FLEXIBLE PIPES: AN OVERVIEW FROM DESIGN TO INSTALLATION

(Chapter 16 - Handbook of Pipeline Engineering)

Contents

FLEXIBLE PIPES: AN OVERVIEW FROM DESIGN TO INSTALLATION

Mario Alfredo Vignoles[1], Anderson Dolinski[2]

This chapter presents an overview of flexible pipe (Note 1) from a brief history (Section 16.2) of its origin as a product for the offshore industry and its development over the last 50+ years. Section 16.3 presents the environment in which these pipes are inserted and their main functions. Section 16.4 provides an overview of the main layers, materials, and flexible pipe types. From these concepts, the chapter evolves presenting in sequence: flexible pipes design, manufacturing and installation.

Note 1: Unbonded Flexible Pipes, as defined in API 17J "Pipe construction consists of separate unbonded polymeric and metallic layers, which allows relative movement between layers".

16.1 INTRODUCTION

The offshore oil extraction began in the 1890s in California from extended piers into the waters of USA west coast. However, in 1947 the first offshore well completed by Kerr-McGee in the Gulf of Mexico at a depth of ~5 m is commonly considered the first success of the offshore industry [1]. Currently, the Stones field (2016) in the Gulf of Mexico, produces at ~2900m, the current water depth oil production record. In Brazil, offshore field developments are also approaching 3000m. Over years, the fast evolution of exploration depth was mainly explained by market demand, onshore oil shortages, and the successive oil crises that began in 1973, which further increased offshore oil production at greater depths (Figure 1).

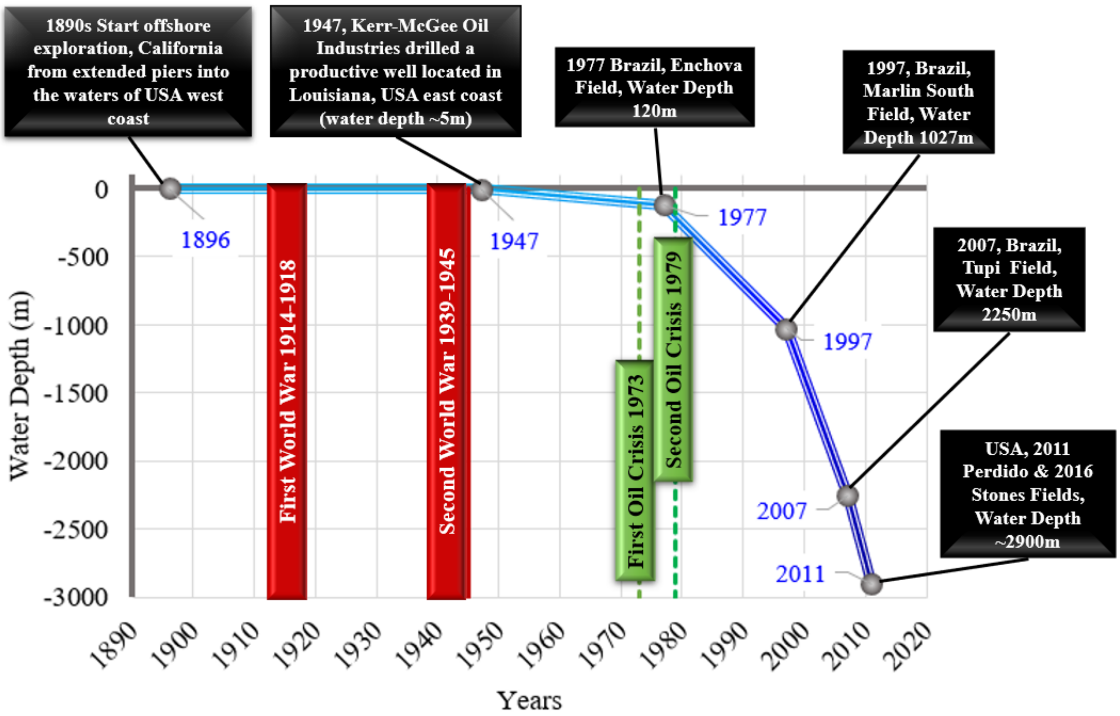


Figure 1: Water depth evolution, in the offshore industry, over the years.

[1]Mario A. Vignoles, MSc, TechnipFMC, Consultant Engineer, mario.vignoles@technipfmc.com
[2]Anderson Dolinski, DSc, TechnipFMC, Manager-EPCI Projects, anderson.dolinski@technipfmc.com

The Gulf of Mexico, North Sea, Africa and mainly Brazil are currently the offshore exploration and production worldwide main regions. There are flexible pipes installed in all these regions, but Brazil has the largest extension of flexible pipes installed, with most of these pipes being operated by Petrobras.
In the 1970s, Petrobras began exploring the Campos Basin, located in the northeast region of Rio de Janeiro. The Campos Basin development was an important milestone in the offshore industry, where the Early Production System (EPS), conceived in the North Sea also in the 70s, was extremely important for its rapid development. Basically, EPS uses a temporary production system until the definitive system goes into operation. The ease of handling, installing, uninstalling and reusing of flexible pipes was very important for the post-salt development success and is also being in the current Brazilian pre-salt fields (Figure 2).

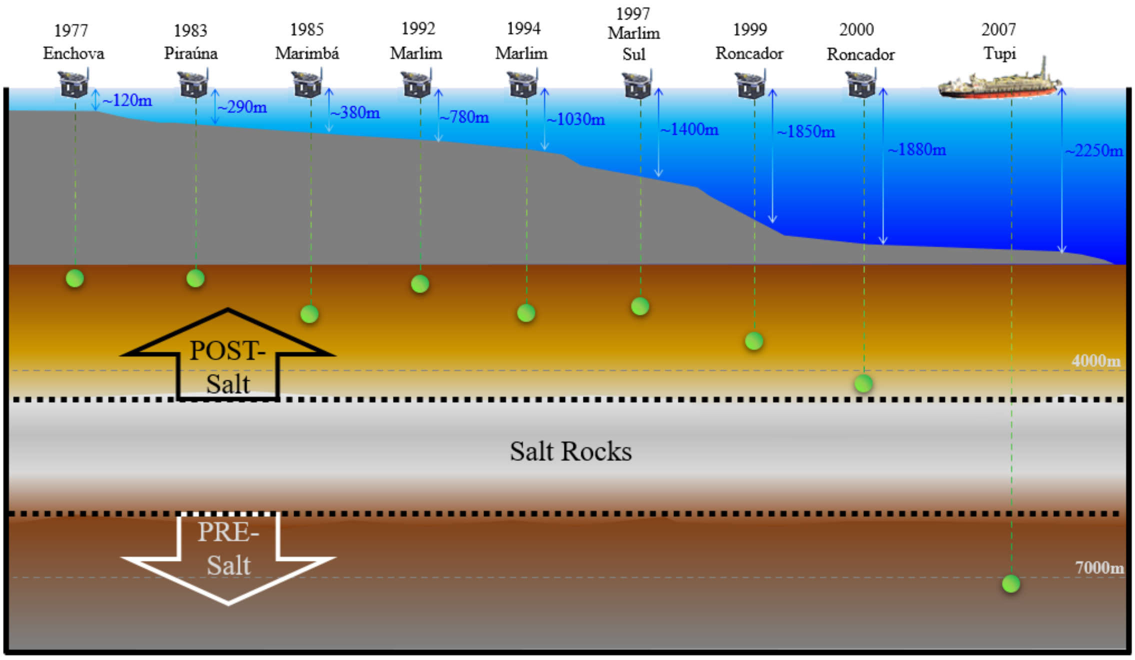


Figure 2: Water depth offshore exploration evolution in Brazil (Petrobras)

Currently, Petrobras is working on subsea field layout concepts for water depth up to 3000m. Presently there are flexible pipes installed with internal diameter ranging from 2.5" to 19" and in some cases operating pressure that can reach 20000psi.

16.2 BRIEF HISTORY

The flexible pipe concept appeared during World War II motivated by easy storage in reels, ease of handling and installation. The operation designated PLUTO (Pipeline Under The Ocean) in 1942, aimed to ensure safe routes for the fuels transport across the seabed between England and France (Figure 3).

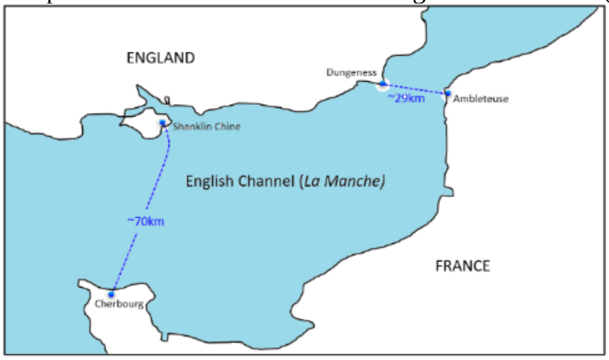


Figure 3: Installation routes of flexibles pipes between England and France during World War II.

Two types of pipes were developed, HAIS (Hartley/Anglo-Iranian/Siemens) (Figure 4) and HAMEL (Hammick/Ellis) both with 3 inches.

Figure 4: Pipeline HAIS Type (Copyright Museums Victoria).
[Pipe Line Section - 'PLUTO', HAIS type, Lead, circa 1943 (museumsvictoria.com.au)]

The HAIS pipe was very heavy due to the use of lead and the HAMEL was lighter but more rigid, which made it difficult to be wound in reels. The final solution was the combination of the 2 types.
More information about the PLUTO operation can be obtained from the following websites:

- Operation PLUTO – Battle of Normandy – D-Day Overlord (dday-overlord.com)
- Operation Pluto - Wikipedia
- Operation Pluto - The Oil/Gasoline Game of WWII (warhistoryonline.com)
- Operation Pluto (1945) - YouTube

Approximately ten years after the end of World War II, the IFP (*Institut Francais du Pétrole*) started the development of this pipe type for offshore oil drilling. This application was unsuccessful, but the concept was patented by IFP, which in 1970 brought together steel wire and cable companies to develop pipes now for transporting the production fluid in offshore fields. The first supply was made in 1971 to the oil company ELF in the Emeraude field (Congo). In 1972, after attending the OTC (Offshore Technology Conference) for the first time, the newly created Coflexip won the first major contract to supply McDermott in the Gulf of Mexico.
Later in 1976, Coflexip signs the first supply contract with Petrobras for the Garoupa field. In 2002 the French companies Technip and Coflexip joined to form the Technip-Coflexip group, and in 2017 a new union with FMC Technologies formed the current TechnipFMC group (Figure 5).

1958	1971	2002	2017	Factories:
ifp Institut Francais du Pétrole	coflexip	TECHNIP-COFLEXIP	TechnipFMC	Bordeaux – France (1971-1977) Le Trait – France (Since 1977) Vitoria – Brazil (1984-2021) Lobito - Angola (Since 2004) AsiaFlex - Malaysia (Since 2010) Açu – Brazil (Since 2013)

Illustration provided by TechnipFMC

Figure 5: Flexible pipes timeline from IFP to TechnipFMC

Over the years, others flexible pipe suppliers emerged, the main ones being the Danish NKT Flexibles (now NOV, National Oilwell Varco) in 1968, operating mainly in the North Sea, and in 1983 the British Wellstream (now Baker Hugues) focused on the Gulf of Mexico. Currently, all these companies have factories in Brazil, which is the largest market for flexible pipes.

The Sureflex Joint Industry Project (JIP-2017) [19] established a report named “Flexible Pipe Integrity Management Guidance & Good Practice”. This report provides, up to 2016, further industry guidance related to flexible pipe population and damage statistics, integrity management and good practices. In terms of statistics, this report also concluded that flexible pipe loss of containment rates compares favorably with rigid pipe, when considering incident rates per installed pipe.

16.3 ENVIRONMENT WHERE FLEXIBLE PIPES ARE INSERTED AND THEIR MAIN APPLICATIONS

This section presents the environment in which the subsea pipelines are inserted, presenting the main environmental and physical conditions that directly affect the design of flexible pipes. The water depth where most flexible pipes are installed is between 100 and 3000m.
Normally, the presence of divers to perform underwater connections and maintenance is only possible up to ~300 m depth, beyond this limit these operations are carried out remotely.
The free surface separates two environments (air and water), the waves formed in this surface produce a cyclic velocity field that decreases in intensity along the water depth and the extension of this region is proportional to the wave height.
The marine currents define a velocities field that varies in intensity and direction along of the whole water depth.
The photic zone is the surface layer of the water column illuminated by sunlight. It can extend to 500-600m depth, which defines the underwater flora and fauna (fish, crustaceans, corals, etc).
In this region, where there is sun action, the water temperature drops rapidly with the water depth. For example, at a depth of 1000m it can reach 3-4°C. After this depth, temperature decay rate is lower. The hydrostatic pressure increases ~1 bar every 10m of depth.
The figure 6 shows, schematically, all this environmental scenario in which the subsea pipelines are inserted.

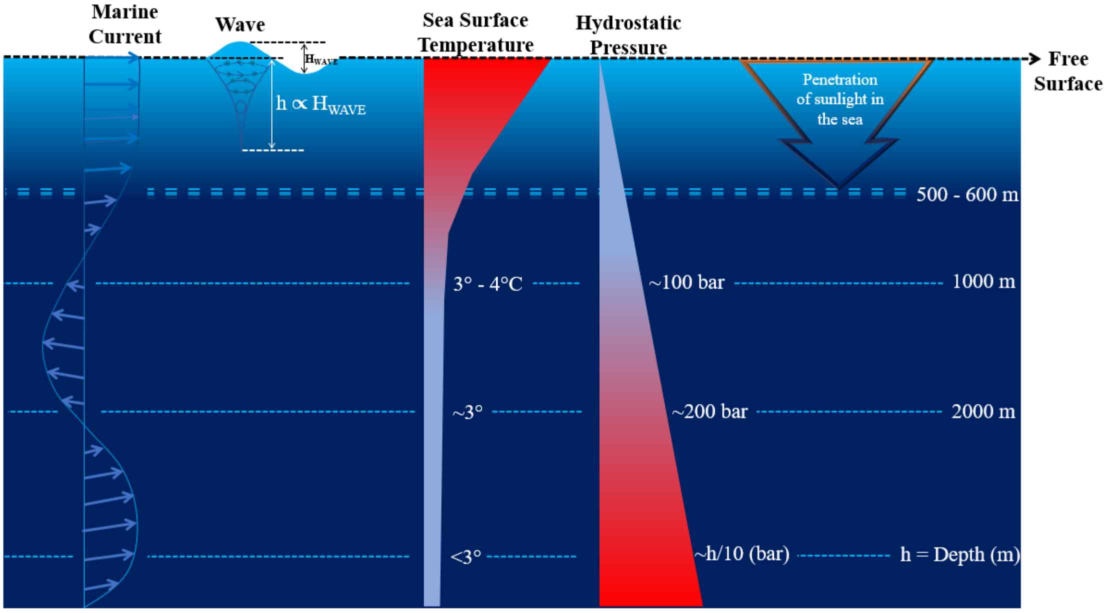


Figure 6: Typical subsea environmental condition (schematic view not representing any specific location).

The seabed is composed by flat parts with a low slope (continental shelf), and rugged parts with a steep slope (continental slope) where formations such as large underwater canyons can occur (Figure 7).

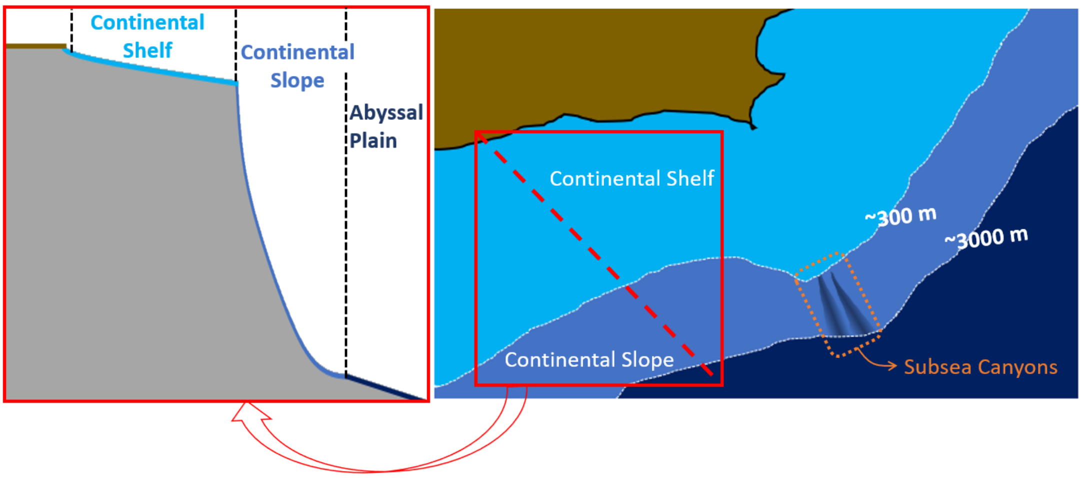


Figure 7: Underwater relief. This is a schematic image, it does not represent a specific location.

