

Recommended Practice for Flexible Pipe

API RECOMMENDED PRACTICE 17B
FIFTH EDITION, MAY 2014

REAFFIRMED, MARCH 2021



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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 H₂S-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;

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 deformation.

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:

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

where $D_{\max}$ and $D_{\min}$ 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 H₂S 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 H₂S 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_D	hydrodynamic drag coefficient
C_m	hydrodynamic inertia coefficient
σ_u	material ultimate stress
σ_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 H₂S 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.).

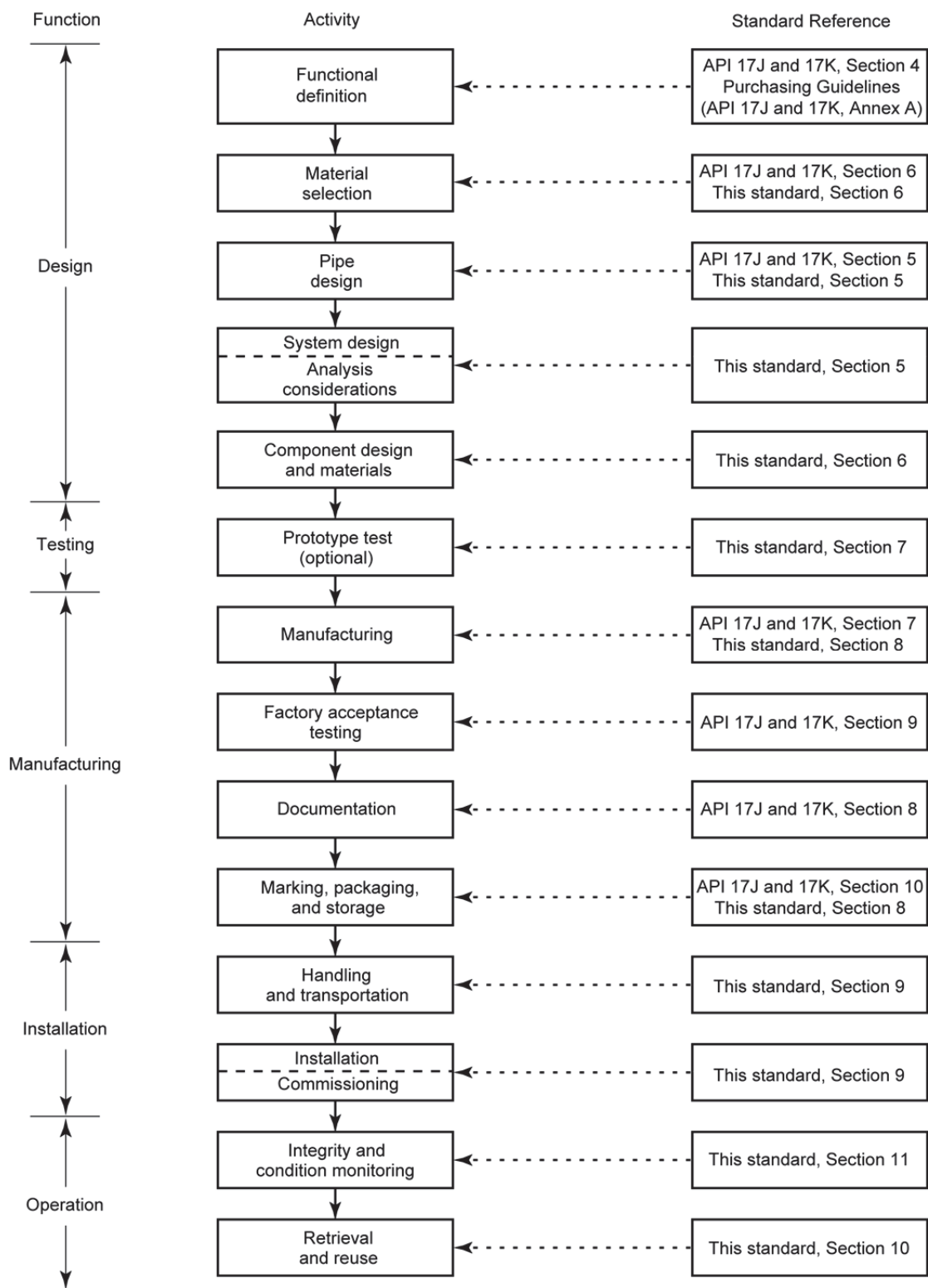


Figure 1—Flexible Pipe Overview

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)

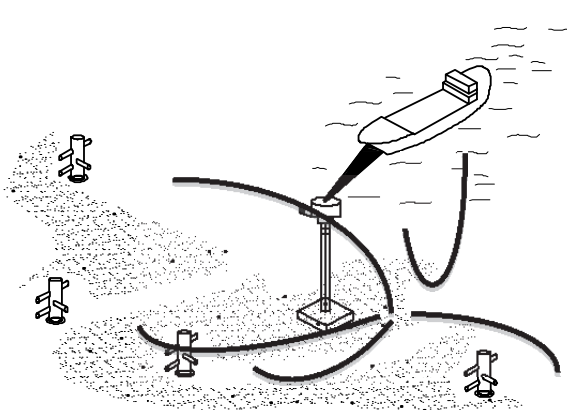
SAs of flexible pipe primarily include flowline and fixed jacket riser service. Flexible pipe is used in these applications to simplify design or installation procedures or for the inherent insulation or corrosion-resistant properties. In addition, reduction of installation and end connection loads and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

