualified if there is no evidence of movement of the barrier.

### A.7.11 Interim Assessment of Service Life

The procedure outlined below may be used if the testing has reached a given percent of DBS ($n$ %) at a point necessary to assess projected service life.

1) The percentage volume change ($v$ %) corresponding to the percentage weight change ($n$ %) achieved in the full-scale test shall be determined.

2) The equilibrium percentage volume change ($e$ %) for the production fluid and maximum production temperature shall be determined in accordance with Annex B.

3) The time ($T_V$) to reach $v$ % under the expected temperature exposure profile shall be determined based on the decay curve with $e$ percent as the asymptote.

4) The projected service life is the time $T_V$, subject to verification of the following:

   a) completion of 10 + 40 temperature cycles,

   b) no evidence of barrier movement under the crimp seal.

Field monitoring is recommended to confirm that $T_V$ is accurate.

## A.7.12 Project-specific Considerations

### A.7.12.1 General

Each project needs to assess which elements of the procedure testing are or are not representative of the project's conditions and exposures. Some possible differences can occur in the following areas:

a) top end hangoff,

b) immersion and insulation,

c) system blowdown.

### A.7.12.2 Top End Hangoff

The methods and mechanical details of the top hangoff of flexible pipe end fittings can affect the heating and cooling rates for the end fitting and pressure sheath, depending on how the structural support may conduct heat from the end fitting or shroud it from wind or other convection or cooling effects. Bend stiffeners and other ancillary devices can also significantly influence the local thermal conditions.

### A.7.12.3 Immersion/Insulation

Two elements of the design surrounding the end fitting can affect both the temperature extremes and rates of heating and cooling. In particular, some end fittings are insulated to provide fire protection while other end fittings are mounted subsea. The former are likely to experience higher steady state temperatures and slower cooling and faster heating rates. Submerged end fittings are likely to experience lower steady state temperatures and faster cooling rates and slower heating rates.

### A.7.12.4 System Blowdown

Gas production system risers may be subject to rapid depressurization or blowdown during process shutdowns or other emergency activities. Because of the Joule-Thomson effects of natural gas, such blowdowns can cause rapid cooling to low temperatures significantly below ambient. It may be important to consider the thermal capacity of the gas when assessing the cooling rates and minimum temperature achieved in the pressure sheath during blowdown.

## A.7.13 Other Test Procedures

Other procedures developed by other groups can exist in addition to this procedure. In particular, SINTEF has conducted end-fitting tests using midscale end-fitting simulators.

### A.7.14 Material Considerations and Failure Modes

This test procedure focuses on the effects of long continuous high temperature exposures with periodic cooldown cycles. These conditions can affect the volatile content of the pressure sheath polymer and the stresses that may develop in the sheath because of thermal expansion and contraction. However, there can be other significant material consideration and failure modes that could affect end-fitting performance. One example of possible material considerations would be changes in the crystallinity of the polymer and the associated free volume because of prolonged high temperature exposures. Additional testing on material samples or end fittings can be required to fully understand other effects.

### A.7.15 Number of Thermal Test Cycles

These procedures expose end fittings to 20 initial and 20 final thermal cycles after the objective plasticized state is achieved. The number of cycles was chosen based on early testing experience and an expectation that the load and strength conditions would be adequately tested in the final 20 cycles. However, it should be recognized that risers and other flexible pipes can be exposed to significantly more thermal cycling due to process “trips” and other shutdowns. It has been estimated that typical North Sea gas plants can experience 1000 thermal cycles over a typical 20-year life. Additional thermal cycling is recommended if there is reason to believe that additional cycling would affect otherwise stable end-fitting performance.

# Annex B
(normative)

# Polyvinylidene Fluoride (PVDF) Coupon Crude Oil Exposure Test Procedure

## B.1 General

The objective of this procedure is to measure the progress to, and the final state of deplasticizing and replasticizing of, PVDF samples representative of flexible pipe liners when exposed to specific liquid hydrocarbon production fluids.

NOTE The procedure described herein includes the heating and handling of hot equipment and hydrocarbon products. It is the responsibility of any individuals or organizations using this procedure to assure that all appropriate safety procedures are implemented to prevent injuries to personnel or damage to equipment or facilities.

## B.2 Test Procedure

### B.2.1 Required Materials

#### B.2.1.1 PVDF Samples

Fourteen samples of PVDF are required, each approximately 35 mm × 75 mm (1.38 in. × 2.95 in.). The samples should be flat and rectangular with opposite sides parallel, adjacent sides perpendicular, and uniform thickness [preferably between 0.5 mm and 3 mm (0.02 in. and 0.12 in.)]. The samples shall be of the same grade and have the same initial amount of plasticizer (0 % to 2 %) as is used in making flexible pipe pressure sheaths, and be taken from examples of extruded sheaths.

#### B.2.1.2 Exposure Fluid

Approximately 1 l [0.26 gal (U.S.)] of liquid hydrocarbon is required to test 14 samples as described above.

NOTE Consideration should be given to using both the gaseous and liquid components (in appropriate ratios) of the production fluid and using an autoclave so that the production pressure can be maintained during the exposures. Although these effects have not been thoroughly evaluated, there are indications that some hydrocarbon components are more effective than others in deplasticizing/replasticizing the PVDF, and the exposure pressure may also affect the interaction.

#### B.2.1.3 Exposure Bottles

Exposure bottles should be 0.5 l or 1 l [0.13 gal (U.S.) or 0.26 gal (U.S.)] inert autoclave sample bottles suitable for use at temperatures of 130 °C (266 °F) with hydrocarbons.

### B.2.2 Measurement Accuracy

The following measurements shall be made:

a) thickness shall be measured to 0.01 mm;

b) weights shall be measured to ±0.000 1 g;

c) temperatures shall be recorded continuously and shall be measured to ±3 °C (±5.4 °F).

d) volumes (using Archimedes' law) shall be measured to 5 mm$^3$ (0.0003 in.$^3$).

### B.2.3 Procedure

The procedure is as follows.

a) Prepare 14 clean dry samples and uniquely mark each sample by notching the edges or in some other way that will not be obliterated by the exposure.

b) Remove any loose edges or debris from the samples, wipe them with a dry cloth or paper towel, and place them in a desiccator for 24 h prior to conducting the following steps.

c) Measure and record the thickness and weight ($W_1$) of each sample. The samples should not be touched with bare hands during the measurements. Calculate the volume of each sample ($V_1$) using Archimedes' law and dedicated balance or picnometer, and average sample thickness ($t_{avg}$).

d) Place 14 samples and approximately 1 l of exposure fluid in a closed container that is suitable for heating the fluid to a temperature, $T$ (2 separate containers with 7 samples and approximately 0.5 l of oil each may be used as an alternative). Heat and maintain the oil temperature at $T$. Place the two remaining samples in a ventilated oven at 220 °C (428 °F) for 24 h and measure the weight ($W_2$) and volume ($V_2$) and calculate the initial plasticizer weight percent and the maximum volume change percent.

Initial experiments may be conducted at $T$ = 130 °C (266 °F) to obtain initial results quickly. It is also necessary to identify the relationship of plasticizer/crude equilibrium with different operating temperatures. It is therefore recommended to complete these exposure tests for a range of temperatures to address this issue. Close attention should be paid to surface preparation and thickness and to oil storage and oxygen content.

e) Calculate the following heating times in hours:

   i) $T_1 = 225 \times (t_{avg})^2$,

   ii) $T_2 = 400 \times (t_{avg})^2$.

The deplastification and crude absorption process is expected to be brought to equilibrium at approximately $T_1$. It should be noted that $t_{avg}$ is thickness expressed in millimeters (inches), and $T_1$ and $T_2$ are times expressed in hours.

f) Remove 2 samples from the oil bath when times $(T_1)/4$, $T_1/2$, $(3 \times T_1)/4$, and $T_1$ are achieved. Wash the samples with a mild soap and water solution, rinse the samples with clean water, and thoroughly dry the surface of the samples by wiping with a clean dry paper or cloth towel.

g) Place the samples in a desiccator to cool for 24 h. Measure and record the length, width, thickness, and weight ($W_2$) of each sample and calculate the volumes ($V_2$) when the samples have cooled. If the samples deform, making direct measurement difficult, weigh initially in air, and then suspended in water; determine the volume by Archimedes' principle. Calculate percent weight and percent volume change.

h) Remove 2 samples from the oil bath then process and calculate [see Step g)] when times $(T_2 + T_1)/2$, and $T_2$ are achieved. Allow the oil bath to cool and dispose of the test oil after removing the final samples. The test oil should not be used for further replasticization tests.

i) As an option, the samples tested in Steps g) and h) may be further processed immediately after measurement, as follows:

— obtain and uniquely mark 7 commercially available inert metal sample cups suitable for weighing the samples from B.1.3.6 and B.1.3.7, place a sample in each cup and measure the total weight of each cup and sample, and place the cups and samples in a vacuum or ventilated oven at 220 °C (428 °F);

— heat for 24 h, remove the samples from the oven and place them in a desiccator to cool for 24 h, then measure and record the weight of each sample.

j) Complete the data form in B.2.4 to calculate the net loss of volatiles weight (net $\Delta$ weight) and the net change in volume (net $\Delta$ volume), and to confirm the total weight change (total $\Delta$ weight percent) to be consistent with the initial plasticizer content.

k) The total $\Delta$ weight percent for the $T_1$, $(T_2 + T_1)/2$, and $T_2$ measurements should be consistent (±0.1 %) between samples. If they are not, the procedure should be repeated with additional samples, and/or consideration given to extended tests on at least 2 samples with longer time $T_2$.

### B.2.4 Data Form

| **Sample ident: ______________** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Data** | | | | | | | | | | | | | | |
| Exposure time (h) | | | | | | | | | | | | | | |
| Thickness | | | | | | | | | | | | | | |
| Weight $W_2$ | | | | | | | | | | | | | | |
| Volume $V_2$ | | | | | | | | | | | | | | |
| **Initial Data** | | | | | | | | | | | | | | |
| Weight $W_1$ | | | | | | | | | | | | | | |
| Volume $V_1$ | | | | | | | | | | | | | | |
| **Calculations for Exposure Time** | | | | | | | | | | | | | | |
| Weight loss $\Delta W = W_1 - W_2$ | | | | | | | | | | | | | | |
| Volume change $\Delta V = V_1 - V_2$ | | | | | | | | | | | | | | |
| Percent weight loss $\Delta W/W_1 \times 100$ % | | | | | | | | | | | | | | |
| Percent volume change $\Delta V/V_1 \times 100$ % | | | | | | | | | | | | | | |
| **Final Data** | | | | | | | | | | | | | | |
| Cup sample weight $W_{7A}$ | | | | | | | | | | | | | | |
| Cup sample weight $W_{7B}$ | | | | | | | | | | | | | | |
| Plasticizer remaining $(W_{7A} - W_{7B})$ | | | | | | | | | | | | | | |
| NOTE Calculations as above may then be used to plot the total content of plasticizer and crude components against time. | | | | | | | | | | | | | | |

# Annex C
(normative)

# Flexible Pipe High Temperature End-fitting Qualification Test Procedure: Low Volatile Content Polymers

## C.1 General

This procedure is a synthesis of the various requirements and objectives of many flexible pipe operators and manufacturers. This test is primarily intended to qualify end fittings generically rather than for specific project requirements. Section C.7 provides discussion of topics that may be appropriate to tests conducted for specific projects and for interpreting the results of tests conducted under this procedure for specific projects. The procedure may also be used together with Annex D to evaluate end-fitting performance when subjected to specific crude oil environments. In addition to the mechanical behavior tested by this procedure, appropriate testing is required to qualify the chemical and physical suitability of the end fitting and pressure sheath materials. The procedure does not qualify the strength or stiffness of the end fittings. See C.7 for other qualification topics.

Pairs of identical samples will be tested to identical conditions. Four end fittings are required to meet the acceptance criteria to achieve unrestricted qualification for the envelope of service covered by the test conditions.

The procedure can be used to qualify static or dynamic end fittings and is recommended for qualification for any new low volatile content polymer materials. This procedure is applicable for unplasticized polymers (those that have only about 2 % by weight volatile content). See Annex A for plasticized polymers.

## C.2 Test Objective

The test procedure defined below provides an industry-acceptable methodology to qualify the mechanical performance of both existing and newly developed end-fitting designs for dynamic flexible pipes made with high temperature polymer internal pressure sheaths for a representative service life of 20 years.

— The procedure is applicable for unplasticized polymer fluid barriers.

— The procedure is applicable for flexible pipes in oil service, gas service, or water injection service.

— This procedure is based on the concepts that the base polymer will lose or absorb volatile components during exposure to the test media to achieve stable equilibrium states in the free polymer and under the seal/grip ring. Further, it is assumed that the equilibrium state in either region can be characterized by the following:

a) weighing small samples of material taken from the region,

b) driving off the volatile content of the samples by heating it to just above the melting temperature of the polymer,

c) determining the change in weight of the sample $\Delta W$ region.

It is assumed throughout this procedure that the volume change ($\Delta V$) is approximately proportional to the weight change ($\Delta W$) and that both changes result from the loss or gain of volatile materials with similar densities. The assumption is made as a simplification that allows the use of easily made weight change measurements to be representative of specific volume changes that may take place under the seal ring where they cannot be measured directly. For some materials and exposures, it may be necessary to establish more complex relationships between changes in volume and weight, based on additional testing.

**SAFETY PRECAUTIONS—This procedure can require a mixture of hydrocarbon or other liquids or gases. Appropriate safety practices will be required to protect test personnel, facilities, and the environment.**

## C.3 Initial Data

### C.3.1 Required Data

Prior to the start of testing, the manufacturer shall specify:

a) the rated service temperature for which the end-fitting design is being qualified ($T_{hi}$);

b) the minimum service temperature for which the end-fitting design is being qualified ($T_{lo}$);

c) the average linear thermal expansion coefficient of the material between the minimum service temperature and rated service temperature ($\alpha$);

d) the $\Delta V_s$ and $\Delta W_s$ of the barrier material (expressed as a percentage of weight change $\Delta W$ or volume change $\Delta V$ as determined by tests carried out according to Annex D, for both unconstrained and constrained regions) are those for which the test will qualify the end-fitting designs.

### C.3.2 Calculations

For unconstrained regions of the polymer, $[1 + \alpha (T_{hi} - T_{lo})]$ is compared with $(1 + \Delta V/100)^{1/3}$, leading to two cases:

Case I:

If $[1 + \alpha (T_{hi} - T_{lo})]$ is equal to or larger than $(1 + \Delta V/100)^{1/3}$, then:

the thermal expansion during initial thermal cycles will be the dominating factor. This is based on the reasonable assumption that the time scale characterizing swelling is one order of magnitude longer than the one associated with a heating period (days vs hours). No special measures, including monitoring assemblies, are required for qualification procedure. Procedures 2, 3, and 4 (see C.5.4) can be omitted.

Case II:

If $[1 + \alpha (T_{hi} - T_{lo})]$ is smaller than $(1 + \Delta V/100)^{1/3}$, then:

volume change is relatively large, and long-term integrity of the seal could be affected. This prompts a procedure where the manufacturer shall specify $\Delta W_s$ and $T_1$ to $T_3$ defined as:

$\Delta W_s$ = 70 % of the total expected change in sample weight under the seal/grip ring, over 20 years, $\Delta W$ seal;

$T_1$ = the time at the upper test temperature required to change volume by one-third of $\Delta W_s$;

$T_2$ = the incremental time at the upper test temperature, beyond $T_1$, required to change the volume by an additional one-third of $\Delta W_s$ for a total of two-thirds of $\Delta W_s$;

$T_3$ = the incremental time at the upper test temperature, beyond $T_2$, required to change the volume by an additional one-third of $\Delta W_s$ for a total of $\Delta W_s$.

## C.4 Test Samples

Two test samples are required. The test samples shall be complete production flexible pipes with all layers and features. All end fittings shall be of the same design and assembled to the same procedure and dimensional tolerance specification. Pipe length shall be 10 m (32.8 ft) or more. The pipe annulus should be vented. The pipe should be manufactured according to normal procedures, in particular, the hydrostatic test shall be at ambient temperature and shall not exceed 1.5 times the rated design pressure.

Alternatively, two midscale test samples can be used. A midscale test sample shall include the following:

a) all layers of the full-sized flexible pipe through the pressure armor; thermal mass or insulation external to the pressure armor should be applied to represent the remaining flexible pipe layers;

b) midscale end fittings that include identical design, dimensions, and tolerancing attributes for the following functions:

   4) anchoring of the internal carcass;

   5) anchoring and sealing of the internal pressure sheath and any sacrificial or tape layers adjacent to the internal pressure sheath;

   6) thermal mass and insulation, which is representative of a full end fitting.

The length of a midscale sample is typically 1 m to 2 m (3.28 ft to 6.56 ft). It shall be demonstrated that the tension force applied to a pressure sheath seal during thermal cycling of a midscale sample is equal to or greater than that in the full-scale sample. This is accomplished by fixed restraints applied to both end fittings. The restraints prevent the midscale sample from changing length during thermal cycling.

The manufacturer shall have available, for review by any interested parties, detailed records of the as-built material, dimensions, fits, and clearances of all pieces of the end fitting and pipe body that may affect the performance of the end fitting during testing. The records shall include the dimensioned and toleranced manufacturing drawings for the pipe and end fittings and all manufacturing and procurement procedures and standards. In addition, the records shall include the calculations associated with the initial data (initial movement, $\Delta W$, $T_1$, $T_2$, $T_3$, etc.).

