INTEGRITY MANAGEMENT OF SUBSEA FLEXIBLE PIPELINES

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by

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ABSTRACT

As offshore oil and gas production continues to expand, the number of subsea flexible pipelines continues to increase. Today, the annual global demand for flexible pipe is estimated at around \$2 billion CDN, corresponding to around 1,200-1,700 km of flexible pipelines per year *(NKT, 2011)*. About 60 km of flexible pipelines are located offshore Newfoundland and account for over half of the oil-and-gas-producing pipelines in this region. The White Rose Field and the Terra Nova Field are two of the three major oil and gas fields in this area; both have been developed using Floating, Production, Storage and Offloading (FPSO) vessels and flexible pipelines tied into turret-moored buoys. Flexible pipelines are critical for successful operation of FPSO; if the flexible pipe fails, the whole system may fail *(Chen, 2011)*. An understanding of flexible pipeline integrity management is thus essential for safe operations of FPSO systems.

This thesis introduces and discusses flexible pipelines and different methods for subsea flexible pipeline integrity management. The thesis begins describing the design, construction, installation, operation, maintenance and decommissioning stages of a flexible pipelines' lifecycle. Subsequently, a hazards and operability study is conducted to identify issues that may interfere with flexible pipelines in different stages of the flexible pipeline's lifecycle.

A framework for Project Risk Analysis of a flexible pipeline project is also developed. The purpose of the framework is to provide a consistent and systematic approach to

handle risk during operations of flexible pipeline systems. This framework allows project teams to proactively identify and prevent problems or minimize their risk.

A detailed Failure Mode Effect and Criticality Analysis (FMECA) is conducted to identify failure modes through risk analysis. This analysis is performed on the main lifecycle stages and critical event failure modes evident for flexible pipelines. Based on the analysis, risk reducing measures are proposed. Future development related to subsea flexible pipeline engineering is briefly described.

Finally, conclusions are drawn and recommendations are made for supplementary works which may serve to reduce risks associated with flexible pipeline systems.

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Faisal Khan for his patience, guidance and support throughout my Master's pursuit. Thank you for encouraging me to succeed.

I would like to thank my co-workers and supervisors at Technip Canada Limited, for introducing me to flexible pipeline engineering and encouraging me to develop my niche in this area.

To my husband and my parents, I would not have finished this without your reminders! Thanks for always encouraging me to do my best.

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List of Symbols, Nomenclature or Abbreviations

ALARP	As Low As Reasonably Practical
API	American Petroleum Institute
A&R	Abandonment and Recovery
ASME	American Society of Mechanical Engineers
DRAPS	Drilling Applications
DNV	Det Norske Veritas
DSV	Dive Support Vessel
FAT	Factory Acceptance Test
FMECA	Failure Modes Effects and Criticality Analysis
FPSO	Floating Production Storage and Offloading
JIP	Joint Industry Project
MOP	Maximum Operating Pressure
MBR	Minimum Bending Radius
MBR_{st}	Minimum Bending Radius for Storage
OD	Outer Diameter
RECE	Reverse End Cap Effect
ROV	Remote Operated Vehicle
RP	Recommended Practice
SCIP	Spirally Cut Impact Protection
SG	Specific Gravity
VLS	Vertical Lay System

1 Introduction

1.1 History

Flexible pipelines have a history of successful use throughout the developed world *(Vinidex, 2000)*. In the North Sea, Brazil, off the coast of Africa and throughout the waters of Australia, developers of oil and gas operations have been using flexible pipelines for oil and gas production since the 1970s *(Technip, 2012)*.

In the 1990s, the concept of Floating, Production, Storage and Offloading systems (FPSO) was developed and implemented as a very cost effective way of exploiting offshore oil and gas resources. Cost is significantly reduced by using FPSO instead of traditional fixed platforms *(Chen, 2011)*. A pipeline solution using a flexible pipe approach provides many technical advantages and cost savings over a rigid pipe approach when considered early in the project *(Society of Petroleum Engineers, 1995)*.

Flexible pipe systems are critical for successful operation of FPSO; if the flexible pipe fails, the whole system may fail *(Chen, 2011)*. Offshore Newfoundland, both the White Rose Field and the Terra Nova Field have been developed using the FPSO concept and flexible pipe systems. An understanding of flexible pipeline integrity management is essential for safe operations offshore. This thesis focuses on flexible pipeline integrity assessment and management.

1.2 Objectives and Scope

The main objective of this thesis is to explain flexible pipeline engineering and to define risks specific to flexible pipelines which must be recognized and resolved to ensure the integrity of subsea flexible pipelines offshore. The flexible pipeline in context to Newfoundland offshore development is explored. The objectives and scope of this thesis are outlined below:

1. The first chapter shall cover definitions and descriptions of flexible pipelines for typical offshore oil and gas applications. Descriptions of the main structural components of a flexible pipeline are included. This section shall give a basis for the further tasks. The primary focus is set on flexible pipelines used for production operations since it is of most relevance to offshore Newfoundland.

2. A framework for Project Risk Analysis for offshore oil and gas projects utilizing flexible pipelines shall be established. This shall give an overview of how to handle risks, methods that may be employed and when to use these methods.

3. Identification and discussion of potential risks and operability problems during subsea flexible pipeline operation shall be performed through a risk analysis. FMECA is chosen to be the method of analysis. The discussion shall contain suggestions of risk reducing measures for the analyzed operation. The costs of the potential risks are not detailed as such information is proprietary and limited.

4. Future development related to subsea flexible pipeline engineering is included in the scope of work. The main future design trends which serve to reduce risks in flexible pipeline operations shall also be studied.

This thesis provides a detailed perspective of flexible pipeline integrity management and serves to prove that once flexible pipeline integrity management is understood, risks associated with the use of flexible pipelines may be brought to an acceptable level. Therefore, flexible pipelines can be seen as viable alternatives to traditional, rigid pipeline solutions.

1.3 Thesis Structure:

This thesis consists of the following seven chapters:

Chapter 1 provides the necessary background information, objectives and scope, and a presentation of the thesis structure.

Chapter 2 gives an introduction to subsea flexible pipelines and the ancillary equipment required in flexible pipeline systems. Definitions and classification of flexible pipelines structures are described. Background information explaining why there is a demand for flexible pipelines is given.

Chapter 3 gives a technical description of the main stages in the lifecycle of a flexible pipeline, discussing flexible pipeline design, construction, installation, operation, maintenance, repair, and decommissioning.

Chapter 4 introduces a framework for project risk analysis in conjunction with subsea flexible pipelines.

Chapter 5 applies the project risk analysis framework to flexible pipelines and covers a description and discussion of the main operational risks of flexible pipelines using a Failure Mode Effect and Criticality Analysis (FMECA).