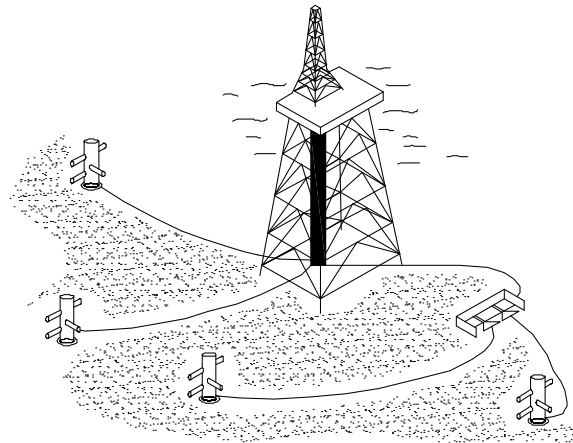
- a) subsea flowline end connections where expensive or difficult operations, such as exact orientation measurements for spool pieces or the use of large alignment equipment to reposition the flowline, can be eliminated;
- b) situations involving gross movements and damage to flowlines because of mudslides 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.

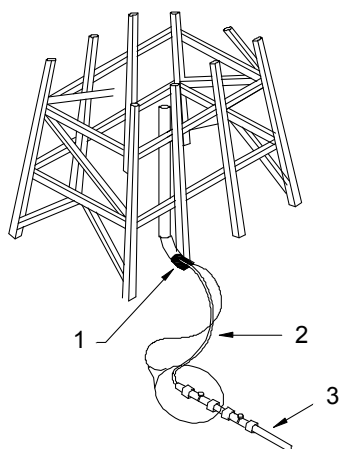
The functional requirements of a flexible pipe flowline are generally the same as for a steel pipe flowline. Significant dynamic loading or motions are generally not experienced, so the flexibility properties of flexible pipe simplify the project transport and installation phases.



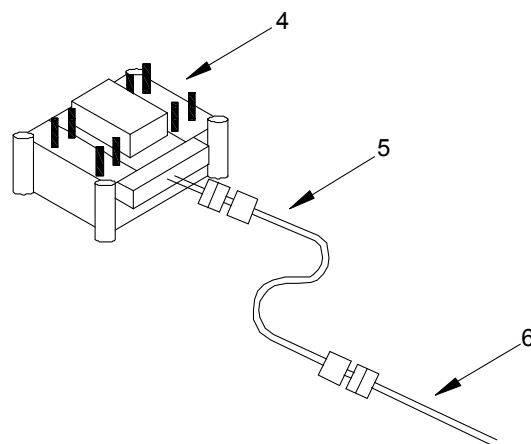
a) Early Field Production Scheme



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.

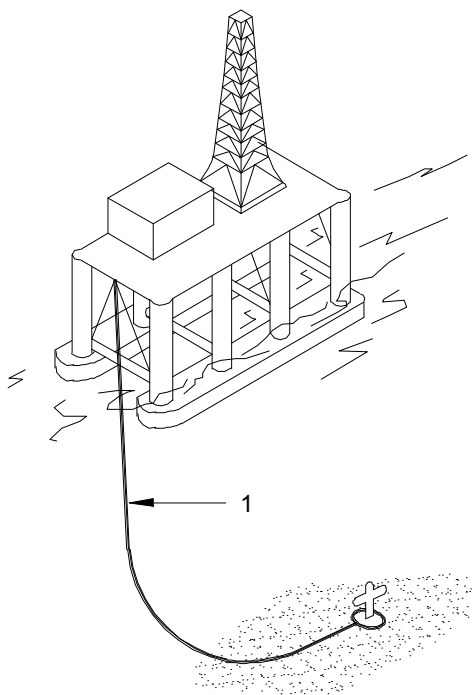
The functions of dynamic jumpers (excluding internal turret lines) are similar to riser systems. Their operation, however, is somewhat different. Jumpers are generally more exposed to wave loading, and the configuration varies between the connected condition and the standoff condition. This loading imposes 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

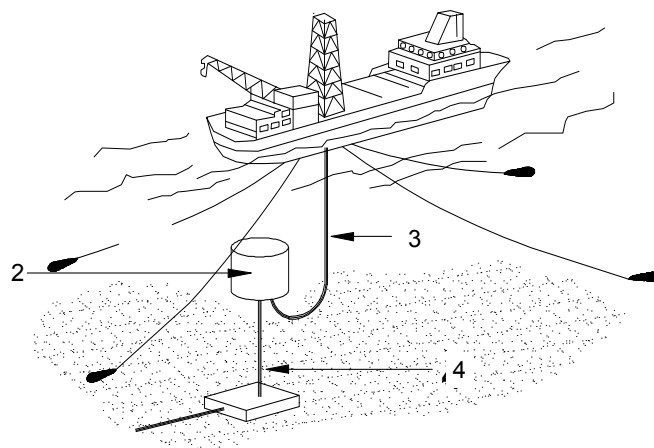
4.3.1 General

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.