Geophysical and geotechnical surveys are performed at the conceptual stage of the oilfield development aiming at obtaining soil data, seabed bathymetry, hazard areas, etc. aiming at defining the optimum pipeline route and soil properties to be used for example in pipe/soil interaction analysis.

Below the seabed, at depths that can reach up to 7km (Figure 2), is the reservoir that normally contains gas, oil and water at high pressure and temperature. Due to the difference of densities between these fluids, the gas will concentrate in the upper part, the oil in the middle part and the water in the lower part of the reservoir. The access wells to the reservoir are defined, basically in 3 different regions (Figure 8):

Gas injection well - Access to the upper reservoir part, where there is gas;
Oil production well - Access to the reservoir middle part, where there is oil;
Water injection well - Access to the reservoir lower part, where there is water.

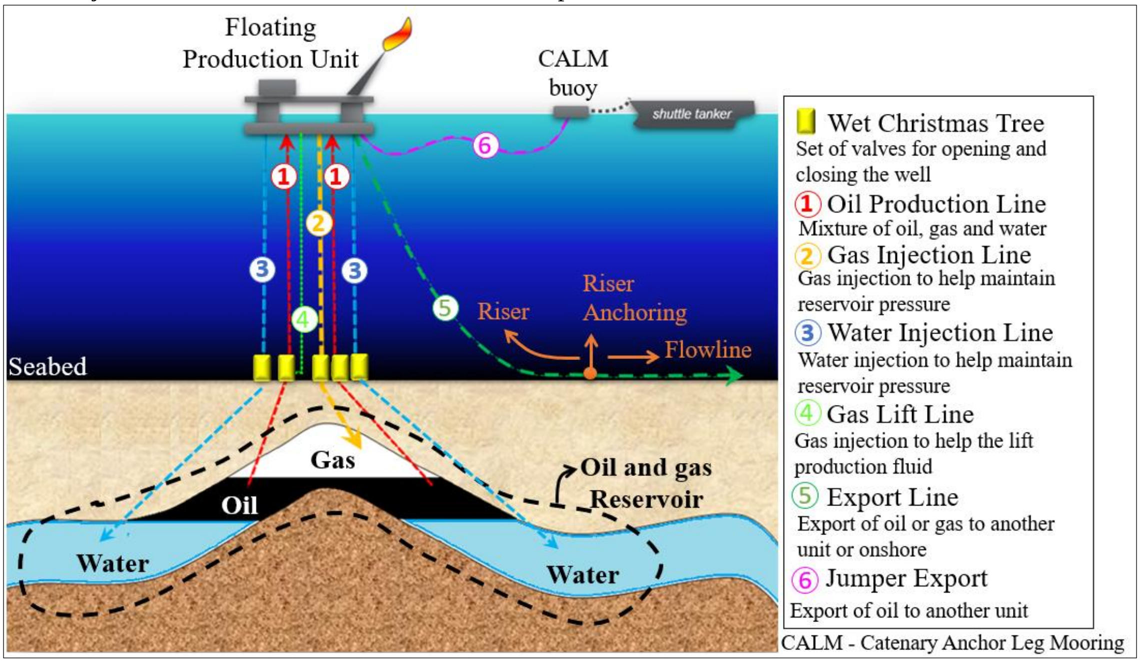


Figure 8: Schematic representation of offshore production oil field (Wet tree completion).

The fluid that flows into the production line (Figure 8, line ①) from the reservoir consists of the gas, oil and water phases, has a high temperature and can reach the seabed above 100°C and pressure above 200 bar.
The production fluid (Figure 8, line ①) when arriving at the floating unit is separated. The oil can be exported (Figure 8, line ⑤ or ⑥) or stored in the unit itself. The gas can also be exported (Figure 8, line ⑤), reinjected into the reservoir (Figure 8, line ②) or help in the production fluid lift (Figure 8, line ④). The water is reinjected into the reservoir (Figure 8, line ③).

All lines can be flexible pipe in figure 8. The lines are often classified according to their dynamic or quasi-static application as follow:

Riser ➔ Suspended part of the line between the floating unit and the riser anchoring (Figure 8, line ⑤). The main loads that risers are exposed are: wave loads (dynamic load, Note 2), marine current (quasi-static load, Note 2), floating unit offset (quasi-static load), thermal and pressure loads (quasi-static load) and riser/soil interaction loads (dynamic load).

Dynamic Jumper ➔ Suspended part of the line between floating units, for example the floating production unit and the CALM buoy (Figure 8, line ⑥). The main loads that dynamic jumpers are exposed are: wave loads (dynamic load, Note 2), marine current (quasi-static load, Note 2) and floating units offsets (quasi-static load).

Flowline ➔ Part of the line between the riser anchoring and a subsea equipment (Figure 8, line ⑤), for example the Wet Christmas Tree. The main loads that flowlines are exposed are: marine current (quasi-static load, Note 2), riser/soil interaction loads (quasi-static load) and thermal and pressure loads (quasi-static load).

Static Jumper ➔ Part of the line between subsea equipment, for example between a Wet Christmas Tree and a subsea manifold. The main loads that static jumpers are exposed are: marine current (quasi-static load, Note 2), riser/soil interaction loads (quasi-static load) and thermal and pressure loads (quasi-static load).

Note 2: There is direct action of the velocity field (hydrodynamic forces), produced by the waves and marine current on the outer riser's surface. The waves and marine current also have an indirect effect on the risers due to the imposed motions on the floating unit, where the riser is connected.

The entire environment, geological characteristics, reservoir characteristics, etc., presented in this section are the bases for the field development. These characteristics change depending on field location, so engineering solutions to meet ecological requirements, field efficiency, etc. can be changed, which allows for a great diversity of solutions (See Section 16.5.3).

More details in references [1], [2] and [3]

16.4 FLEXIBLE PIPE BODY - LAYER BY LAYER

This section provides an overview of the flexible pipes body (Note 3) layer by layer, presenting their functions, materials and main failure modes. A typical basic flexible pipe body is presented initially. Following the section sequence some other flexible pipes types are shown.

Note 3: As defined in API 17J "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.".

Flexible pipes are structures composed of several superimposed and concentric layers, with extruded polymeric materials or in tapes, and metallic materials arranged in a helical arrangement that provides low bending stiffness.
The flexible pipes treated here are "unbonded", a pipe construction that consists of separate unbonded polymeric and helical reinforcement layers, which allows relative movement between layers [14].
The figure 9 shows a typical flexible pipe structure:

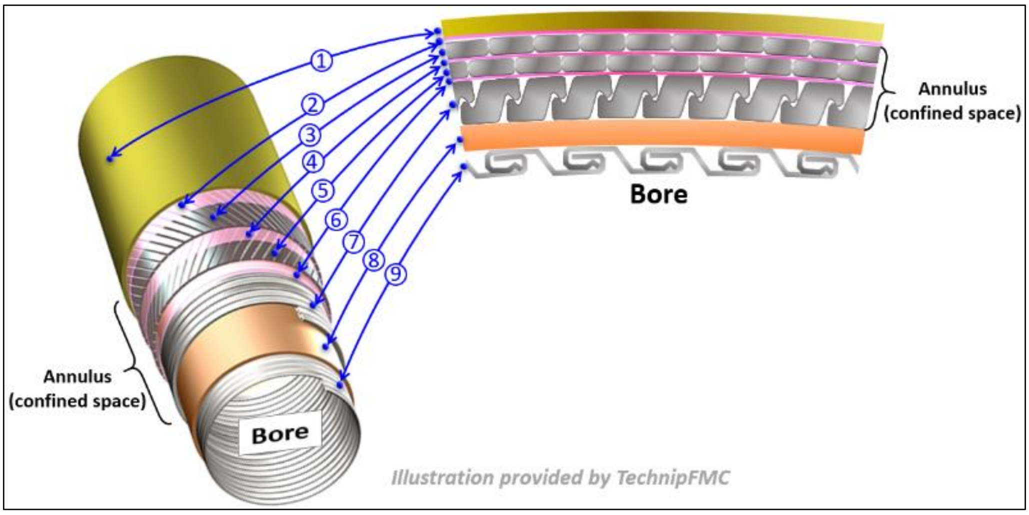


Figure 9: Typical flexible pipe structure.

① EXTERNAL SHEATH:

The External Sheath is an extruded polymeric layer. This is the outermost layer of the flexible pipe and sometimes can be double, that is, two adjacent extrusions.

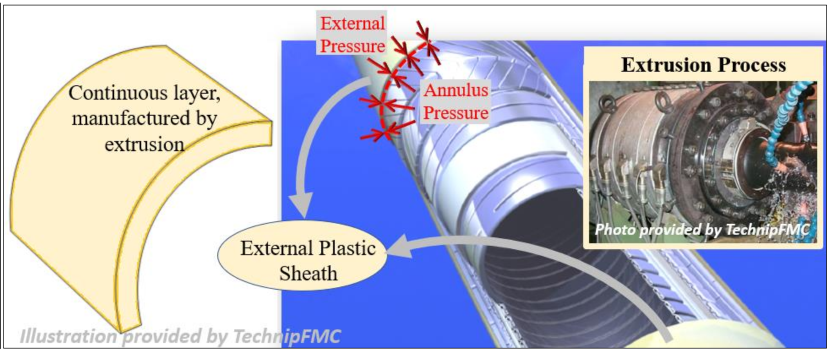


Figure 10: External Plastic Sheath.

Main Function:

- Prevent seawater ingress into the annulus
- Mechanical protection against the action of external agents, e.g., abrasion with other lines, structures or soil;
- The external sheaths are leak-proof, thus ensuring the tightness of the annular space;
- Prevent the entry of marine soil sediments (sand, clay, etc.) and marine growth into the annular space.

Main Materials: Polyethylene, Polyamide, TPE-Thermoplastic Elastomer

Material Selection: The material selection will be determined by layer temperature and the application type, static (flowline) or dynamic (Riser) (Section 16.3). The materials with good thermal performance and/or thickness can be used efficiently for the pipe thermal insulation.

Main associated failure modes: This is the most exposed layer of the tube, which is prone to tears, holes, etc. The damage to the external sheath triggers the annulus flooding by seawater, which may also be associated with the following failure modes:

- Corrosion of the metallic layers ③, ⑤ and ⑦;
- Tensile armours (layers ③ & ⑤) lateral buckling (Figure 14-B);
- Tensile armours (layers ③ & ⑤) radial buckling (Birdcage, Figure 14-A);

Therefore, the flexible pipe design normally considers both dry and accidentally flooded annulus condition.

② ANTIBUCKLING TAPE:

Antibuckling Tape is a set of overlapping tapes arranged in helical, which are wrapped alternatively clockwise and counterclockwise

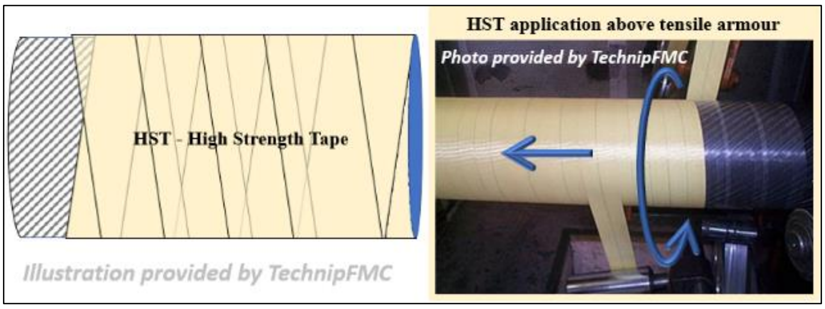


Figure 11: Antibuckling Tape.

Main Function:

- These tapes are tailored to give to the pipe a greater resistance to the Reverse End-Cap Effect (RECE), if needed.
  The RECE occur when, for example, the differential pressure between the tube parts outside and inside (Bore) generates a compression load on the pipe (Figure 12).

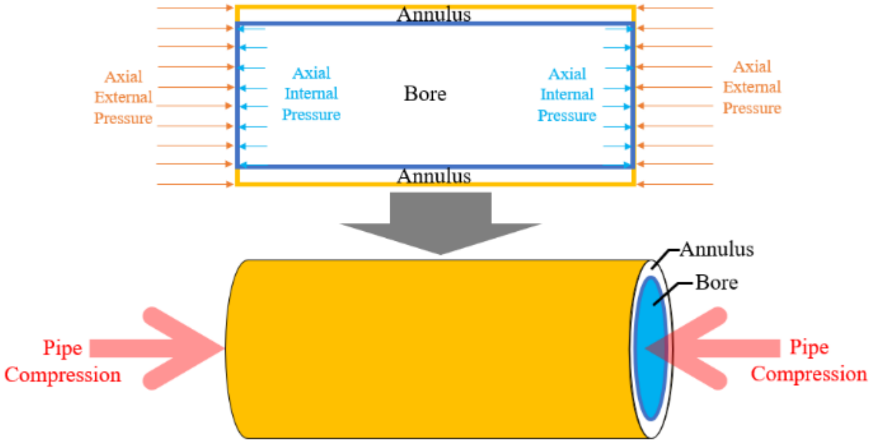


Figure 12: Reverse End-Cap Effect - RECE

Main Materials: Aramid Tape

Material Selection: The material selection will be determined by required strength and number of tapes to avoid failure mode. The annulus fluid condition (fluid composition, temperature and pressure, Section 16.4.1) must be considered, because under such conditions the tape may age with the consequent the tape strength mechanical loss, so, the associated long-term properties are accounted at design stage.

Main associated failure modes: The mechanical actions that damage the external sheath can reach the tapes and cause damage to them. The damage to the Antibuckling Tapes can been associated with the following failure mode Radial Buckling (RB) or birdcaging (layers ③ & ⑤, Figures 14 - A & B).

③ & ⑤ TENSILE ARMOURS:

Tensile Armour is a set of wires arranged in helical configuration, usually with armouring angle between 20° and 45°. The tensile armours are always assembled in pairs and in clockwise and counterclockwise sense. The armour wires have a rectangular cross section with width greater than the thickness for better moment of inertia efficiency.

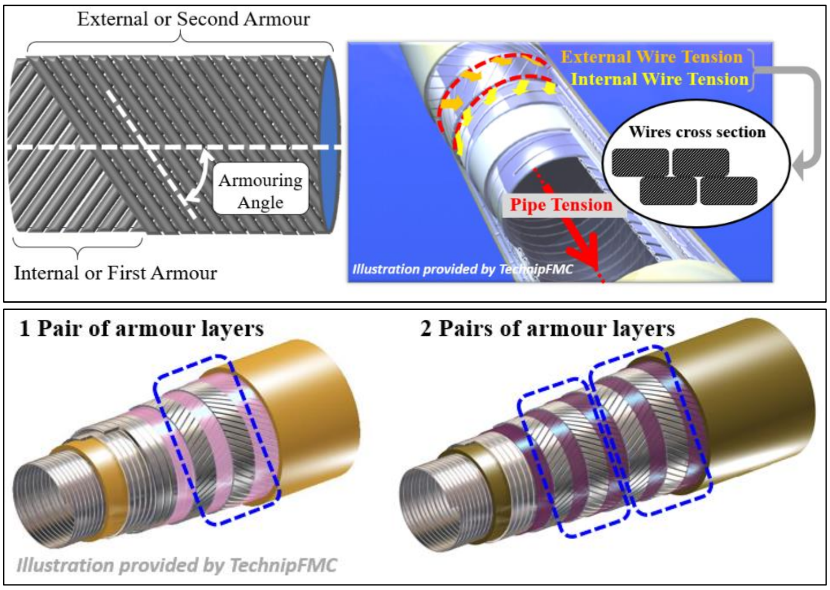


Figure 13: Tensile Armours.