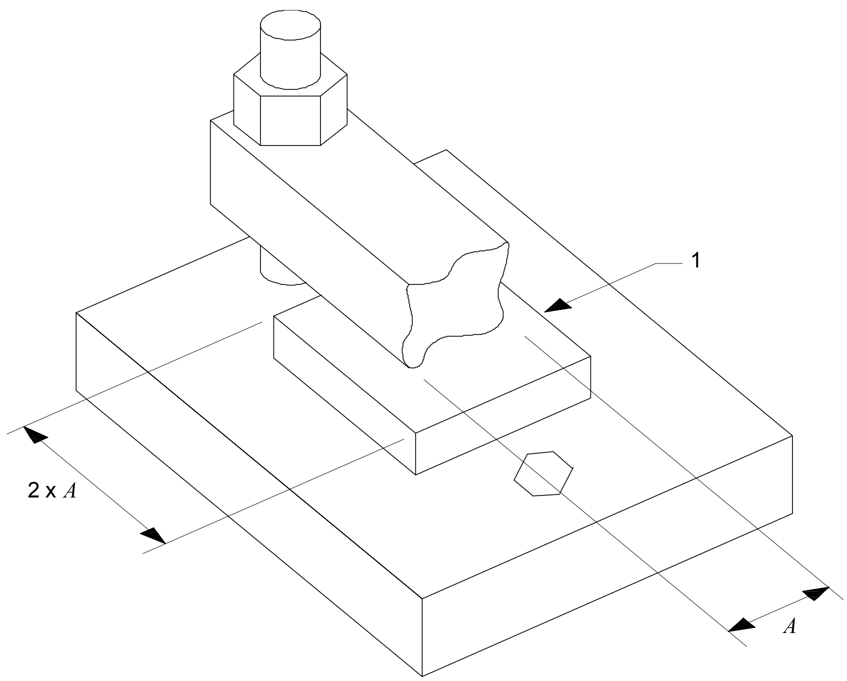
Four monitoring assemblies (see Figure C.1) shall be placed inside each test pipe (Case II only). Each assembly may consist of a square pressure barrier material sample with edge dimensions at least twice the width of the seal grip ring. The barrier material shall be compressed between a rigid plate that is larger than the material sample and a rigid bar that is at least as wide as the seal/grip ring and longer than the material sample width. The percent compression of the material sample shall be equal (±5 %) to the compression achieved under the seal/grip ring.

Alternative monitoring assembly configurations may be accepted, by agreement. The purpose is to quantify changes in the volatile content of the seal ring region. It is assumed that a validated analytical or empirical model will be developed by each manufacturer using this procedure for the relationship between volatile components in the content of the pipe and at the seal grip ring. Validation will include survey of the barrier condition in the seal area from a dissected end fitting, after a documented exposure process.

## C.5 Test Procedures

### C.5.1 Test Setup

The test samples shall be set up initially for static temperature cycling, and subsequently in a dynamic test bench or alternative test structure, to allow flexing of the upper end of the test riser. The static phases (Procedure 1, Procedure 4, see below) may be carried out with the sample on a workshop floor. The dynamic test procedures shall be carried out with the test sample(s) mounted in a testing apparatus suitable to flex the riser upper end sufficiently to ensure any effects of inter-layer friction are removed from the temperature cycling. Dynamic flexing is not required in the midscale test samples as the axial stiffness of the hoop strength layer alone is negligible. Therefore, the inter-layer friction between the internal pressure sheath and the hoop strength layer will not affect the load on the internal pressure sheath anchoring.




**Key**

1 Material sample

*A* Seal/grip ring width

**Figure C.1—Monitoring Assembly (Case II Only)**

Thermocouples shall be installed on the inside and outside of each end fitting approximately in the plane of the seal grip ring. Additional thermocouples may be applied for data gathering, at the manufacturer's discretion.

The test samples shall be filled with an oil that yields a representative amount of equilibrium volume change of the polymer. Suitable safety precautions shall be taken for all testing.

Load cells shall be installed between the fixed restraints and the test samples so that axial loads generated during thermal cycling may be measured.

## C.5.2 Test Temperatures and Pressures

An upper (maximum) and lower (minimum) test temperature shall be specified by the manufacturer.

It is intended that this procedure may be used for qualification without the application of design margins. The maximum service temperature for which the pipe becomes qualified shall be the average upper test temperature. The minimum service temperature for which the pipe becomes qualified shall be the average lower test temperature.

NOTE An industry objective upper service temperature is 130 °C (266 °F). An industry objective lower service temperature is –25 °C (–13 °F) but no higher than 0 °C (32 °F). An acceptable value for lower temperature for operations excluding blowdown may be –5 °C to –8 °C (23 °F to 17.6 °F).

The internal pressure shall vary with the temperature such that no less than atmospheric pressure is induced at ambient temperature and a maximum pressure of approximately 2 MPa (20 bar) is induced at the top flange at maximum test temperature. Relief valves shall be provided so that the internal pressure does not fall below ambient at any time (no vacuum).

Cooling rates should be no slower than those predicted for a typical field application. Cooling shall be controlled so as to simulate these typical operating conditions. Heating at a slower rate than predicted for typical field applications is acceptable but will increase the time required to complete the temperature cycling process.

NOTE An industry basis for cooling rate has been agreed as a riser termination at the deck level of an FPSO turret or a semisubmersible in air. See C.7.10 for discussion of "hangoff" and "insulation" effects.

## C.5.3 Thermal Cycling Procedure

### C.5.3.1 Full-scale Test

Each thermal cycle shall consist of the five steps described as follows.

1) The pipe internal temperature shall be raised to the test temperature.

2) After internal and external thermocouples on the pipe reach a stable temperature, the test temperature shall be maintained for an additional 24 h.

3) The test pipe shall be cooled until the internal and external thermocouples stabilize at ambient temperature. Dynamic pipes shall be flexed at least two times while at this step. Cooling shall be at a rate equivalent to natural convection, with representative temperature gradient within the end fittings.

4) The temperature shall be reduced to the lower temperature by controlled cooling, until the internal and external thermocouples stabilize.

5) The temperature shall be maintained at the lower temperature for a minimum of 1 h.

NOTE The soaking period is related to the creep and relaxation behavior of the polymer that is considered. The 24 h period is valid for PVDF, while other polymers may require different values.

### C.5.3.2 Midscale Test

Each thermal cycle shall consist of the five steps described as follows.

1) At installation, the restraints shall be adjusted so that the axial force is within 0 N to 500 N while the sample is at ambient temperature.

2) The pipe internal temperature $T_{hi}$ shall be raised to the test temperature.

3) The pipe internal temperature shall be maintained at $T_{hi}$ until 24 h from the start of the heating cycle.

4) The pipe internal temperature shall be reduced to the lower temperature by controlled cooling until the pipe internal temperature reaches $T_{lo}$.

5) The pipe internal temperature shall be maintained at $T_{lo}$ until 24 h from the start of the cooling cycle. The cycle is repeated at C.5.3.2, Item 3).

## C.5.4 Test Procedures

### C.5.4.1 Descriptions

#### C.5.4.1.1 Procedure 1

Procedure 1 consists of 10 cycles of static thermal cycling. The bore of each end fitting shall be inspected after 5 (±1) and 10 (±1) cycles.

During Procedure 1 thermal cycling, the pipes should be essentially horizontal, and fittings may be raised for convenience in filling, inspecting, etc. with the pipes free to expand and distort as a result of heating and induced loads.

#### C.5.4.1.2 Procedure 2

Procedure 2 (Case II only) consists of exposure at the test temperature for no less a period of time than $T_1$. At the end of the procedure, a pressure test shall be conducted, one of the monitoring assemblies shall be removed from the test pipe, and the change of weight in the center of the material sample shall be compared with the manufacturer's predictions. If the predicted change has not been achieved, the exposure times for all procedures shall be recalculated to achieve the change of the objective fractions of $\Delta W$ and the current procedure shall be continued to achieve the recalculated time. If the expected change has been exceeded, the future times shall be recalculated and reduced accordingly.

#### C.5.4.1.3 Procedure 3

Procedure 3 (Case II only) consists of a repeat of Procedure 2, for no less than duration $T_2$, including any necessary adjustment of $T_2$ to achieve the intended level of change.

#### C.5.4.1.4 Procedure 4

Procedure 4 (Case II only) consists of a repeat of Procedure 2 for no less than duration $T_3$. Achievement of the objective $\Delta W$ in monitoring assemblies is to be confirmed before proceeding to Procedure 5.

#### C.5.4.1.5 Procedure 5

##### C.5.4.1.5.1 Static Flexible Pipes

Procedure 5 consists of at least 40 cycles of thermal cycling.

If any apparent movement is recorded by changes in dimensions during the first 40 cycles, the thermal cycling shall be continued until 20 cycles without any dimensional changes occurring or until a steady rate of change is achieved.

Each end fitting shall be inspected after 10 (±1) cycles and thereafter every 10 (±1) cycles if no changes occur or every 5 (±1) cycles if apparent movement occurs.

#### C.5.4.1.5.2 Dynamic Flexible Pipes

Procedure 5 consists of at least 40 cycles of thermal cycling while dynamically flexing the pipe. Flexing is not required on the midscale tests.

If any apparent movement is recorded by changes in dimensions during the first 40 cycles, the thermal cycling shall be continued until 20 cycles without any dimensional changes occurring or until a steady rate of change is achieved.

Each end fitting shall be inspected after 10 (±1) cycles and thereafter every 10 (±1) cycles if no changes occur or every 5 (±1) cycles if apparent movement occurs.

During Procedure 5, flexing of at least one end of the test pipe shall be carried out by lifting or flexing in a hinged frame to a radius of curvature equal to the design minimum for the pipe structure. The flexure shall be repeated at least two times in each temperature cycle, while the pipe is at ambient temperature.

#### C.5.4.1.6 Procedure 6

Procedure 6 consists of dissecting the end fittings and measuring the content of volatile species in the polymer under the seal/grip ring and at $2t$ and $4t$ ($t$ is the uncompressed sheath thickness) on either side of the seal grip ring center to confirm that the acceptance criteria have been met. If the objective weight percent $\Delta W$ is not achieved under the seal/grip ring in the first pipe end fittings, the second pipe shall not be dissected until it has been subjected to a $T_3$ duration recalculated to achieve the objective.

#### C.5.4.2 General

The second test pipe shall not be subjected to Procedure 4 testing until the first test pipe has completed Procedure 6 and the total deplasticizing time ($T_1 + T_2 + T_3$) has been confirmed or corrected. Thereafter, the exposure times ($T_2$ and $T_3$) of the second test pipe shall be adjusted according to the test results for the first pipe.

To facilitate testing, deplasticizing in Procedures 2, 3, and 4 can be continued while monitoring assemblies are evaluated and exposure times ($T_1$, $T_2$, $T_3$) are adjusted.

### C.5.5 Inspection and Test Activities

#### C.5.5.1 Inspection

The bore areas of each end fitting shall be inspected for movement of the layers. The position of the fluid barrier and any sacrificial or metallic layers adjacent to the fluid barrier that are retained in the end fitting by the seal/grip ring, relative to a fixed reference location, shall be measured and recorded. Special “ports” or “windows” could possibly need to be cut in the carcass or other layers, or through the end-fitting body, to facilitate such measurements.

#### C.5.5.2 Pressure Testing

Each pipe shall be subjected to a 2-h leak test at design pressure and room temperature at the end of each test procedure. For the midscale test samples, the test pressure should be sufficiently high to achieve axial extension equal to or greater than that which would be experienced in the full-scale test.

## C.6 Acceptance Criteria

The acceptance criteria are as follows.

a) The objective weight percent change shall have occurred under the seal/grip ring in at least two end fittings and achieved within 0.5 weight percent in the others.

b) There shall be no leakage, cracking, splitting, blistering, or other degradation.

c) There shall be no evidence of movement under the seal/grip ring, or the movement shall be steady, predictable, and progressing at a rate that would not cause failure within 20 years.

## C.7 Technical Issues—Discussion of Parameters

### C.7.1 General

The following sections are a commentary as advice upon qualification, criteria, or interpretation of results from the testing. Although the procedure is aimed to be material independent, the technical issues discussed below are somewhat more specific to PVDF, for historical reasons.

### C.7.2 Volumetric Stability

Unplasticized materials will swell to some equilibrium, which is related to the exposure media.

The end fitting, on assembly, may be “oversqueezed” to simulate the maximum expected swell condition and test carried out in a “nonswelling” oil, or the fluid used for testing should be verified as causing swell greater than the operational fluid.

Small-scale swell exposure tests, as in Annex D, should be carried out to calibrate barrier response prior to the qualification tests.

In the long term, shrinkage will be larger than (fluid absorption induced) swell if the barrier material will relax at high temperature over time, including response to swell. Cycle time for temperature cycling should take account of relaxation time, which should be determined by small-scale testing beforehand.

### C.7.3 Number of Temperature Cycles for Qualification

Based on tests with plasticized PVDF, it is accepted that 10 (static) cycles are sufficient to ”precondition” a test pipe, (generate the predicted tensile load in the barrier when cooled to the lowest test temperature) and reduce the hysteresis in the response to a stable level.

Based on the rate of decay to “failure” of previous design end fittings in service, and an empirical relationship of 1:2 between cycles in the field versus cycles in test pipes, it is proposed that a further 40 cycles (static or dynamic depending on the pipe application) after completing the specified deplastification process are sufficient to demonstrate fitness for purpose. Alternatively, if temperature cycling is carried out in stages during the exposure, the final temperature cycling series may be reduced to 20 cycles, subject to the minimum total being 50 cycles.

Zero movement may be interpreted as permanently stable. If steady movement is identified, this may be projected linearly, based on the progression of the early test specimens.

Simulation of field applications where the service life is 20 years and operations involve frequent temperature cycles would require several years of continuous cycling. In practice, therefore, the most practical approach may be to accept qualification for the service period simulated by the testing, introduce markers in the PVDF barrier, and set up a monitoring program to calibrate against the full-scale test data.

### C.7.4 Number and Nature of Dynamic Flexures for Qualification of Dynamic Pipe

It is necessary to flex at least one end of the test pipe sufficiently that any interlayer friction between the PVDF layers and the carcass/PVDF/pressure armor is released. This will then ensure that the tension generated in the critical PVDF layers will be delivered to the crimped seal. Flexing is not required on the midscale tests.

It is not necessary to apply a program of flexures as for a riser mechanical fatigue test, because the bend stiffener will reduce the loading at the end fitting to varying tension load, which is considerably smaller than the temperature-induced loading.

### C.7.5 Diameter Scaling

The key parameters to polymer barrier behavior in the seal ring area are percentage indentation and the related stresses in the crimp zone. If test results are to be used for other diameters, then the indentation of the sheath in radial direction as percentage of the barrier thickness should be constant. The following elements shall be evaluated in calculating the percentage indentation or crimp:

a) crimp geometry (generally scaled to ensure similar stress distribution),

b) deflection of any underlying steel supporting inserts,

c) manufacturing and assembly tolerances—these should be adjusted so that the designs being compared have the same minimum barrier compression under the crimp ring.

### C.7.6 Number of End Fittings and Alternative Methods of Interpretation

While one pipe (two end fittings) may be sufficient to identify mechanisms and provide a preliminary basis for qualification, a second test (one pipe, two end fittings) is required to verify repeatability of results and interpret variability of manufacturing tolerances.

It may be possible to use test pipes with end-fitting designs that are sufficiently similar rather than identical. The criteria for acceptance of marginally different end fittings are to be established (see below).

### C.7.7 Carcass Weight

The inner layer of PVDF (for multilayer PVDF fluid barrier risers) intrudes into the spiral spaces in the carcass. The weight of the carcass is transferred to this PVDF layer via these protrusions. If the PVDF is single layer construction, it also protrudes into the spiral spaces of the pressure armor. By this means, for a static line, any weight loads are distributed along the suspended pipe length.

Multiple layer risers have a smooth surface between the PVDF layers. Unless the internal pressure is able to transfer the weight loading (plus the temperature cycling induced tensile loads), the weight and temperature-induced load (proportional to barrier thickness) is transferred direct to the upper end fitting. Based on typical examples of in service conditions, it is likely that the barrier weight loading would increase the total loading by 10 % to 15 %.

### C.7.8 Dimensional Tolerances

The effect of dimensional tolerances on performance is specific to the manufacturer’s end-fitting design. No general guidance can be given with the exception that production end fittings shall be able to be verified to have assembly tolerances equal to or better than the tolerances achieved for the test pipe end fittings. Minimum barrier indentation percentage shall be greater than or equal to the indentation percentage of the qualification samples.

The manufacturer detailed design, design basis, and tolerances all need documentation with the tests as a benchmark to provide this verification.

### C.7.9 Assessment of Service Life for Pipes in Crude Oil Service

To qualify for long-term service, the percent change $\Delta W$ achieved in the test pipe shall be greater than 70 % of that determined by exposure testing as in Annex D for the maximum operating temperature of the pipe in the given crude, or equivalent. The service life shall be determined by the creep rate based on temperature cycles over the service life if there is evidence of movement of the barrier in the end fitting. The pipe shall be considered qualified if there is no evidence of movement of the barrier.

### C.7.10 Project-specific Considerations

#### C.7.10.1 General

Each project shall assess which elements of the procedure testing are or are not representative of the project's conditions and exposures. Some possible differences can occur in the areas described in C.7.10.2 to C.7.10.4.

#### C.7.10.2 Top End Hangoff

The methods and mechanical details of the top hangoff of flexible pipe end fittings can affect the heating and cooling rates for the end fitting and pressure sheath depending on how the structural support may conduct heat from the end fitting or shroud it from wind or other convection or cooling effects. Bend stiffeners and other ancillary devices can also significantly influence the local thermal conditions.

#### C.7.10.3 Immersion/Insulation

Two elements of the design surrounding the end fitting can affect both the temperature extremes and rates of heating and cooling. Some end fittings, in particular, are insulated to provide fire protection while other end fittings are mounted subsea. The former are likely to experience higher steady state temperatures and slower cooling and faster heating rates. Submerged end fittings are likely to experience lower steady state temperatures and faster cooling rates and slower heating rates.

#### C.7.10.4 System Blowdown

Gas production system risers can be subject to rapid depressurization or blowdown during process shutdowns or other emergency activities. Such blowdowns can cause rapid cooling to low temperatures significantly below ambient, because of the Joule-Thomson effects of natural gas. It can be important to consider the thermal capacity of the gas when assessing the cooling rates and minimum temperature achieved in the pressure sheath during blowdown.

### C.7.11 Other Test Procedures

Other procedures developed by other groups can exist in addition to this procedure. In particular, SINTEF has conducted end-fitting tests using midscale end-fitting simulators.

### C.7.12 Material Considerations and Failure Modes

This test procedure focuses on the effects of long continuous high temperature exposures with periodic cooldown cycles. These conditions can affect the volatile content of the pressure sheath polymer and the stresses that may develop in the sheath due to thermal expansion and contraction. However, there can be other significant material consideration and failure modes that could affect end-fitting performance. One example of possible material considerations would be changes in the crystallinity of the polymer and the associated free volume as a result of prolonged high temperature exposures. Additional testing on material samples or end fittings can be required to fully understand other effects.