Chapters 6 presents future trends in flexible pipeline engineering which may help reduce some of the risks identified in the preceding chapters.

Chapter 7 concludes the thesis and gives recommendations for further work.

2 Flexible Pipelines

2.1 General

Flexible pipelines are used offshore Newfoundland for both static and dynamic, oil and gas applications. They are composite structures, comprising several layers of interconnecting thermoplastic, tapes, metallic components and insulation. Figure 2-1, below, displays the cross section of a flexible pipeline, revealing its compsite nature.

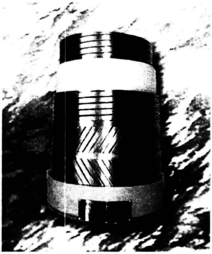

Figure 2-1: Standard Flexible Pipeline Structure (Technip, 2011)

Flexible pipelines may be used subsea, as well as offshore on topsides for jumpers. There are many applications for flexible pipelines. The main types used for subsea applications include:

- Production – multi-phase hydrocarbon applications
- Water Injection – re-injected water
- Gas Lift – gas injected to aid production

- Gas Injection – gas injected to increase reservoir pressure
- DRAPS – drilling applications
- Offloading – dynamic hydrocarbon offloading riser

2.2 Classification of Flexible Pipelines

There are two fundamentally different classes of flexible pipe structures: rough bore and smooth bore. The rough bore structure may be used in virtually all applications, while the smooth bore has restrictions placed on the type of service that it may undertake.

The two classifications are based on the composition of the inner layer of the pipe structure. For a rough bore structure the innermost layer is manufactured from an interlocked steel carcass, as shown in Figure 2-2. The term "rough" is representative of the profile of the interlocked steel strip. The actual surface of the steel on the carcass of a rough bore structure has a very smooth finish.

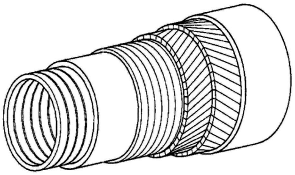

Figure 2-2: Rough bore flexible pipe structure (SUT, 2002)

A smooth bore structure represents a flexible pipe where the fluid-pipe interface is a thermoplastic tube, as shown in Figure 2-3.

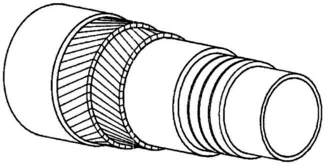

Figure 2-3: Smooth bore flexible pipe structure (SUT, 2002)

The choice between smooth bore and rough bore is usually dependent upon the composition of the transported fluid or client-driven preferences. Where gaseous multiphase, low-density fluids are to be transported, a rough bore structure is usually adopted. Production, gas injection and gas lift structures are therefore typically rough bore structures.

For single-phase flexible pipeline applications, such as in water injection systems, a smooth bore structure is adopted. If a smooth bore structure is to be used for multi-phase fluids, the design must consider that gas within the transported fluid that diffuses into the structure annulus may produce sufficient pressure to collapse the thermoplastic tube. The annulus of a flexible structure is considered the voids formed between continuous thermoplastic layers.

2.3 Ancillary Equipment

To supplement the functionality of the flexible pipelines, two critical pieces of ancillary equipment are needed. This equipment includes end fittings and bend stiffeners, which are further explained below.

2.3.1 End Fittings

The end fitting terminates the end of the pipe, maintaining the integrity of the pipe structure, sealing the inner and outer extruded layers, and providing a fixture to transmit tension and pressure loads to the pipe structure *(Flexsteel, 2010)*. An image of an end fitting is shown below in Figure 2-4.

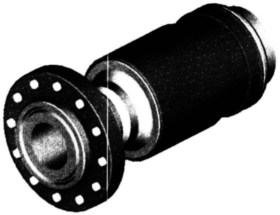

Figure 2-4: Flexible Pipe End Fitting (Technip, 2011)

The end fitting comprises three parts:

- Body: Inside which the pipe layers are terminated including the rear crimping flange and cover.
- Termination: The interface between adjacent structures e.g. a flange or hub.

- Vault neck: Connects the body to the termination.

The design of the main parts of the end fitting is in accordance with the requirements of API 17J. Other API and American Society of Mechanical Engineers (ASME) specifications, such as API 6A "Specification for Wellhead and Christmas Tree Equipment" and ASME B16.5 " Pipe Flanges and Flange Fitting" may also be referenced in end fitting design.

Each end fitting is designed to withstand the maximum loads it will experience due to the combined effects of internal and external pressure, axial loads, shear forces and bending moments. The body of the end fitting is designed for an internal pressure equal to the bursting pressure of the flexible pipeline to which it is attached. The end fitting shall have pressure integrity and load bearing capacities greater than the pipe *(CNLOPB, 2009)*.

2.3.2 Bend Stiffeners

At the termination point of a flexible riser, umbilical or cable, the stiffness of the system undergoes a step change *(Exsto, 2012)*. This sudden change in stiffness creates high levels of stress if the flexible is bending away from the termination point. In a dynamic situation, this can lead to fatigue failure in the flexible riser *(Exsto, 2012)*. Bend stiffeners are therefore required at a built-in connection of a dynamic riser behind its end-fitting or along the line at the bottom end of an I-tube.

Bend stiffeners are constructed of a cone of polyurethane to create a continuous stiffness variation, where the cone dimensions are defined to satisfy the Minimum Bending Radius

(MBR) of the pipe and service life criteria specified by the operator. Figure 2-5 shows a typical bend stiffener.

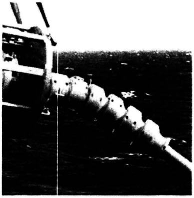

Figure 2-5: Typical Bend Stiffener (Exsto, 2012)

Design of bend stiffeners is such that the bend radius of the risers within their stiffeners shall be greater than the minimum bending radius of the riser multiplied by the factors of safety as specified within API 17J and summarized below in Table 2-1. The maximum percent strain on the extreme fibres of the bend stiffener and its position along the stiffener is maintained within allowable values as specified by the manufacturer.

Loading Condition	MBR Factor of Safety
MBR of External Sheath (m)	-
Normal operation (intact and fatigue conditions)	1.50
Abnormal operation (survival conditions)	1.25

Table 2-1: Minimum Bend Radius Values (API, 2009)

2.4 Why Flexible Pipelines are Needed

Where rigid pipelines are not feasible, flexible pipelines offer highly technical pipeline solutions for a variety of applications.

Flexible pipelines may be preferred over their rigid counterparts for a variety of reasons. Their low bend radii provide simplified pipeline routing opportunities, shorter crossing lengths and eliminate the need for free span correction; their multi-layer composition offers excellent built-in insulation. External corrosion resistance is provided by a thermoplastic external sheath, which surrounds the pipe and provides a water tight seal with the external environment.