Main Function:

- Tensile loads resistance (suspended line length weight + dynamic load);
- Axial compression loads resistance (hydrostatic load + dynamic load).

Main Materials: Carbon steels (with options for service conditions "sweet" and "sour", as defined in Section 16.4.1), Carbon -Fiber Composite.

Material Selection: The steel grade will be suitability to annulus environment (see Section 16.4.1). Safe domains for HIC (Hydrogen induced cracking), SSCC (Sulfide Stress Corrosion Cracking) and SCC (Stress Corrosion Cracking), for example, are part of the flexible pipes design and qualification requirements.
The wire cross-section is configured to provide required strength to tensile or compressive axial loads, while accounting for corrosion effect.
As with Antibuckling Tapes, the annulus condition can age the Carbon-Fiber Composite wires, with the consequent wire strength mechanical loss, so, the associated long-term properties are accounted at design stage.

Main associated failure modes: Among the main tensile armours failure modes, it is possible to mention the failure by fatigue (air and corrosion fatigue, see Section 16.4.1), Radial Buckling (RB) and Lateral Buckling (LB).

The Radial Buckling (RB) is commonly known as birdcaging (Figure 14-A) due to the configuration that the tensile armours forms after failure. The compression load produced by RECE (Figure 12), will be resisted by the tensile armature wires, which can buckle in the radially tube direction (Figure 14). The set of Antibuckling Tapes eliminates this failure mode as long as they are not damaged.

The Lateral buckling (LB) is a failure mode due to the compression load produced by RECE (Figure 12) combined with the variation of the pipe curvature. This loads association can cause the armour wire to fail by buckling, laterally (Figure 14-B).

More details in references [5],[6],[7],[8] and [9]

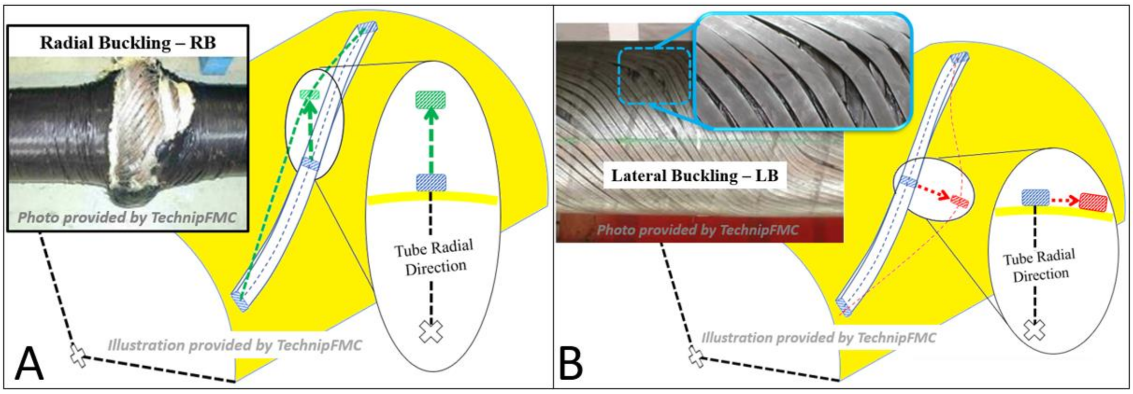


Figure 14: Failure mode A - Radial Buckling (RB) and B - Lateral Buckling (LB).

④ & ⑥ ANTI-WEAR TAPE:

Anti-wear tapes are arranged in a helical shape, applied without overlapping with free space between helix to prevent disorganization while the pipe bending.

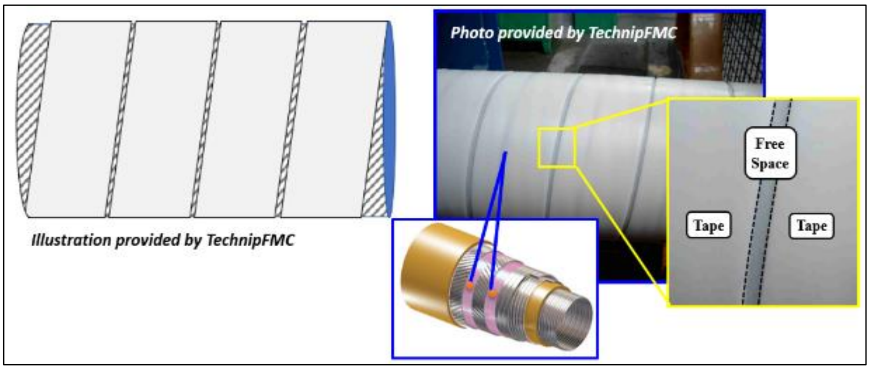


Figure 15: Anti-Wear Tape.

Main Function: The Anti-Wear function is to suppress wear between adjacent metallic layers subjected to relative movements with each other.

Main Materials: Polyamides, PVDF (polyvinylidene difluoride)

Material Selection: The anti-wear material must withstand large contact pressures under high temperature conditions (Operating Temperature), as it is applied between metallic layers subjected to relative movements with each other and are under strong contact load. This contact load is due 2 effects combined, “squeeze” and “sandwich” effect

Squeeze Effect → The armour tensile have a spring behavior, that is, when they are tensioned, there are an axial strain and reduce the internal diameter (Figure 16-A), this effect compresses one armour against the other and tightens the lower layers.
Sandwich Effect → The bore fluid pressure acts on the inside of the pressure sheath ⑧, the external pressure ① acts on the outside of the external sheath. This effect compresses all layers in the annulus space, causing the “sandwich” effect. This effect only happens if the two sheaths (① & ⑧) are watertight (Figure 16-B).

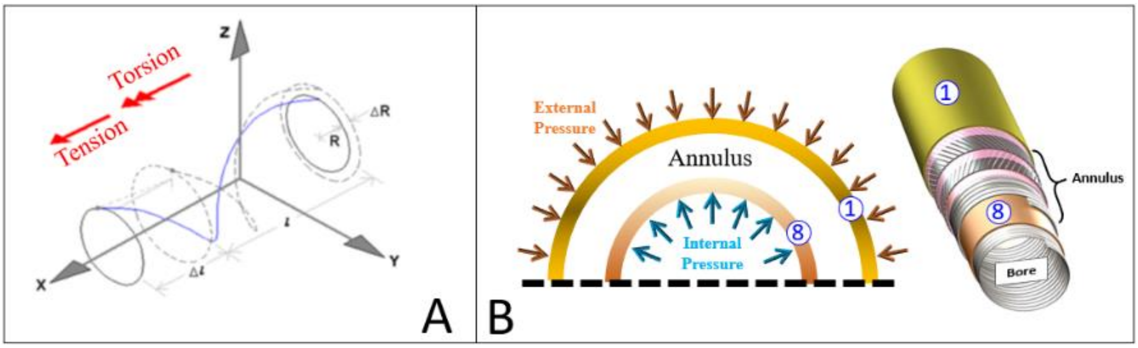


Figure 16: A – “Squeeze” Effect, B – “Sandwich” Effect.

Main associated failure modes: If the anti-wear layer is damaged, there can be direct contact between metallic layers. The high contact pressure associated with the relative movement between the metal layers can cause wear with consequent reduction in cross section and increased stress. This situation can also power the fatigue of metallic layers due to the fretting phenomenon [4].

⑦ PRESSURE ARMOUR or PRESSURE VAULT:

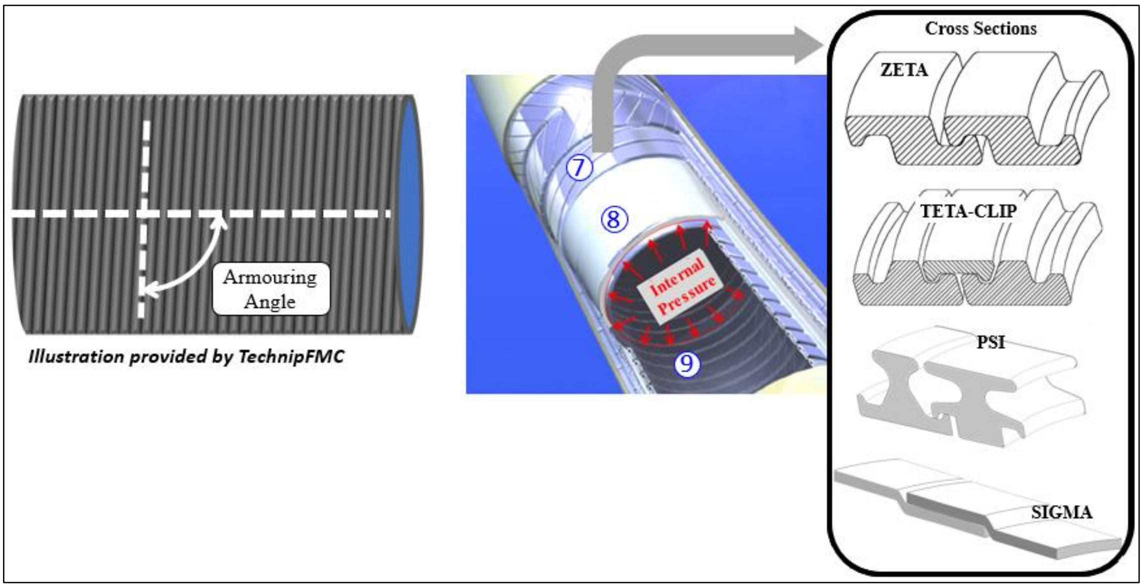


Figure 17: Pressure Armour.

Pressure Armors consist of helicoids with transversal profiles with specific geometry, developed to resist the internal pressure in order to guarantee a better moment of inertia and reduction of the cross-section area in order to reduce the weight per meter. The armouring angle is close to 90 °, and the helicoids can be interlocked with each other (ZETA,Teta-Clip and PSI). The SIGMA profile is not interlocked but the strip is spiraled with an overlapping of approximately 50%. This configuration ensures a continuous masking of the internal sheath outer interface which can reduce gas diffusion into the tensile armour annulus (Section 16.4.1). Reference [10]

Main Function:

- Internal pressure resistance, transferred by the pressure sheath ⑧;
- It has a secondary function of confining the carcass ⑨, thus increasing the resistance to collapse.

Main Materials: Carbon steels (with options for service conditions "sweet" and "sour", as defined in Section 16.4.1).

Material Selection: The steel grade will be suitability to annulus environment (see Section 16.4.1). Safe domains for HIC (Hydrogen induced cracking), SSCC (Sulfide Stress Corrosion Cracking) and SCC (Stress Corrosion Cracking), for example, are part of the flexible pipes design and qualification requirements.
The wire cross-section is configured to provide required strength to tensile or compressive axial loads, while accounting for corrosion effect.

Main associated failure modes: The main pressure armours failure mode is the failure by fatigue (mainly fatigue-corrosion, Section 16.4.1)

⑧ PRESSURE SHEATH:

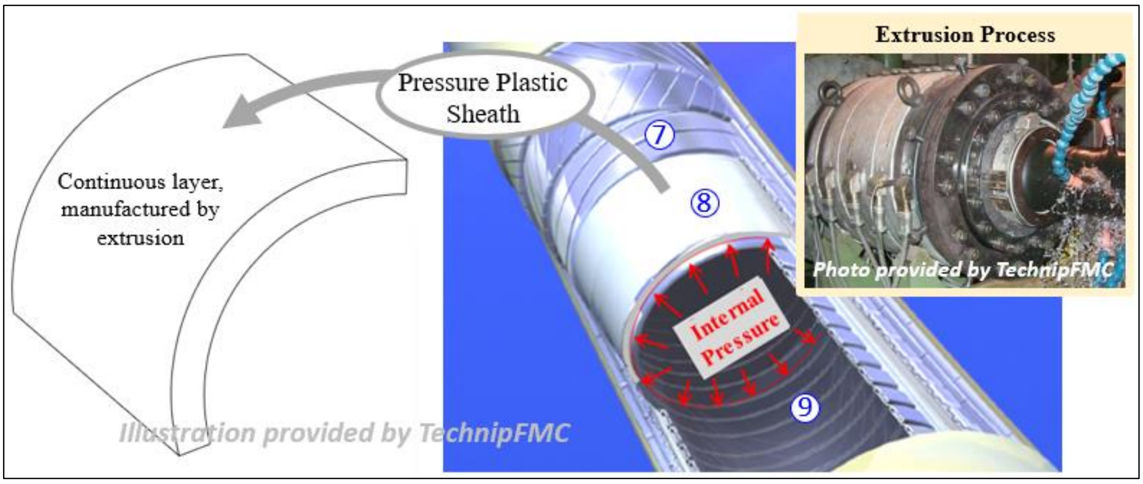


Figure 18: Pressure Sheath.

The Pressure Sheath is an extruded polymeric layer. This can be considered the main layer, the "heart" of the flexible pipe ensures internal-fluid integrity. It can be said that all other layers exist to protect this sheath. Another important point to be considered is that the pressure sheath is in direct contact with the fluid of the bore and the annulus (Figure 9) and through it the gas diffusion happen from the bore to the annulus (Section 16.4.1).

Main Function:

- Ensure the tightness of the internal fluid flow;
- Transfer the internal pressure to the pressure armour ⑦ (Figure 18);
- When the annulus is not seawater flooded (Figure 19-A), the external pressure efforts are mechanically transferred through the layers (① to ⑧), and from the pressure sheath ⑧ to the carcass ⑨;
- Transfer the hydrostatic pressure to the carcass ⑨, when the annulus is seawater flooded (Figure 19-B).

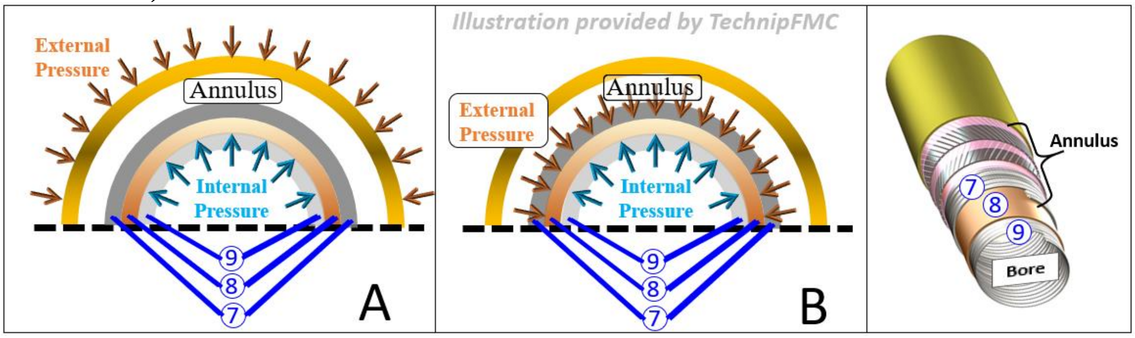


Figure 19: Annulus dry (A) and flooded by sea water (B).

Main Materials: Polyamide, Polyethylene, PVDF (polyvinylidene difluoride)

Material Selection: The pressure sheath polymer when extruded onto the carcass ⑨ tends to mold to its outer surface, this phenomenon is called thermocreeping (Figure 20). A similar phenomenon happens when in operation (fluid in the bore in high temperature and pressure) squeezes pressure sheath ⑧ onto pressure armour ⑦, inducing some deformation in gaps between adjacent spirals, this is called creeping (Figure 19). The following points should be considered during the pressure sheath material selection:

- ➢ Creeping shall be considered to select the appropriate pressure sheath material and thickness;
- ➢ The fluid condition (fluid composition, temperature and pressure, Section 16.4.1), mainly on the bore (usually more severe).