### C.7.13 Number of Thermal Test Cycles

These procedures expose end fittings to 20 initial and 20 final thermal cycles after the objective plasticized state is achieved. The number of cycles was chosen based on early testing experience and an expectation that the load and strength conditions would be adequately tested in the final 20 cycles. However, it should be recognized that risers and other flexible pipes may be exposed to significantly more thermal cycling because of process "trips" and other shutdowns. It has been estimated that typical North Sea gas plants may experience 1000 thermal cycles over a typical 20-year life. Additional thermal cycling is recommended if there is reason to believe that additional cycling would affect otherwise stable end-fitting performance.

# Annex D
(normative)

# Polymer Coupon Crude Oil Exposure Test Procedure

## D.1 General

The objective of this procedure is to measure the progress, the final state of deplasticizing and replasticizing of polymer samples representative of flexible pipe liners, when exposed to specific liquid hydrocarbon production fluids.

NOTE The procedure described herein includes the heating and handling of hot equipment and hydrocarbon products. It is the responsibility of any individuals or organizations using this procedure to assure that all appropriate safety procedures are implemented to prevent injuries to personnel or damage to equipment or facilities.

## D.2 Test Procedure

### D.2.1 Required Materials

#### D.2.1.1 Polymer Samples

Fourteen samples of polymer are required, each approximately 35 mm (1.4 in.) × 75 mm (3.0 in.). The samples should be flat and rectangular with opposite sides parallel, adjacent sides perpendicular, and uniform thickness [preferably between 0.5 mm (0.02 in.) and 3 mm (0.12 in.]. The samples shall be of the same grade and have the same initial amount of plasticizer (0 % to 2 %) as is used in making flexible pipe pressure sheaths, and be taken from examples of extruded sheaths.

#### D.2.1.2 Exposure Fluid

Approximately 1 l [0.26 gal (U.S.)] of liquid hydrocarbon is required to test 14 samples as described above.

#### D.2.1.3 Exposure Bottles

Exposure bottles should be 0.5 l or 1 l [0.13 gal (U.S.) or 0.26 gal (U.S.)] inert autoclave sample bottles suitable for use at temperatures of 130 °C (266 °F) with hydrocarbons.

### D.2.2 Measurement Accuracy

The required measurement accuracy is as follows.

a) Thickness shall be measured to 0.01 mm (0.0004 in.).

b) Weights shall be measured to ±0.0001 g ($3.5 \times 10^{-6}$ oz).

c) Temperatures shall be recorded continuously and shall be measured to ±3 °C (±5.4 °F).

d) Volumes (using Archimedes law shall be measured to 5 mm$^3$ (0.03 in.$^3$).

### D.2.3 Procedure

#### D.2.3.1 Procedure Outline

Prepare 14 clean dry samples and uniquely mark each sample by notching the edges or in some other way that will not be obliterated by the exposure.

Remove any loose edges or debris from the samples, wipe them with a dry cloth or paper towel, and place them in a desiccator for 24 h prior to conducting the following steps.

Measure and record the thickness and weight ($W_1$) of each sample. Do not touch the samples with bare hands during the measurements. Calculate the volume of each sample ($V_1$) using Archimedes law and dedicated balance or picnometer, and average sample thickness ($t_{avg}$).

Place 14 samples and approximately one liter of exposure fluid in a closed container that is suitable for heating the fluid to a temperature ($T$), two separate containers with 7 samples and approximately one-half liter of oil each may be used as an alternative. Heat and maintain the oil temperature at $T$. Place the two remaining samples in a ventilated oven at 220 °C (428 °F) for 24 h and measure the weight ($W_2$) and volume ($V_2$) and calculate the initial plasticizer weight percent and the maximum volume change percent. Close attention should be paid to surface preparation and thickness, and to oil storage and oxygen content.

NOTE Initial experiments may be conducted at $T$ = 130 °C (266 °F) to obtain initial results quickly. It is also necessary to identify the relationship of plasticizer/crude equilibrium with different operating temperatures. It is therefore recommended to complete these exposure tests for a range of temperatures to address this issue.

Calculate the following heating times in hours:

$$T_1 = 225 \times (t_{avg})^2$$

$$T_2 = 400 \times (t_{avg})^2$$

The deplastification and crude absorption process is expected to be brought to equilibrium at approximately $T_1$. It should be noted that $t_{avg}$ is thickness in millimeters, $T_1$ and $T_2$ are times in hours.

When times $(T_1)/4$, $(T_1)/2$, $(3 \times T_1)/4$, and $T_1$ are achieved, remove 2 samples from the oil bath. Wash the samples with a mild soap and water solution, rinse the samples with clean water, and thoroughly dry the surface of the samples by wiping with a clean dry paper of cloth towel.

Place the samples in a desiccator to cool for 24 h. Measure and record the length, width, thickness, and weight ($W_2$) of each sample and calculate the volumes ($V_2$) when the samples have cooled. Weigh the samples initially in air, and then suspended in water, and then determine volume by Archimedes principle if the samples deform and make direct measurement difficult. Calculate the percent weight and percent volume change.

Remove 2 samples from the oil bath and process and calculate as in D.2.3.6 when times $(T_2 + T_1)/2$ and $T_2$ are achieved. Allow the oil bath to cool and dispose of the test oil after removing the final samples. The test oil should not be used for further replasticization tests.

### D.2.3.2 Option

As an option, the samples tested above can be further processed immediately after measurement as described below.

Obtain and uniquely mark 7 commercially available inert metal sample cups suitable for weighing the samples from D.2.3.6 and D.2.3.7. Place a sample in each cup and measure the total weight of each cup and sample. Place the cups and samples in a vacuum or ventilated oven at 220 °C (428 °F).

Remove the samples from the oven after heating for 24 h and place them in a desiccator to cool for 24 h. Measure and record the weight of each sample when the samples have cooled.

### D.2.3.3 Data Form

Complete the data form below to calculate the net loss of volatiles weight (net $\Delta$ weight) and the net change in volume (net $\Delta$ volume) and to confirm the total weight change (total $\Delta$ weight percent) to be consistent with the initial plasticizer content.

The total $\Delta$ weight percent for the $T_1$, $(T_2 + T_1)/2$, and $T_2$ measurements should be consistent (±0.1 %) between samples, If they are not, the procedure should be repeated with additional samples, and/or consideration given to extended tests on at least 2 samples with longer time $T_2$.

## Data Form

| **Sample ident: ____________** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Data** | | | | | | | | | | | | | | |
| Exposure time (hours) | | | | | | | | | | | | | | |
| Thickness | | | | | | | | | | | | | | |
| Weight $W_2$ | | | | | | | | | | | | | | |
| Volume $V_2$ | | | | | | | | | | | | | | |
| **Initial Data** | | | | | | | | | | | | | | |
| Weight $W_1$ | | | | | | | | | | | | | | |
| Volume $V_1$ | | | | | | | | | | | | | | |
| **Calculations for Exposure Time** | | | | | | | | | | | | | | |
| Weight loss $\Delta W = W_1 - W_2$ | | | | | | | | | | | | | | |
| Vol change $\Delta V = V_1 - V_2$ | | | | | | | | | | | | | | |
| Percent weight loss $\Delta W/W_1 \times 100$ % | | | | | | | | | | | | | | |
| Percent volume change $\Delta V/V_1 \times 100$ % | | | | | | | | | | | | | | |
| **Final Data** | | | | | | | | | | | | | | |
| Cup sample weight $W_{7A}$ | | | | | | | | | | | | | | |
| Cup sample weight $W_{7B}$ | | | | | | | | | | | | | | |
| Plasticizer remaining ($W_{7A} - W_{7B}$) | | | | | | | | | | | | | | |
| NOTE Calculations as above can then be used to plot the total content of plasticizer and crude components against time. | | | | | | | | | | | | | | |

# Annex E
(normative)

# Pressure Buildup Test (Unbonded Flexible Pipe Only)

## E.1 General

The objective of this procedure is to assess the annulus free volume from the time to build up the unbonded flexible pipe annulus pressure to a stated maximum value. Figure E.1 below shows a schematic of a typical topside piping arrangement for pressure buildup tests. The content of this section of the annex is based on the UKOOA Guidance Note [61].

A relief valve should be included in the isolated section with a low pressure setting such as 2 barg. A flowmeter is necessary to measure the volume of gas vented from the annulus space after the upper pressure level is achieved. The amount of permeated gas is dependent on the operating conditions of the riser and its construction. Records should be retained every 4 h to obtain a plot of pressure versus volume. However, the test may take several days to perform. On reaching a pressure of 1.5 barg, the pressure is released to 0.5 barg and then to 0 barg with the time and volume of gas exhausted monitored.

The annulus volume can be assessed based on the pressure buildup rate and measurements of the pressure and gas volume exhausted. The test procedure takes approximately 4~5 days to perform. The advantage of this prolonged test is the availability of annulus gas for analysis. The annulus free volume should be assessed when the annulus condition is expected to have achieved steady state based on calculations, then periodically thereafter to evaluate if the annulus has become flooded with condensed water due to permeation and/or seawater due to an outer sheath breach.

## E.2 Test Procedure

The outline procedure for this test is as follows.

a) Perform risk assessment for performing the offshore test procedure.

b) Rig up equipment per Figure E.1.

c) Review previous annulus test results and predictions from permeation analysis.

d) Record riser bore conditions during the test. This should measure pressure and temperature.

e) Raise permit to work in accordance with standard offshore procedures.

f) Pressure test the equipment to 110 % of the operating pressure and hold for 15 min.

g) Check vent ports for flow. Flow substantially greater than predicted.

h) Verify isolation integrity.

i) Isolate the vent system and permit pressure buildup.

j) A flowmeter should be positioned to measure the volume buildup gas while it is exhausted. Continuity of vent ports and the annulus should be checked from the FAT.

k) Monitor and record pressure every 4 h until the reading approaches 1.5 barg, typically several days.

l) Take gas sample if required, then release pressure slowly, recording time taken for pressure to drop to 1.0 barg, 0.5 barg, and ambient. The volumes of gas exhausted should be recorded during this process.

m) Reposition all valves to normal settings.

n) Calculate annulus free volume from the pressure and volume of exhausted gas.

o) Gas sample may indicate a wet annulus from water vapor.

## E.3 Acceptance Criteria

The annulus free volume should be comparable to that attained for the previous pressure buildup test; otherwise this indicates possible flooding of the annulus.

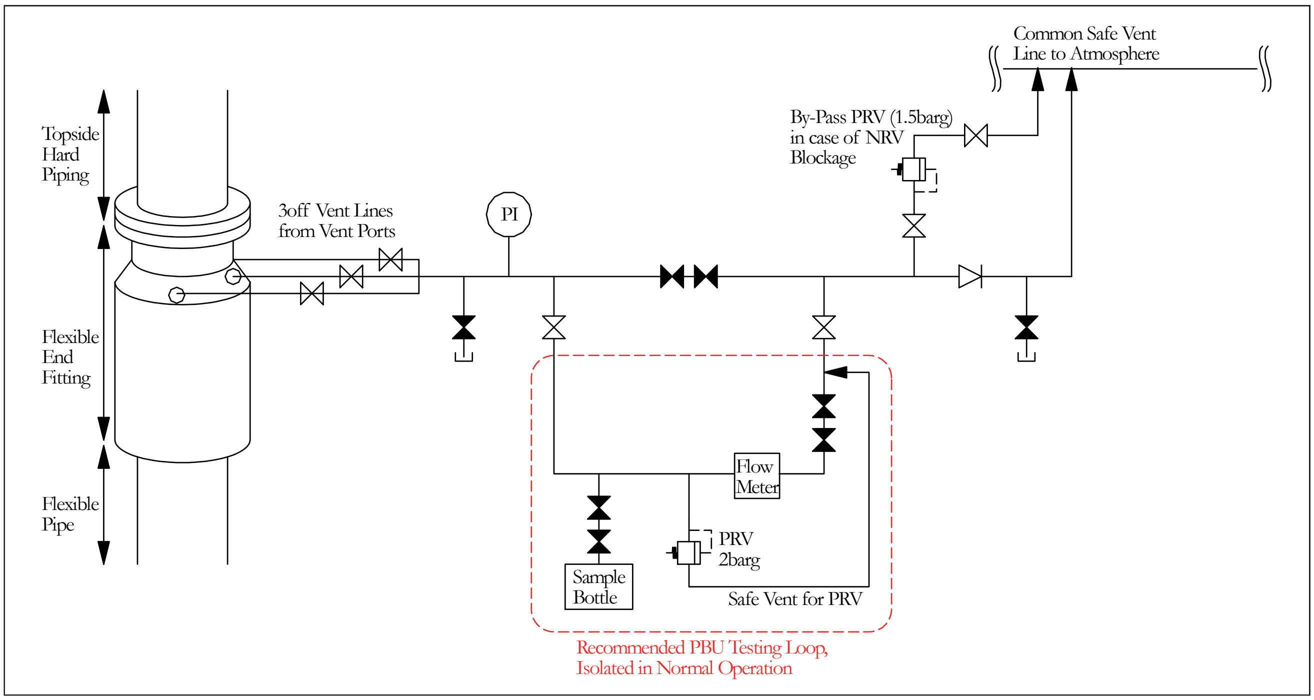



**Figure E.1—Schematic of Possible Test Pipe Arrangements**

# Annex F
(normative)

# Vacuum Test (Unbonded Flexible Pipe Only)

## F.1 General

The objective of this procedure is to confirm the integrity of the outer sheath by its ability to maintain a stable vacuum in the pipe annulus. Figure F.1 below shows a typical topside pipework arrangement for vacuum testing.

The content of this section of the annex is based on the UKOOA Guidance Note [61]. The annulus vacuum test should be assessed when the annulus condition is expected to have achieved steady state based on calculations, then periodically thereafter to evaluate if the annulus has become flooded with condensed water due to permeation and/or seawater due to an outer sheath breach.

## F.2 Test Procedure

The vacuum test procedure isolates the annulus vent system to draw a partial vacuum in the annulus space. The vacuum in the annulus is then filled with a known quantity of nitrogen to determine the free or unflooded annulus volume. The vacuum is typically achieved using a water driven vacuum pump. A pressure gauge is fitted into the isolated section and should be carefully monitored to ensure overpressurization of the annulus is not possible. The volume of nitrogen used to replace the vacuum is a measure of the free annulus space and the potential level of flooding.

A typical procedure is described as follows.

a) Rig up equipment.

b) Review previous annulus test results and predictions from permeation analysis.

c) Record riser bore condition during test. This should involve pressure and temperature and environmental temperature.

d) Raise permit to work in accordance with standard offshore procedures.

e) Pressure test equipment to 110 % of the operating pressure and hold for 15 min.

f) Check the vent ports for flow.

g) Verify isolation valve integrity.

h) Isolate vent system and begin to evacuate the annulus while recording the annulus pressure with time.

i) Reduce the annulus pressure and then isolate from the vacuum pump. Allow the annulus pressure to stabilize.

j) Release the vacuum in the annulus using bottled nitrogen, noting the pressures in the nitrogen bottles both before and after testing.

k) Reposition all valves to normal operating condition.

l) Calculate the annulus volume from the amount of nitrogen required to fill the partial vacuum in the annulus.

## F.3 Acceptance Criteria

The annulus volume should be comparable to that attained for the previous vacuum test accounting for the effects of measured temperature and pressure; otherwise this indicates possible flooding of the annulus.

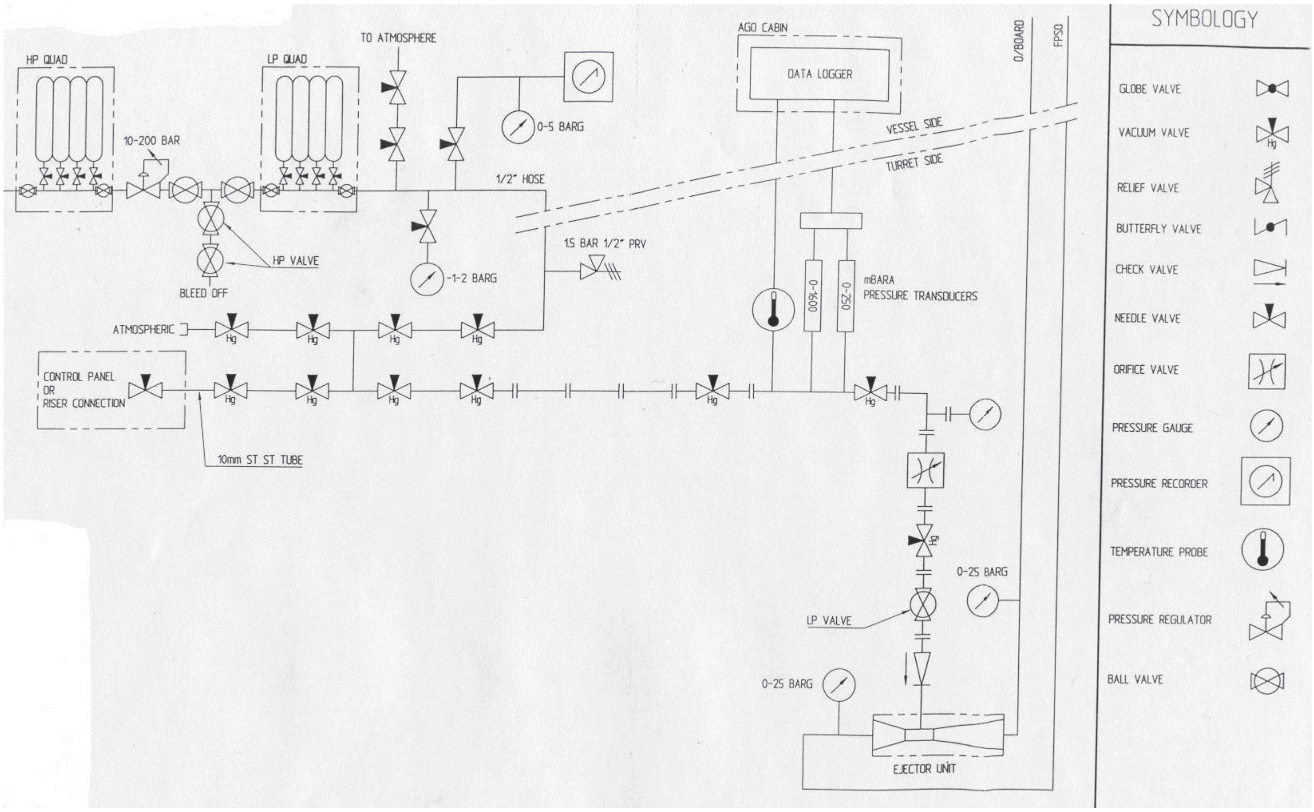



**Figure F.1—Schematic of Typical Topside Pipework Arrangement for Vacuum Testing**

# Annex G
(normative)

# Fatigue Analysis Methodology for Unbonded Dynamic Risers

## G.1 General

Annex G provides a general overview of the best practices for performing fatigue analysis of unbonded flexible risers in offshore environments. Figure G.1 presents the overall fatigue analysis methodology. A more comprehensive set of guidelines can be found in the RealLife JIP report [55].