Due to the advantages that flexible pipelines offer, they are recognized as advantageous over rigid pipelines, with the following functional benefits *(NKT, 2012)*:

- Flexible pipelines are purpose designed products, optimized for each specific application;
- Flexibles pipelines' design combines the flexibility of a polymer pipe with the strength and weight of a steel pipe;
- Flexible pipelines follow the natural contours of seabed thus eliminating the susceptibility to free pipeline spans;
- Flexible pipelines allow for minimization of external corrosion effects owing to encapsulation of the steel armour inside a continuous polymer outer sheath;
- They accommodate misalignments during installation and tie-in operations;
- Provide the possibility of diverless installation without the need for metrology;
- Load-out and installation is safer, faster and cheaper than any other pipe application;
- They can be retrieved and reused for alternative application thus enhancing the overall field development economics and preserving the environment.

- Flexible pipelines have excellent inherent thermal insulation properties.

Flexible pipelines are generally dynamically stable and provide upheaval buckling control and may be trenched under pressure. Their use also avoids the requirement for tie-in spools, which may be costly and consume offshore time for installation. Flexible pipelines can also be re-routed and reused thus cost effective.

Flexible pipes rely upon their ability to deform from imposed loads *(KWH, 2002)*. Some standards define a flexible pipe as one that can deflect more than 2% without cracking *(KWH, 2002)*. Only a small portion of imposed loads are actually carried by the flexible pipe itself. Instead, load is transferred to the surrounding bedding material *(KWH, 2002)*.

2.5 Industry Codes and Standards

Today, there are three main fabricators of flexible pipelines: Technip, based out of France; NKT Flexibles, based in Denmark, and Wellstream, which was acquired by GE in 2011 *(Wellstream, 2012)*, operating out of England. Each manufacturer of flexible pipe has proprietary methods of designing their flexibles however, to ensure their product is accepted by industry, their designs must follow a common standard.

Until recently, no design codes / standards specifically developed for flexible pipe existed. Each operator had their own specifications with different requirements. A Joint Industry Project (JIP) launched in early 1990s served to define an industry standard specification for flexible pipe *(SUT, 2002)*. Contributions from a wide range of operators, manufacturers, contractors and regulatory authorities resulted in American Petroleum Institute (API) standards for flexible pipe:

- API-17J – Specification for Unbonded Flexible Pipe
- API-RP-17B – Recommended Practice for Flexible Pipe

Flexible pipe design is now largely governed by these American Petroleum Institute guidelines for unbonded flexibles. Particularly, the specification API-17J, which specifies the minimum requirements for the design, material selection, and manufacture, testing, marking and packing of unbonded flexible pipe, is accepted throughout industry. Additionally, API-RP-17B provides supplementary recommendations to API-17J and provides a set of guidelines for the design, analysis, manufacture, testing, installation and operation of flexible pipes *(API, 2009)*. Further information on the contents of API- RP-17B and API-17J follow:

2.5.1 API-17 J – Specification for Unbonded Flexible Pipe

"This specification defines the technical requirements for safe, dimensionally and functionally interchangeable flexible pipes that are designed and manufactured to uniform standards and criteria" *(API, 2009)*. It specifies the "minimum requirements for the design, material selection, manufacture, testing, marking and packing of flexible pipes" *(API, 2009)*.

API-17J covers the following aspects:

- Functional and Design Requirements
- Materials Requirements, Qualifications and Quality Assessment requirements

- Manufacturing Requirements
- Documentation
- Factory Acceptance Tests
- Marking and Packing

2.5.2 API-RP-17 B – Recommended Practice for Flexible Pipe

"This recommend practice (RP) provides guidelines for the design, analysis, manufacture, testing, installation and operation of flexible pipes and flexible pipe systems for onshore, subsea and marine applications. This RP supplements API-17J specifications" *(SUT, 2002)*

API-RP-17B covers the following aspects:

- System, Pipe and Component Description
- Pipe Design Considerations
- Materials
- System Design Considerations
- Analysis Considerations
- Prototype Testing
- Manufacturing
- Handling and Installation
- Retrieval and Reuse
- Integrity and Condition Monitoring

3 Flexible Pipelines' Lifecycle Description

The main stages in the lifecycle of a flexible pipe are shown in the below schematic, Figure 3-1, and consist of design, construction, installation, operation, maintenance and life extension or decommissioning stages. Each of these stages is described in this chapter in the context of a flexible pipe for production offshore Newfoundland.

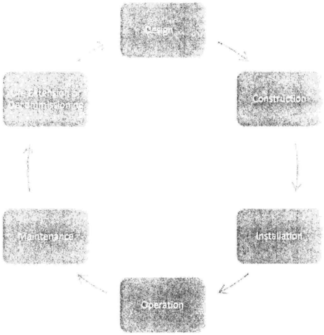

Figure 3-1: Lifecycle of a Flexible Pipeline

3.1 Design

3.1.1 Function and Material of Flexible Pipe Structure Layers

As noted previously, flexible pipelines are designed as composite structures. Their multi-layer composition makes adjustable to project specific constraints. A flexible pipe is made up of several different layers. The main components are leak-proof thermoplastic barriers and corrosion resistance steel wires *(Technip, 2011).*

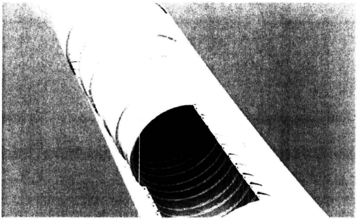

Figure 3-2: Typical flexible pipe structure (SUT, 2002)

3.1.1.1 Carcass

The internal interlocked stainless steel carcass is the fluid-pipe interface. The inner interlocked carcass is only present on rough bore flexible pipes. The function of carcass is to prevent the collapse of the pressure sheath and provide crushing resistance to the flexible pipe.

The carcass is made from spiral wound steel strip which is interlocked along the length of the pipe. The carcass is typically made of austenitic stainless steel. The strip is partially formed prior to being wound around a mandrel of the appropriate diameter, where the final forming takes place to create the interlock. A typical carcass strip is shown in Figure 3-3.

Figure 3-3: Carcass strip (SUT, 2002)

In normal service the carcass is subject to no loading as the subsequent layers withstand the effects of the internal pressure and associated loads. The carcass is, however, designed to withstand the occasional loads, such as crushing loads during installation and/or recovery of the flexible pipe offshore.

3.1.1.2 Pressure Sheath

The pressure sheath layer seals the internal bore and transfers the loads due to the internal pressure to the overlying metallic layers. The thermoplastic pressure sheath is selected for the fluid transportation application and the range of temperatures and pressures that the pipe will see over its service life. Typical materials used for thermoplastic sheaths include polyethylene, polyvinyl dichloride and polyamide. These three classifications of materials enable flexible pipe manufacture for fluid temperatures ranging from -20°C to +130°C, for both static and dynamic applications, and for pressures in excess of 1000 bar.