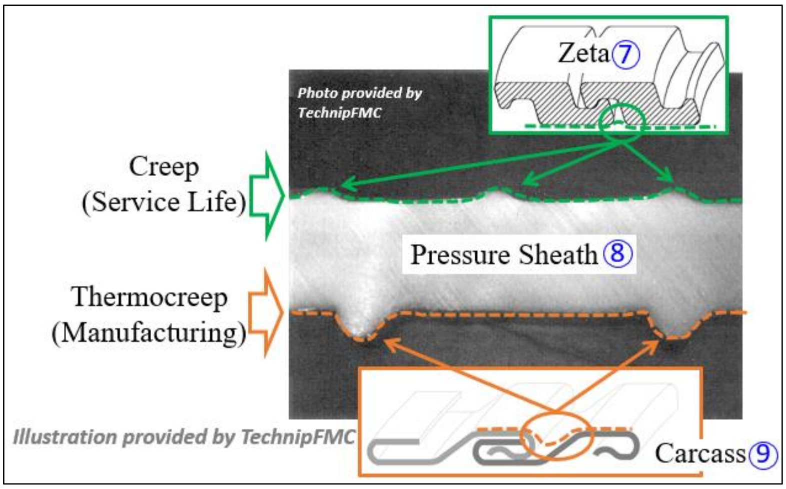


Figure 20: Pressure sheath - Thermocreeping over the carcass and creep created in the pressure armour gaps during the flexible pipe operation.

Main associated failure modes: The creep occurrence on both sides of the pressure layer (Figure 19) can thin the sheath and potentially result in leakage.
In dynamic applications, cracks can occur in the region close to the creep, which can lead to the rupture of the pressure sheath.

⑨ INTERLOCKED CARCASS:

Interlocked Carcass consist of helicoids with specific geometry transversal profile, developed to resist to the external pressure. The laying angle is close to 90 °, and the helicoids are interlocked. The S-carcass introduce an insert to the standard carcass profile, ensuring masking of the internal corrugations. This configuration creates a smooth internal surface that suppresses possible occurrence of FLIP and reduces the internal fluid pressure drop (Figure 21). Flexible pipes with carcass are normally classified as Rough Bore.

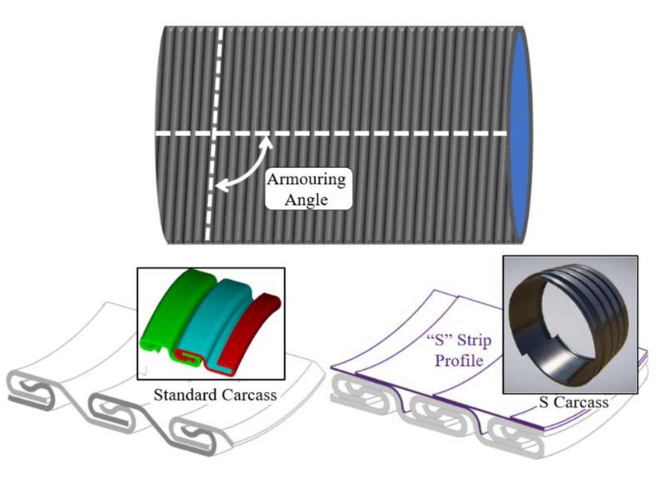


Figure 21: Standard and S Carcasses.

Main Function:

- Hydrostatic pressure resistance;
- Radial load resistance in tensioner belt, during the pipe laying process, in the installation's ship (Figure 22-2);
- Resistance to the "Squeeze" effect (Figure 16-A);

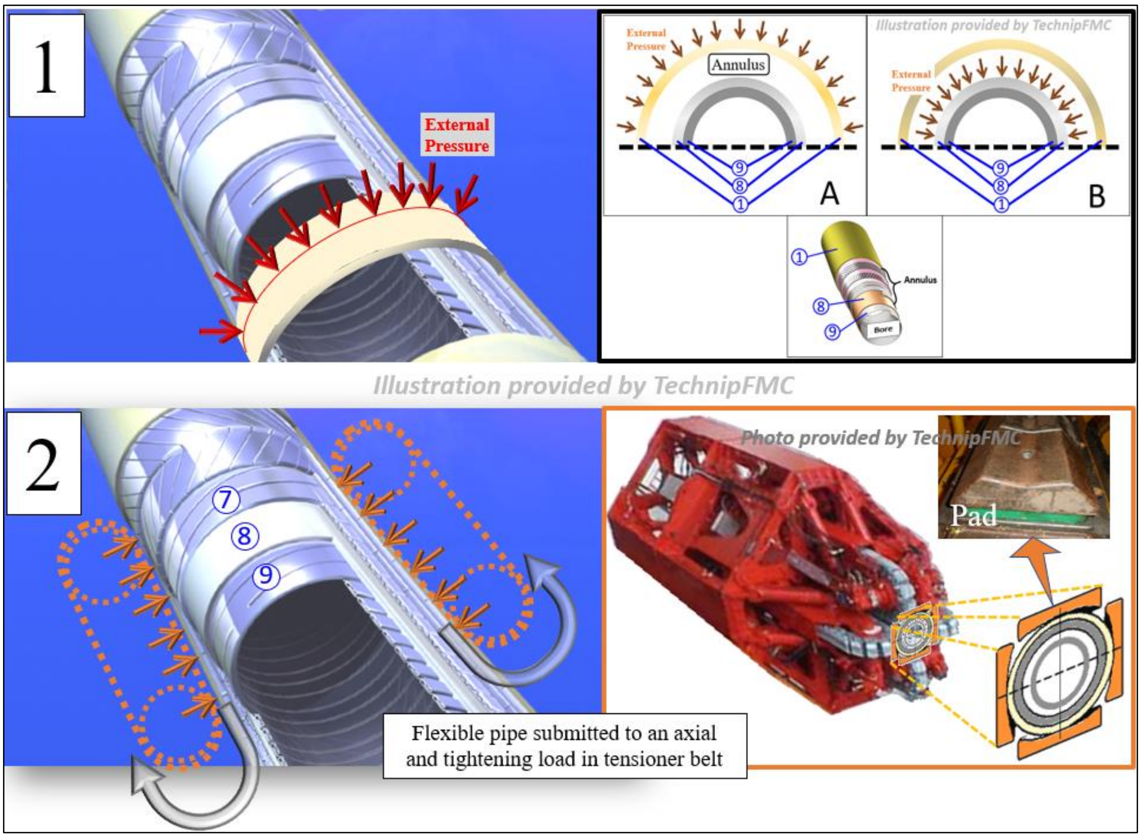


Figure 22: Typical loads resisted by carcass.

Main Materials: Austenitic Stainless Steel (AISI 304L and 316L), Duplex Stainless Steel (2205, 2304 and 2101) and Super Duplex Stainless Steel (2507)

Material Selection: The material will be selected based on the required hydrostatic and tightening loads resistance. The bore fluid condition (fluid composition, temperature and pressure, Section 16.4.1) must be considered to select the material with the appropriate corrosion resistance.

Main associated failure modes: The main carcass failure mode is collapse (Figure 23), with bend collapse being the main design condition for its dimensioning.

More details in reference [11].

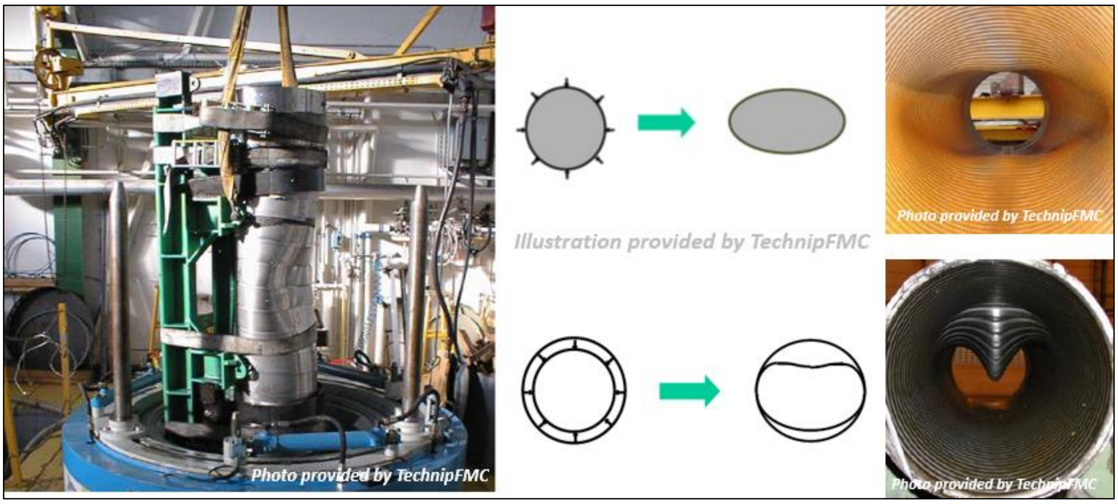


Figure 23: Typical carcass collapse failure mode.

16.4.1 Bore and Annulus Fluid Conditions

The flexible pipe is characterized by 2 main regions or spaces (Figure 9):
Bore ➔ Internal pipe region, through which the fluid flows.
Annulus ➔ Region or space between the external sheath ① and the pressure sheath ⑧ (Figure 9);
During the field development phase, flow assurance analyses are performed, where the fluid global molar composition, temperature and pressure profiles of the line functions as shown in section 16.3 (Oil Production, Gas (injection or lift) and Water injection).
The basic data to obtain the bore fluid condition are:

- Internal temperature and pressure;
- Bore fluid composition. Mainly CO_2, H_2S and CH_4 concentration and water ionic composition (mainly Cl^-,HCO_3^-);

From this information it is possible to calculate the bore fluid condition:

- Partial pressure of H_2S (bar) = %mol H_2S x Design Pressure (bar) x 10^{-6} (Note 4);
- Partial pressure of CO_2 (bar) = %mol CO_2 x Design Pressure (bar) x 10^{-6} (Note 4);
- pH of the water phase;

Note 4: The partial pressure is used in a preliminary approach to be revisited with the fugacity (Note 4) calculus.

From these information it is possible to select the material of carcass (Figure 9,⑨) and pressure sheath (Figure 9,⑧).
It is important to note that the H_2S presence will define the type of flexible pipe service condition. The "Sour" service condition is when the H_2S content exceeding the minimum specified by ISO 15156 (replaces NACE MR0175) [15]. Otherwise the service condition is considered "Sweet" service condition.

The annulus fluid condition is obtained from a permeation analysis, performed with a specific software. Diffusion is the transport of gases and/or liquids through the polymeric layer's microstructure. In fact, the diffusion process is driven by the fugacity (Note 5), temperature and pressure gradients on the sheath (Figure 24).

Note 5: Fugacity has a dimension of pressure and takes into account the interactions between petroleum components, and for a gas, it is a correction of the partial pressure considering the gas not ideal.

The end-fitting are assembled at the flexible pipe's extremity, where to fix layers and the annulus is connect to the external environment in two ways (Figure 24B): Vent to floating unit (atmospheric pressure) or through the Gas Relief Valve (GRV), in this case, the valve opens when the differential pressure reaches, for example, $\Delta P > 2.5$bar.
(ΔP = Annulus Pressure – External Pressure)

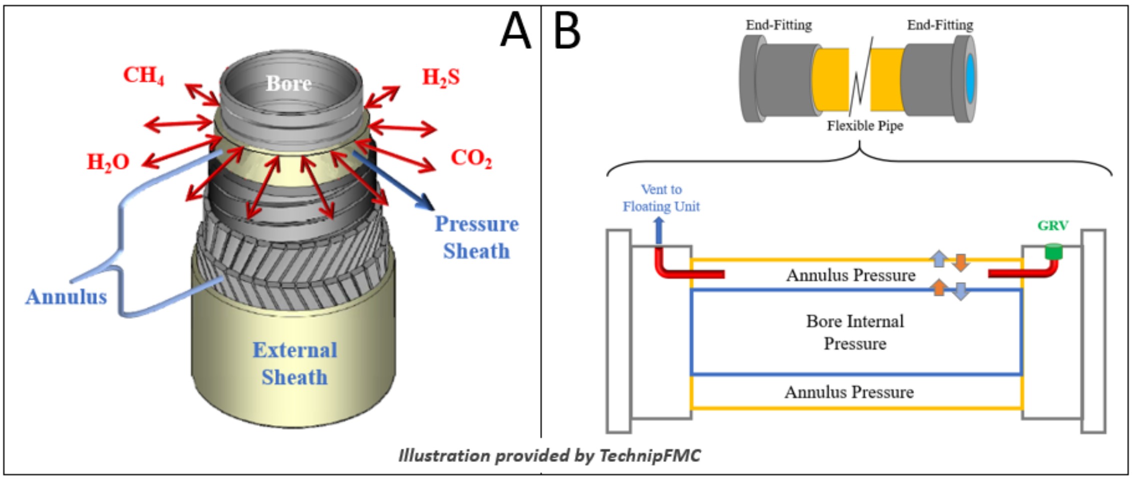


Figure 24: Diffusion from the bore to the annulus.

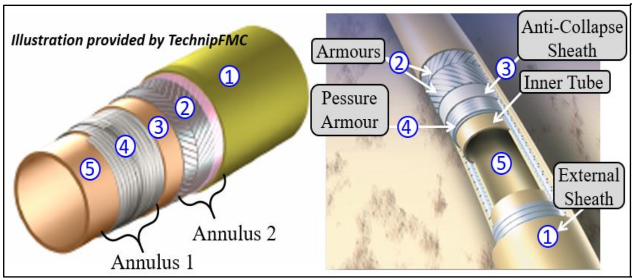
DIFFUSION ANALYSIS	
INPUT DATA ➢ BORE – Pressure, Temperature and Fluid Composition; ➢ ANNULUS – Geometry, Pressure (Figure 21B) and Seawater (if flooded); ➢ EXTERNAL ENVIROMENT – Temperature	MAIN OUTPUT DATA ➢ ANNULUS – H2O (liquid and/or gas), pH, partial pressure (or fugacity) (H_2S, CO_2).

From the diffusion analysis output data it is possible to select the material of External Plastic Sheath (Figure 9,①), Antibuckling Tape (Figure 9,②), Tensile Armours (Figure 9,③&⑤), Anti-Wear Plastic Layer (Figure 9,④&⑥) and Pressure Armour (Figure 9,⑦).
The similar diffusion process also take place, through the external sheath, between the annulus and the outer environment.
It is should be noted that the annulus can be flooded by seawater or by water that permeated from the bore and condensed in the annulus. The state of the art to determine annulus conditions also considers, in flooded annulus conditions under high hydrostatic pressure, the effect tortuosity due to complex annulus geometry (several layers of metallic wires with different shape, size and laying angle) leading to heterogeneity and fugacity gradient to be considered in design.

16.4.2 Flexible Pipe Options

The multilayer characteristic of flexible pipes allows a very large number of configurations, not only in terms of material and dimensions for each layer, but also in terms of number layers combinations. At the beginning of this section the standard flexible pipe, with its main layers was seen in detail, in this section other flexible pipe options are presented.

- **Smooth Bore Flexible Pipes**

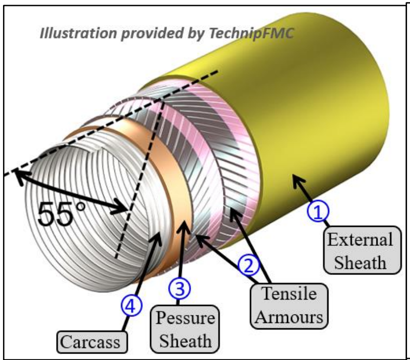


In Smooth Bore flexible pipe, there is no carcass. The first internal layer is leakproof polymeric tube (Inner Tube, ⑤). To protect this inner tube against collapse, a leakproof polymeric sheath is extruded above the pressure armour (Anti-Collapse Sheath, ③), so in this case there are 2 annulus spaces.

Figure 25: Structure Smooth Bore.

As in pressure sheath case (Figure 19 A&B), this layer will transfer mechanical and hydrostatic pressure efforts to the pressure armour ④. which will resist both external and internal pressure. This type of structure is mainly used with fluids that do not contain gas. In case of fluid with gas, the gas can diffuse to annulus 1 (Figure 23) and when the bore is depressurized the Inner Tube ⑤ could be collapsed.

- **Structure 55°**



55° flexible pipes do not have pressure vault. The tensile armour armouring angle is 55°, making tensile armour layers more resistant to internal pressure. The tensile armour layers ② will resist to axial tension load, internal and external pressure. Usually, this type of flexible pipes is used in large diameter pipes that operate with relatively low internal pressure. They are lighter than flexible pipes with pressure vault, thus facilitating handling and installation, and reducing cost.