## G.2 Global Fatigue Analysis

### G.2.1 Overview

The keys steps in global analysis are as follows.

a) Collate the external environmental conditions for the fatigue loading.

b) Assemble a global structural analysis model of the flexible pipe system.

c) Simulate the global motions or load response of the flexible pipe system.

d) Collate the global responses for input to the local analysis stage.

These steps should be subject to sensitivity and calibration checks in relation to the fatigue life of a flexible pipe. The following global responses are required for local analysis of the armor wires.

a) Pipe tension.

b) Measures of pipe bending, which may comprise:

  i) angular motion relative to an interface provisionally hinged in the global analysis,

  ii) components of bending curvature or moment.

The global load response is required to potential fatigue-critical locations where the pipe motion is comparatively high. Locations include the following.

a) Topside interface between the flexible pipe and FPU.

b) Hog and sag bends of a wave riser configuration.

c) Seabed touchdown of a catenary riser.

d) Other locations merited by the design of the flexible pipe system.

### G.2.2 Wave Selection Procedures

#### G.2.2.1 General

The main topics addressed in the wave selection procedure are as follows.

a) Modal screening—Identifies important wave periods to avoid a nonconservative fatigue analysis.

b) Blocking the scatter diagram—condenses the number of wave load cases.

c) Wave selection for deterministic and stochastic analysis—select specific wave parameters for the global analysis.

#### G.2.2.2 Modal Screening

The following guidelines are recommended for selecting fatigue analysis wave periods from the modal screening results.

a) From the initial blocking of the scatter diagram, determine the weighted average period of each load case.

b) Modal screening related changes to the weighted average period should limit the change in period of the load case to a maximum of ±2 sec.

c) Select the natural periods of the flexible pipe bending response rather than axial response, if the natural periods are within ±2 sec of the weighted average period. Natural periods from the tension response are usually not critical.

d) Balance the natural periods with a suitable choice of other periods to avoid a nonconservative and an overly conservative fatigue life.

e) Wave periods that give a local minimum in bending response should not be used.

f) The selection procedure applies to both deterministic and stochastic analyses. The selected wave periods apply to the mean zero-crossing period in the case of a stochastic analysis, as this is the most representative average period of the global response.

#### G.2.2.3 Scatter Diagram Blocking

The following guidelines are recommended for blocking scatter diagram.

a) Scatter diagrams are generally blocked with a small to moderate number of representative wave heights and periods. A minimum of five blocks should be used.

b) The wave bin selected to represent a load block should produce the most conservative global response of the block. This requires the wave height to be the largest in the block and the wave period to be the period that produces the most conservative bending response in the block. This is determined from the modal screening results. The modal screening produces a balanced set of wave periods intended to avoid a nonconservative and an overly conservative fatigue life. In the case of stochastic analysis, the mean zero-crossing period ($T_z$) is the period parameter that should be compared to modal screening results.

c) Use of the weighted average period of a load block is not recommended; this can produce a potentially unconservative fatigue life.

d) The occurrences assigned to the wave representing the load block should be equal to the total occurrence for the entire block.

## G.2.3 Deterministic Global Analysis

### G.2.3.1 General

There are several ways in which the wave environment can be characterized in a deterministic global analysis. The following are the recommended methods.

a) Maximum wave method—converts the significant height to the most probable maximum wave height and an associated period.

b) Significant wave method—applies the significant height and mean zero-crossing period (subject to modal screening) as a regular wave.

c) Individual wave method—uses the scatter table of individual waves.

The conservatism of the approaches outlined above should be confirmed with an irregular sea analysis.

### G.2.3.2 Maximum Wave Method

The maximum wave method is the most conservative characterization of the wave loading. The method converts a characteristically large $H_s$ value to a wave with the most probable maximum height $H_{max}$ and an associated period $T_{ass}$. As this approach generates overly conservative results, it is recommended to proceed to a significant wave or individual wave methodology if the maximum wave methodology with the 100-year event does not meet the fatigue criteria.

### G.2.3.3 Significant Wave Method—$H_s$ and $T_z$

The significant wave method directly applies the seastate height and period parameters as a regular wave in a deterministic fatigue analysis. The wave parameters are selected as follows.

— Wave height: $H = H_s$.

— Wave period: $T = T_z \pm 2$ sec.

A regular analysis based on $H = H_s$ and $T = T_z$ may not necessarily produce a conservative global response. Therefore, to ensure conservatism the period to be used is in the range of $T_z \pm 2$ sec, with the period modified using the results from modal (frequency) screening.

### G.2.3.4 Individual Wave Method

The individual wave scatter diagram method gives the most accurate deterministic representation of the wave environment and hence blocking can be as refined as is required up to the point where every wave in the scatter diagram is analyzed. The scatter diagrams describe the zero-crossing waves that will occur at a particular location.

### G.2.3.5 Derivation Methods for Deterministic Scatter Diagrams

In the absence of deterministic scatter diagrams in the metocean report, the individual wave data can be computed from a stochastic seastate scatter diagram using an appropriate wave spectrum and probability distribution of the individual waves. The Longuet-Higgins and Borgman distributions are recommended. An alternative method is to stochastically simulate the individual seastates several times and count the height and period of the individual waves using zero-crossing method.

### G.2.4 Multimodal and Multidirectional Seastates

The following is a summary of recommended methodologies for performing fatigue analysis in multimoded and multidirectional environments.

a) Perform full 3D stochastic global and local analysis. Depending on format of the available data, various blocking approaches can be used to reduce the number of load cases to a manageable number.

b) For unidirectional multimoded environments, perform stochastic analysis of the seastates and generate a deterministic scatter diagram by counting the zero-crossing waves.

c) For geographical areas where there is a distinct difference between the local sea periods and swell periods, generate individual deterministic scatter diagrams for the two conditions, analyze separately, and sum the damages.

d) With Item c) above if there is a concern or potential for coupling effects between the local sea and swell conditions, then one options is to perform deterministic analysis of the swell scatter diagram, with a representative sea wave included in all analysis. In this case, the period of the dominant wave would be used to determine the number of cycles for this load case.

e) If multimoded or multidirectional seastates have similar energy levels or significant period overlaps, then one option is to analyze the seastates individually and subsequently combine the damages based on equivalent stresses rather than simply adding damages. With this methodology, the damages from the individual seastates would be summed without accounting for location on the circumference.

### G.2.5 Combining Fatigue Damage Contributions

From the damages calculated for the local sea and swell scatter diagrams, equivalent stresses are calculated based on the Palmgren-Miner rule. The equivalent stress is used as a representative stress in the below equation for combining fatigue damages:

$$D = D_1 + D_2 \left( \frac{\sigma_1 + \sigma_2}{\sigma_2} \right)^m - D_1 \frac{n_2}{n_1}$$

where

$D_1$ is the calculated fatigue damage in one year for the local sea scatter diagram;

$D_2$ is the calculated fatigue damage in one year for swell scatter diagram;

$\sigma_1$ representative stress range for the local sea response;

$\sigma_2$ representative stress range for the swell response;

$n_1$ is the number of cycles in one year for the local seas;

$n_2$ is the number of cycles in one year for the swell seastates.

The number of cycles in one year for each scatter diagram can be taken as the number of seconds in one year divided by the weighted average zero-crossing period of the scatter diagram. The above equation is for a single slope S-N curve. For a double sloped curve, it is conservative to use the slope from the high cycle's section of the curve.

## G.2.6 Non-wave-related Considerations

### G.2.6.1 General

There are parameters that vary over the life of the riser and may have a reasonably significant impact on fatigue performance and hence should be carefully considered in load case selection. These parameters may not cause cyclic stresses on the riser themselves but may influence the riser's response to wave loading such that they have an adverse effect on the riser's fatigue performance. If this is the case, they will need to be taken into account to ensure conservative results.

### G.2.6.2 Current

Generally current is expected to hydrodynamically dampen the fatigue motions of a riser and it is therefore conservative to apply no current in the fatigue analysis. However, the damping effect of current in combination with waves is sometimes dependent on the wave period when the fluid velocities from both loading components are combined to determine the total drag. In this case, it may prove difficult to assess if it is conservative to conduct the analysis with or without current, and a representative current should be used (e.g. 50 % exceedence profile). Current can affect the direction of the bending plane.

### G.2.6.3 Marine Growth

The main load parameters for marine growth include increases of the flexible pipe outside diameter, wet weight, inertia or mass and surface roughness associated with the drag coefficient. The loading from marine growth normally increases the bending response of the flexible pipe system. Marine growth should therefore be included in the fatigue analysis if it has time to develop during the service life, which is normal for most designs.

### G.2.6.4 Hydrodynamic Coefficients

Hydrodynamic loading on flexible risers is normally based on use of Morison's equation. This requires specification of drag and inertia coefficients.

It is generally assumed that a lower drag coefficient (e.g. 0.7) gives a conservative fatigue result as this reduces the damping on the riser. However, this is not always the case with flexible riser. In many cases, higher drag coefficients will give larger responses at FPU hangoff, when responses are largely driven by the vessel motion. Modal screening and sensitivity analyses should be used to verify the conservatism of the selected coefficients.

The hydrodynamic inertia loading of flexible pipes is less significant than drag. A value of the Morison's inertia coefficient between 1.8 and 2.0 is normally applied for rough and smooth surfaces, respectively.

## G.2.7 Vessel Motion

### G.2.7.1 Vessel Draft

In general, vessels tend to be most dynamic in the ballasted or empty condition with motion magnitudes decreasing as the draft increases. In a critical design, a series of drafts should be considered in the fatigue analysis with the appropriate probability of occurrence, while in less critical design only the most onerous draft can be considered with it being assumed to occur for 100 % of the time.

#### G.2.7.2 Static Offset

Ideally, offset magnitude and direction would be specified with each seastate in the fatigue scatter diagram. In the absence of such data, the first step in evaluating how to account for static offsets should be to perform sensitivity analysis to assess the influence of offset on fatigue performance. An efficient way to do this is to compare modal screening load RAOs for a couple of different offset magnitudes and directions to those generated in the nominal position to see if they increase or decrease with offset. If offset is seen to have a significant impact on fatigue performance, then a methodology that conservatively accounts for it should be developed.

#### G.2.7.3 Wave Frequency Vessel Motion

##### G.2.7.3.1 Motion RAOs

Motion RAOs determine the vessel response to an incident wave in 6f degrees of freedom depending on the wave amplitude, period, and heading of incidence of the wave on the FPU. Motion RAOs assume that the vessel response is linear with respect to the wave height. If the vessel response shows significant nonlinearities with wave height, then the RAOs to be used should be representative of fatigue seastate environments.

##### G.2.7.3.2 Motion Timetraces

Using motion timetraces in stochastic fatigue analysis, timetraces of motion in the 6 spatial degrees of freedom are applied to a point on the vessel for the duration of an analysis to simulate the vessels response to wave loading. Both vessel offset in response to current or wind loads and low frequency vessel motions can be included in these timetraces.

A disadvantage of the motion timetrace method is that an actual wave cannot be applied in an analysis with the timetraces due to the fact that the wave loading and vessel motions would not be in phase for these independently generated random occurrences. This means that direct wave induced water particle loading on the risers is neglected and the risers are effectively being moved in still water at their vessel interface. If timetraces are used, it should be verified that the exclusion of direct wave loading is not significant.

##### G.2.7.3.3 Coupled Analysis

Coupled analyses can be performed for both deterministic and stochastic analyses. Using a coupled analysis methodology, all forces acting on the vessel are computed within the riser global analysis. Resultant vessel motions are determined from the equilibrium of forces acting on the vessel, riser, mooring lines, and any other modelled ancillary components.

The use of a coupled analysis methodology does, however, represent a step change in complexity in terms of model setup, input data required, and finite element computations. Hence the use of this method from a setup and simulation duration point of view is much more time consuming and should only be used where it is felt it is needed to accurately predict the response of a particular system.

#### G.2.7.4 Low Frequency Vessel Motions

Low frequency vessel motions arise from second order wave loads acting on the hull of an FPU. If low frequency vessel motions are considered to be significant, they can be included in the wave fatigue analysis as superimposed sinusoidal motion or alternatively they can be analyzed separately with the fatigue damages from the first and second order load conditions added together. If the damage from second order is significant, the combined fatigue life should be determined from the addition of stresses rather than the addition of fatigue damage.

## G.2.8 Dynamic Analysis Issues

### G.2.8.1 Deterministic Wave Modelling

There are several regular wave models that can be used in deterministic fatigue analysis, with some being linear and others nonlinear. In general, linear models are sufficiently accurate to use in most fatigue analysis, though for some environments nonlinear wave models will be specified and hence should be used.

### G.2.8.2 Stochastic Seastate Modelling

In the case of stochastic analysis, the wave environment is characterized by the sum of a number of sinusoidal regular waves. In order to facilitate this summation, the basic wave model used must be a linear model.

### G.2.8.3 Frequency Domain vs Time Domain

Dynamic analysis can be carried out in time or frequency domain. The time domain employs a nonlinear solution and is generally regarded as more accurate than the frequency domain that employs a linearized solution. The frequency domain dynamic analysis is typically performed by linearizing the nonlinear response of the riser with respect to a mean static configuration of the flexible riser, and it requires specifying the first and second order motions of the vessel in the frequency domain. Analysis durations in the time domain can be orders of magnitude longer than those for equivalent analysis in the frequency domain.

Analysis durations for regular wave deterministic analysis is not an issue so time domain should be used exclusively. For stochastic analyses, time domain analyses can take hours where the equivalent frequency domain analysis could take minutes. Where frequency domain analysis is employed, it should be verified against the time domain for a number of critical seastates. In certain cases the time domain results can be used to calibrate the frequency domain model.

## G.2.9 Structural Damping Model

The key guidelines for defining the structural damping model are as follows.

a) Only stiffness proportional damping should be considered.

b) Some global analysis programs allow different coefficients to be specified for bending, axial, and torsional stiffnesses. If this is the case, the selection of coefficients for each behavior mode should be carefully and independently considered.

c) Generally, axial and torsional damping coefficients have small effect on global fatigue and should be set at values below 5 % critical.

d) Bending stiffness damping effects can be significant due to the loss of energy from friction effects during hysteresis. Values up to 20 % or 30 % of critical damping have been reported. For fatigue analysis, the recommended maximum bending stiffness related damping to be used should be 5 % or less of critical, unless appropriate test data is available to justify higher values.

e) For fatigue seastates, the hysteretic damping effects can be small if resulting riser curvatures are below the slip curvature. In particular for deepwater risers, much of the riser will be operating in the nonslip mode.

f) There are a number of different approaches for incorporating Rayleigh damping into standard riser analysis programs. For example, the stiffness matrix used to calculate the damping force can include both linear and geometric stiffness contributions. The damping model used should therefore be validated to ensure that the correct level of damping is applied.

g) Where intermediate models of finite element local models are used, it is important to ensure that hysteretic damping effects are only accounted for once in the analysis process (i.e. they are not considered in both the global and local models). The effect of hysteresis on bending stiffness can be accounted for in all stages of the analysis.

## G.3 Global to Local Transposition

### G.3.1 General

Global to local transposition is the extraction of global response at key locations on the flexible pipe and the transfer of the data into a format suitable for local analysis of the armor wires in the flexible pipe.

### G.3.2 Fatigue Hotspots

Global to local transposition is conducted at locations where the bending (or possibly tension) ranges, as well as the mean component stresses or strains, of the flexible pipe are comparatively large. These locations are called hotspots in fatigue analysis. The standard deviation of the global bending response provides a method for determining the fatigue hotspots.

A fatigue critical section of the flexible pipe might be characterized at a single hotspot if this location consistently shows the highest bending range. A less consistent trend in the bending ranges will require a series of hotspots in the fatigue critical section. A conservative approach identifies the largest bending range within a critical section for each load case and assumes these always occur at the same hotspot.

The global analysis mesh should be refined to ensure the location and magnitude of the largest bending ranges is identified with sufficient accuracy. Examples include 0.1 m and 0.5 m mesh lengths within central region of the critical section and typically not more than 1.0 m in the other parts of the section. Away from the critical region longer element lengths may be used.

### G.3.3 Global Responses for Transposition

#### G.3.3.1 Riser Interface

##### G.3.3.1.1 General

Data can be transferred in a number of ways at the flexible pipe and FPU interface. The choice of method depends mainly on how the interface is modelled in the global analysis and the requirements of the local analysis.

##### G.3.3.1.2 Tension Angle Transposition

Transposition of the global tension angle response is used when the local analysis models the bend limiter and a short length of pipe. The tension angle data is applied in local analysis to predict the curvature of the flexible pipe in bend limiter. The global analysis does not include the bend limiter with this method of transposition and the flexible pipe is instead provisionally pinned or hinged to the FPU. The pinned connection is made at the location on the FPU where the bend limiter is to be mounted. The transposition only involves the tension angle response at the pinned connection.

The rotational response in the pinned connection is measured relative to a datum line and intended built-in direction of the bend limiter. It is recommended that the static direction of the datum line is set so that the full extent of the rotational response is clearly identified.

The static direction set for the datum line depends on the principal range used for the rotational angle of the pinned connection. The static direction is ideally set to the intended built-in angle of the bend limiter, provided the rotation is returned on a principle range between –90° and 90°.