3.1.1.3 Pressure Vaults and Armour Layers

The pressure vault and tensile armour wires are contained in what is known as the annulus of a flexible pipe, which is the area isolated by thermoplastic sheaths. The annulus of the pipeline has a unique environment, cause by its pressure, temperature and gas diffusion from the bore.

The pressure vault consists of a spiraled wire wound at an angle close to perpendicular to the pipe's lateral axis. This angle enables the wires to resist the axial loads (including reverse end cap effect) and radial loads (hoop stress) resulting from the applied internal pressure. The wire in the pressure vault has a unique geometry which minimizes creep of the underlying thermoplastic sheath once the pipe is pressurized. An example of such a pressure wire is shown in Figure 3-4.

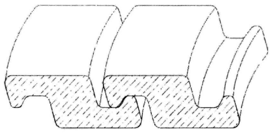

Figure 3-4: Pressure wire (SUT, 2002)

Following the pressure vault are the tensile armour layers. They consist of two layers of carbon steel wires, laid in pairs at a pitch angle appropriate to the design. The wires of each pair are cross wound, i.e. laid in opposite directions, in order to provide torsional balance. These wires resist tension of the pipe and are particularly important during installation and in-service for risers. Tensile armour wires are shown in Figure 3-5, below.

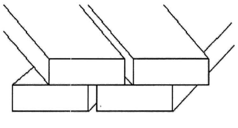

Figure 3-5: Tensile armour wires (Technip, 2012)

The considerations for the selection of material for the tensile layers are strength, toughness, and resistance to the chemicals in the annulus environment. The tensile layers are not exposed to the bore fluid; instead they are in the considerably milder annulus environment *(Flexsteel, 2010)*.

3.1.1.4 Anti-Wear Tape

Anti-wear tape is a plastic layer in the form of a tape, inserted between metallic layers, to prevent wear and fretting fatigue of these metallic layers. As per API 17J, this is required for dynamic applications only *(API, 2009)*.

3.1.1.5 High Strength Tape

High strength tape is wound over the armour layers of the flexible structure to prevent the reverse end cap effect while the pipe is in-service, i.e. prevent the wires from distorting radially. High strength tape assemblies typically consist of Kevlar® wrap yarns and glass fibre weft yarns. The weft fibre function is to guarantee an even spacing of Kevlar® yarns during tape laying on the flexible pipe. Application of high strength tapes over the armour wires is shown in Figure 3-6.

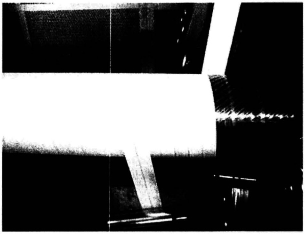

Figure 3-6: Application of High Strength Tapes (*Technip, 2011*)

3.1.1.6 External Sheaths

External and protective sheaths are thermoplastics which are suitable for dynamic applications which exhibit favorable material properties such as abrasion resistance. They seal the pipe from the external environment and have in-service functions such as increasing the pipe's bending stiffness and adding to the pipe's thermal resistance. Flexible pipes having sheaths at maximum allowable thicknesses are commonly designed to take advantage of the insulating properties of the thermoplastics in order to control heat loss and increase the flexible pipe's thermal performance. Quality control of an external sheath is shown in the below picture, Figure 3-7.

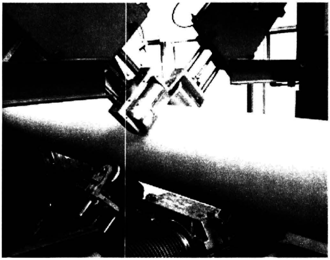

Figure 3-7: External Sheath of a Flexible Pipe (Technip, 2012)

3.1.2 Design Calculations

At the design stage, several critical calculations are required. These calculations are explained below.

3.1.2.1 Annulus Calculations of the Flexible Pipe

During service the steel layers of the flexible pipes (armour and pressure wires) become surrounded by the gases that diffuse through the pressure sheath or inner tube. It is important to determine the composition of this gaseous environment to ensure that the steel layers are not compromised by the presence of CO_2, H_2S and water in the annulus. This does not indicate that the pipe can be operated with a damaged external sheath for the field life. Wire dimensions after corrosion will be assessed to ensure wire stresses do not exceed the allowable stresses under extreme conditions as specified in API 17J.

Gas diffusion and CO_2 corrosion calculations are performed to ensure the structure materials are suitable for annulus conditions. The results of the gas diffusion calculations are also used to determine the annulus composition for the assessment of corrosion fatigue.

3.1.2.2 Minimum Bend Radius

The storage minimum bend radius (MBR) is calculated as the minimum bend radius which satisfies all the requirements of API 17J, including the following:

- Maximum allowable strain 7.7% for PA-11 and polyethylene
- Maximum allowable strain 7.0% for polyvinyl difluoride (PVDF)

The storage MBR shall be at least 1.1 times the MBR to cause locking in the interlocked layers. As per API 17J, the operating MBR for static applications (all loading conditions) shall be a minimum of 1.0 times the storage MBR, and for dynamic applications (all loading conditions) shall be a minimum of 1.5 times the storage MBR. For dynamic applications the safety factor on operating MBR may be reduced from 1.5 to 1.25 for abnormal operation and normal operation with accidental loads.

3.1.2.3 Pressure and Tension Resistance of the Flexible Pipe

The flexible risers will be checked for resistance to internal and external pressure and applied tension.

The design cases detailed below in Table 3-1 will be checked for each flexible structure:

Case	Operation Type	Internal Pressure	External Pressure	Tension
1	Recurrent	Maximum Operating Pressure	0 bar	Maximum load cases for recurrent operation from dynamic analysis
2	Extreme / Abnormal	Design Pressure	0 bar	Maximum load cases for extreme and abnormal operation from dynamic analysis
3	Installation (Functional)	Ambient Pressure	0 bar	Maximum tension estimated for installation
4	Post-Installation (Pressure Test)	Offshore Strength Test Pressure	0 bar	Maximum load cases for offshore strength test from dynamic analysis
5	Factory Acceptance Test (FAT)	FAT Pressure	0 bar	Zero

Table 3-1 Pressure and Tension Design Cases

The utilization factors within each layer are defined by API 17J, according to the type of operation, and are presented in Table 3-2 below.