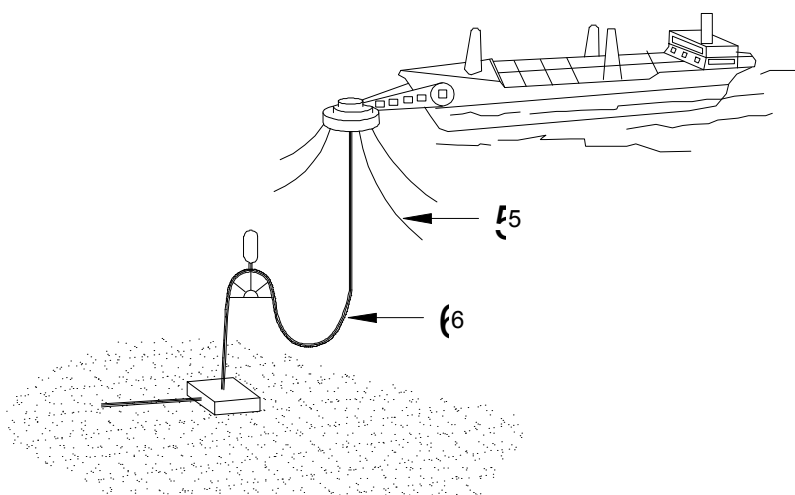
A flexible pipe generally combines low bending stiffness with high axial tensile stiffness, which is achieved by a composite pipe wall construction. This is more applicable to unbonded rather than bonded flexible pipe. The two basic components are helical reinforcement layers and polymer sealing layers, 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

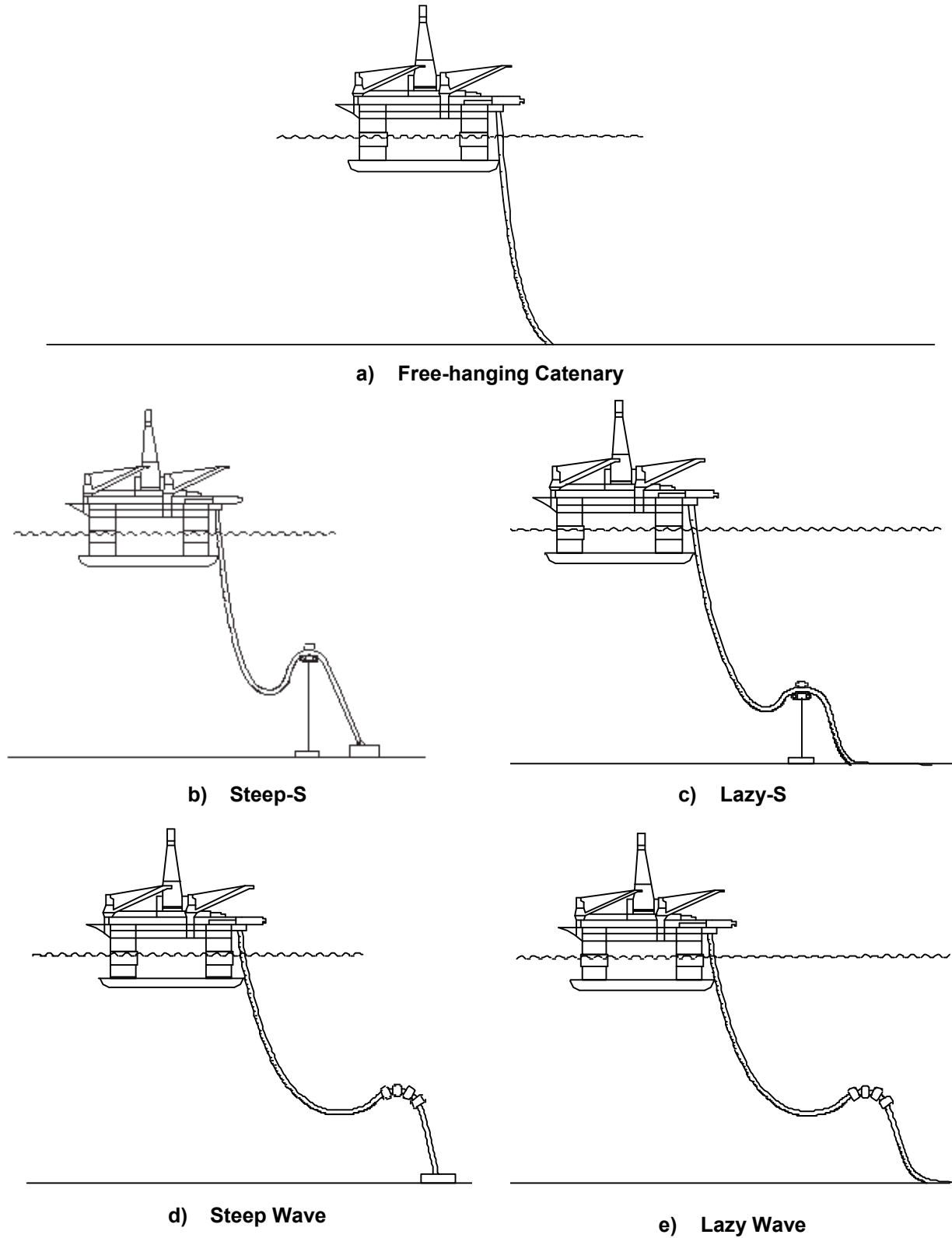
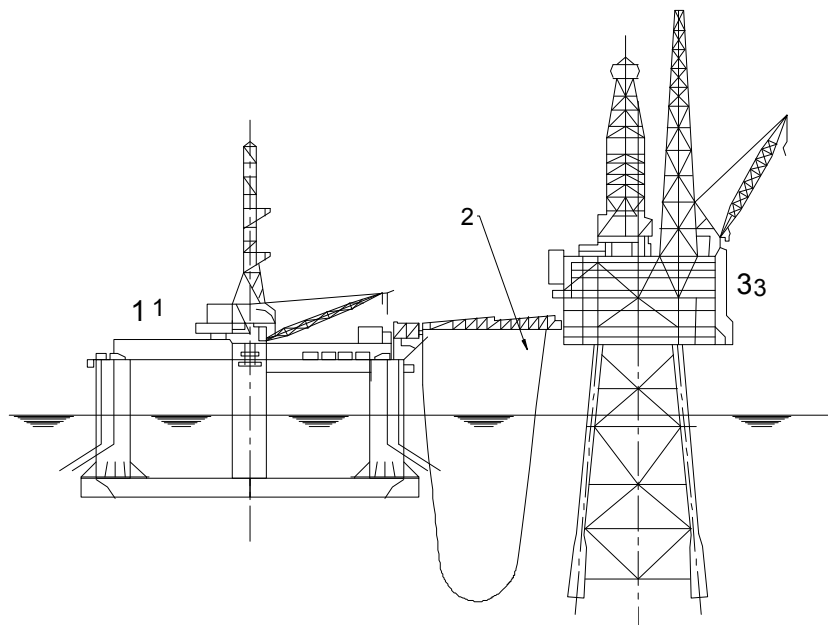
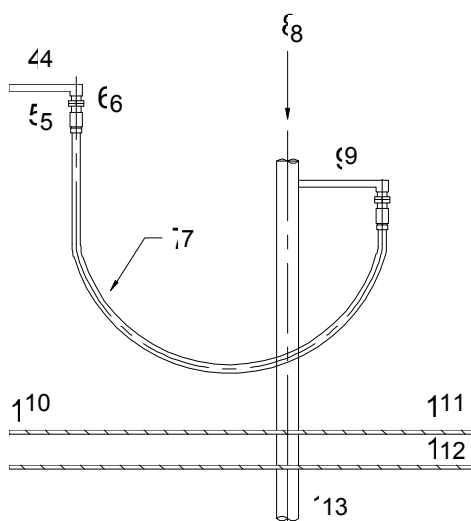