There may be cases where the static direction of the datum line is not ideally set to show the true extent of the rotational motion at the pinned connection. A conservative approach around this would be to identify the maximum rotation and define this as the amplitude with the range set to twice this value. An alternative approach could process the timetrace of the absolute rotation to reconstruct the zero crossings of the datum line and thereby recover the true extent of the rotational response.

#### G.3.3.1.3 Tension Curvature or Tension Moment Transposition

Transposition of the tension curvature or tension moment response is used when the bend limiter is included in the global analysis. The global curvature (and tension) response is normally applied directly to the flexible pipe in the local analysis. The global analysis should accurately model the bend limiter in addition to applying the most representative boundary conditions between the flexible pipe and FPU.

It is preferable that the transposition outputs the curvature if the local analysis does not involve the bend limiter. A local analysis may account for frictional damping of the pipe bending if this has not been performed in the global analysis and in this case the transposition should include both the curvature the moment.

#### G.3.3.2 Other Riser Sections

Sections of flexible pipe away from the FPU interface may also experience relatively high cyclic variations of curvature and tension and are potentially fatigue critical. Examples include the seabed touchdown region in free hanging catenary risers and the hog or sag bend regions of wave configured risers. Global to local transposition of the tension curvature/moment as described above also apply to these other sections of flexible pipes and proceed in the same manner. The use of tension angle results for local analysis of midriser sections is not recommended.

### G.3.4 Transposition Formats

#### G.3.4.1 General

The format of the data to be transposed from global to local models depends on the type of global analysis undertaken and the requirements of the local analysis.

#### G.3.4.2 Deterministic Analysis

#### G.3.4.2.1 General

Transposition from a deterministic global analysis can use any of the responses described in G.3.3 pending the requirements of the local analysis. There are three different data transfer formats that can be used.

#### G.3.4.2.2 Ranges Only

The simplest transposition format uses mean and range of each global response or, alternatively, the minima and maxima. The ranges are transferred to the local analysis without defining the relative phasing between the responses. A conservative approach assumes the global response ranges are in phase. This assumption is overly conservative for a tension angle response and in this case some phase information can be transferred.

#### G.3.4.2.3 Ranges and Relative Phases

This format is similar to the range-only format except that the transposition includes the relative phasing between the tension and angle/curvature/moment. The phase information can be determined from a harmonic analysis of time domain global responses, although this approach is not widely practiced. A global frequency domain analysis normally provides the phase information as a direct output.

The phase information can also be defined using maximum and associated responses. This is normally practiced for tension angle transposition. The transposition should also include the minimum with the associated or conservative approach that mirrors maximums and associated values about the mean responses.

#### G.3.4.2.4 Timetraces

Transposition of the tension and angle/curvature/moment timetraces provides the most complete transfer of data to the local analysis. It is recommended that at least two wave periods of the steady state global response be transposed to the local analysis. The phasing of the friction-induced axial stress is improved if the transposition ramps the tension and angle/curvature/moment responses from the mean values. The duration of the ramp only needs to be comparatively short (i.e. for a quarter period). This ramping also avoids large transients in the stress response.

### G.3.4.3 Stochastic Analysis

#### G.3.4.3.1 General

Transposition of stochastic global responses also proceeds in a similar manner to deterministic formats described above, although the format for ranges with phases is replaced by a two-dimensional histogram. The global stochastic analyses should be of sufficiently long duration to generate reliable response statistics. A full 3-h duration is potentially required for irregular sea analysis. A shorter duration may be used if it can be demonstrated by sensitivity analysis to be representative of the full duration of the seastate.

#### G.3.4.3.2 Ranges Only

The simplest transposition format uses the mean and statistical range of each global response. The number of cycles is based on the $T_Z$ of the seastate. A conservative alternative applies the minimums and maximums of the stochastic response. The significant range of four times the standard deviation of the timetrace is a more representative conservative range. The smaller rms range $2\sqrt{2}$ times the standard deviation of the timetrace is less conservative, although its reliability would need to be demonstrated.

#### G.3.4.3.3 Two-dimensional Histogram

Two-dimensional histogram format first computes histograms of the tension and bending (angle/curvature/moment) response and then combines the two histograms assuming statistical independence. The first step of computing the separate tension and curvature histograms follows standard procedures for cycle counting a stochastic response. The percentage occurrences from both histograms are multiplied together in a scalar manner to produce the two-dimensional tension curvature histogram. The tension curvature histogram allows a small curvature range to occur with a large tension range and vice versa, which results from the assumption of statistical independence and compensates for the lack of information on the relative phasing.

The upper range values in the paired tension and curvature bins are transposed to the local analysis as deterministic responses and these are assumed to act in-phase. The number of cycles from the curvature histogram is assigned to the combined histogram as curvature variations are generally more critical.

#### G.3.4.3.4 Timetraces

Transposition of the tension and angle/curvature/moment timetraces follows the same format as described in G.3.4.2.4. The recommendation of the transposition ramping the tension and angle/curvature/moment responses from the mean values still applies as this ensures correct phasing of the friction-induced axial stress.

The local analysis normally requires the reversal points in the tension and bending (angle/curvature/moment) timetraces and relatively few points between the reversals. This reduction is readily implemented as part of a transposition procedure and can reduce the number of points in a timetrace by an order of magnitude.

Timetraces of the global load of interest need to be synthesized from load spectra generated by the frequency domain solution. Timetraces can be synthesized from load spectra using the following equation, where $r$ is the parameter for which the timetrace is to be synthesized:

$$r(t) = \sum_{n=1}^{N} A_n \cos(\varpi_n t + \phi_n)$$

where

$n$ is an index for the harmonics;

$N$ is the total number of harmonics into which the spectrum is split;

$A_n$ is the amplitude;

$\omega_n$ is the angular frequency;

$t$ is the time;

$\Phi_n$ is the phase angle.

### G.3.5 Directionality

#### G.3.5.1 General

A flexible pipe that dynamically bends out-of-plane from the static configuration requires careful consideration to ensure that the global response is transposed to the local analysis in a consistent and conservative fashion. Local analysis tools are often only able to accept two-dimensional data; if this is the case, the transposition becomes more complicated as the 3D global response needs to be transformed into an equivalent 2D global response for direct input to the local model. The complication only arises in the case of the bending component as tension transfer is independent of the manner in which the riser is bending.

#### G.3.5.2 Deterministic Analysis

In a deterministic analysis, the bending component ranges in the two local planes of curvature can be combined to produce a single total bending component range, using the following equation:

$$\mathrm{BC}_{\text{tot,range}} = \sqrt{\left(\mathrm{BC}^2_{\text{y,range}} + \mathrm{BC}^2_{\text{z,range}}\right)}$$

where $BC_{y,range}$ and $BC_{z,range}$ are the local bending component ranges and $BC_{tot,range}$ is the total bending component range. The equation assumes the component bending ranges act in-phase. A similar relation also determines the resultant of the mean bending component, as follows:

$$BC_{res,mean} = \sqrt{\left(BC_{y,mean}^2 + BC_{z,mean}^2\right)}$$

The fatigue analysis applies either the resultant mean and range values or alternatively, the minimum and maximum component, defined as follows:

$$\left(BC_{res,min}, BC_{res,max}\right) = BC_{res,mean} \pm 0.5BC_{tot,range}$$

The resultant bending component range along with accompanying tension range can then be transferred to a local analysis tool as equivalent two-dimensional inputs. The guidelines in G.3.4.2.3 on phasing also need to be considered.

### G.3.5.3 Stochastic Analysis

In the case of a stochastic analysis, the conversion of 3D bending components in two dimensional bending components is more complicated than in the deterministic case. The process involves mapping the two local bending components into a plane of principal bending such that a timetrace in the plane of principal bending is derived.

A mathematical method exists for computing the orthogonal first and second planes of bending. The method relies on computing the variance and co-variance of the two local bending components for the duration of the timetraces and assembling the results into a 2 × 2 matrix as follows:

$$\begin{bmatrix} Var_y & CoVar_{yz} \\ CoVar_{zy} & Var_z \end{bmatrix}$$

The subscripts y and z denotes the riser local-axes of bending. The eigenvalues and eigenvectors of the matrix are then computed. The vector associated with the larger eigenvalue is the principle plane of the riser bending response and the vector associated with the second eigenvalue is the second principle plane of riser bending. When the two local planes of bending components are vectorially projected onto these planes, the two principal bending component responses are obtained. Where the second plane of bending is much less significant than the first, it can be discarded. If both are of close to equal magnitudes, they should both be separately transposed to the local model with associated tension.

The separation of the pipe bending planes allows local analysis to independently process the two set of transposed timetraces using methods based on a single plane of bending. If the stress is computed at several points on the pipe cross section, then these locations are preferably referred back to a consistent local axes system to nonconservatively account for directionality of the global loading. This avoids lumping the damage from hotspots in the far, cross and transverse directions of global loading.

If pipe bending in the second principle plane is significant, then the stress components can be combined with the analysis in the first principle plane as follows.

a) The axisymmetric stress is identical in both analyses and is included only once in the combined stress.

b) The wire bending stress components in both analyses are independent and are summed.

c) The axial friction stresses from both analyses are summed to give a conservative combination. In this approach, the total friction accumulated as the tensile armor slips will exceed the true available limit.

d) Combining the bending and axial friction stress requires the wire locations in the first and second principle planes of bending to refer to a consistent local axis system.

## G.4 Local Fatigue Analysis

### G.4.1 General

The local fatigue analysis converts the global loading at selected hotspots to stress in the armor wires. The analysis requires a numerical model of the flexible pipe cross section and an interface that is compatible with the global to local transposition procedures.

### G.4.2 Local Model Data

#### G.4.2.1 General

The key local modelling input data are defined in Table G.1. The level of detail to be provided for the cross section will depend on the focus of the fatigue analysis.

**Table G.1—Key Local Modelling Input Data**

| Category | Parameters | Recommended Values | Comments |
|---|---|---|---|
| Pipe data | Layer-by layer data: dimensions, lay angle, fraction-fill/mass/no. of wires, Young's modulus, Poisson's ratio, etc. | Use nominal properties | Consider sensitivity accounting for corrosion on wire dimensions or effect of dimensional tolerance |
| Friction coefficient | Coefficient between wires and adjacent layer; wires, or antiwear tape/sheath | Use results from small-scale tests or value calibrated from full-scale tests | Consider sensitivity with bounding range |

#### G.4.2.2 Friction Coefficient and Interlayer Pressure

The friction coefficient between the steel tensile armors and adjacent layers can have a major impact on fatigue analysis. The combination of friction coefficient and interlayer contact pressures control the hysteretic response of the pipe. A constant contact pressure is normally assumed and is based on the normal operating pressure and mean tension. Some models can account for the effect of the tension variations and pipe bending loads on the contact pressure. Variation of the internal pressure within a load case is generally not considered in the fatigue analysis.

There are significant uncertainties in the selection of the friction coefficient to be used in the local analysis. This can be affected by issues such as the following:

a) temperature in the annulus,

b) wire/sheath surface condition (new vs aged),

c) lubricant condition (whether lubricants applied in fabrication are still active),

d) wire corrosion,

e) annulus environment (wet or dry),

f) variations between internal and external surface of wires.

The results from full-scale tests can be used to calibrate friction coefficients in local analysis models. Representative values of the friction coefficient vary between 0.1 and 0.2, although higher values can be applicable under adverse conditions. Due to the uncertainties associated with the friction coefficient, it is recommended that an upper bound conservative value be applied.

### G.4.3 Local Models

There are a variety of local models that can be used in the fatigue analysis and generally these are categorized as follows:

a) analytical or semianalytical models,

b) finite element models.

The minimum requirements for the local analysis models are as follows:

a) verified against full-scale measurements;

b) capable of modelling tension and curvature ranges;

c) account for hysteresis;

d) calculate stresses at four corners of the wire;

e) take into account the effects of external pressure;

f) preferably output stresses at eight points around the circumference, so that directionality effects can be considered.

If distribution of damage around the circumference is to be accounted for in the solution, then this will require a clear understanding of any torsional rotational effects, such as due to turret rotation, pressure effects, 3D environments loads, etc.

### G.4.4 Pipe Hysteresis

Hysteresis in flexible pipe caused by friction loading on the tensile armors generated in response to the global bending and interlayer contact pressure. The hysteresis mainly affects pipes operating with a high internal pressure or deepwater lines with large external pressure or high tension loads. Hysteresis modifies the pipe bending stiffness by two or more orders-of-magnitude within a wave loading cycle, and the nonelastic nature of the stiffness potentially dampens the global curvature response.

The hysteresis characteristic of a flexible pipe has a major influence on the fatigue performance of the system, as follows:

a) the armor wire stress is strongly affected by the interlayer frictional loading,

b) the pipe bending stiffness changes substantially in a wave loading cycle,

c) the nonelastic component of the hysteresis removes energy from the bending response.

The latter two effects have significant potential to reduce/redistribute the global curvature response and are often conservatively ignored in a fatigue analysis. The curvature reduction effect of hysteresis can be accounted for with a variety of methods in either a global or local analysis or, alternatively, an intermediate analysis.

## G.4.5 Wire Stresses—Tensile Armors

### G.4.5.1 General

The local fatigue analysis should account for the following contributors to stress in the tensile armors:

a) effect of tension ranges (axisymmetric loading),

b) wire bending due to global bending in the pipe,

c) friction induced axial stresses.

The axisymmetric and friction induced components of the stress are uniform over the cross section of the wire. The bending component linearly varies over the cross section of the wire. Due to phasing differences between local curvatures about the two principal axes of the wire, the resultant bending stress will produce different ranges at the four corners of the wire. The stress components from the two local curvatures should be conservatively combined unless the model explicitly computes the stress at all four corners of the wires.

### G.4.5.2 Local Axisymmetric Analysis

The local axisymmetric analysis refers to the stress response from the tension and internal/external pressure as applied to a straight line pipe. The axisymmetric stress responds linearly to the applied loading and this allows for the response of the tensile armor to be calibrated using a matrix of influence coefficients. The influence coefficients give the stress in the wires per unit loading of tension and internal/external pressure.

### G.4.5.3 Local Bending Analysis

The local bending analysis involves determining the pure bending stress and axial stress induced from effects of bending and friction. An armor wire locally bends about the principal cross sectional axes parallel to the thin and thick edges of the wire.

The analysis should be calibrated against full-scale tests to validate the combined effect of the several modelling assumptions that are normally required. The frictional component of the stress causes a hysteretic response in the pipe.

## G.4.6 Wire Stresses—Pressure Armors

Fatigue in pressure armors is generally more critical for high pressure pipes, and the key drivers are internal pressure and dynamic curvature ranges. Other parameters that affect the pressure armor fatigue characteristics include wire shape, material, manufacture process, and test pressure history. Fretting is one fatigue mechanism that affects the pressure armor, and this is due to partial slip between the nub and groove within the interlock profile. Another factor that influences the fretting fatigue is residual tensile stress at the surface of the wire. The residual stress results from the manufacturing process of the wires and can be reduced, if required, by careful selection of the test pressure. A small overpressurization under factory-controlled conditions is sometimes necessary.

## G.4.7 Key Trends

In understanding the results from local stress analysis of tensile armor wires, the following are useful trends to consider.

a) In the initial bending of a pipe, prior to armor slip, the maximum dynamic stresses generally occur in the plane of bending as a result of axial friction stresses that build at a high rate prior to armor slip.

Axial friction stresses have their maximum value in the plane of bending and minimum at the neutral axis. Dynamic stress contribution from local wire bending around their width might also contribute offsetting the location of maximum combined stress towards the neutral axis where local bending stresses have their maximum value.

b) As curvature of the pipe progressively increases, the armor wires will slip and the rate of axial friction stress increase is significantly decreased while the bending stresses will keep increasing at the same rate as prior to wire slip leading to progressively shift of the location of maximum dynamic stress towards the neutral axis.

c) The bending induced stresses generally dominate over the dynamic tension induced stresses. However, due to the exponent effect of the S-N curve, where damage is a function of total stress range raised to the power of $m$ (S-N curve exponent), even a relatively small tension contribution will give a significant reduction in fatigue life. Therefore, this annex recommends that tension effects are always included in the fatigue damage calculations. The local analysis may consider the dynamic loading from tension and bending as separate analyses and then combine the stress ranges with or without phasing information

d) Decisions on selecting load cases or analysis parameters should be based on the significance of impact on the dynamic curvatures. Dynamic tensions in deepwater also have a significant effect on the fatigue life as well as the distribution of the load case occurrences.

e) Most flexible pipe fatigue analysis methodologies accumulate fatigue damage from the worst locations on the pipe circumference (i.e. the full distribution of damage around the circumference is not considered in the analysis). This distribution may prove beneficial in critical cases, though in general, the benefit is less significant than for steel pipe. The reason for this is that curvature in the flexible riser induces dynamic stresses all around the circumference, including at the neutral axis of pipe bending, which is not the case with steel risers.

f) When considering fatigue curvatures for the tensile armor, the mean curvature has a secondary effect, as it has a relatively small impact on the dynamic stress range due to the hysteresis effect. Mean curvature effects on the pressure armor fatigue stresses can be significant.

g) The layout of the riser spread can be used to improve the fatigue life of critical pipe by aligning it with the global direction that gives the least damage. The difference between aligning the riser in the least and most optimal directions affects the fatigue life by up to a factor of three. An early screening study is required to determine a near-optimal heading for a fatigue critical riser so that the impact on the field layout is known well in advance.

## G.5 Fatigue Design Calculations

### G.5.1 Overview of Methodology

#### G.5.1.1 S-N Curve

##### G.5.1.1.1 General

The S-N curve is the link between computing the stress in the armor wires and the expected fatigue life. The curve is developed from laboratory tests and can be shifted from the position of mean-fit to give a smaller failure probability. The Basquin (power-law) relationship for the S-N curve is defined below:

$$N = \frac{C}{\Delta\sigma^{m}}$$

where

$N$ is the life in terms of the number of loading cycles to failure;

$\Delta\sigma$ is the constant amplitude stress range;

m is the negative inverse slope of the S-N curve;

$C$ is a large constant equivalent to the theoretical life for a unit stress range (N-intercept).

The intercept value generally depends on the mean value of the stress range or the R-ratio of minimum/maximum stress.

#### G.5.1.1.2 Endurance Limit

A flat high-cycle section for a two-part curve represents the endurance limit of the material. Stress ranges below the endurance limit produce an indefinitely long fatigue life. Before an endurance limit can be used, API 17J requires that it be a documented and verifiable quantity that has been established by testing and approved by purchaser.