Case	Operation Type	API 17J Allowable Utilisation Factors	
		Pressure Wires	Tensile Wires
1	Recurrent Operations	0.55	0.67
2	Extreme / Abnormal Operations	0.85	0.85
3	Installation (Functional)	0.67	0.67
4	Post-Installation (Pressure Test)	0.91	0.91
5	FAT	0.91	0.91

Table 3-2 Pressure and Tension Design Cases Allowable Utilization Factors

3.1.2.4 CO_2 Corrosion

The net corrosion rate of steel layers of the flexible pipe due to the diffused CO_2 combining with iron (Fe) and water will be assessed and demonstrated that this loss is not sufficient to compromise the integrity of the steel layers when submitted to the loads they are expected to encounter during the design life of the flexible risers and flowlines.

The CO_2 flow rate to consider is the stabilized flow rate of CO_2 through the pressure sheath for a damaged external sheath for the risers and flowlines respectively.

The acceptance criteria is that the flexible risers and flowlines remain compliant with API 17J design requirements in their "end of field life" condition, after considering the maximum potential thickness loss to the armour wires due to CO_2 corrosion.

3.2 Construction

This section outlines the general procedures used in the manufacture of flexible pipe structures.

3.2.1 Inner Interlocked Carcass

The material sourced for the manufacture of the interlocked carcass, typically stainless steel, starts off as coiled strips. Each strip is cold-rolled to form a semi-profiled shape before it is wound around a mandrel of the correct diameter, interlocked and crimped by adjustable rollers. When a coil is emptied of its strip, a new coil is loaded on a profiling machine and butt welded to the end of the previous strip. The finished carcass is coiled onto a receiver by a roller device.

3.2.2 Pressure Sheath

Thermoplastic sheaths begin as plastic pellets. These pellets are loaded into a hopper and are then carried to the inlet of the extruding machine. The plastic becomes viscous under the action of heating and friction on a screw which is designed to move the plastic forward, mix it, pressurize it and homogenize it before reaching the extrusion head.

The extrusion head is perpendicular to the screw and consists of a mandrel that distributes the viscous plastic over the die, allowing the inner carcass to pass through the center. The sheath is cooled after the die by water jets and immersion in a tank.

The pipe travels uninterrupted, drawn by a caterpillar device. The combination of caterpillar speed and screw rotation speed determine the thickness of the sheath. After cooling the extruded plastic layer is inspected to ensure the correct diameter, thickness and length.

3.2.3 Armour Wires

The armour wire is delivered to the flexible pipe plant on the wire manufacturer's spools. The spools are mounted in two cages, each of which holds as many spools as there are wires in each layer. The two cages contra-rotate to simultaneously feed two layers to form opposing helices. The wires are subject to bending and torsion while passing through adjustable rollers so that all wires are applied tightly to the pipe.

When the spools are empty, full spools are loaded onto the armouring machine and the wires butt-welded together in accordance with the applicable welding procedure. The pipe that is to hold the armours is strong enough to resist collapse, so the wires are drawn by the pipe. A caterpillar device draws the pipe while the cages are rotating. The pitch of the armour wires is set by the speed of the caterpillar device and the rotation speed of the cages. The outside diameter is set by the diameter of the pipe onto which the armours are laid and the thickness of the wire.

During fabrication a visual inspection is carried out and the diameter, pitch and length are measured and recorded. Fabric tape is wound onto the armours during the armouring operations to retain the wire in place until the next layer is added. The finished pipe section is coiled onto a receiver reel by a roller device.

3.2.4 External Sheath / Protective Sheath

Manufacturing of the external and protective sheaths of a flexible pipeline follow the same process as the pressure sheath, outlined in Section 3.2.2. The extruded plastic layer is then visually inspected, with diameter, thickness and length being measured and recorded. The finished pipe section is coiled onto a receiver reel by a roller device. Plastic wrapping protects the ends until end fitting mounting takes place.

3.3 Installation

3.3.1 General

Following their manufacture in a factory, flexible flowlines are loaded onto an installation vessel. An example of an installation vessel, more specifically a deep water flexible pipelay vessel, is shown below in Figure 3-8.

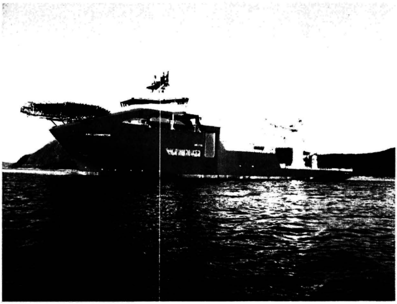

Figure 3-8: Connector – Deepwater construction/flexible pipelay (EMAS, 2011)

The flexible flowlines can either be transported to the installation vessel on reels (Figure 3-9) or loaded onto a carousel. Reels are available in various sizes depending on product size and length. For longer lengths and larger diameter lines, a carousel can be used. Additional equipment may be required with use of a carousel, such as a tensioner to act as a holdback system and control the lay speed of the product.

Figure 3-9: Flexible pipeline load out on reels (Technip, 2011)

Installation vessels are equipped with systems to allow the installation of the flexible. Such systems include chutes, whereby the flexible pipes are installed over the side of the installation vessel, or Vertical Lay Systems (VLS), which allow installation of the flexible pipeline through the vessel's moon pool.

The majority of the lay operation is normally carried out diverless, i.e. all subsea operations will be carried out utilizing Remote Operated Vehicle (ROV) support only. In relatively shallow subsea areas, such as offshore Newfoundland, the use of divers is still required to make up flanged connections onto manifolds and other preparatory subsea works.

3.3.2 Installation Sequence

Installation of flexible pipelines is most often conducted in the following sequence of four events, which are explained further below:

- Preparatory Works
- Flexible Pipeline Initiation
- Route Lay
- Flowline Laydown

3.3.2.1 Preparatory Works

Prior to flowline installation, the following works are typically completed:

- Installation analysis by use of Finite Element Analysis (FEA) software to determine the required laybacks at the tensions allowed by the flexible at all possible environmental conditions specified as acceptable for the project;
- Glory hole excavation;
- Pre-lay survey of the flowline lay route, and any debris removal;
- Attachment of the initiation clump weight or initiation rigging;
- Installation of any turning post required.

3.3.2.2 Flexible Pipeline Initiation

Flexible pipelines are initiated using an initiation wire linked to the end fitting pulling head. This wire is hooked by an ROV to a wire loop pre-installed onto an initiation clump weight or an existing strongpoint on a subsea asset (e.g. strong point on the manifold).

Typical initiation operations include the following steps:

- Route of the first end of flowline from reel / carousel over VLS to working table, using crane to support weight of end fitting. See Figure 3-10.

Figure 3-10: Maneuvering end of flexible pipe with ROV hook (Technip, 2011)

- Install pig launcher / receiver onto end fitting and set up valves as required (depending on whether the flowline is being free flooded, laid dry, or already flooded), as well as making up any intermediate connection (end fittings flanged together)
- Attach anodes to the end fitting, as required. See Figure 3-11, below.