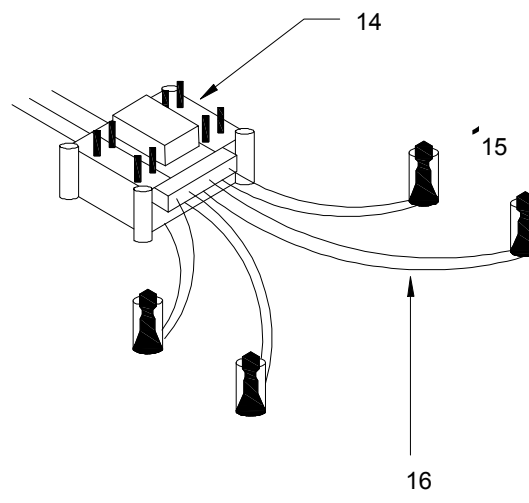
Figure 4—Examples of Common Flexible Riser Configurations



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. 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. 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. Figure 7 shows the typical profiles of pressure armor wires. 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. 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. 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. 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. 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: a) radial buckling or "birdcaging," 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. 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. 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.

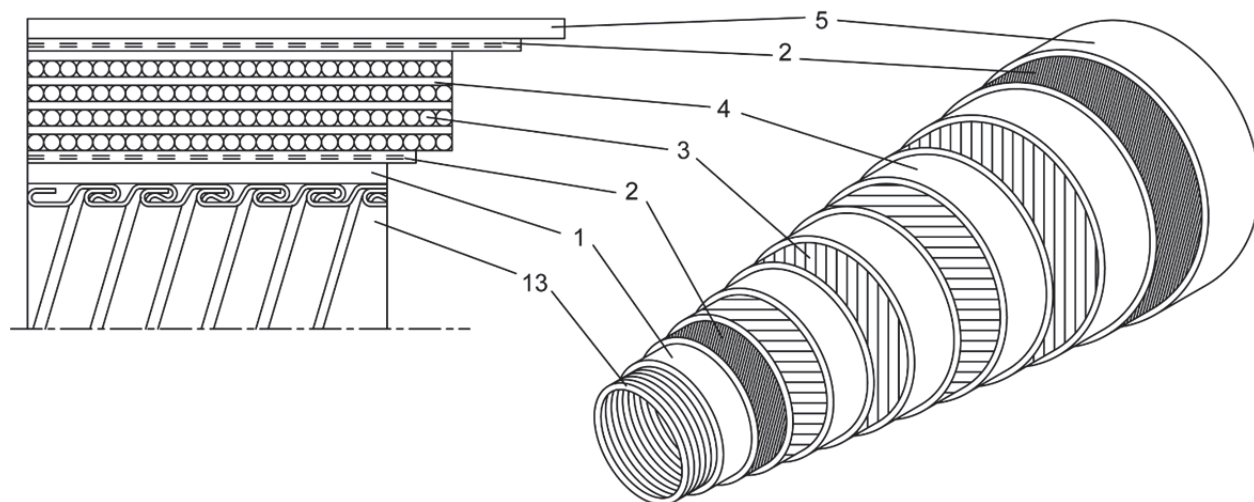
4.3.6 Integrated Pipe Umbilicals (IPUs)

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.

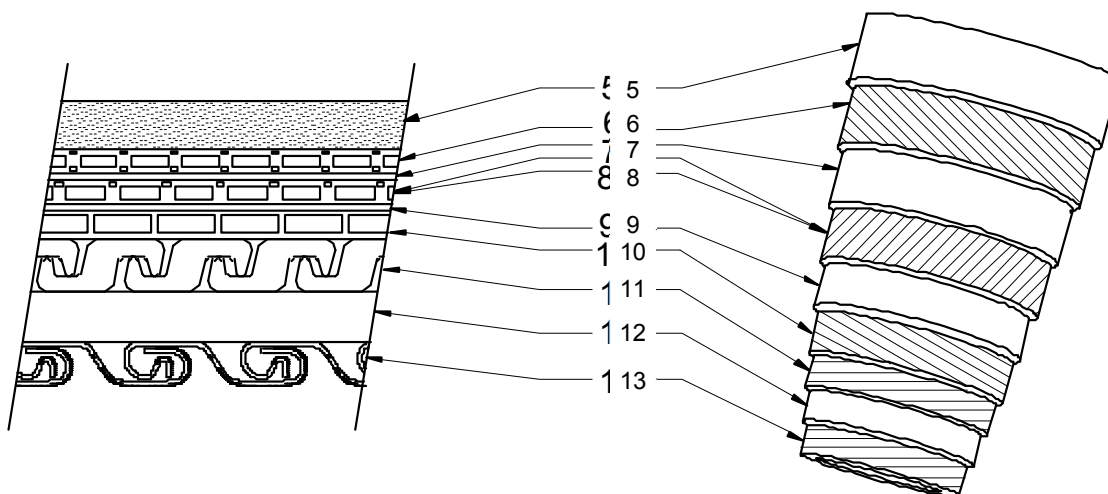
Spacers (fillers) are included between the umbilical lines to increase the crushing load resistance of the IPU. The assembly is covered by a protective outer sheath. In some cases, a layer of helical or sinusoidal armoring is applied between the control lines and the outer sheath. This layer increases 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