The Bastenaire relationship gives a single component S-N curve for materials with an endurance limit and is defined as follows:

$$N = A\frac{\exp\left(-\frac{\sigma_{\text{max}} - \sigma_{\text{e}}}{B}\right)}{\sigma_{\text{max}} - \sigma_{\text{e}}}$$

where

$N$ is the fatigue life as previously;

$\sigma_{\text{max}}$ is the maximum stress;

$\sigma_{\text{e}}$ is the endurance limit;

$A$ and $B$ are the constants that effect the initial slope and rate of decay of the curve.

The fatigue life becomes indefinitely long, as $\sigma_{\text{max}}$ approaches $\sigma_{\text{e}}$. The constants $A$ and $B$ also depend on the mean stress or R-ratio as described above.

### G.5.1.2 Palmgren-Miner Rule

The Palmgren-Miner rule determines the fatigue life where the loading history contains multiple stress ranges. The rule applies for stress ranges determined from regular or irregular loading histories. The rule is briefly summarized as follows. An occurrence of a single stress cycle incurs an increment of damage defined as:

$$d_{\text{i}} = \frac{1}{N_{\text{i}}}$$

where

$N_{\text{i}}$ is the life (number of cycles to failure) as computed from the S-N curve for the $i$-th stress range.

The incremental damages sum gives the total damage as follows:

$$D_{\text{tot}} = \sum_{n} n_{\text{i}} d_{\text{i}}$$

where

$n_{\text{i}}$ is the number of occurrences of the $i$-th stress range.

The Palmgren-Miner rule states that fatigue failure is expected or unfactored fatigue life is defined as the inverse of the total damage per year ($d_{\text{fat}}$), as follows:

$$\text{nonfactored fatigue life} = \frac{1}{d_{\text{fat}}} \text{ (year/unit damage)}$$

The damage rule is normally applied with a FOS.

## G.5.2 Flexible Pipe Specific Issues

### G.5.2.1 Annulus Environments

A wide range of annulus environments can be experienced by flexible risers from benign to corrosive gas condensates or seawater flooded. The probability and expected duration for each condition should be determined and accounted for in the fatigue analysis. In general, the following annulus environments should be considered:

a) in-air conditions,

b) predicted normal operating conditions (using a validated annulus permeation model),

c) accidental conditions such as seawater flooded.

Appropriate S-N data should be available for all of the above annulus conditions. Fatigue with seawater flooding should be analyzed for the cases of water exchange between the annulus and ocean by using an aerated seawater S-N curve and by using a deaerated seawater S-N curve for the case where such exchange is prevented.

### G.5.2.2 Fatigue Design Check

#### G.5.2.2.1 General

The fatigue design checks are required to verify that the computed fatigue life exceeds the intended service life with a specified FOS. The objective is to ensure a high level of reliability in the fatigue design.

#### G.5.2.2.2 Single Environment in Annulus

The key parameters in the fatigue design check are as follows.

a) Service life ($T_{\text{ser}}$)—the period of time during which the flexible pipe is to fulfil all performance requirements.

b) Fatigue safety factor (FSF)—applied to increase the minimum requirement on the design fatigue life. The factor accounts for uncertainties in the fatigue assessment process, the in service behavior of the riser, the consequences of failure, and the relative difficulty of inspection and repair. API 17J defines what FSF to use.

c) Calculated fatigue life ($T_{fat}$)—the computed fatigue life for the S-N curve that applies to the annulus environment.

d) Calculated annual fatigue damage ($d_{fat}$)—the computed fatigue damage per annual distribution of global loading with the applicable S-N curve.

The fatigue design is considered safe when the following criterion is achieved:

$$T_{fat} \geq T_{ser} \times \mathrm{FSF}$$

The criterion is also expressed as follows:

$$T_{ser} \times d_{fat} \leq 1/\mathrm{FSF}$$

The second format of the criterion generalizes to multiple or transitional annulus environments.

#### G.5.2.2.3 Multiple Annulus Environments

An assessment that involves multiple or transitional annulus environments requires a series of fatigue design calculations. The fatigue design calculation is repeated with the appropriate S-N curve for each environment. The global and local analysis does not need to be repeated unless the change in annulus environment is expected to have a significant effect on the local response.

The fatigue design check is then conducted for the combined series of annulus environments. The following format of the fatigue design criterion is suitable for general transitional loadings or environments:

$$\sum_{i} T_{i} \times d_{i} \leq 1/\mathrm{FSF}$$

where

$d_i$ is the damage per year for the applicable S-N curve in each phase of loading;

$T_i$ is the associated period of the loading.

The alternatives to the above are as follows.

a) In the first case, the assumption is that the pipe should remain in service for the design service life, even if the pipe annulus is flooded. In this case the seawater flooded annulus is considered to be a design case. The fatigue damage is then computed using; $T_{ser} \times d_{fat} \leq 1/\mathrm{FSF}$, with the applicable S-N curves for all potential annuli conditions, including seawater flooded annulus. The seawater-flooded case is usually the most onerous, and if it satisfies the design criterion then no replacement of the riser is required.

b) If the seawater flooded annulus is not specified to be a design case, it is still necessary to perform the fatigue calculation to determine the minimum period available in which to replace the riser. In this case more accurate assessment of the remaining fatigue life after seawater flooding in the case of an otherwise noncorrosive annulus is determined in the below equation. The equation assumes normal operating conditions prior to flooding. It can be modified to calculate the allowable duration to keep an annulus seawater flooded pipe in service ($T_{ser,sw,all}$) as shown.

$$T_{ser,nor} \times d_{fat,nor} + T_{ser,sw} \times d_{fat,sw} \leq 1/\mathrm{FSF}$$

$$T_{ser,sw,all} = \left(1/\mathrm{FSF} - T_{ser,nor} \times d_{fat,nor}\right) / d_{fat,sw}$$

c) A more complex situation occurs when seawater is flushed out of the annulus. The transitional environments may include an initial dry period, corrosive gas dissolved in the seawater flooding, and a reduced rate of fatigue damage after the annulus is flushed with an inert fluid. This situation is more readily handled by $\sum_{i} T_\mathrm{i} \times d_\mathrm{i} \leq 1/\mathrm{FSF}$ adapted to the precise transitional environments of the annulus.

The objective is to determine that the remaining service life with a flushed annulus will satisfy the fatigue criteria.

#### G.5.2.3 Cycle Counting

##### G.5.2.3.1 General

The number of cycles associated with each stress range is required to implement the Palmgren-Miner rule. The number of cycles associated with a given stress range is dependent on the method of global analysis.

##### G.5.2.3.2 Deterministic Analysis

The number of cycles in one year for a stress response based on a regular wave is the number of seconds in one year divided by the period of the wave and multiplied by the yearly probability of occurrence of the wave. Where the analysis includes multiple regular waves, then the period of the dominate wave should be used to derive the number of cycles.

##### G.5.2.3.3 Stochastic Analysis

Timetraces of the stress response from a stochastic analysis should be cycle counted using the Rainflow counting technique per ASTM E1049 [23], or an equivalent method accounting for the probability of occurrence of the particular seastate. This extracts stress ranges with associated number of cycles from the timetrace. An alternative is to cycle count based on the frequency spectrum of the stress using established narrow or wide band methods.

#### G.5.2.4 Stress Concentrations Factors

Generally, for tensile armors a stress concentration factor of 1.0 is used in fatigue analysis. For pressure armors, the stress concentration factor is dependent on the wire geometry. If notching in the wires due to fabrication or corrosion issues is a concern, then this could be addressed in the fatigue analysis by applying an additional stress concentration factor.

#### G.5.2.5 Mean Stress Effects

S-N data for armor wires is generated by either using constant mean stress or constant R-ratio (i.e. min stress divided by max stress).The most commonly used mean stress correction methods are Goodman and Gerber methods.

#### G.5.2.6 Endurance Limits

An endurance limit is defined as an alternating stress range below which no fatigue damage will occur even for an infinitely large number of stress cycles. Endurance limits are often used for armor wire in-air S-N curves. If a given S-N curve has a clearly defined endurance limit, a fatigue analysis can be as simple as assessing if any of the stress ranges occurring are above the specified endurance limit. If none are, the fatigue life can be assumed to be infinite, while if some ranges are above the endurance limit a fatigue life calculation should be undertaken. Before an endurance limit can be used, API 17J requires that it be a documented and verifiable quantity that has been established by testing and approved by purchaser.

Goodman (Haigh) and Gerber diagrams if plotted with an endurance limit curve can be used to assess the fatigue critical alternating stresses for different mean stress ranges. In this instance, these diagrams contain more information than S-N curves as the endurance limit over a range of mean stresses if given as opposed to an S-N curve that only gives a single endurance limit corresponding to the mean stress the S-N curve was generated for.

A constant-life diagram is a generalization of the Haigh diagram and includes stress ranges that are larger than the endurance limit. The lines of constant life on these diagrams should not be interpreted as a series of endurance limits where the fatigue safety factor does not apply.

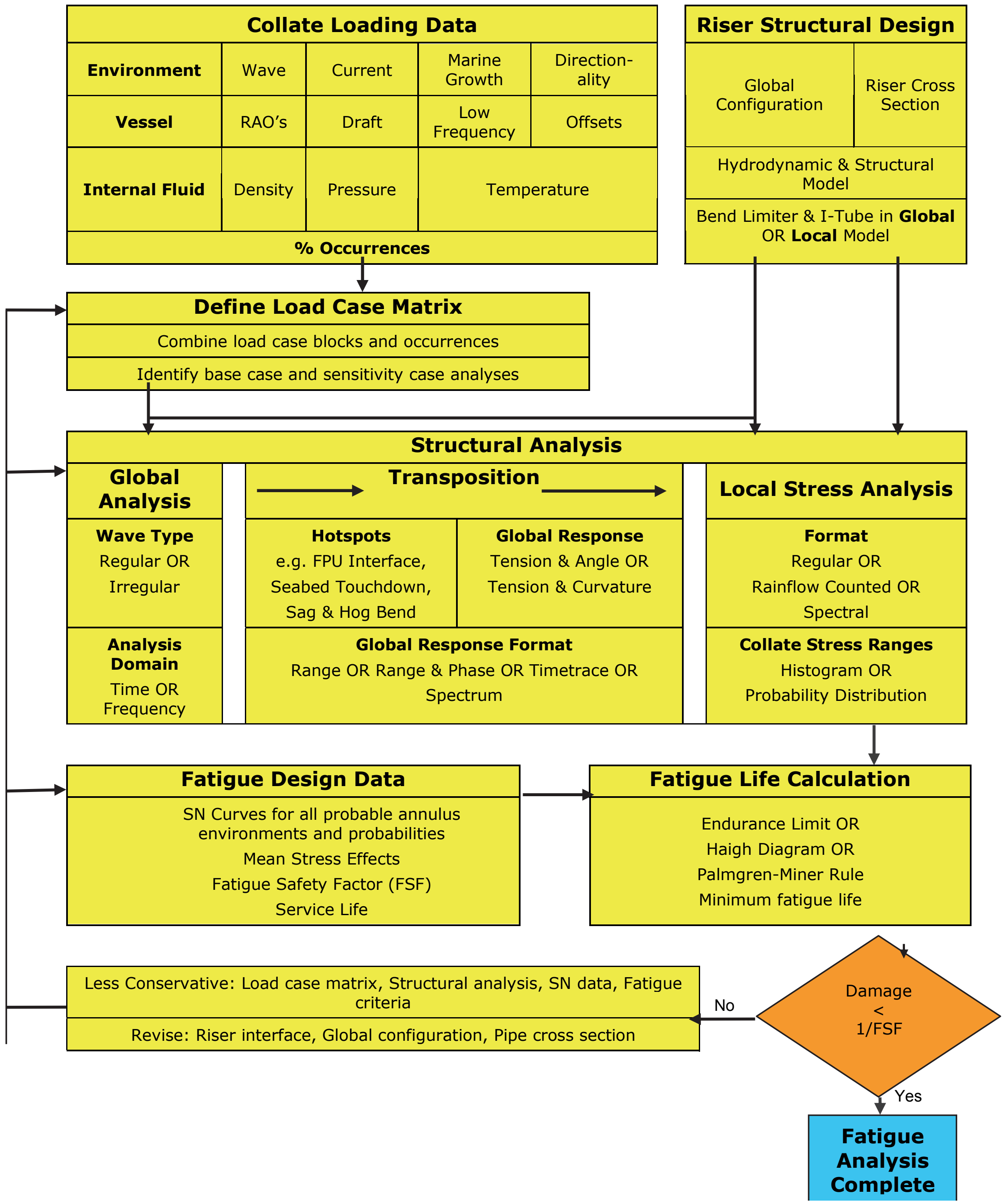



**Figure G.1—Flowchart of Overall Fatigue Analysis Methodology**

# Annex H
(informative)

# Composite Armor for Unbonded Flexible Pipe

## H.1 General

This annex provides recommendations for the application of FRP materials for pressure armor and tensile armor in unbonded flexible pipe. Hereafter, these layers are referred to as composite armor.

Since API 17J specifies that it does not apply to flexible pipe that employs nonmetallic materials for the pressure and tensile armor, this annex is written in order to establish recommendations for modifications to API 17J, including additional requirements, specifically for composite armor. DNV OS-C501 provides guidelines for composite components used in offshore applications. The recommendations for unbonded flexible pipe employing composite armor are based on appropriate principles from API 17J and DNV OS-C501, to ensure safe design, manufacture, installation, and operation for offshore applications.

Each flexible pipe manufacturer may employ different design methodologies, layer materials, and configurations for composite armor and have different levels of field proven experience. Therefore, verification by an IVA that review and certification of the design methodology has been conducted in accordance with API 17J, Section 5.2 is recommended. The IVA should have demonstrated expertise in verification of design of unbonded flexible pipe as well as verification of design of similar FRP reinforced structures for offshore applications. Similar structures might include FRP reinforced umbilicals or tethers.

The requirements for the internal carcass, internal pressure sheath, anticollapse sheath, antibuckling tapes, metallic tensile armor, and pressure armor wires (when included in hybrid flexible pipe designs that include both metallic and composite armor), insulation, and outer sheath for a composite armored unbonded flexible pipe are assumed to be identical to those for a metallic armored unbonded flexible pipe, except as recommended herein. The manufacturer should demonstrate the validity of this assumption in the design methodology documentation.

## H.2 Introduction

With proper material selection and evaluation by testing, FRP may offer a range of beneficial properties for the pressure and tensile armor when compared to steel, including the following:

a) high strength-to-weight ratio,

b) improved fatigue resistance,

c) resistance to corrosion and degradation by most oil field chemicals and seawater.

Note that these characteristics are highly dependent on the composite matrix, reinforcing fibers, temperature, and chemical environment.

FRP is also potentially subject to different failure mechanisms than metallic materials, such as matrix cracking, delamination, and loss of properties due to ageing in service environments. Therefore, due consideration in design, material selection, analysis, testing, qualification, fabrication, and inspection is recommended. Guidelines on addressing these aspects in accordance with DNV OS-C501 are provided herein.

The main potential for use of composite armored flexible pipes is where the weight reduction can be significant compared to steel armored flexible pipes such as deep water or high pressure applications. In addition, composite armored flexible pipe may have advantages in sour or highly corrosive service applications. Service life determination is a less mature technology for FRP than for steel and should be carefully evaluated by the manufacturer based on comprehensive material and full-scale test data.

The reinforcing fibers used in composites can include glass, basalt, polyethylene, carbon, aramid, or other fibers. Often, the reinforcing fibers are orientated parallel to the longitudinal axis of the reinforcing element. The matrix materials used include various thermoset and thermoplastic polymers.

## H.3 Functional Guidelines

The manufacturer should request the operator to provide any additional functional requirements that are not specified in Section 4 of API 17J that may be relevant to the use of composite armor to ensure a safe design and operation of the unbonded flexible pipe employing composite armor.

## H.4 Design Guidelines

### H.4.1 General

The composite armor design analysis should be conducted in accordance with DNV OS-C501. Following is a summary of the recommended principles the manufacturer should follow in design based on the requirements specified therein.

For each composite armor layer, a review of potential failure modes and associated failure mechanisms should be conducted to determine design criteria considering the loads, environment, and temperature the composite armor may experience during installation and operation over the service life of the pipe. The design methodology, material, and product qualification testing should address the potential failure mechanisms. Typical failure mechanisms to consider for unidirectional laminates are provided below as found in DNV OS-C501, Chapter 6, Table A1. The manufacturer should conduct a comprehensive review of Chapter 6 of DNV OS-C501 in order to determine failure modes, failure mechanisms, and design criteria based on their particular design for each composite armor layer as noted in DNV OS-C501, Chapter 2, Section B200 and Chapter 6, Figure 1.

Possible failure mechanisms may include:

— fiber tensile failure;

— fiber compression (buckling);

— matrix cracking;

— debonding and delamination (interlaminar and intralaminar shear);

— elastic or global buckling;

— unacceptably large deformation;

— stress rupture or stress corrosion due to permanent application of loads/aggressive environment as discussed in DNV OS-C501, Chapter 6, Section J400;

— fatigue;

— crack propagation;

— wear;

— impact;

— chemical decomposition, ageing, or other degradation mechanisms;

— environmental stress cracking;

— swelling effects—gas/fluid absorption;

— component failure in compression.

Combinations of failure mechanisms should also be considered in the design methodology, material and product qualification with the associated environments in contact with each material, applied strain/stress, and rate and duration of load application, as applicable. For example, matrix cracking can lead to accelerated fatigue. Matrix cracking in combination with ageing and other degradation mechanisms can further accelerate fatigue.

### H.4.2 Design Methodology Guidelines

It is recommended to use the load resistance factor design method to check each composite armor layer for each load case as discussed in DNV OS-C501, Chapter 2, Section C600:

$$\gamma_{\mathrm{F}} \cdot \gamma_{\mathrm{Sd}} \cdot S_{\mathrm{k}} \leq \frac{R_{\mathrm{k}}}{\gamma_{\mathrm{M}} \cdot \gamma_{\mathrm{Rd}}}$$

where

$\gamma_{\mathrm{F}}$ is the partial load effect safety factor;

$\gamma_{\mathrm{Sd}}$ is the partial load model safety factor;

$S_{\mathrm{k}}$ is the local stress or strain based on characteristic load effect;

$R_{\mathrm{k}}$ is the characteristic resistance;

$\gamma_{\mathrm{M}}$ is the partial resistance safety factor;

$\gamma_{\mathrm{Rd}}$ is the resistance model safety factor.