Figure 3-11: Fitting anodes on flexible pipe (SUT, 2002)

- Lay the flowline through the vessel's moonpool;
- The ROV will connect the initiation wire to the pre-installed initiation loop rigging on the clump weight;
- Using vessel movements, the initiation wire will be laid away from the initiation clump weight and along the lay route;
- Through adjustments in the vessel layback, the end fitting is laid onto the seabed;
- The flowline is then laid away along the previously surveyed lay route. During this time, the ROV will monitor the lay operation/ touchdown point.

3.3.2.3 Route Lay

The flowline is laid along pre-determined lay corridors, generally from the FPSO to manifold or well, depending on the required lay direction. Over-length is taken up in loops laid along the lay route at each end. Turning posts are utilized at each end (if required) to aid in achieving the required flowline radii. The purpose of these loops is to provide sufficient over-length for the flowline to manifold / platform tie-ins to be completed.

Mid-line connections are provided where necessary in each flowline to allow the flowline length to be carried on several reels. These connections generally consist of Grayloc flanges which have been modified to allow nitrogen back seal testing. All midline connections are assembled in the VLS by supporting the weight of one flowline section off a hang-off clamp and rigging, while the next section is initiated into the VLS and flanged to the first.

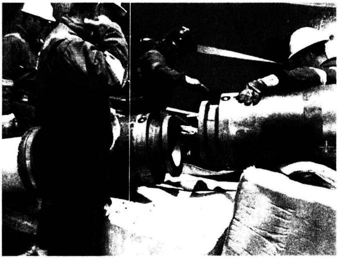

Figure 3-12: Workers assembling flowline's midline connections

An annulus leak test is undertaken on the connection prior to it going subsea. It is normal for mid-line connections to be fitted with bracelet anodes to provide cathodic protection for the end fittings. The lay operations continue as previously.

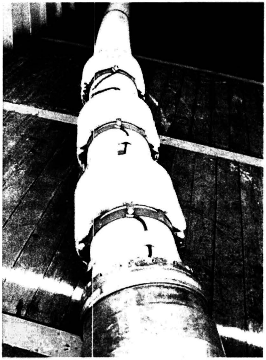

Figure 3-13: Bracelet anodes on flexible pipeline

3.3.2.4 Flowline Laydown

Once the final flange is passed into the VLS, it is supported by the hang off clamp and rigging. The pig receiver / launcher (or pull-in head) is fitted to the flange, and any required bracelet anodes are installed at the rear of the end fitting. The laydown operation is conducted by attaching a sacrificial strop between the A&R (Abandonment and Recovery) winch and the pig launcher / receiver. The hang off clamp is removed and the A&R wire lowered to allow the flange to be lowered onto the seabed.

As the final laydown location approaches, the length of the remaining flowline is monitored to determine the over-length allowance. Any adjustments are made by altering the laydown loop to ensure the final flange lands within the specified target box. Once the flange is laid on the seabed the ROV will cut the sacrificial strop and the A&R wire is recovered to the vessel.

If the flowline requires to be pigged, pigs will be pre-installed in the flowline to enable flooding and testing. The flooding works can be performed from the Construction vessel or Dive Support Vessel (DSV). The testing works are performed during a later campaign by the DSV, once the flowlines have been connected to the platform and subsea manifold. A DSV is shown in Figure 3-14.

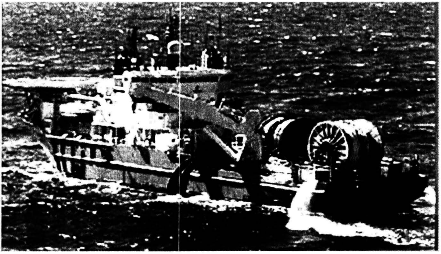

Figure 3-14: Dive Support Vessel (SUT, 2002)

3.3.3 Installation Loads

During this stage, loads are imposed on the flexible. Determination of installation loads via finite element analysis or static analysis is required before the flexible is installed offshore such that the flexible is not crushed through the installation process.

3.3.3.1 Crushing

Flexible pipelines must be analyzed for crushing capacity during normal installation and recovery. Normal installation is a functional activity and recovery is an accidental activity as defined by API 17J. Crushing capacity calculations are performed for installation and operational purposes. The appropriate API 17J safety factors for the installation (i.e. 0.67), recovery (i.e. 0.85) or operational (i.e. 0.55 for recurrent or 0.67 for abnormal) phases will be applied to the ultimate crushing capacity of the pipe to calculate the allowable tension in the pipe. In addition, the bend radius of the flexible pipes must stay above 1.0 x MBR during installation.

The crushing capacity of the flexible pipe is determined using finite element analysis software which can calculate the stresses induced by a gutter radius and/or tensioners associated with axial tensile load induced during installation and operations.

The limiting value is the most conservative value of:

- Plastification: When the yield stress is reached in the carcass material and the pressure vault material (failure is deemed to occur)
- Ovalisation: When 2% ovalisation has been reached in the inner diameter of the carcass

Whichever of these occurs first determines the maximum allowable tension for the flexible pipe for the specific installation/operational scenario.

3.4 Operation

3.4.1 General

Flexible pipelines should be operated to ensure that the required service life will be respected. The typical design life of the flexible riser is between 20-30 years of operation after installation. Achieving this service life is dependent on whether the pipeline is operated within its normal operating envelope and at the normal operating pressures and temperatures specified at the time of design.

3.4.2 Operating Records

Operating records should be compiled every six months for the operating life of the flexible pipe incorporating, but not limited to, the following:

- Pressure
- Temperature
- Flow rate
- Pressure test history
- Storm frequency and durations
- Chemical injection records
- Pipeline movements

This information can be periodically assessed in order that actual operating conditions can be verified against design.

3.4.3 Operational Loads and Phenomenon

3.4.3.1 Reverse End Cap Effect

Reverse End Cap Effect (RECE) is an effect of external pressure. Design for external pressure must consider longitudinal effects, namely the RECE, for which the design of the tensile armours under potentially high compressive loads must be considered.

When a flexible structure is subject to axial compression, the armour helix tends to swell. See Figure 3-15:

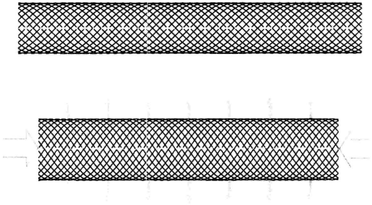

Figure 3-15: Swelling of Armour Helix (Technip, 2011)

The design of the armour layers such that they are intentionally disorganized supports the armour wires against RECE, however, criteria for radial gap must be met consistent with API-RP-17B, which states that the radial gap is not to exceed half of the armour thickness *(API, 2008)*.