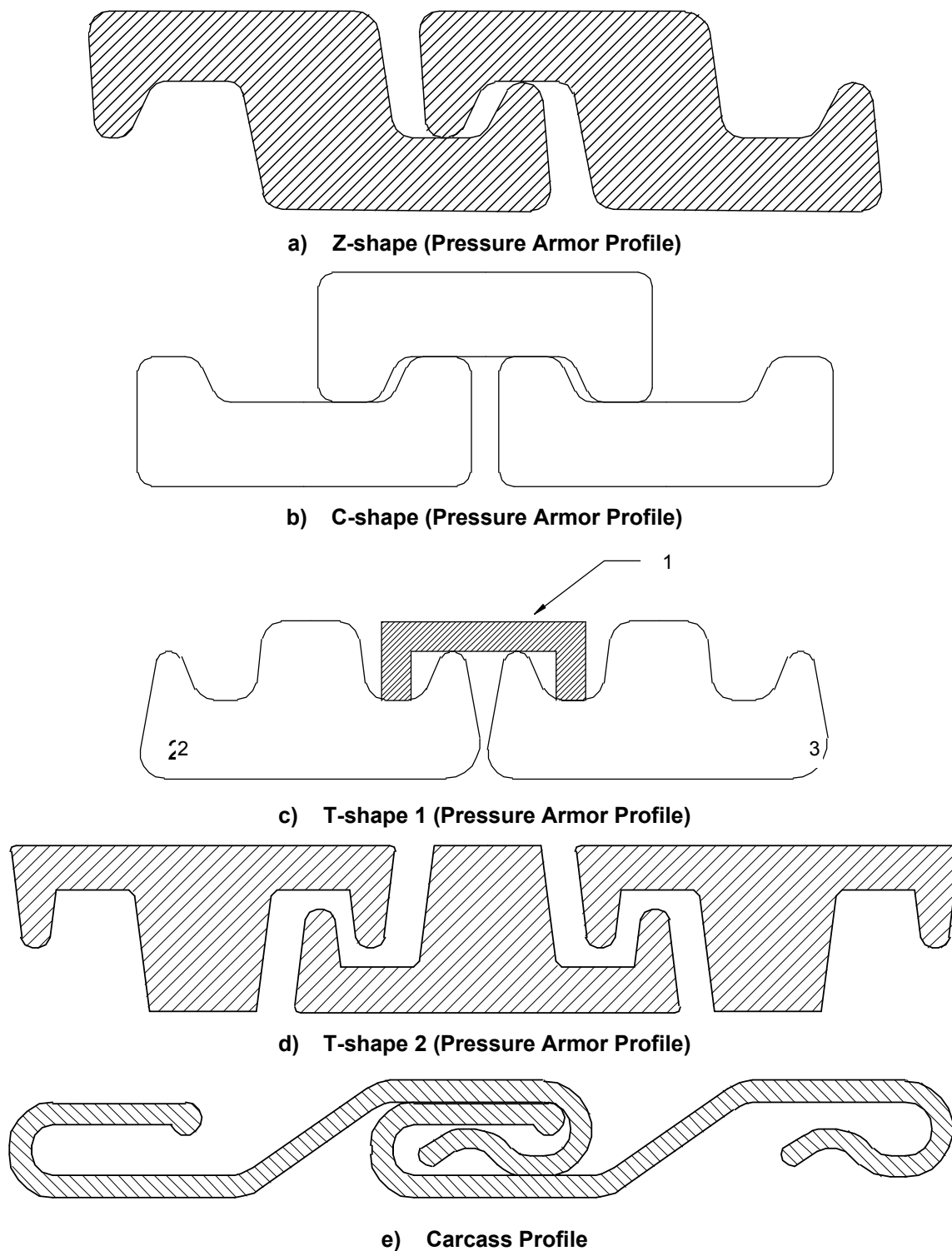


b) Unbonded Flexible Pipe

Key

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

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

**Key**

- | | | | |
|---|---------|---|---------|
| 1 | Clip | 3 | T. Wire |
| 2 | 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.

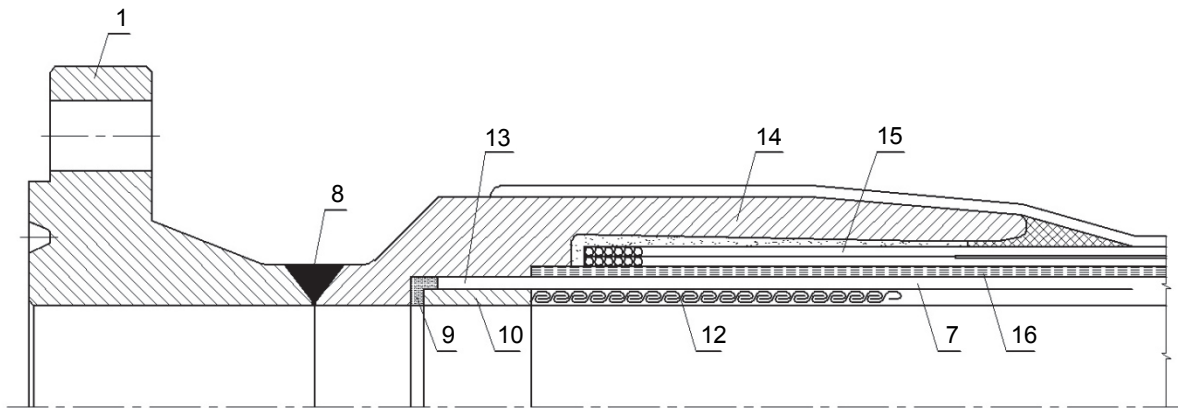
4.3.7 Multibores

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.