The guidance note in DNV OS-C501, Chapter 2, Section C605 provides definitions of the partial safety factors.

The load cases for the composite armor layers design check should be defined in accordance with API 17J, Section 5.1, duly supplemented by any additional functional requirements that may be relevant to the use of composite armor to assure safe design and operation of the unbonded flexible pipe employing composite armor.

The design methodology documentation for the composite armor layers should include the following:

— the potential pipe failure modes as a result of the loads;

— the failure mechanisms in the composite armor associated with the pipe failure modes;

— the design equations for pipe failure modes and mechanisms associated with limit states;

— the calculation procedures and software tools used to predict the response of the pipe and composite armor to the loads;

— the characteristic resistance, stiffness specification, and justification based on material testing conducted in accordance with H.5;

— the partial safety factor selection and justification for the composite armor based on DNV OS-C501 requirements;

— the validation of failure modes, failure mechanisms, and calculation procedure and software tool prediction, with tests conducted in accordance with H.5 and H.7.

The recommended design approach noted in DNV OS-C501, Chapter 2, Section D100 for the composite armors should be based on combination of an analytical approach and testing per DNV OS-C501, Chapter 2, Section D400 considering that full-scale component testing is essential to confirm the predictions. Design approach based only on component testing per DNV OS-C501, Chapter 2, Section D100 and Chapter 7, Section B100 is not recommended, to reduce risk in extrapolating the design methodology to new pipe designs, or in using a pipe design that was qualified for one application in another application per DNV OS-C501, Chapter 2, Section D303.

Selection of partial safety factors should consider the following.

a) The ultimate limit state category—recommended for the design analysis per DNV OS-C501, Chapter 2, Section C200.

b) Normal safety class—recommended for nonhydrocarbon conveying applications, such as water injection service per DNV OS-C501, Chapter 2, Section C302.

c) High safety class—recommended for hydrocarbon conveying applications per DNV OS-C501, Chapter 2, Section C302.

d) Brittle failure target reliability levels—recommended per DNV OS-C501, Chapter 2, Section C502.

e) Ductile failure target reliability levels—may be considered per DNV OS-C501, Chapter 2, Section C502.

Additional guidance on partial safety factor selection is provided in DNV OS-C501, Chapter 8.

The characteristic resistance and stiffness should be determined by material qualification testing in accordance with DNV OS-C501, Chapter 4, and take into account material degradation due to combined loads, environments and temperatures experienced by the composite armor over the service life of the pipe. For example, end of life properties should be determined and used for the characteristic values for load cases modeling end of service life load conditions.

The design methodology should account for the effects of progressive failure mechanisms and degradation on the component behavior over the specified service life. Full-scale and component tests should be designed in order to verify the modeling predictions.

Verification of the design methodology should be conducted by the IVA according to API 17J, Section 5.2, duly adapted for the composite materials and further recommendations defined in this annex.

## H.4.3 Additional Requirements

### H.4.3.1 Design Criteria

The pipe structure should be designed to the criteria specified in API 17J, Section 5.3, and the additional criteria specified in this section for composite pressure armor and tensile armor.

The pipe should be designed to take into account that mechanical properties depend on the load conditions and the environment as discussed in DNV OS-C501, Chapter 4, Section A509. Permanent static loads may induce effects on the matrix and fibers, such as creep per DNV OS-C501, Chapter 4, Section C204, stress rupture and static strength reduction per DNV OS-C501, Chapter 4, Section C401, whereas permanent static deformation may have other effects, including stress relaxation and reduction of elastic properties (due to matrix cracks formation or other ageing mechanisms), fatigue failure, and static strength reduction. Also, if applicable, matrix rupture due to shear should be considered in addition to stress rupture of fibers per DNV OS-C501, Chapter 4, Section C306.

The pipe design should demonstrate that the structure will not fail within service life and also that the structure will resist the extreme loads at the end of the service life as discussed in DNV OS-C501, Chapter 4, Sections C103/104. The pipe design should also address the effects of cyclic loads, which may induce the following: reduction of elastic properties (due to the formation of matrix cracks or other ageing mechanisms), fatigue failure (material may lose strength leading to failure after certain time), and short-term static strength reduction (residual strength) per DNV OS-C501, Chapter 4, Sections C105/C500. The effects of the change of material elastic parameters under long-term loads should be considered in the structural analysis for initial and changed stiffness per DNV OS-C501, Chapter 4, Section C111. Furthermore, the pipe design should account for the changes in the modulus of elasticity under cyclic fatigue per DNV OS-C501, Chapter 4, Section C600.

In order to fully demonstrate the compliance with the service conditions, the elastic parameters of the structure should also be analyzed before fatigue damage has taken place and after fatigue damage has taken place as discussed in DNV OS-C501, Chapter 4, Section C604. The analysis should consider, for instance, that fatigue damage may cause changes in the modulus of elasticity and drop of structural capacity. The fatigue methodology should select relevant R ratios for the application so to use proper S-N curves. For such purpose, refer to DNV OS-C501, Chapter 4, Sections C709 to C711.

The manufacturer should demonstrate that the failure mechanisms, characteristic stiffnesses and characteristic resistances selected for the design analyses, and all other functional requirements are satisfied considering the predicted reduction in cross section and any kind of degradation of the structural layers that may be present over the specified service life, such as the mechanisms listed above in H.4.

#### H.4.3.2 Design Requirements for Pipe Layers

##### H.4.3.2.1 Pressure Armors

The pressure armors should be designed for the required hoop strength and should account for the control of gaps between adjacent armor spirals, deformation, and residual stress from the manufacturing process.

##### H.4.3.2.2 Tensile Armors

The tensile armors should be designed for the required axial strength and stiffness. The design should also account for any requirements for torsional properties, control of gaps between adjacent armor spirals, and hoop strength, in particular for pipe designs that do not include pressure armor, and account for deformation and residual stress from the manufacturing process.

##### H.4.3.2.3 Antiextrusion Layer

The antiextrusion layer is a new concept that is intended to enable the use of noninterlocked armor spirals for the pressure armor. Therefore, the design methodology for the antiextrusion layer should be validated by qualification testing that effectively simulates the short- and long-term static and cyclic loading in intact and flooded annulus environments. The antiextrusion layer should assure that the internal pressure sheath and intermediate sheath meets the requirements specified in API 17J, Table 8 considering the following:

a) the maximum gap tolerance between adjacent armor spirals in the reinforcement layer adjacent to the antiextrusion layer,

b) the minimum thickness tolerance of the internal pressure sheath,

c) extension of the gaps between adjacent armor spirals resulting from repetitive bending of the pipe to predicted bend radii over the service life of the pipe,

d) creep and ageing degradation of the antiextrusion layer over the service life of the pipe.

#### H.4.3.3 End Fitting

The end fittings should be designed to the criteria specified in API 17J, Section 5.3.3 and the additional criteria specified in this section for termination of composite pressure armor and tensile armor within the end fitting.

Reference is made to Section 7 of DNV OS-C501 for each manufacturer to consider additional requirements for composite armor termination in the end fitting. The design approach based only on component testing is not recommended as discussed in H.4.2.

The design methodology documentation for the composite armor breakage, anchoring, and composite to metallic force resistant transition sections in the end fitting should include the following:

— the potential failure modes of the composite armor, the anchoring, and transition section as a result of loads at the end fitting;

— the failure mechanisms in the composite armor, the anchoring, and transition section associated with the failure modes;

— the design equations for composite armor breakage, the anchoring, and transition section associated with limit states;

— the calculation procedures and software tools used to predict the response of the composite armor anchoring and transition section to the loads;

— the characteristic resistance and stiffness selection and justification based on material and component testing conducted in accordance with H.5;

— the partial safety factor selection and justification for the composite armor based on DNV OS-C501 requirements;

— the validation of failure modes, failure mechanisms, and calculation procedure and software tool prediction, with tests conducted in accordance with H.5 and H.7.

Degradation, delamination, or matrix cracking of armor layers at the end-fitting interface should not cause damage to any sealing barrier or locking mechanisms.

API 17J, Table 10 only applies to the metallic pressure containing and load bearing components in the end fitting. Composite tensile armor breakage and anchoring failure mechanisms and design criteria should be based on DNV OS-C501 principles. Particular attention should be paid to evaluating the potential for matrix cracking, delamination, and debonding due to tensile armor bend back for installation of the end fitting. Changes to characteristic properties and fatigue resistance, e.g. as a result of tensile armor bend back, considering the end-fitting annulus environment should be evaluated over the specified service life.

#### H.4.3.4 Service Life Analysis

##### H.4.3.4.1 General

The service life analysis should be conducted in accordance with API 17J, Section 5.3.4 and the additional criteria specified in this section for composite pressure armor and tensile armor.

For annulus flooded with seawater conditions, the effect of degradation of composite components in the annulus should account for permanent contact with water of appropriate salinity and corrosive gas ingress rate.

#### H.4.3.4.2 Service Life—Dynamic Applications Only

If splices of the composite pressure and tensile armor cannot be avoided in the fatigue-critical areas (e.g. hangoff and touchdown areas), then these splices should be validated for the fatigue loads expected at the locations of the splices. Characteristic resistance values should take into account splices. Such validation can be achieved by testing of spliced samples to confirm the fatigue performance assumed in the design or by developing S-N curves for spliced composite armor for the same annulus conditions.

#### H.4.3.4.3 Fatigue Analysis of Composite Armor in the End Fitting

The fatigue analysis should account for changes in composite armor properties, residual stresses and stress concentrations, and composite armor deformation due to the mounting process.

The design methodology should consider composite armor geometry, e.g. fish-scaling, inside the end fitting, if applicable.

## H.4.4 System Design Requirements

### H.4.4.1 General

The composite armored flexible pipe should meet the system design requirements specified in API 17J, Section 5.4, and the additional requirements specified in this section.

### H.4.4.2 Cathodic Protection

Composite reinforced flexible pipes may not have electrical continuity to provide a conductive path for cathodic protection. Therefore, anodes may need to be applied only to end fittings, and impressed current systems may require an electrical conductor to be incorporated into the flexible pipe structure.

Where electrically conductive materials (such as carbon) are employed for the reinforcement, care should be taken to avoid electrical continuity between the reinforcement and any metallic layer to prevent galvanic corrosion, unless it can be demonstrated that galvanic corrosion will not occur.

# H.5 Materials

## H.5.1 Material Requirements

### H.5.1.1 General

The material requirements should be in accordance with API 17J, Section 6 and the additional requirements specified in this section for antiextrusion, composite pressure armor, and tensile armor materials, as delivered to the pipe manufacturer by suppliers and subject to manufacturing processes employed by the manufacturer.

### H.5.1.2 Composite Pressure and Tensile Armor

The manufacturer should document the properties of the material for the composite armor as specified in Table H.1 that define the prequalified range and combination of exposure conditions for each of the armor materials used for the antiextrusion layer, pressure armor, and tensile armor. The composite materials used for the pressure and tensile armor may be unidirectional laminates or another material family described in DNV OS-C501 Chapter 4, Section A402. Chapter 4 of DNV OS-C501 defines material property requirements for laminates to be used in offshore composite components. The materials testing requirements outlined herein are typical for unidirectional laminate materials. If the material is not a unidirectional laminate, then other material qualification requirements may need to be considered. The material tests should be conducted on armor sections that are representative of those used in the design and manufacture process of the composite armored flexible pipe. Samples should also be tested to assure that the design complies with the partial safety factors for the last day of the component service life considering all potential degradation mechanisms.

**Table H.1—Typical Property Requirements for Composite Materials**

| Characteristic | Tests and Properties | Pressure and Tensile Armor (1) (5) (6) | Antiextrusion Layer |
|---|---|---|---|
| Mechanical/physical properties (7) | Tensile properties (ultimate strength/strain, Young's modulus, Poisson's ratio in principal directions needed for analysis), including splices if any | X | X |
| | Shear properties (strength and modulus) | X | |
| | Flexure test (strength and modulus) | X | |
| | Compression properties (ultimate strength/strain, Young's modulus, Poisson's ratio in principal directions needed for analysis) | X | |
| | Wear resistance (with antiwear layer) | X | |
| | Density | X | X |
| | Fracture toughness | X | |
| | Fatigue, including fatigue of splices where applicable (3) (7) | X | |
| Loss of strength under constant load in environment | Creep resistance and stress rupture test | X | X |
| Thermal properties | Coefficient of thermal conductivity | X | O |
| | Coefficient of thermal expansion | X | |
| | Heat capacity | X | O |
| | Glass transition temperature (7) | C | |
| Permeation characteristics | Fluid permeability | X (2) | X (2) |
| Compatibility and ageing | Fluid compatibility (7) | X | X |
| | Ageing tests (4) | X | X |
| | Water absorption (7) | X | — |

NOTE 1 X (required for design), C (comparative, cannot be used directly for design), O—optional.

NOTE 2 Only required if masking by the antiextrusion layer and composite armor is considered in the permeation analysis.

NOTE 3 Fatigue testing for pressure and tensile armor should be conducted in simulated flooded and intact annulus environments, as well as aged and degraded samples.

NOTE 4 The effect of ageing in annulus environments and temperatures on tensile properties, compression strength, and flexure strength of splices and adhesives should be evaluated.

NOTE 5 Conduct tests to evaluate effects of combined failure mechanisms and ageing, as discussed in H.5.1.2.

NOTE 6 Conduct tests to evaluate the effect of tensile armor bend back for end-fitting installation on characteristic properties and fatigue resistance.

NOTE 7 The effect of composite armor splices, splice frequency, and positioning in each of the composite armor layers should be comprehensively evaluated. The evaluation should consider the effect of degradation of the splice over the service life in each layer per Note 4. The evaluation could be a combination of analysis, materials tests, and small-, medium-, and full-scale tests. The evaluation should be included in the design methodology, material qualification, or pipe qualification documentation.

Mechanical/physical property tests should be carried out on unaged as well as on aged materials as diffusion of annular fluids into the matrix material and into the matrix/fiber interface may have a profound impact on the ultimate material properties. This is especially true when it comes to compressive tests where a weakened matrix may lead to fiber buckling.

Tests should be conducted to evaluate appropriate failure mechanism combinations, based on the failure mode and mechanism analysis. Test protocols should consider sequencing cyclic loading with ageing in the intact or flooded annulus environments, as expected over the service life.

Changes in characteristic properties used in analysis due to combined failure mechanisms and ageing over the service life should be determined in the material qualification program.

## H.5.2 Testing Requirements

### H.5.2.1 General

#### H.5.2.1.1 Test Requirements

The physical, mechanical, chemical, and performance characteristics of the antiextrusion, composite pressure armor, and composite tensile armor should be verified by the manufacturer through a documented test program. The program should confirm the adequacy of each material based on test results and analysis that should demonstrate the suitability of the material for the specified service life of the flexible pipe. Test procedures listed in Table H.2 should be used to determine the properties specified in Table H.1. If the test method is not specified in Table H.1, guidance should be obtained from DNV OS-C501 or the manufacturer may use its own methods, subject to the requirements of H.5.2.1.3. The qualification of materials by testing should consider all processes (and their variation) adopted to produce the pipe that can impair the properties and characteristics required by the design. If qualification tests cannot be carried out on processed materials, the manufacturer should justify in the documented qualification program why the selected material provides equivalent characterization as the processed material. Use of nonprocessed materials should be subject to IVA or purchaser approval.

#### H.5.2.1.2 Applicability

Only materials with identical specified chemistry and material manufacturing process (e.g. heat treatment, cold forming, etc.), as used in the qualification testing, should be regarded as qualified.

Documented operational experience may be accepted as verification of long-term properties in environments that are equal to or less severe than the documented experience. The environmental factors considered for composite materials should include temperatures, strains, pressures, concentrations of water, aromatics, alcohols, $H_2S$ and $CO_2$, UV exposure, acidic conditions (lower pH or higher TAN), and other annulus environment conditions deemed by the manufacturer or purchaser to be detrimental.

#### H.5.2.1.3 Test Methods

The test methods should be as specified in Table H.2. Where test methods are not specified, the manufacturer may use their own methods and/or criteria or alternative methods developed by the raw materials supplier. In such cases, the methods and/or criteria should be documented and the results correlated with the specific material application. Where test methods are specified but alternative methods are preferred to be followed, the manufacturer should justify in the documented qualification program why the alternative methods used provides equivalent or better characterization than the specified test methods. Nonstandard test methods should be verified by an IVA or approved by the purchaser.

NOTE Use of equivalent ISO or ASTM standard test procedures does not require justification.

### Table H.2—Test Procedures for Composite Armor and Antiextrusion Layer Materials (1)

| Property/ Characteristic | Parameter | Test Procedure (1) (3) | | Comments (2) |
|---|---|---|---|---|
| | | ISO or Section Number (2) | ASTM (2) | |
| Mechanical/ physical properties | Resistance to creep, stress rupture, and stress corrosion | ISO 899-1 | ASTM D2990 | Testing should be conducted in simulated annulus environments and predicted annulus temperature range |
| | Tensile properties | | ASTM D3039 | Aged and unaged material<br>Variance with temperature should be evaluated |
| | Shear properties | | ASTM D5868 | |
| | Compression properties | | ASTM D6641/D1621 | |
| | Flexure properties | | ASTM D7264 | |
| | Abrasion resistance | 7.1.2.6 | | Wear resistance between antiwear layer and composite armor with contact pressure, relative movement, temperature, and annulus environment to be evaluated |
| | Density | ISO 1183 (all parts) | ASTM D792 | Or ASTM D1505 |
| | Fatigue | | ASTM D3479 | See H.5.2.1.5 |
| | Fracture toughness | | ASTM D5528 or ASTM D6671 | To determine acceptable defect size and configuration |
| Thermal properties | Coefficient of thermal conductivity | ISO 8301 or 8302 | ASTM C177 or ASTM C518 | |
| | Coefficient of thermal expansion | ISO 11359-2 | ASTM E831 | — |
| | Heat capacity | ISO 11357-1<br>ISO 11357-4 | ASTM E1269 | — |
| | Glass transition temperature | — | ASTM D4065 (DMA) or ASTM D7426 (DSC) | Aged and unaged material |
| Permeation characteristics | Fluid permeability | 7.2.3.1 | — | As a minimum to $CH_4$, $CO_2$, $H_2S$, methanol, and $H_2O$ where present. ISO 2556 may be considered as an alternative. Only required if the composite armor is considered as masking the internal pressure sheath in permeation calculations |
| | Fluid compatibility | 7.2.3.3 | — | — |
| | Ageing tests | 7.2.3.4 | — | — |

| Property/ Characteristic | Parameter | Test Procedure (1) (3) | | Comments (2) |
|---|---|---|---|---|
| | | ISO or Section Number (2) | ASTM (2) | |
| | Water absorption | 7.2.3.5 | | Guidance can be found in ISO 62/ASTM D570 |

NOTE 1 See DNV OS-C501, Section 4 for additional guidelines in developing the material qualification test program.