Excessive radial gap can lead to uncontrolled swelling of the armour helix under external pressure, which results in a birdcage of the flexible pipeline and pipe failure, as shown in Figure 3-16 .

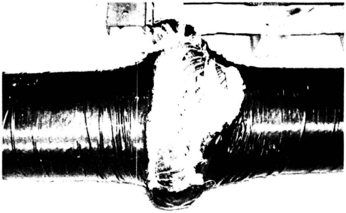

Figure 3-16: Birdcage Failure of Flexible Pipe (Technip 2011)

3.4.3.2 Hydrostatic Collapse

In operation, the vault and the carcass of a flexible pipeline are subjected to the radial effects of external pressure. These effects, if not properly accounted for during the design phase, may cause failure to the pipe through hydrostatic collapse during operation. A pipe subject to such a failure is shown below in Figure 3-17. Therefore, an understanding of the ultimate hydrostatic collapse capacity of the flexible pipe is required for flexible pipelines operating in both straight and curved configurations.

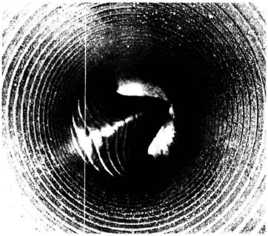

Figure 3-17: Flexible pipe carcass collapse

The "bent" or curved collapse pressure corresponds to the flexible being bent to its minimum operational bending radius (MBR). The storage minimum bend radius (MBR) is calculated as the minimum bend radius which satisfies all the requirements of API 17J, including the following:

- Maximum allowable strain between 7.0% and 7.7% in the external sheath of the structure. The exact percentage of allowable strain is dependent on material type; for PA-11 and polyethylene, the allowable strain is 7.7%, for other thermoplastics this value reduces to 7%. (API, 2009)
- The storage MBR shall be at least 1.1 times the MBR to cause locking in the interlocked layers. (API, 2009)

As per API 17J, the operating MBR for static applications (all loading conditions) shall be a minimum of 1.0 times the storage MBR, and for dynamic applications (all loading conditions) shall be a minimum of 1.5 times the storage MBR. For dynamic applications the safety factor on operating MBR may be reduced from 1.5 to 1.25 for abnormal operation and normal operation with accidental loads.

The design parameters for hydrostatic collapse are the maximum hydrostatic pressure due to the water column (inclusive of wave crest). The pipe will be conservatively assumed to be empty with atmospheric pressure in the bore in the first instance. In the event that the required utilization factors are not met then the analysis will consider the minimum product density for operational / disconnected cases and either partial or full flooding for installation purposes.

3.4.3.3 Lateral Buckling

When a flexible pipe structure is submitted to cyclic bending under high differential pressure, the armour wires are subject to compressive stresses and lateral displacements that may lead to their disorganization and failure. This phenomenon is known as 'lateral buckling' of the armour wires.

To protect the pipeline against lateral bucking, in operation, the minimum allowable radius for lateral bucking should be kept less than the design radius. Lateral buckling is typically only of concern when the flexible pipe structures are subject to differential pressures in excess of 50 bar and are subject to cyclic bending.

3.4.4 Pipeline Protection in Operation

3.4.4.1 Dropped Objects Impact Resistance

The linear impact resistance of the flexible risers and flowlines to dropped objects is determined through finite element analysis. Calculations of stresses induced by a crushing load, and can be used to determine the maximum impact energy that the pipe can absorb by unit length.

The acceptance criterion typically adapted by industry used to calculate the maximum allowable impact energy is that the flexible riser or flowline shall resist the maximum linear impact energy that will induce a 5% maximum deformation in the vault or provide a stress beyond the allowable.

Should there be insufficient resistance to dropped objects; Dropped Object Protection (DOP) is added to the pipeline or over the pipeline.

To provide protection from dropped objects, and sometimes from abrasion, the most typical type of mechanical protection added to flexible pipes are products manufactured from polyurethane or rubber. "Spirally Cut Impact Protection" (SCIP) is secured on the pipe with the aid of a banding system *(Dunlaw, 2012)*. This banding is manufactured from polymer or metallic materials. SCIP can be produced with high density polyurethane to help stabilize flexible pipes. SCIP is shown in Figure 3-18.

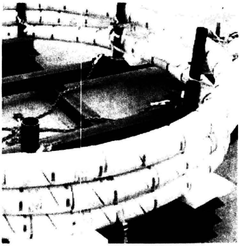

Figure 3-18: SCIP (Dunlaw, 2012)

Other types of impact protection, such as the structures seen below in Figure 3-19, are available, which act as a physical barrier against dropped objects. Such impact protection is typically produced out of aluminum, to take advantage of aluminum's energy absorbing properties.

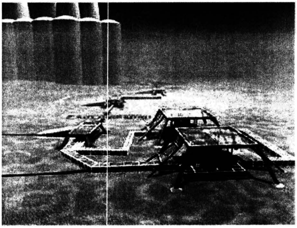

Figure 3-19: Dropping Objects Protection Structures (Goltens, 2012)

3.4.4.2 Cathodic Protection

The standard construction of flexible pipes ensures that the load-bearing armour wires are shielded from internal and external corrosive fluids by thermoplastic sheaths, and are thus well protected from corrosion. There are, however, certain events which may cause the external sheath to be damaged, such as anchor dragging, which may tear the external sheath and expose the underlying metallic wires to seawater. It is for this reason that cathodic protection (CP) with sacrificial anodes is normally applied. Cathodic protection in the form of bracelet anodes, a common type of CP used for flexible pipelines, is shown in Figure 3-20.

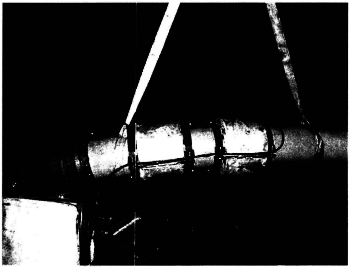

Figure 3-20: Cathodic Protection in Bracelet Anode Form

The CP is designed to protect the end fittings and armour wires over the design life of the flexible structures. The internal stainless steel carcass is not protected by the CP system since it is electrically isolated from both the end fittings and armour wires. This ensures that there are no potential differential corrosion issues between the flexible lines and the carbon steel end fittings to which the flexible structures are connected.

3.4.4.3 On-Bottom Stability

Pipeline on-bottom stability refers to the ability of a pipeline to maintain its general position on the seabed under external wave and current forces. If a pipeline does not have sufficient weight to resist imposed hydrodynamic loads, the entire pipeline, or significant sections of it may move. On-bottom stability is important for flowlines, since they are intended to be static, unlike dynamic risers, which are built to move.

Limited local movement during storms may be acceptable within the design; however pipeline movement can cause failure of the pipeline integrity through overstressing, fatigue, or wear / abrasion. The limiting movement criteria should be considered on a case-by-case basis and on a longer pipeline it may change along the length of the route.