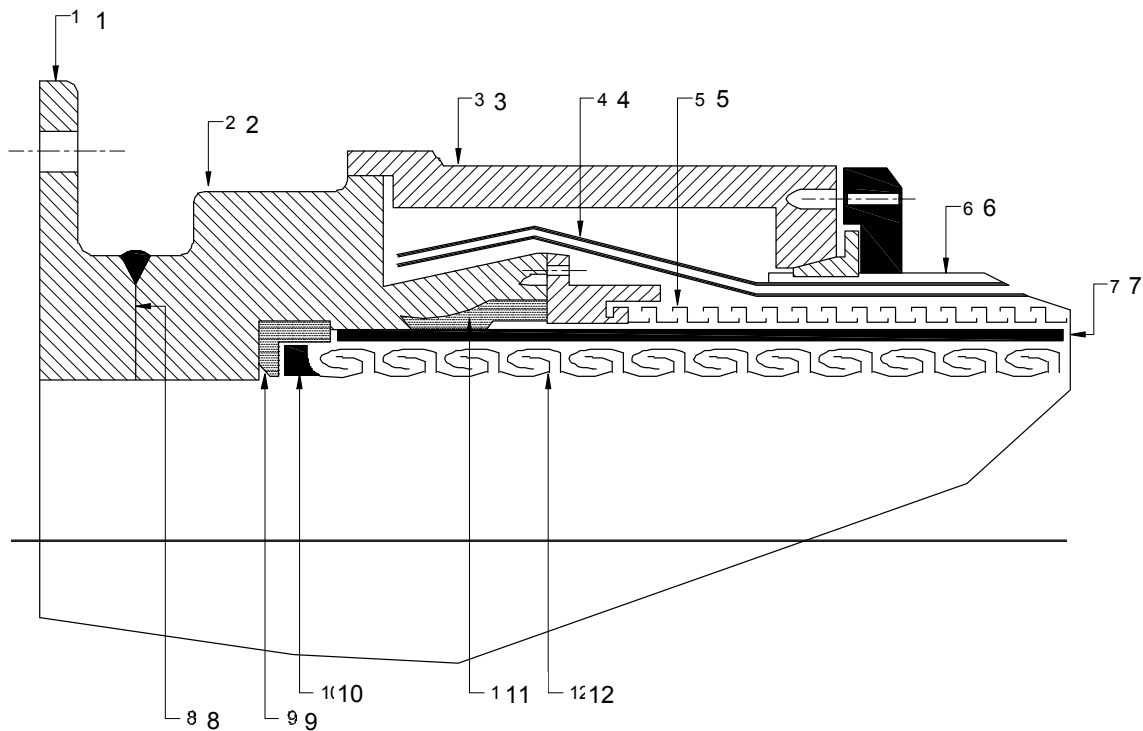
Figure 10 illustrates some examples of multibore constructions. The individual pipes are helically or sinusoidally wound and filler/spacer materials are used to obtain a circular cross section. External armoring may be applied outside the bundle. A polymer sheath is extruded over the bundle and provides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