NOTE 2 Section numbers are per API 17J. For the purposes of the requirements for the listed test, the ASTM reference(s) listed is/are equivalent to the associated ISO international standard, where one is given. Example: For the purposes of the procedure for the resistance-to-creep test, ASTM D2990 is the equivalent of ISO 899-1.

NOTE 3 Where test methods are not specified, such as for combined failure mechanisms, the manufacturer may use their own methods as per the requirements of API 17J, Section 7.2.1.4.

Test procedures listed in Table H.2 should be used to determine the properties specified in Table H.1. For test program planning, special attention should be given to evaluating mechanical property changes over time due to the load conditions and the environment experienced by the composite armor over the service life. Refer to H.4.2 for examples of relevant aspects to be taken into account in the test program preparation.

#### H.5.2.1.4 Ageing Tests

The manufacturer should have verified ageing models for each composite armor material in the flexible pipe, where applicable. The models should be based on laboratory testing and field experience, if available. These models should predict the deterioration of the composite armor under the influence of relevant annulus environmental and load conditions.

The ageing models may include accumulated damage concepts based on blocks of time or operational cycles of temperature/pressure under different exposure conditions. Ageing may be determined by change in either specified mechanical properties or in specified physico-chemical characteristics, which may include reduction in the plasticizer content of the material and uptake of constituents from the fluid environment. Ageing tests and models should consider all conditions and combination of conditions that may be relevant for the long-term performance of the composite armor for the defined operation. Relevant conditions will be annulus fluid composition, temperature, and pressure. In addition to chemical degradation, the ageing tests and models should also, depending on the type of material, address other effects such as deplasticization, fluid absorption, and dimensional stability. Mechanical loads and possible confinement should be taken into consideration where relevant.

For antiextrusion layer materials, the assessment of ageing should include the effect of temperature and annulus environment.

The fluid used in ageing-resistance tests should be representative of the annulus environment fluid. Materials that are tensile- or compressive-loaded in service should be tested with similar stresses induced.

#### H.5.2.1.5 Fatigue Resistance

For dynamic applications, composite armors should be subjected to the following testing and evaluation or equivalent documentation provided. Specimens should retain as received surface condition. The effect of manufacturing process including end-fitting mounting should be documented. In particular, testing should supplement and validate analyses conducted to evaluate stress concentrations and fatigue resistance of the tensile armor anchoring in the end fitting. It is recommended to conduct fatigue testing with both aged and unaged samples to evaluate the effect of combined ageing and fatigue failure mechanisms.

S-N data should be documented, justified or generated for the following test environments:

a) exposed to air, at atmospheric pressure and ambient temperature and maximum operating temperature;

b) exposed to seawater (minimum 3 % NaCl), at atmospheric pressure and either ambient or maximum operating temperature, whichever results in the most severe fatigue damage in Item a);

c) exposed to the predicted intact annulus environment inclusive of $H_2S$, $CO_2$, and condensed water levels for relevant transported fluids at atmospheric pressure and either ambient or maximum operating temperature, whichever results in the most fatigue damage in Item a).

NOTE 1 Refer to ASTM E739-91 for recommendations on the number of samples to be used to generate S-N data.

NOTE 2 The proposed standard ASTM D3479 for conducting fatigue tests is tension-tension loading in order to avoid compressive loading. Significant compression loading can cause premature failure due to fiber buckling. The standard is relevant only if the composite armor is not subject to fiber buckling in riser sections subject to fatigue loading under operating conditions. In tension-tension fatigue testing, environment can be challenging to reproduce on the test sample due to the requirement for dynamic seals. The manufacturer may propose alternatives to the operator and IVA, such as the use of low volatility acids to reproduce pH levels resulting from $CO_2$ and $H_2S$ presence in the annulus environment, or other demonstration that environmental degradation does not accelerate fatigue damage.

## H.5.3 Quality Assurance Requirements

### H.5.3.1 General

All antiextrusion and composite armor materials used in flexible pipe should be purchased in accordance with either a written material specification or an industry standard. The specification should include measurable physical, mechanical, chemical, and performance characteristics and tolerances.

All suppliers to the manufacturer should have a documented quality assurance system.

As a minimum, base materials should be certified to ISO 10474:1991, Certificate 3.1 (EN 10204:2004, 4.1). Base materials should be tested in accordance with the requirements specified in Table H.3. Test results should be recorded on material test certificates.

Test results should conform to the manufacturers' specifications. The results of all tests made by the manufacturer and/or suppliers should be available for review by the purchaser.

Requirements and criteria for surface condition of composite armor materials should be established and documented by the manufacturer. As a minimum, the composite armor materials should have a surface finish free from defects that exceed the acceptance criteria set by the manufacturer and documented in the manufacturing quality plan or fabrication specification.

### H.5.3.2 Documentation Requirements

The manufacturer's written specifications for polymer, composite, and metallic materials should include, as a minimum, the requirements of Table H.4.

### H.5.3.3 Storage

The manufacturer's quality plan should show procedures for handling, storage, and control of raw materials, which reflects the importance of material cleanliness, dryness, purity, and traceability during each stage of manufacture.

All raw polymer material should be protected from contamination and water ingress during handling and storage. Contaminated material should be rejected.

### H.5.3.4 Traceability

Materials should be traceable and suitably marked for easy identification.

**Table H.3—Minimum Raw Material Quality Control Test Requirements**

| Material | Test | Frequency | Comments |
|---|---|---|---|
| Polymers | Viscosity | One per batch (1) | Sheath material (PA-12 and PA-11 only); ISO 307 (2) procedure |
| | Extractables | One per batch | Applies to plasticized materials only |
| | Impurities | One per batch | Sheath material (3) (with exception of pigmented plastics) |
| | Density | One per batch | Sheath material (polyethylene only); ASTM D1505 procedure |
| | Melt flow index | One per batch | Sheath material; ISO 1133/ASTM D1238 procedures |
| Metallic wires and strips | Chemical composition | One per batch | All wires and strips |
| | Tensile test | Two per coil (4) | All wires and strips |
| | Bend test | Two per coil | All wires and strips |
| | Hardness test | Two per coil | All wires and strips |
| | Dimensions | Two per coil | All wires and strips; start and end of coil (ASTM A480 procedures for strip) |
| End fittings | Chemical composition | One per heat (5) | Body material |
| | Tensile test | Two per heat | Body material |
| | Charpy V-notch | One set per heat | Body material; subject to 6.2.5.1.4 and 6.2.5.1.5 |
| | Hardness test | One per heat | Body material; subject to 6.2.5.1.6 |
| | Radiography | One | Welded neck only |
| | Ultrasonic | One | Body material |
| | Magnetic particle or liquid penetrant | One | Carbon and low-alloy steel surfaces |
| Antibuckling layer material | Tensile test | One per batch | |
| | Linear weight | | For fiber material only |
| Epoxy | Compression test | — | See 7.6.4.2 |
| Composite armor materials | Volume contents of fiber and polymer matrix, void volume content | Statistically valid to 3σ for the entire lot/batch. | All armor materials |
| | Tensile test | | |
| | Compressive test | | |
| | Density | | |
| | Onset glass transition temperature (Tg) of the composite by dynamic mechanical analysis or differential scanning calorimetry | | |
| | Dimensions | | |
| Antiextrusion | Tensile test | Statistically valid | |

| | | | |
|---|---|---|---|
| layer materials | Dimensions | to 3σ for the entire lot/batch. | |

NOTE 1 Only a measurement of viscosity or melt flow index, but not both, is required.

NOTE 2 For the purposes of this provision, ASTM D2857 is equivalent to ISO 307.

NOTE 3 Pigmented plastics cannot be evaluated for impurities.

NOTE 4 A coil is a continuous length of wire from the same forming process, cast, and heat treatment batch. Slitting of mother coils does not change mechanical properties so slit strip does not require further mechanical testing after certification of the mother coil. If intermediate welds used to join coil sections for transport have been validated by the subcontractor in accordance with the manufacturer's procedures, these welds may be kept during winding onto the pipe. If these welds have not been validated, they should be cut out of the coil during the winding of the pipe.

NOTE 5 Per heat refers to heat treatment batch.

**Table H.4—Requirements of Material Specifications**

| Requirements | Metallic Material | Polymer Material | Composite Material |
|---|---|---|---|
| Material composition requirements, with tolerances | X | — | X |
| Generic base polymer (in accordance with ASTM D1418) | — | X | — |
| Physical and mechanical property requirements | X | X | X |
| Allowable melting and forming practices | X | — | — |
| Heat treatment procedures | X | — | — |
| Storage and age control requirements | X | X | X |
| NDE requirements | X | X | — |
| Acceptance and/or rejection criteria | X | X | X |
| Certification and records requirements | X | X | X |
| Marking, packaging, handling, and traceability requirements | X | X | X |

## H.6 Manufacturing Requirements

### H.6.1 Quality Assurance Requirements

#### H.6.1.1 General

The composite armor flexible pipe manufacture should be in accordance with the requirements of API 17J, Section 7, and the additional requirements specified in this section for composite pressure armor and tensile armor.

The supplier of composite armor materials and the flexible pipe manufacturer should review and consider the requirements specified in DNV OS-C501, Section 11 for fabrication of composites in defining additional manufacturing, process control, and quality assurance requirements. Splicing should be considered as a "special process" for which the manufacturer should maintain documentation on the qualification for review by the purchaser or a mutually agreed IVA.

#### H.6.1.2 Process Control

The antiextrusion and composite tensile and pressure armor manufacturing process should be subject to inspection. The manufacturer's quality plan should specify inspection points, inspection methods, and acceptance criteria. Results of all inspections should be recorded. The manufacturer should record every nonconformance verified during manufacture of the layers. All manufacturing nonconformance reports and actions adopted to correct it should be available for review by the purchaser and included in the as-built documentation; see API 17J, Section 8.8. Process control should be performed as a minimum for the following manufacturing process as applicable:

a) composite pressure armors: preparation of armor tape, feeding of pipe, winding of pressure armor and adhesive application, tape splicing, and coil reeling;

b) composite tensile armor: preparation of armor tape, feeding pipe, winding of armor and adhesive application, tape splicing, application of tape, and coil reeling;

c) end fittings: mounting process, preparation and temporary deformation of the armor laminates, resin injection, and cure;

d) antiextrusion layers: preparation of tapes, winding and placement, splicing.

For each manufacturing condition that is outside the qualified manufacturing procedure, qualified engineering personnel should assess and justify corrective actions and define objective acceptance criteria.

During manufacture, the manufacturer should take measures to ensure that all measurements are within manufacturer's tolerances.

## H.6.2 Pressure and Tensile Armor Layers

### H.6.2.1 General

Manufacturer should have documented procedures for the application of the pressure and tensile armor layers onto the pipe, which should ensure that the armor spirals are laid to the design requirements. The procedures should include requirements for the condition of the armor spirals prior to winding and for the condition of the finished layer, such that the layer and underlying or overlying layers meet the manufacturer's specifications.

The procedures should specify all parameters and allowable tolerances that are to be monitored and recorded at intervals verified by the manufacturer to be acceptable. The recorded values should conform to manufacturer's specifications. As a minimum, diameter and pitch (for lay angle) should be measured, as well as the circumference of the pressure and tensile armors and gap between adjacent armor spirals in order to ensure that the pitch is within the tolerances (in order to avoid any future pressure armor gap opening above the design value or increases in stress concentration). During the production run pressure and tensile armor should be checked against fish-scaling that exceed allowable tolerances.

All splices should be staggered along the length of the pipe in conformance with the manufacturer's specifications, which should specify a minimum separation between splices.

Splices on the pressure armor spirals should be avoided in the fatigue critical areas (e.g. hangoff and touchdown areas).

### H.6.2.2 Inspection and Acceptance Criteria

The pressure and tensile armor layers should be visually examined in accordance with the requirements of H.6.2.2.

The outside diameter, pitch (or lay angle), ovality, and the circumference (to check the gap between pressure armor and internal pressure sheath) of the pressure armor should be measured and recorded at least every 10 m for the first 50 m and subsequently at intervals verified by the manufacturer to be acceptable and during each stop/reversal cycle. Diameter measurements should take due account of the effects of ovality on the measured diameter. The results should be within the tolerances specified in H.6.8. Armor layers should be additionally inspected for wires on edge, fish-scaling, and wire twist.

### H.6.3 Antiextrusion Tape Layers

#### H.6.3.1 General

The manufacturer should ensure that antiextrusion tapes are applied in accordance with documented procedures. The procedures should include requirements for control and monitoring of tape application and should document acceptance criteria for flaws.

#### H.6.3.2 Inspection and Acceptance Criteria

The external surface of the antiextrusion tapes should be visually examined over the entire length for flaws, including damage, distortion, folds, and lack of interlock (for profiled insulation strip). Identified flaws should conform to the manufacturer's specifications.

The outside diameter should be measured and recorded. The pitch and width (between adjacent layers) of antiextrusion layers should be measured and recorded during setup and at each stop for change. These measurements should be subsequently verified at intervals by the manufacturer to be acceptable. The results should be within the tolerances specified in H.6.8.

### H.6.4 Processes Requiring Validation

#### H.6.4.1 Splicing

##### H.6.4.1.1 Validation

All splicing operations should be performed by qualified personnel in accordance with the manufacturer's approved procedures. Splicing procedures, splicing qualification records, and personnel qualifications should be documented and should be available for review by the purchaser. Splicing procedure validation should be witnessed and approved and records of personnel qualification should be reviewed by an IVA who is qualified to witness and approve the standards and criteria being used. The purchaser should have the option of witnessing the validation of all splicing procedures and the qualification of all personnel and should be given appropriate notice of the timing by the manufacturer. Procedures should include acceptance/rejection criteria.

As a minimum, qualification testing for spliced antiextrusion, pressure, and tensile armor layers should include visual inspection and five tensile tests each on spliced and unspliced armor sections. The splice configuration for qualification test samples should be the same as the splice configuration to be used in the manufacturing process. Where the armor spiral is a unidirectional laminate, the splice configuration should be qualified for variations in tape thickness and number of tapes. The splice tensile test results should have an ultimate tensile value equal to or greater than the minimum acceptable splice tensile value established by the manufacturer for the design application. Minimum tensile values should be included in the splice procedure specification. Ageing tests should be conducted on spliced samples.

The manufacturer should have documented procedures for storage, handling, and drying of splicing consumables.

##### H.6.4.1.2 Antiextrusion and Armor Layers

Every time there is a change in splicing machine setup, a minimum of two test splices should be made to verify the setup. The samples should be made to the same standard and techniques used in production. The sample splices should be subjected to the following tests as a minimum:

a) tensile strength,

b) 100% visual examination.

Results from all tests should be documented and should be within the manufacturer's specifications.

Production splices should exhibit a smooth surface across the full strip width and the tapes should be in line. Thickness should be maximum 1 mm (0.04 in.) above the surface, or as otherwise defined in the manufacturing specification and justified in the design methodology documentation. All splices should be smooth to prevent damage to overlying and underlying layers.

Splices used for armors should be subjected to 100 % visual examination.

### H.6.5 Manufacturing Tolerances

The manufacturer should document the tolerances to be used for each antiextrusion and composite armor layer of the flexible pipe. These tolerances should be verified in the design process to be acceptable, such that the functional requirements of the individual layers and pipe are unaffected by variations within the specified tolerances and changes in uses are in accordance with API 17J, Section 5.2. As a minimum, tolerances should be specified for the following parameters:

a) pressure and tensile armors: external diameter, pressure armor ovality, pitch (or lay angle), and fish-scaling;

b) tensile armors: external diameter, pitch (or lay angle), and fish-scaling;

c) antiextrusion tapes: pitch (or lay angle) and overlap (between adjacent layers).

For pipes without pressure armor, the manufacturer should demonstrate that tensile armor gaps are controlled such that the design requirements are met. For pipes with noninterlocked pressure armor, the manufacturer should demonstrate that the pressure armor gaps are controlled such that the design requirements are met.

## H.7 Qualification Testing

The guidelines on the requirements for prototype testing in Chapter 6 of this document apply to unbonded flexible pipe with composite armor. Additional guidelines are provided below. Chapter 10 of DNV OS-C501 provides recommendations for additional testing which may be relevant to the composite armor.

The manufacturer should define the qualification test program to assure that the analysis methods based on the failure mechanisms identified per H.4 are validated. Additionally, composite armor related potential failure modes involving multiple layers and their combined behavior should be addressed and accounted for in the qualification test program.

Nondestructive examination (NDE) and appropriate sensors should be used during prototype testing to verify that applied loads result in deformations and failure mechanisms as predicted in the design methodology.

End-fitting anchoring system should be tested against static and fatigue loads. For the end-fitting qualification, the strain/stress under static and cyclic loads should be measured. NDE should be used to inspect the laminates against matrix cracking during the end-fitting mounting in the sample to be used in the full scale dynamic test of the end fitting. NDE or destructive examinations may also be considered for matrix crack detection after sample is subjected to fatigue test to simulate the service life related part of the test. Smaller scale end-fitting anchoring tests might be considered in lieu of these examinations if it can be demonstrated that the tests are representative of the design and loading in a full scale test and in service. The results of the examinations should be used to validate the end-fitting design methodology, in particular with regard to H.4.3.

The effect of creep and material degradation of the composite armor over the service life should be considered in developing the qualification test program.

It may be desirable to conduct small-scale and midscale tests to simulate the loading experienced on individual pipe layers and confirm the deformations and failure mechanisms compare favorably with the analytical models.

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