Figure 26: Structure 55°.

➢ Flexible Pipe with Thermal Insulation

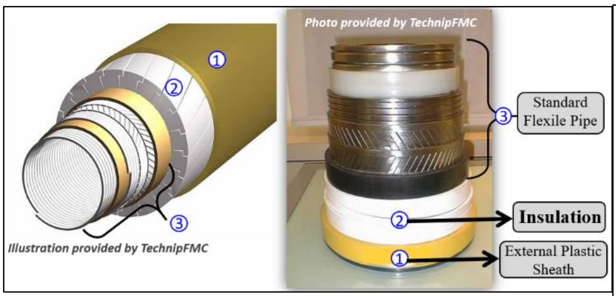


Figure 27: Flexible pipe with insulation.

Insulating layers can be added for flow assurance purposes (Avoid hydrate or paraffin formation). In order to increase the thermal insulation of the flexible pipe, insulation tapes or profiles ② are usually wound above the outer layer (now called the Intermediate Sheath), above the insulation the external sheath ① is extruded, which results in a new annulus space. In deep water application, this annulus is usually designed to be flooded to reduce the reverse end-cap effect as explained in figure 12.

➢ Electrical Traced Heated – Heating Cable Replacing Armour Wires – ETH-HCRAW

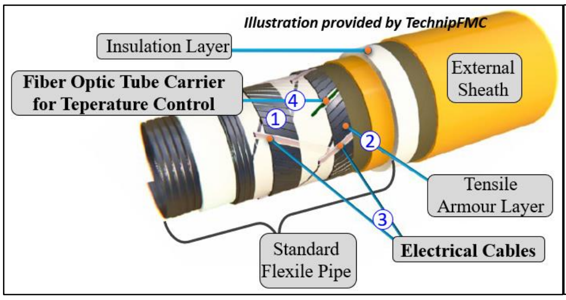


Figure 28: Flexible pipe ETH-HCRAW.

➢ The ETH-HCRAW flexible pipe is similar to the IPB in terms of the intelligent active heating system, however the electrical cables ③ are helically wound replacing some of the tensile armour wires (①&②). A tensile armour wire is also replaced by a small metallic tube ④ in which the optical fiber is inserted. Reference [12].

➢ Integrated Production Bundle - IPB

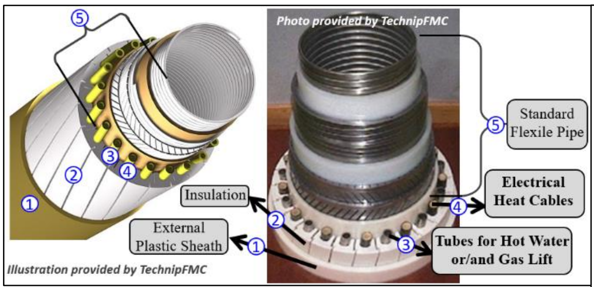


Figure 29: Integrates Production Bundle (IPB).

Integrated Production Bundle - IPB is a standard flexible pipe ⑤ plus hoses ③ and/or cables ④ for heating (by Joule effect). This pipe has an optical fiber along its length to monitor the bore temperature. The electrical cables and optical fiber are part of an intelligent systems that heats the pipe whenever the monitored temperature drops below a pre-established value.

Present IPB as offering yet greater heating power capability than ETH-HCRAW, thanks to dedicated layer. The hoses can be used for example for gas lift injection, in this case the flexible pipe would have 2 functions combined (Production and Gas Lift, Figure 8).

➢ Carbon-Fibre Tensile Armours Riser – CFTAR

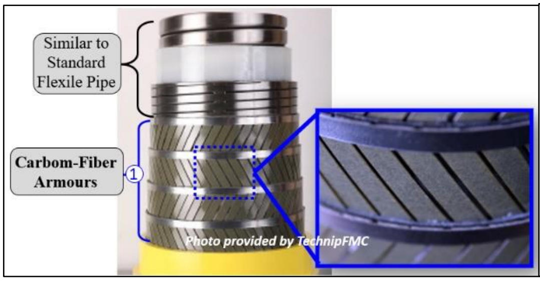


Figure 30: Flexible pipe CFTAR.

CFTAR flexible pipe replaced metallic tensile armour wires by carbon fiber composite armour wires ①, considerably increasing the tensile strength and reducing the pipe weight. These characteristics favor its use as a riser top section (connected to floating unit) for ultradeep water applications under "sour" service conditions.

➢ **Hybrid Flexible Pipe – HFP**

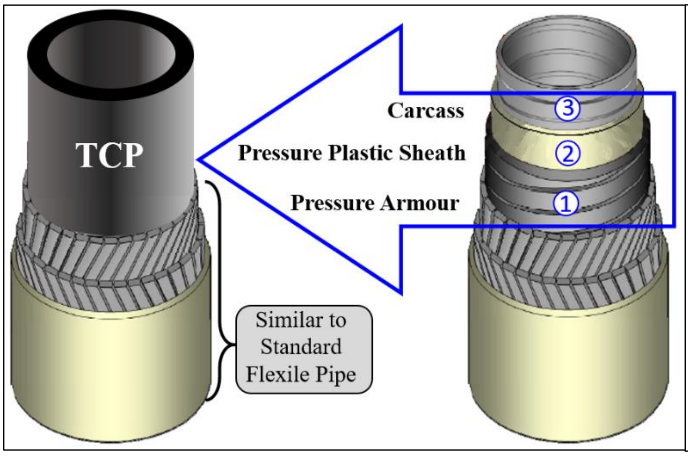


Figure 31: Flexible pipe HFP.

HFP is considered the new generation of flexible pipes. In this new design, 3 layers (pressure armour①, pressure sheath ② and carcass ③) are replaced by a single tube in composite material (TCP - Thermoplastic Composite Pipe, ④). Compared to conventional flexible pipes, there is a considerable reduction in the pipe weight and diffusion through the TCP, from the bore to the annulus.

16.5 DESIGN OF FLEXIBLE PIPES

This section provides an overview of flexible pipe design, starting from the required input data, cross-section design, and verifying the design suitability for extreme conditions, service life (fatigue) and installation.

16.5.1 Flexible Riser Design

As defined in section 16.3, riser is the suspended part of the line. It is submitted to all environmental loads as described in this same section (Figure 6.).
The main information required for the riser design are:

- Design and operating water depth;
- Service life (Typically 20-30 years);
- Internal design pressure and temperature;
- Fluid conditions (molar composition, density, temperature and pressure profiles);
- Environmental conditions (Waves, Currents, Temperature along the water depth, etc.) for both extreme and fatigue conditions;
- Floating unit characteristics:
  - RAO (Response Amplitude Operator - RAO) tables where the 6 degrees of freedom of a specific point of the floating unit (CoM - Center of Motion) are presented in function of wave periods and direction;
  - Slot position, in relation to CoM, where the riser will be connected to the floating unit;
- Floating unit offset for 1-year, 10-year and 100-year return period environmental conditions;
- Specific wave and current conditions are usually considered for installation analysis;
- PLSV (Pipe Laying Support Vessel) characteristics:
  - RAO (Response Amplitude Operator - RAO) tables where the 6 degrees of freedom of a specific point of the PLSV (CoM - Center of Motion) are presented in function of wave periods and direction;
  - Tensioner position (Figure 20-2), in relation to CoM;
  - Number of tracks, track length, pad material and geometry (Figure 20-2);
- Marine soil composition at the location (sand, clay, occurrence of rocks and/or corals), and geotechnical survey data;
- Standards and codes applicable to the project. Usually the flexible pipe design must meet API (American Petroleum Institute) standards:
  - API RP 17B – Recommended Practice for Flexible Pipe [13];
  - API Spec 17J – Specification for Unbonded Flexible Pipe [14].

Some oil companies also have their own technical specifications and/or define specific codes (for example DNV) to be followed in the project.
The main components designed during the riser project are shown in Figure 32.

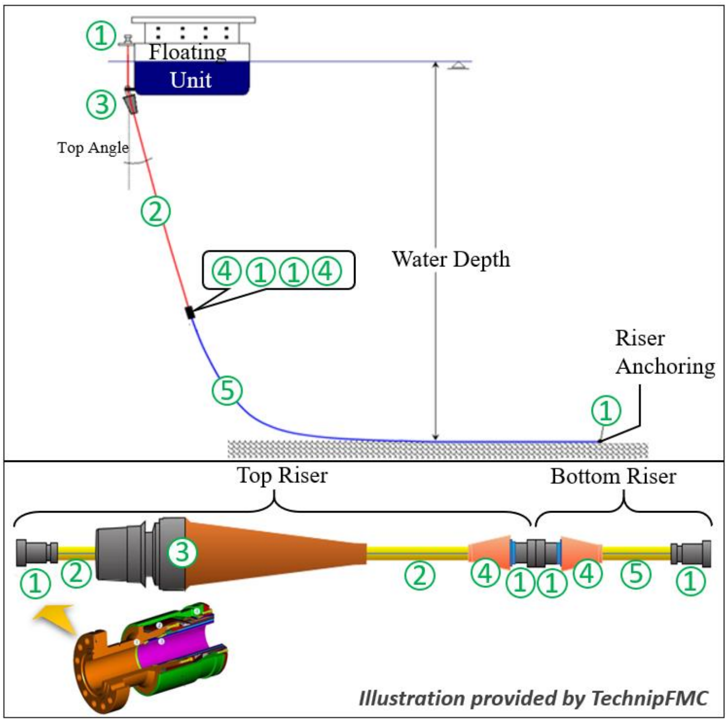


Figure 32: Riser’s components.

① End-Fitting ➔ The end fittings are assembled at the ends of each flexible section, where all layers are fixed;
② Riser Top and ④ Bottom sections ➔ The risers can be divided into sections (2 or more) to optimize the flexible structure due to loads (e.g. top and bottom regions) and/or due to manufacturing and installation limitations;
③ Bend Stiffener ➔ The Bend Stiffener is a polyurethane cone that makes a smooth transition of bending stiffness between the floating unit connection and the flexible pipe, ensuring a better pipe curvature distribution along of this region.

The simplified riser's design flowchart is shown in Figure 33.

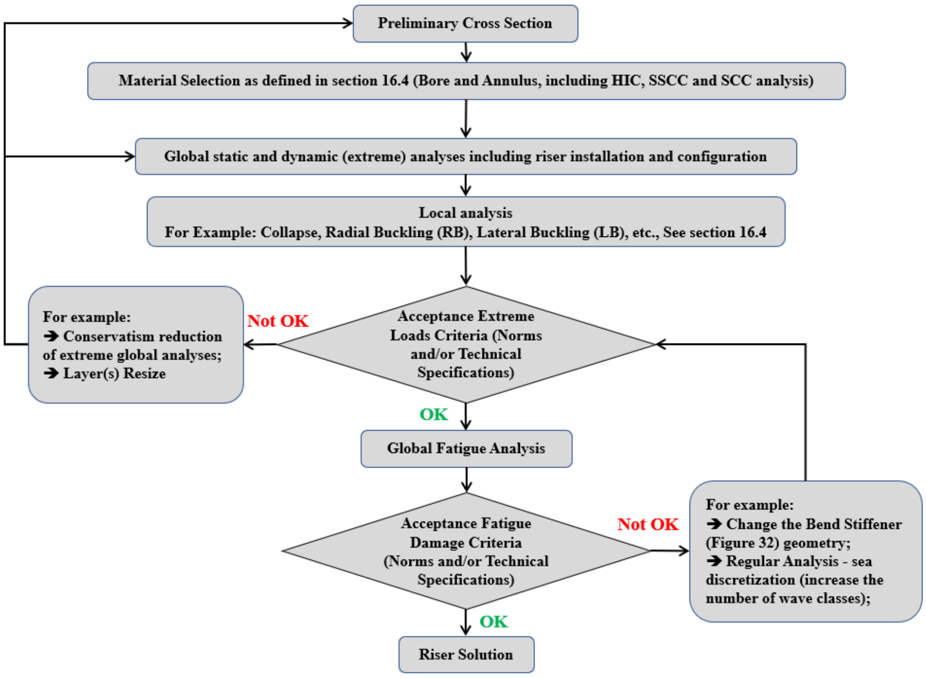


Figure 33: Riser's design flowchart.

Some important points in the riser´s design flowchart:

- Global analyses are simulations of production systems (Floating Unit + Riser) under the action of environmental loads (waves and marine currents) in dedicated software, for example DeepLines, ORCAFLEX and FLEXCOM. Global analyses are performed to check extreme (decennary and centenary recurrence), fatigue (annual recurrence) loads applied to the riser under static and dynamic conditions during its lifetime, and installation loads;
- The extreme global analysis, fatigue and installation are usually initially performed considering "regular wave approach", where the real waves are approximated by regular waves (i.e. monochromatic) or sets of regular waves. For each regular wave combined with the marine current profile, simulations are performed.
  When needed, global analyzes can be carried out from irregular waves, where the sea is represented by an energy density spectrum, which is considered as a more realistic approach;
- The tensions and curvatures along of the riser, obtained from the global analyses are the input for local analyses. TechnipFMC developed a dedicated local analyses software for each failure modes as presented in section 16.4;
- The flexible risers main types of configuration are shown in Figure 34. Whenever possible, the free hanging catenary configuration is selected, due to its low cost and installation simplicity. However, some limitations found during the riser design (e.g. high and inacceptable curvature levels at seabed) can be solved by changing the riser configuration. For example, a lazy wave configuration can almost decouple the floating unit motions from part of the riser close to seabed. It will also reduce the loads at the top side.

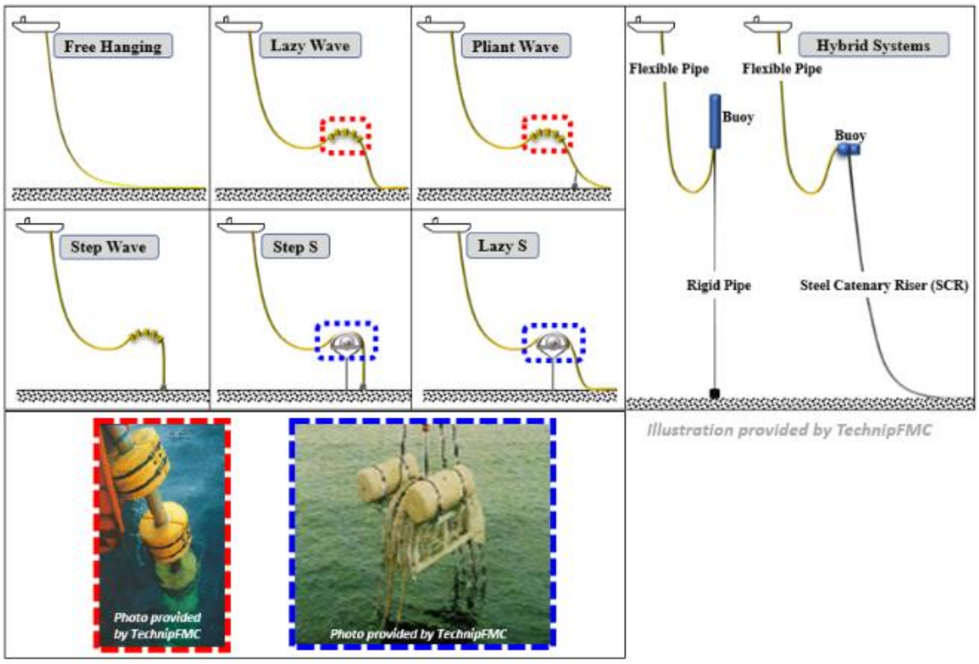


Figure 34: Flexible Riser's main configurations.

More details in references [16], [17], [18] and [20]

- As shown in figure 32 the riser can be split in 2 or more sections. The length of each section must be analyzed according to the manufacturing capacity, reel storage (Section 16.6) and handling during installation in the PLSV (Pipe Laying Support Vessel). The riser's weight per meter and external diameter must also be analyzed from the same point of view.