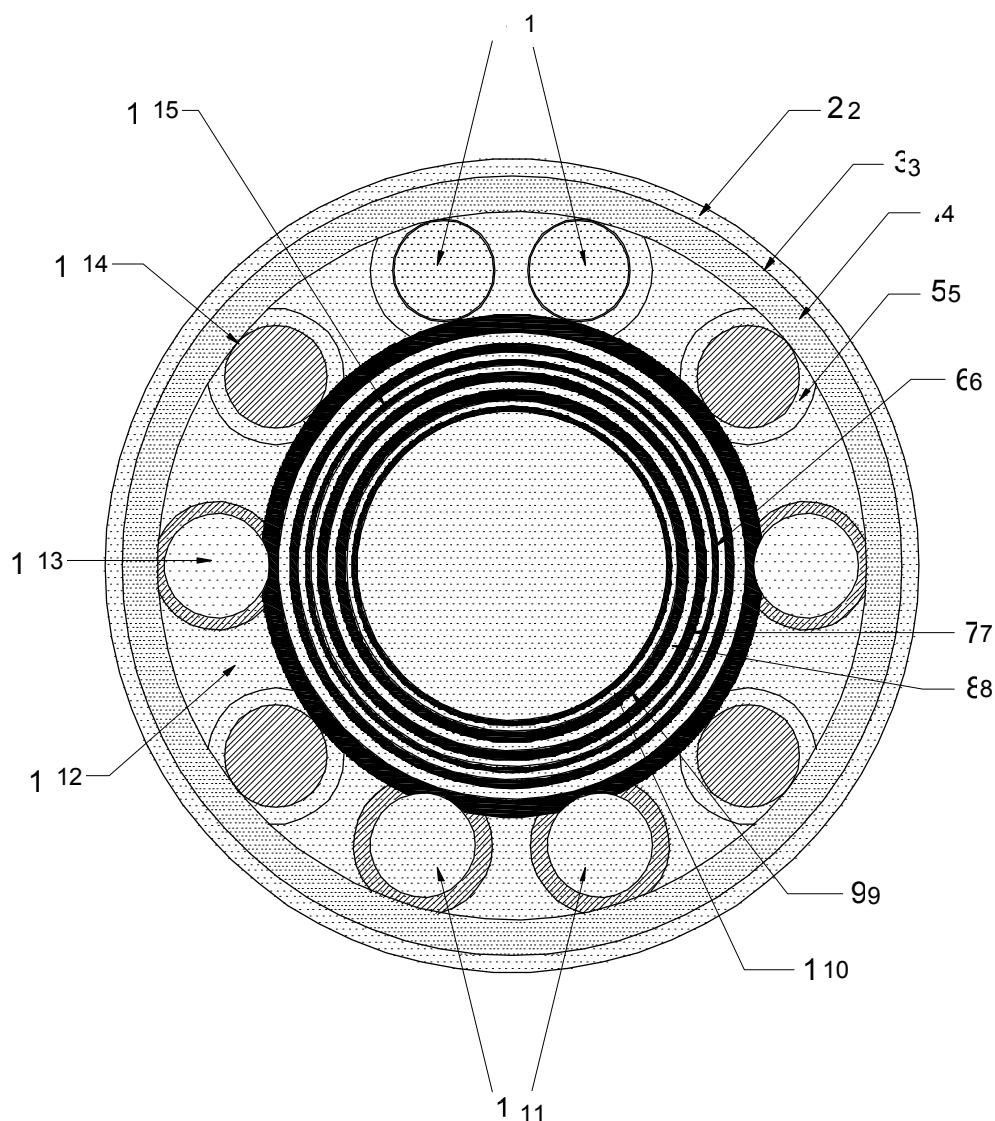


b) Unbonded Flexible Pipe End Fitting

Key

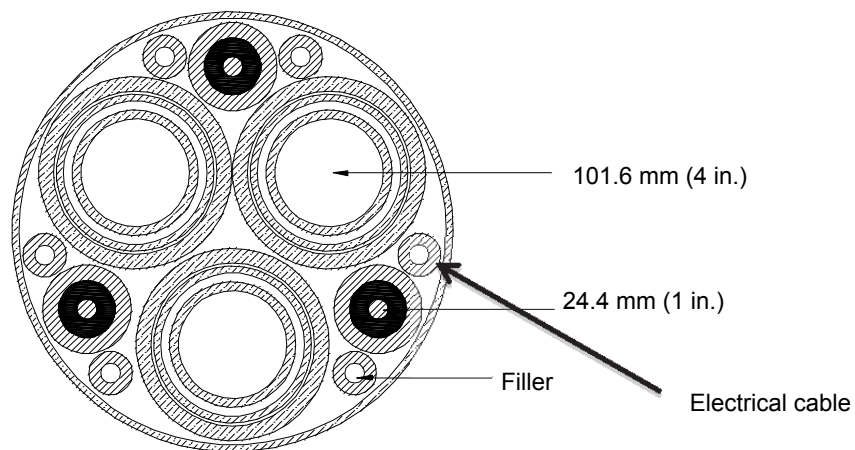
- | | |
|---|-------------------------|
| 1 Mounting flange | 9 Insulator |
| 2 End-fitting housing (inner casing) | 10 Carcass end ring |
| 3 End-fitting housing (outer casing) | 11 Seal ring |
| 4 Tensile armors (embedded in epoxy) | 12 Carcass |
| 5 Pressure armor layer | 13 Sealing |
| 6 Outer sheath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

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

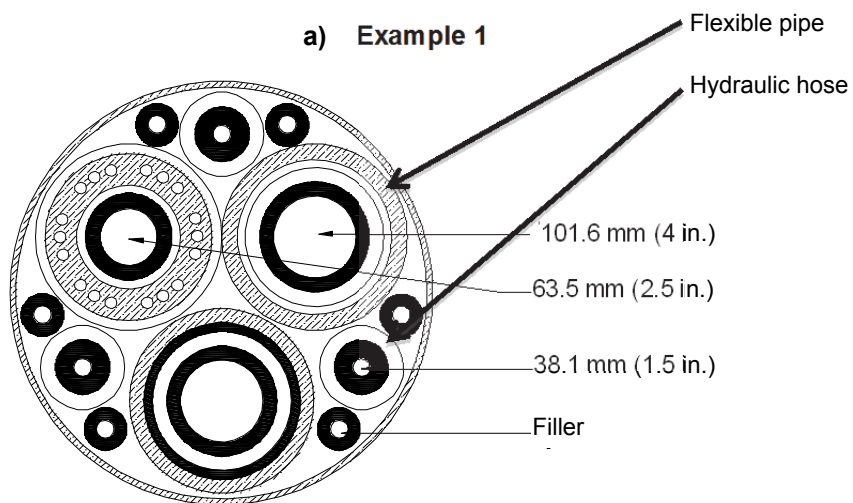
**Key**

- | | | | |
|---|------------------------------|----|--------------------------|
| 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 | | |

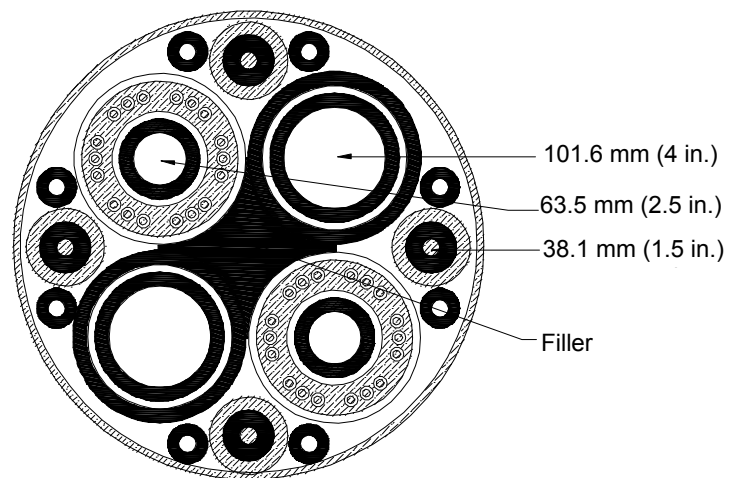
Figure 9—Schematic Drawing of an Example Integrated Pipe Umbilical



a) Example 1



b) Example 2



c) Example 3

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 $0.75d_{ult}$, where d_{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.

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.