16.5.2 Flexible Flowline Design

As defined in section 16.3, flowline is the static part of the line after de riser anchoring (Figures 8 and 32), and subject to marine current, riser/soil interaction loads and thermal and pressure loads, as described in this same section (Figure 6). The main information required for the Flowline design are:

- Design and operating water depth;
- Service life;
- Internal design pressure and temperature;
- Fluid conditions (molar composition, density, temperature and pressure profiles);
- Location environmental conditions (Currents, Temperature along the flowline track on the seabed, etc). Normally, this information must have annual, decennary and centenary recurrence to check the flowline stability on the seabed;
- Specific wave and current conditions are usually considered for installation analysis;

- PLSV (Pipe Laying Support Vessel) characteristics:
  - RAO (Response Amplitude Operator - RAO) tables where the 6 degrees of freedom of a specific point of the PLSV (CoM - Center of Motion) are presented in function of wave periods and direction;
  - Tensioner position (Figure 20-2), in relation to CoM;
- Number of tracks, track length, pad material and geometry (Figure 20-2);
- Marine soil composition at the location (sand, clay, occurrence of rocks and/or corals), and geotechnical survey data;
- Standards and codes applicable to the project. Usually the flexible pipe design must meet API (American Petroleum Institute) standards:
  - API RP 17B – Recommended Practice for Flexible Pipe [13];
  - API 17J – Specification for Unbonded Flexible Pipe [14].

Some oil companies also have their own technical specifications and/or define specific codes (for example DNV) to be followed in the project.
The main components designed during the flowline project are shown in Figure 35.

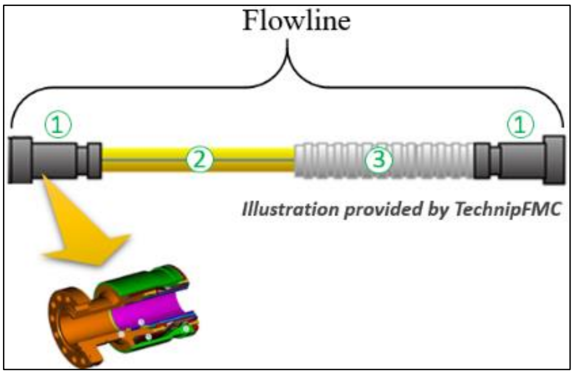


Figure 35: Flowline’s components.

① End-Fitting ➔ The end fittings are assembled at the end of the flexible tubes, where all layers are fixed;
② Flowline
③ Bend Restrictor ➔ The Bending Restrictor is assembled at the flowline extremity that will connect with subsea equipment, it is designed to protect the flowline against unacceptable bending radius during installation and operation.

The simplified flowline’s design flowchart is shown in Figure 36.

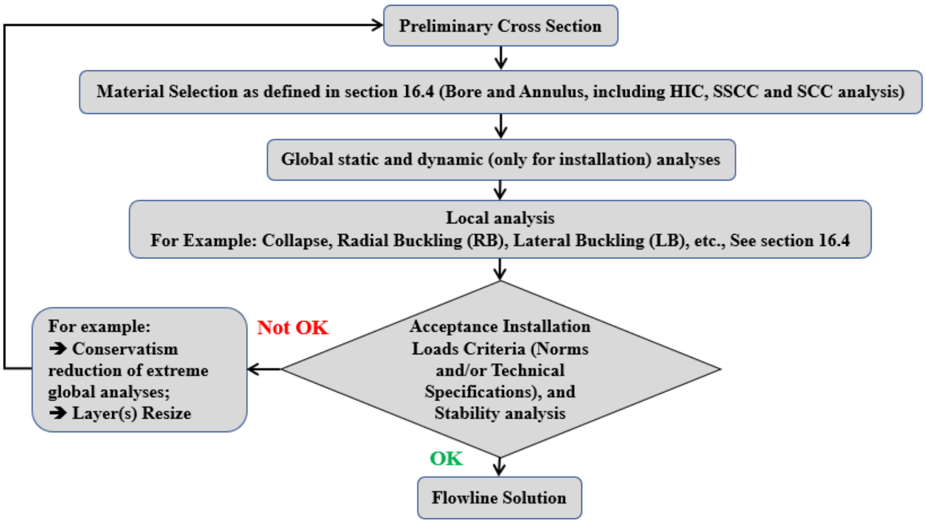


Figure 36: Flowline’s design flowchart.

Some important points in the flowline´s design flowchart.

- In the flexible flowline design, usually are performed installation global analysis only to installation, of the regular type;
- The tensions and curvatures along of the flowline, obtained from the global analyses are the input for local analyses software. TechnipFMC developed a dedicated local analyses software for each failure modes as presented in section 16.4;
- The flowline length must be analyzed according to the manufacturing capacity, reel storage (Section 16.6) and handling during installation in the PLSV (Pipe Laying Support Vessel). The flowline’s weight per meter and external diameter must also be analyzed from the same point of view.

16.5.3 FIELD DEVELOPMENT AND DESIGN CONDITIONS OVERVIEW

The field layout and pipeline system technology selection shall consider all the functional and operational requirements, operator preference, project schedule and contractual requirements including but not limited to local government legislation, environmental regulations and local content policy.
Gas and Oil exportation strategy is crucial for the field development. Distance field to shore and country infrastructure (refineries and local market demand) shall be considered aiming at selecting the best option.

Pipeline system shall fulfill the design and installation requirements and meet the field layout constraints. Despite pipelines offering the safest and most efficient means of transporting hydrocarbons, they are not immune to failure and therefore routine inspection and maintenance shall be detailed during project phase based on past experience and failure criticality. Monitoring system is often installed to the pipeline.
The flowlines and static jumpers network varies as function of the reservoir technology (vertical, inclined or horizontal). The layouts with dual flowlines and drill centers are very typical in West Africa, Gulf of Mexico and North sea. In Brazil, mainly in the pre-salt area, wells are spread out on the field and therefore the flowline network varies from looped flowline with several ILSs, named daisy-chain configuration, to single flowlines tie-back to the Floating Production Unit (FPU) and the production looping formed through the piggable christmas tree (Petrobras style).

Development in the pre-salt and post-salt area demands different challenges associated with CO_2 content, chloride content in the formation water and pressures. Currently, CO_2 is often re-injected in the wells aiming at mitigating climate change and increasing the production recovery (Enhanced Oil Recovery method). The CO_2 re-injection significantly increases the CO_2 concentration in the production and injection fluids which combined with high pressures leads to highly corrosive environment and pipe design challenges.
All these aspects above have straight consequence on the field layout development strategy and project CAPEX. During field layout development, pipeline, subsea production system, installation and construction teams shall work together. A comprehensive screening of different field layouts shall be prepared for cost evaluation, risk assessment and Technology Readiness Level (TRL). Engineering teams shall prepare the preliminary Material take-off and Material Equipment List. Installation and construction teams shall perform the vessel screening and prepare the preliminary project execution plan and schedule. Supply chain team shall be involved providing support for the project team. The level of detail and quality of the information is crucial for the decision made on the most cost-effective field layout solution.

The flexible pipe technology enables the positioning of the FPU in close vicinity of the wellheads, which is a positive feature in terms of exploration and project CAPEX. The beneficial feature of flexible pipe is its ability to accommodate high curvature, allowing ease installation and absorption of dynamic motions arising from the FPU and environmental loads. Installation costs are very low when compared with rigid pipe solution requiring less installation aids and usually allowing high sea state for installation.

Although the flexible pipe cross-section definition is more complex, the overall design and installation engineering activities are less time consuming than for the other pipe technology. Flexible pipe solution minimizes all costs related to the thermo-mechanical effects suppression like global lateral buckling and pipe walking due to operating cycles (start-up/ shutdown). Due to the flexible pipe ability to accommodate on the seabed bathymetry, no free span is expected along the route. Such features make the flexible pipe a cost-effective solution minimizing the overall project cost including engineering, material and vessel time.

Flexible pipe solution often avoids intermediates subsea equipment and jumpers since the flexible pipe can be directly connected to the Christmas trees. The pull-in and hang-off systems are much simpler than those ones for rigid riser. Flexible riser enables early pre-commissioning activities since topside spool installation is not required, e.g. after pull-ins operation the flexible riser' end connector is clamped on the FPSO (Floating Production, Storage and Offloading) deck. Pre-commissioning scope is often limited to leak test. Such features allow to speed-up the 1st Oil.

16.6 MANUFACTURING OF FLEXIBLE PIPES

This section presents the main process of flexible pipes (Note 1) manufacturing using reels, from a step-by-step description of a typical flexible pipe as presented in section 16.4.

Main considerations in the manufacture of flexible pipes by reels:

- Reels are steel structures, built especially for the flexible pipe manufacturing, storage and transport. This structure consists of a "drum" coupled to 2 "flanges" (Figure 37).

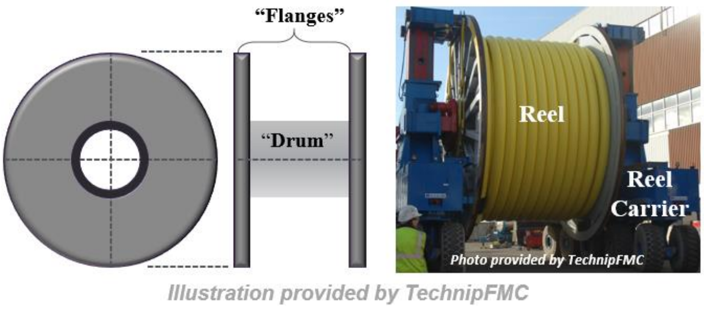


Figure 37: Reel and vehicle to reel transport (reel carrier).

- As mentioned in section 16.5, the maximum continuous length of flexible pipe which can be manufactured is limited (in terms of weight and volume) by the capacity of the reel;
- During manufacturing, two reels alternate between pay-off reel (previous manufacturing stage storage) and take-up reel (current manufacturing storage);
- After each manufacturing step machine there is a tensioner that pulls the manufactured pipe. There must be perfect synchronism between the emission reel unroll and the receiving reel roll;
- All pipe manufacturing, whether of Rough Bore or Smooth Bore pipes, are started on a calibrator tooling that guarantees the flexible pipe internal diameter.
- Each manufacturing step requires a manufacturing over-length to reach the layer manufacturing tolerances. These over-lengths are monitored and at the end of manufacture they are discarded;
- After the flexible pipe manufacturing, the end-fittings are assembled at the pipe extremities, and the reel is taken to a safe area where a hydrostatic test is performed (FAT - Factory Acceptance Test Pressure). The pressure must remain above the nominal test pressure and below the maximum test pressure for 24 hours. Typically, the nominal test pressure is 1.5 (for dynamic application) or 1.3 (for static application) x Design pressure and the maximum test pressure is between 1.05 and 1.1 x nominal test pressure.

The figures 38 to 42 shows flexible pipe manufacturing stages by reel:

Stage 1: Carcass Manufacturing

The carcass is manufactured by cold forming a strip with a profiling machine.

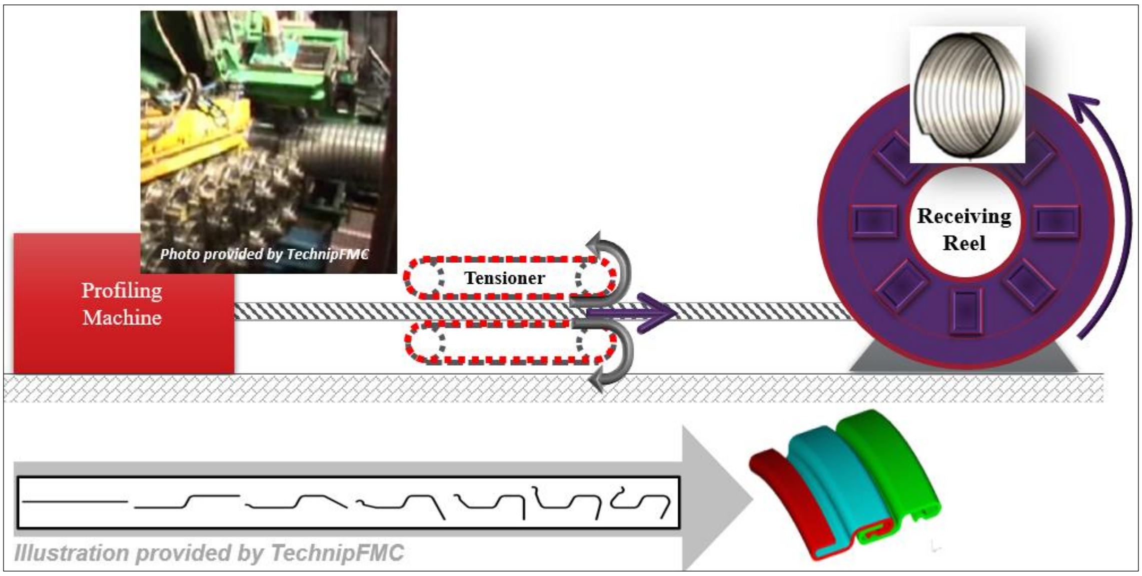


Figure 38: Carcass profiling machine.

Stage 2: Pressure Sheath Extrusion

The thermoplastic pellets are heated and mixed, forming a circumferential melt that is distributed uniformly around the flexible pipe and cooled by water spraying and water tanks.

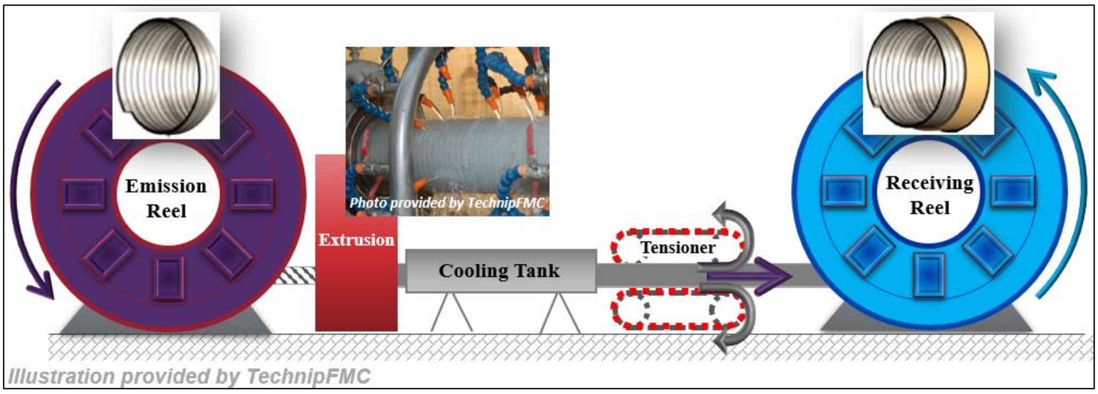


Figure 39: Pressure Sheath extrusion.

Stage 3: Pressure Armour Manufacturing

A shaped wire, as shown in the section 16.4, is wound to form the pressure armour.

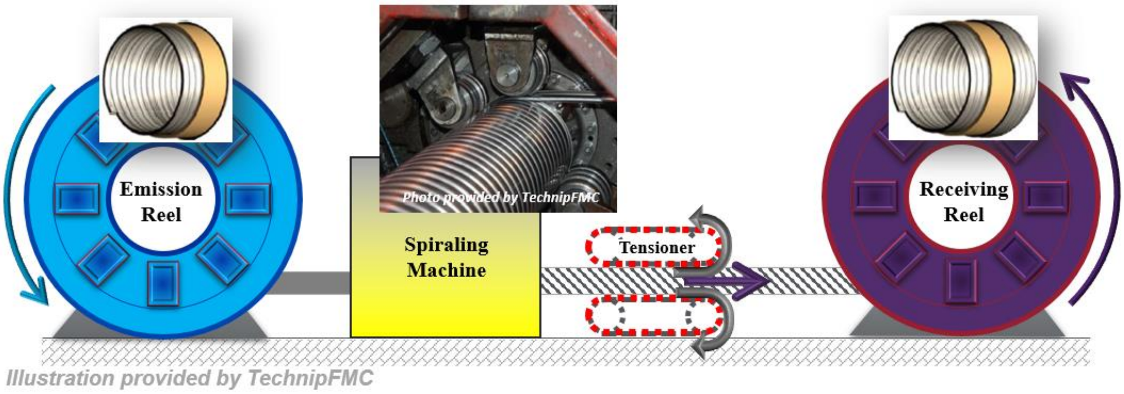


Figure 40: Pressure Armour spiraling machine.

Stage 4: Tensile Armours Manufacturing

The tensile armour layers are manufactured by winding two layers of flat steel wires in a helicoidal shape. Between the tensile armour layers manufacturing stages and after the external armour manufacturing, tapes can be applied (auxiliary fabrication tapes, anti-wear and/or antibuckling tapes, as presented in section 16.4).

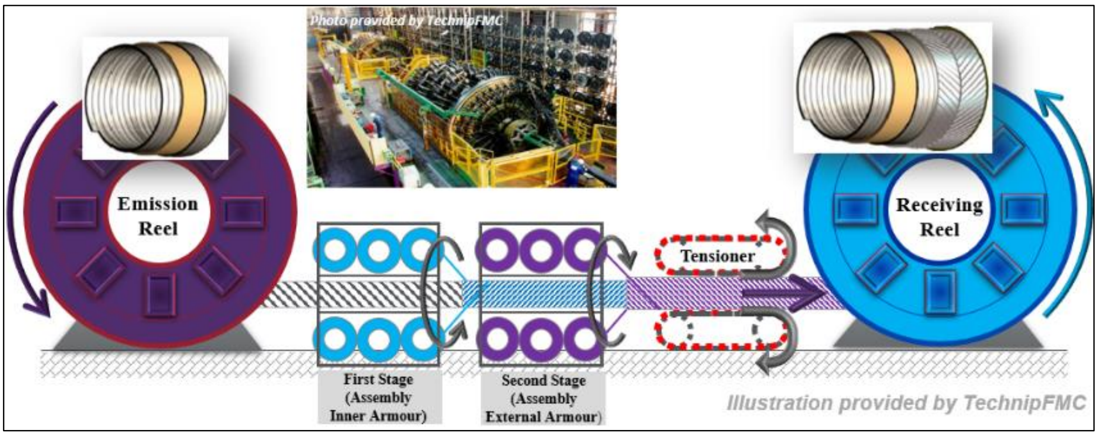


Figure 41: Tensile Armours manufacturing.

Stage 5: External Plastic Sheath Extrusion

The thermoplastic is heated, distributed uniformly around the flexible pipe and cooled by water spraying and water tanks.

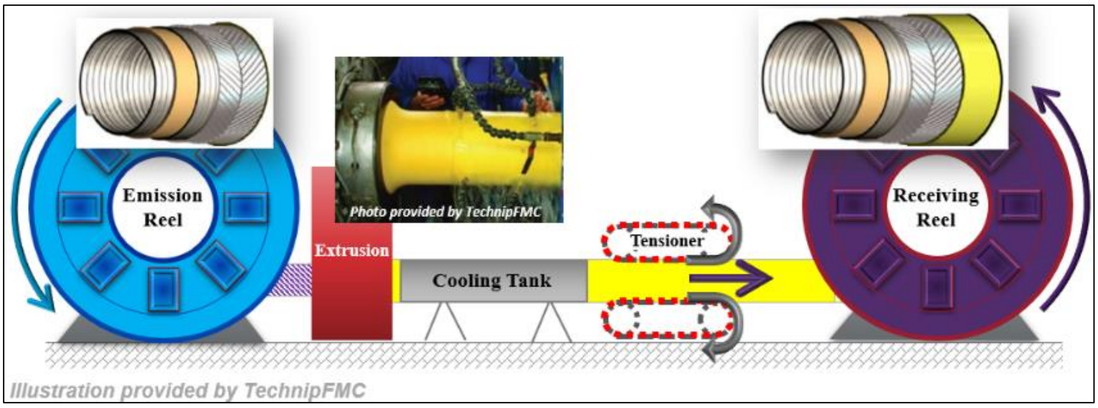


Figure 42: External Sheath extrusion.

Sometimes the flexible pipe exceeds the capacity of manufacturing in reels, so there is the possibility to manufacture in carousels. In this case, the pipe is transferred between manufacturing stages through guides (special conveyors) throughout the factory. At the manufacturing end it is stored in carousels (Figure 43).

Figure 43: Manufacturing carousels in TechnipFMC (Flexifrance - Le Trait).

16.7 FIELD CONSTRUCTION WITH FLEXIBLE PIPES

Field construction strategy shall be defined based on the contractual requirements, field layout architecture including water depth, pipeline system configuration, subsea equipment design among other factors.

Field construction phase encompasses manufacturing, fabrication and installation activities of the several pipeline systems. Installation activities will typically include pre and post intervention works, logistics, installation, tie-in and pre-commissioning. The goal of the installation activities is to deploy the subsea equipment and interconnect the infrastructures between them and to the FPSO as defined by the field layout.

The planning and management of the offshore operations are crucial for the success of the project. All engineering activities shall be performed based on the Project Quality and HSE Plan. Lessons Learnt, Design and Constructability Review and Hazard Identification and Risk Assessment (HIRA) sessions shall be held with all stakeholders during the engineering phase in preparation to the offshore construction phase.

As a thumb of rule, the detailed design engineering and installation engineering works shall be performed aiming at minimizing offshore operation risks and maximizing the vessel scope and operability. The vessel operability shall be assessed during the early stage of the project for confirmation of the flexible pipe design with regards to allowable significant wave height (Hs) for installation. The installation loads shall be used for confirming the selected vessel and designing of the pipeline, subsea equipment and installation aids.

Installation engineering works shall cover installation aids design, flexible pipe packing and installation and construction procedures. The installation team shall interface with the pipeline and structural design teams providing assistance and support on the optimum design, e.g. cost-effective and installation friendly. In large projects, the installation engineering team can be split into different groups as follows: umbilical installation team, flexible pipe installation team, rigid pipe installation team, construction team including ROV(Remotely Operated Vehicles) intervention, pre-commissioning and commissioning team, etc. Each team has a leader responding to the Project Installation Engineering Manager, or sometimes to the Project Operations Manager.

The Installation and Construction procedures shall be performed based on project requirements and shall include, but not limited to, the following minimum documents:

1. Installation Vessel Mobilization and Demobilization Procedure
2. Flexible Pipe and Material Loadout Procedure
3. Installation Vessel Positioning and Calibration Procedure
4. Pipeline System Installation Analysis including initiation, normal pipelay and riser transfer to FPU
5. Pipeline System Installation Procedure
6. Pipeline System Pre-commissioning Procedure

Installation analyses, based on numerical models and 3D softwares, are performed to support the installation and construction procedures. The offshore construction works including pre-lay survey of the installation corridor, Long Base Line (LBL) array installation and subsea equipment installation are also required for field development. All works shall be strictly performed as per approved procedures.
Flexible pipe factory shall have quayside access for flexible pipe loadout onto the installation vessel or reels transportation to a proper loadout base is required. Figure 40 shows the installation vessel mobilization.

Figure 44: Vessel Mobilization at TechnipFMC Flexible Pipe Factory in Açu Port

Depending on the contractual requirements and project strategy, flexible pipe factory quayside is also used as onshore logistic base for storage of other project's materials and equipment which will be loaded out on the installation vessel as part of the project offshore installation execution plan. TechnipFMC has the ability to provide the design, manufacturing and installation of the flexible risers and flowlines.

When flexible pipe factory doesn't exist in country, flexible pipes are manufactured abroad and transported overseas using charter vessel or heavy lift vessels (HLV). Once in-country, the flexible pipes are transferred to barges or offloaded to the port quayside for posterior loadout on the installation vessel. Flexible pipes are manufactured, stored and transported for installation in reels and/or carrousels. Figure 45 shows the flexible pipe transpooling from the storage carrousel to the Deep Blue vessel carrousel at bay. Deep Blue is a Reel-lay vessel capable to install rigid pipe and flexible pipe/ umbilical in water depth up to 3000m.

Figure 45: Flexible Pipe Overseas Transportation and Transpooling to Deep Blue

A dedicated logistic team shall be set-up within the project aiming at facilitating and organizing most of the logistics issues (i.e. customs, transport, accommodation, storage area, local supplies, etc.). The logistic team shall interface with the procurement and operation teams to support all logistic requirements. Material and equipment lead time shall be considered in the procurement and logistic plan ensuring the project schedule by having them at the right location, the right time, the right quality and the right cost.

Before commencement of the pipeline system installation, preparatory works shall be performed as follow:

- Pre-lay survey for confirmation of the seabed bathymetry and natural or man-made obstruction
- When required, LBL array installation and calibration including the installation of marker buoys
- Subsea equipment installation as-planned in the offshore schedule

Pre-lay survey shall be performed along the laying corridor of all pipeline systems including the locations of subsea equipment. The goal is to confirm the laying corridor centerline bathymetry and identify debris, rock outcrops, depressions, among other features within the laying corridor which can compromise the pipe integrity or become the route unfeasible. Marker buoys may be installed at each installation target box for visual monitoring by ROV. Concrete mattresses are installed in locations where pipe crossing is planned.

The encompassment of the preparatory works and the synergy with other construction works will define the required vessels characteristic for field development. The date at which the preparatory works shall commence depends on the project contractual requirements, i.e. how long in advance pre-lay survey can be performed prior to pipeline installation, and the float between installation activities. There are several possibilities for preparatory works performance. The decision shall take into account the preparatory works scope, the installation vessel arrival date in field and the installation sequence. The goal is to minimize the project cost by reducing the number of vessels to be mobilized and optimizing the in-field vessels scope.

There are several techniques for underwater acoustics positioning, for instance: Long Baseline (LBL), Short Baseline (SBL), Long and Short Baseline (LSBL) and Ultra Short Baseline (USBL). As a thumb of rule, pipe laying is performed using USBL system while subsea equipment and transition riser x flowline are installed using LBL system due to the tight installation target box. Survey team shall optimize as much as practical the number of LBL arrays. The strategy behind the number of LBL arrays and their re-positioning during the offshore works shall be evaluated based on the cost and the offshore schedule planning.

Flexible pipes packing strategy plays an important role in the project cost and shall be established based on suppliers limitation, flexible pipe size, weight and length and pipeline system configuration. The pipe length which can be stored in the carrousel or reel is limited by weight or volume criteria. Due to the large weight and size, flexible pipe stored in carrousel are often transpooled to the vessel carrousel. Flexible pipes stored in reels can be directly loaded on the vessel deck or alternatively transpooled to the vessel carrousel. The transpooling from reels to the vessel carrousel shall strictly follow the installation sequence. Figure 46 shows a typical flexible pipe loadout sequence. When flexible pipes are installed from reels, TR winches are used to control the flexible pipe pay-in/ out from the reel to the installation vessel laying system.

Figure 46: Typical Flexible Pipe Loadout Sequence

The goal of the packing strategy is to optimize the vessel deck space and to loadout the longest pipeline length aiming at reducing the number of vessel's trips for field development. The loadout duration plays an important role in the overall project cost. Flexible pipes packed in reels expedite the loadout duration, while flexible pipe transpooled into the vessel carrousel takes longer. Depending on the available deck space, supply vessel is required for offshore transfer of containers, materials, etc. to the installation vessel.

During vessel mobilization marine warranty surveyors shall be mobilized to inspect the vessel spread and to certify the loadout and sea fastening of the flexible pipe reels and loose items such as appurtenances, accessories, containers, spares, test equipment, etc. storage on the vessel deck. All material lifting activities shall strictly follow the lift plans included in the mobilization and/or installation procedures.

Once the installation and construction documentation package is approved, preparatory works are complete and installation vessel loadout is performed, the field construction can commence. Flexible pipe can be installed empty or flooded with seawater (free flooding). The flexible pipe designer must define the flexible pipe installation conditions together with the installation team and based on project requirements.

The installation of flooded pipe can largely increase the installation catenary top tension possibly impacting the selected installation vessel (tensioners capacity). Sometimes, flexible pipes shall be installed flooded to prevent pipe collapsing at the installation catenary sag bend or to ensure their stability during installation. How long the carcass material can be exposed to raw seawater shall be confirmed by the pipe designer and compared with the offshore installation schedule. During pre-commissioning and commissioning activities the raw seawater shall be flushed from the pipe and replaced by filtered and treated seawater (cocktail of corrosion inhibitor and oxygen scavenger) or commissioning fluids such as diesel, glycol or methanol.

There are several flexible pipe installation vessels available on the market. Installation vessel deck layout including pipe laying equipment varies from project to project basis as function of the selected installation vessel and field subsea arrangement. It is the installation engineer responsibility to define the most suitable installation vessel deck layout and the required equipment for the offshore installation. The tensioners type, vertical or horizontal, and its constructive form, three or four caterpillars including their length, has an important role on the flexible pipe design and must be evaluated by design and installation engineers.

Figure 47 presents some flexible pipe installation vessels from TechnipFMC fleet. The tensioners load capacities varies from 270Te to 650Te allowing flexible pipe installation in water depth up to 3000m.

Figure 47: Flexible Pipe Installation Vessels (TechnipFMC Fleet)

Field development often includes the installation of several pipelines systems, e.g. production, gas and/or water injection, gas and/or oil export and umbilical. The pipeline length shall be sufficient long to connect the relevant locations and to avoid complex seabed topography/ features likes pockmarks and escarpments. The goal is to find feasible paths that minimize the overall pipeline length and installation cost.

Figure 48 presents a typical flexible pipeline system arrangement for ultra-deepwater application. Flexible pipe installation direction can be from christmas tree to FPSO or from FPSO to christmas tree. The first laying direction is called 2nd End Riser pull-in while the second one is called 1st End Riser pull-in. The most common laying direction is from christmas tree to FPSO. Laying direction shall take into account the riser configuration including adjacent risers, FPSO pull-in winch capacity and project contractual requirements.

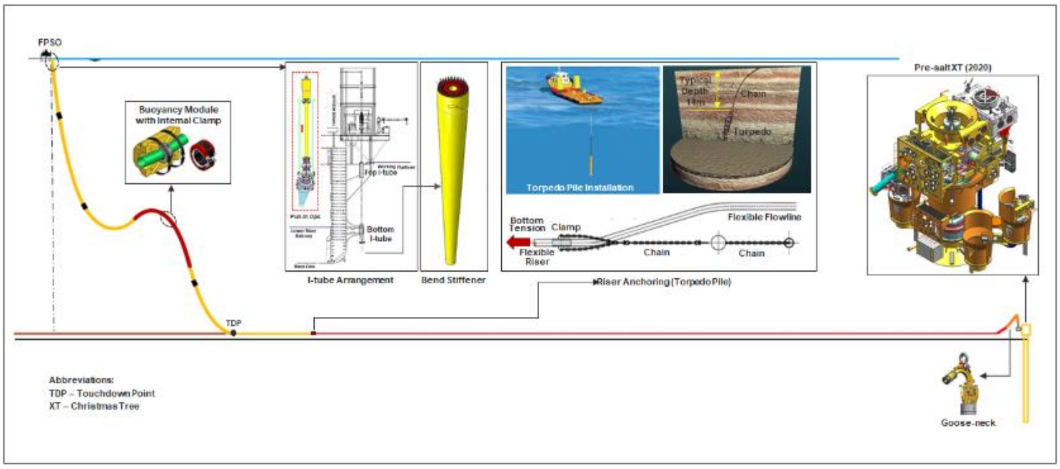


Figure 48: Typical Flexible Pipeline System Arrangement.

Flexible riser in free hanging configuration is the most attractive choice for the riser system. The free hanging configuration provides a simpler and cost-effective riser solution due to its low material cost and fast installation time. Flexible riser in lazy wave configuration is used to cope/ absorb the large motions of the spread-moor FPSO under harsh environmental conditions as-found in the pre-salt area. The drawback of the lazy wave are as follows: (1) the configuration requires buoyancy modules which impact the project cost and (2) the buoyancy module section increases the riser susceptibility to clash with adjacent riser
A high level installation procedure is presented below for 2nd End riser pull-in as follow:

1. Transfer the 1st End end-fitting from reel to working table through laying tower using the winch cable
2. Once the 1st End end-fitting is at working table, perform visual inspection and connect end equipment
3. The end-fitting connection (bolts makeup) can be performed using tensioning tool or torque tool. After bolts makeup, perform flange back seal test and install bend restrictor or any other ancillary as required
4. Payout flexible pipe flowline on tensioners and deploy end equipment to depth. When the flowline length is made by several flexible pipe sections, the following applies:
   - Each flexible pipe section is passed independently through the laying tower
   - 1st End end-fitting and 2nd End end-fitting installation procedure follows the standard procedure
   - 2nd End end-fitting is lowered to the working table using the A&R winch from the tower top
   - Once the 2nd End end-fitting is at the working table, the end-fitting is secured by a hang-off clamp
   - The 1st End end-fitting of the next flexible pipe section is routed through laying tower
   - The 1st End end-fitting and 2nd End fitting intermediate connection is then made up in the working table: bolts makeup and flange back seal test. Ancillaries are installed if/as required
   - These steps shall be repeated until the flowline length is complete as required for installation

5. When the end equipment is near the seabed, ROV will connect the vessel crane to the end equipment sling and perform the connection to the subsea asset (or land the equipment on the seabed)
6. The flowline laying will continue along the installation route until the transition riser x flowline (TRF) reaches the working platform. During laying crossing with pre-installed pipe may exist.

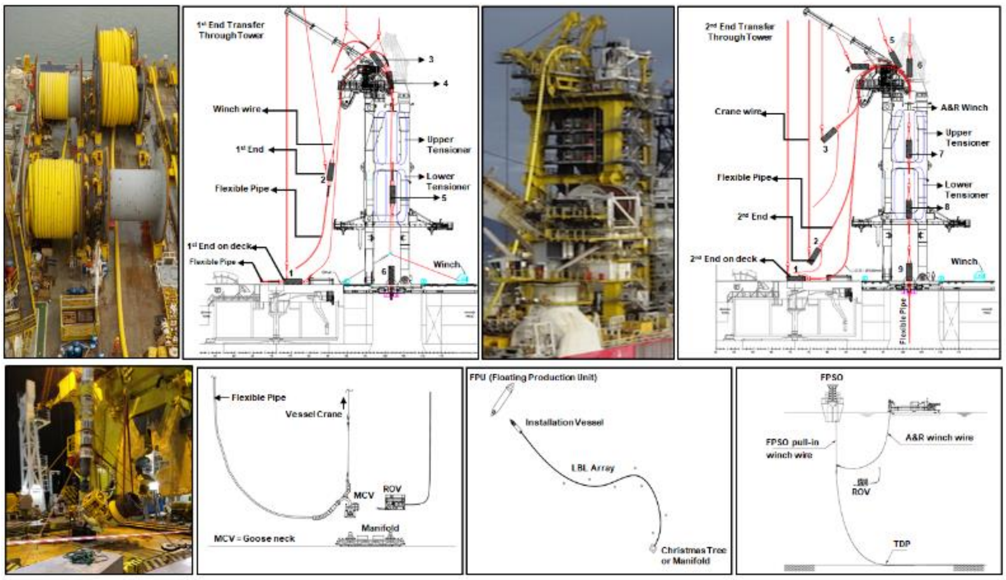


Figure 49: 1st End and 2nd End End-fitting Transfer and Subsea Equipment Connected

7. Survey team shall confirm the transition riser x flowline installation target box. If required, flowline overlength is laid laterally on the seabed to ensure the transition riser x flowline landing at target box
8. Commence riser installation and install buoyancy modules following the required spacing
9. Once the bend stiffener reaches the working table, riser transfer procedure shall be followed
10. Riser transfer procedure typically encompasses the following steps:
    — FPSO pull-in winch wire is passed through the I-tube and lowered to depth
    — FPSO pull-in winch wire is recovered to the vessel deck and connected to the riser pull-in head
    — Vessel to payout A&R winch wire until the riser pull-in head reaches the load transfer depth
    — Once the riser load is fully transferred to the FPSO pull-in winch, vessel A&R winch wire is disconnected from the riser pull-in head by ROV
    — FPSO pull-in winch wire is paid-in until the bend stiffener is locked by the dogs to the I-tube bottom end and the flexible riser end-fitting is above the I-tube upper end. Split flange is installed and the end-fitting is positioned and secured to the support flange on top of the I-tube
    — FPSO pull-in winch wire is disconnected from the riser pull-in head
    — Pre-com activities can commence as/ if required
    — Divers may be required to completely secure the bend stiffener to the I-tube bottom end

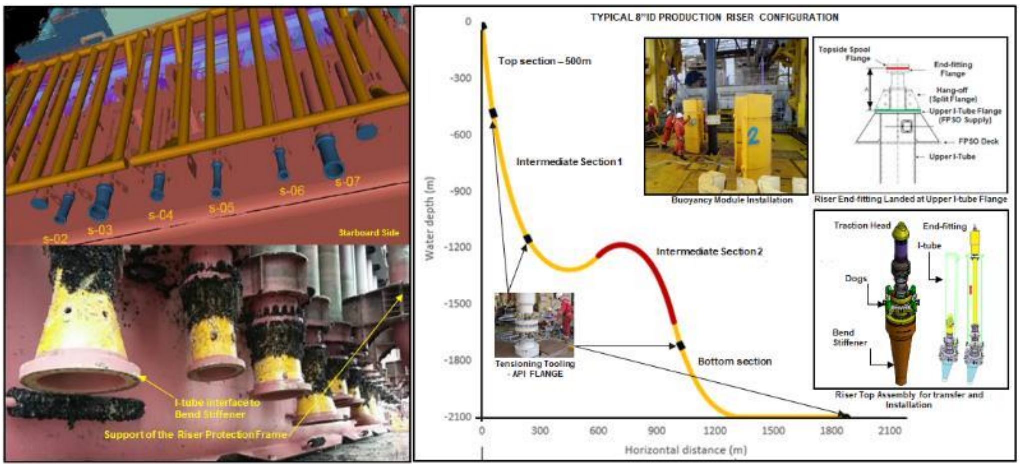


Figure 50: FPSO I-tube Arrangement, Riser Top Assembly and Fixation to I-tube

Fan beam reflector tube and radius transponders are often installed at the FPSO for installation vessel positioning relative to the FPSO hull. The positioning equipment location will need to have clear line-of-sight to the installation vessel. As installation vessel makes her approach for riser transfer to the FPSO pull-in winch, there may be communication between the installation vessel bridge and FPSO team.

Different installation procedures can be defined based on contractual requirements, accessories dimensions and weight, installation vessel characteristics and FPSO riser balcony location and hang-off design. The 1st End riser pull-in follows a similar installation procedure being the difference in the two ends as follows:

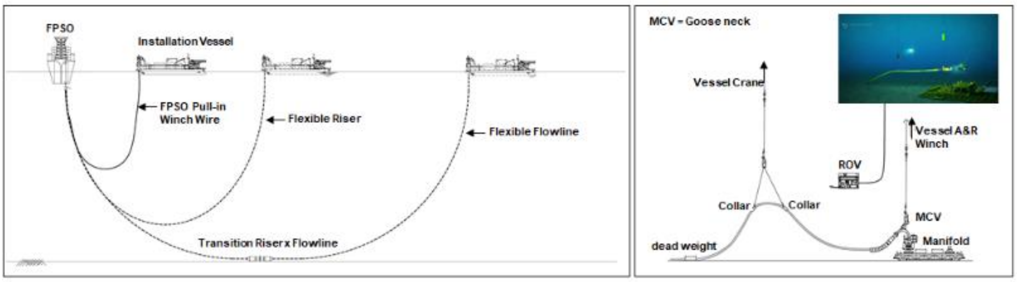


Figure 51: 1st End Riser Pull-in Installation Sequence

As a thumb of rule, flexible riser minimizes the costs related to the riser pull-in and hang-off systems. Flexible riser enables to commence the pre-commissioning works earlier since the pipe end is pulled up to the FPSO working deck. Such feature enables to speed-up the 1st Oil and minimizes the risks related to diving works during riser hook-up to the FPSO typically required for rigid riser installation. The installation procedures detailed above can be also used for umbilical system installation.

API 17B [13] and 17J [14] present the recommendations and acceptance criteria for flexible pipe pre-commissioning activities. As part of the factory acceptance test, flexible pipes are typically gauge plate pigged and pressure tested at the fabrication yard. Unless otherwise indicated in the project contractual requirements. Offshore pre-commissioning works are often limited to the leak test to confirm no leakage at the connection points.

If required by the contract, the pre-commissioning strategy shall be defined based on the subsea field layout and contractual requirements. Flooding and pigging operation involves the passage of least one pig (multi-purpose pig) for cleaning and gauging. Gauge plate pig is used to confirm pipe integrity, i.e. no excessive ovalization. Pig moves inside the pipeline by internal pressure differential from pig launcher to pig receiver. Chemicals are often mixed to the flooded water (raw or filtered seawater): corrosion inhibitors, dye and oxygen scavenger. The pigging direction can be from subsea to FPSO or vice-versa. Subsea pump or FPSO deck pump is used to push the pig inside the pig receiver. Once the pig is at the receiver, the pig is removed for inspection of the gauge plate. Points such as grooves and plate deflection are noted. Upon completion and acceptance by all parties, the pressure test (also called hydrostatic pressure test) can commence.

Pressure testing involves internally pressurizing the pipeline until the test pressure is reached and stabilized. The pressure test duration, after test pressure stabilization, varies as operator by operator basis. Typically, the test pressure hold period is 24 hours for the hydrostatic test and 6 hours for the leak test. Throughout the test, temperature and pressure variations are recorded and then compared against the design acceptance criteria. The biggest difference between the hydrostatic test and the leak test is that, in the first, the focus is on verifying the structural integrity of the pipeline after installation and, in the second, the focus is on leak detection in the end's connections. Offshore hydrostatic test pressure is defined as 1.25 times system design pressure while leak test pressure is 1.1 times system design pressure. Upon pressure test completion and acceptance by all parties, commissioning operations can commence. Brazilian regulation (ANP) requires that pre-commissioning works shall be certified by third party aiming at getting approval for field start-up.

Commissioning activities involves the start-up the subsea system including the product filling and bringing it up to operation. Commissioning activities often encompass dewatering, drying and inertization with N2. Diesel, crude oil, methanol, glycol or a combination of them are typically used to displace the seawater left inside the pipeline from the pressure test. A pig train may be used for commissioning purpose. The goal is to remove any residual water inside the pipeline preventing hydrate formation during operation start-up.

The Brazilian government authorities are responsible to oversee environmental regulation attendance for onshore and offshore operations. The pre-commissioning and commissioning activities shall consider, as minimum, the following requirements:

- Chemicals (e.g. Biocide, oxygen scavenger …) cannot be discharged in seawater. Chemicals shall be treated before discharging in seawater or recovered in tanks onboard the installation vessel or FPSO
- MEG(Mono-Ethylene Glycol), Glycol or similar products cannot be discharged in the seawater. They must be recovered in tanks onboard the installation vessel or FPSO
- Fluorescein (dye) usage and discharged in seawater is typically accepted. However, the environmental license for field development shall reflect and consider the discharge in the seawater of the fluorescein

Filtered and untreated seawater (with no chemical) can be discharged in the seawater

More details in references [21],[22] and [23]

REFERENCES

[1] – Chakrabarti, Subrata K.; 2005. Handbook of Offshore Engineering – Volume I and II, ELSEVIER

[2] – Bai, Yong; Bai, Qiang ; 2005, Subsea Pipelines and Risers, ELSEVIER

[3] – Palmer, Andrew C.; King, RogerA.; 2004, Subsea Pipeline Engineering, 1ª edition, Pennwell Books

[4] – Fuchs, H. O.; Stephens, R.I.; 1980, Metal Fatigue in Engineering, New York

[5] – Feret, J.; Bournazel,C.H.; " Calculation of Stresses and Slip in Structural Layers of Unbounded Flexible Pipes "; 1987. Journal of Offshore Mechanics and Artic Engineering (OMAE), Vol.109. pages 263-269

[6] – Feret, J.; Leroy, J.M., Estrier, P.; "Calculation of Stresses and Slips in Flexible Armour Layers with Layers Interaction", 1995. Journal of Offshore Mechanics and Artic Engineering (OMAE), Vol.V. pages 469-474

[7] – Leroy, J.M., Estrier, P.; "Calculation of Stresses and Slips in Helical Layers of Dynamically Bent Flexible Pipes", 2001. Oil & Gas Science and Technology – Rev. IFP, Vol. 56, No. 6, pp. 545-554

[8] – Leroy, J.M., Perdrizet, Timoyhée. Core, V., 2010."Stress Assessment in Armour Layers of Flexible Risers", Offshore Mechanics and Artic Engineering Conference (OMAE), OMAE2010-20932

[9] – Caleyron, F., Leroy, J.M., Guiton, M., Duchêne, P., Estrier, P.; Vraniskoski, K., Damiens, A., 2017."Stresses in Tensile Armour Layers of Unbounded Flexible Risers Loaded with External Pressure – Application to Lateral Buckling Mode", Offshore Mechanics and Artic Engineering Conference (OMAE), OMAE2017-61133

[10] – Vraniskoski, K., Phelut, R., Legeay, S., Gros, P., 2018. "New Flexible Pipe Cost Effective for Static Application", Offshore Technology Conference (OTC), OTC-28559-MS

[11] – Caleyron, F., Core, V., Paumier, L., 2017. "Effect of Installation on Collapse Performance of Flexible Pipes", Offshore Mechanics and Artic Engineering Conference (OMAE), OMAE2017-61100

[12] – Lefer, B., Dessaint R., Marchand, D., 2018. "ETH-HCRAW a Cost Effective Flexible Pipe for Active Heating", Offshore Technology Conference (OTC), OTC-28765-MS

[13] – API 17B; 2014. Recommended Practice for Flexible Pipe. 5th ed. American Petroleum Institute.

[14] – API 17J; 2014. Specification for Unbonded Flexible Pipe. 4th ed. American Petroleum Institute.

[15] – ISO 15156-1;2015. Petroleum and natural gas industries – Materials for use in H_2S – containing environments in oil and gas production.

[16] – Luppi,A., Sullivan, R., Cousin, G., Degenetais,G., Haldy, C., 2004. "Hybrid 'S' Riser (HySR™) Designed and Tested for Deepwaters", Rio Oil&Gas Expo and Conference, IBP33004

[17] – Vivet, R., Minguez, M., Berhault, C., Jacquin, E., Ptrie, F., Flamand, O., 2011. "Flat Buoy Concept for Freee Standing Riser Application: An Improvement of the In-Place Hydrodynamic Behavior", Offshore Mechanics and Artic Engineering Conference (OMAE), OMAE2011-49329

[18] – Minguez, M., Luppi,A., Berger, A., 2012. "Slender Boy FSHR Vortex Induced Rotations", Offshore Mechanics and Artic Engineering Conference (OMAE), OMAE2012-83406

[19] – Wood Group, Sureflex JIP Members, 2017, Flexible Pipe Integrity Management Guidance & Good Practice, J000621-00-IM-GLN-001 – Rev.0

[20] – Silva, J.V., Damiens, 2016. "3000m Water Depth Flexible Pipe Configuration Portfolio", Offshore Technology Conference (OTC), OTC-26933-MS
[21] – Hopkins, B.C., Williams, M.R., Skeels, H.B., 1986. "Diverless Lay-Away Flowline Connector System", Offshore Operations Symposium-ASME, PD-Vol.1-Pages 107-114
[22] – Skeels, H.B., Terrell, R.K., Costa, M., Davis, K.D., 1992. "The State of The Art of Flexible Pipe Lay-Away Pipeline Installations", Offshore and Artic Operations-ASME, PD-Vol.42-Pages 17-32
[23] – Skeels, H.B., Martins, J.A., Singeetham, S.P., 1989. "Detail Design of a Guideliness Subsea Satellite Completion", Offshore Technology Conference (OTC), OTC-5885

Contributions
Brian Skeel – Senior Techincal Advisor (TechnipFMC);
Philippe Lembeye – Directeur Propriété Intellectuelle (TechnipFMC);
Guillaume Pringuay – Senior Manager Flexibles Technology (TechnipFMC);
Felipe Reis – Head of Flexibles Technology Brazil (TechnipFMC);
Bruno Guigon – Manager Flexibles Technology Brazil (TechnipFMC);
Phellip Frigeri – Manager Flexibles Technology Brazil (TechnipFMC);
Rafael Stikan – Manufacturing Process Flexibles Manager (TechnipFMC);

Acknowledgements
Will Davie – Vice President Product Management (TechnipFMC);
Catie Tuley – Director Public relations (TechnipFMC);
Tina Kruse – Manager Marketing (TechnipFMC);
Marianna Pietrani – Manager Marketing (TechnipFMC);