Where the pipeline is restrained laterally or within close proximity of a fixed object, zero lateral displacement is desired. The amount of lateral displacement that may be permitted will be limited by national regulations, seabed obstruction, the width of the survey corridor, the distance from points of restraint, etc.

Pipeline stability is a complex issue involving the combined wave and current loading on a pipeline and the corresponding seabed (geotechnical) restraint.

3.5 Inspection and Maintenance

3.5.1 General

The scope of inspections is to detect degradation of the flexible pipe which may jeopardize the safety of personnel and equipment, which may cause any damage to environment, or which may affect the production capacity of the facilities. Early detection of damage and the identification of suitable preventive actions will minimize the down-time necessary to perform repairs. Guidelines in this section are based on general practices recommended by flexible pipeline manufacturers.

3.5.2 Visual Inspection

To ensure integrity, the external sheath of the flexible pipe, the end fittings and bend restrictors should be inspected by ROV for evidence of any abrasion damage, tears, structural deformation or other anomalies.

At the location of any trenched or rock dumped area, visual inspection should check for the presence of protruding pipe. At the flowline glory hole locations, which are specific to offshore Newfoundland, DOP installed on the flexible pipe external sheath should be inspected by ROV for damage or other anomalies. Figure 3-21 shows an ROV performing such subsea inspection.

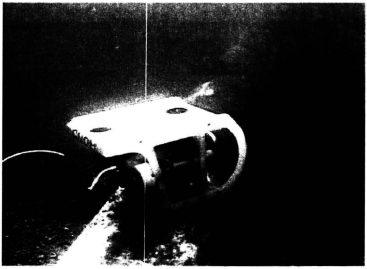

Figure 3-21: Subsea inspection performed by ROV (Gnom rove, 2012)

3.5.2.1 Flexible Pipe

Flexible pipes should be inspected at a minimum once a year. Additional inspections should be conducted after dropped object incidents or following extreme storm conditions (for example, 50-year storm conditions).

The general condition of the external sheath should be evaluated to ensure its integrity. Any tears in the sheath, such as a tear should be confirmed as shallow and superficial, not to allow a breach and the ingress of water. Such damage may affect the flexible pipe's service life.

The pipeline should also be inspected for abrasion. Should abrasion be spotted, it should be ensured that there is not significant material loss. Mitigating measures can be put in place to prevent further abrasion.

The possibility of any further visible damage to the pipe should be eliminated. Pigging operations can assist in confirming that there is no reduction in the bore diameter in the pipe.

3.5.2.2 End Fittings

Like flexible pipes, end fittings should be inspected at a minimum once a year. Additional inspections should be conducted after dropped object incidents.

The general condition of the end fittings should be conformed along with the condition of the nuts and bolts it contains. There should be no evidence of corrosion or cracking, leaks or visible damage of any kind.

Corrosion requires repairs, which are generally conducted on the deck of a vessel by the manufacturer, while leaks indicated failure of the sealing mechanism within the end fitting's flange, namely a gasket in the case of hub-style end fitting flanges, or seal rings in the case of larger, bolted flanges, such as an API weld neck or swivel flange.

3.5.2.3 Bend Restrictor

The general condition of a bend restrictor as well as the condition of the nuts and bolts it contains should be inspected at a minimum frequency of once a year.

Bend restrictors along with their nuts and bolts should be free of visible corrosion and intact "as left." While corrosion may be repaired, any further damage to the bend restrictors, nuts and bolts generally requires their replacement.

3.5.3 Maintenance

3.5.3.1 Flexible Pipe

Normally no maintenance will be required for the flexible pipe during its design life.

For cleaning of the flexible pipe, attention must be given to whether the pipe is classified as "rough bore" or "smooth bore." As previously noted, a flowline is considered to be a rough bore flexible pipe structure, when the innermost layer is a profiled, interlocked stainless steel strip. It is possible to use cleaning pigs with steel brushes or abrasive layers qualified by the manufacturer in situations where the flow rate is decreasing in "rough bore" structures, e.g. due to hydrate formation or wax deposition.

For flexible pipe in which the internal layer is a thermoplastic tube, "smooth bore," it possible to use a cleaning pig made from foam or polyurethane flat discs.

Cleaning pigs are available in a variety of sized and shapes, as shown below in Figure 3-22.

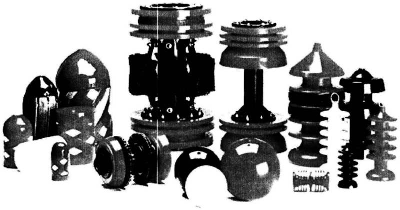

Figure 3-22: Flowline cleaning pigs (Farwest Corrosion, 2012)

3.5.3.2 End Fittings

There is no specific requirement for maintenance of the end fittings. In cases where the end fitting termination is disconnected, it should always be protected with a blind flange or a project-specific method in order to protect the ring groove and flange face.

3.5.3.3 Bend Restrictor

There is no specific requirement for bend restrictor maintenance.

3.6 Repair

3.6.1 Flexible Pipe

It is normally not possible to repair a flexible pipe in place. In cases of minor damage to the external sheath, the flexible pipe can be recovered and repaired on board the installation vessel. In cases of serious damage, the flexible must be brought onshore for repair.

3.6.2 End Fittings

Damaged end fittings can be replaced by re-terminating the flexible pipe. This operation can be done onboard the installation vessel after line recovery, but in some cases must be done onshore. Minor damage to the coating or small corrosion can be repaired offshore.

3.6.3 Bend Restrictors

Damage to the bending restrictor will normally be repaired by replacing the faulty component.

3.7 Life Extension and Abandonment

Once the life of the flexible is up, the flexible may be abandoned and recovered. If required, i.e. if oil reserves deem it profitable, a new flexible may be installed as a replacement.

An alternative to abandonment / decommissioning is life extension, whereby the conditions during operation are revaluated to determine whether or not the flexible's life may be extended beyond what was initially prescribed. Generally, this may be an option if the pipeline was operated at conditions well under the anticipated maximum operating conditions upon which the flexible's life assessment was initially based.

Precise record keeping of the operation of the flexible over its design life is important in this context. Without accurate record keeping, there is nothing to base life extension calculations on and the assessing party must again keep on the side of conservatism and assume that the deign life of a flexible pipeline is reached after a set period of time.

During life extension assessments of flexible pipelines, the original engineering design checks must be reiterated based on the record of operating data provided by the operator. With ageing fields around the world, many operators have turned to this approach and have been able to extend the life of their flexible pipelines, realizing significant cost savings. This is common in the North Sea, where there are plenty of ageing assets using flexible pipelines.

4 Framework for Flexible Pipeline Project Risk Analysis

4.1 Introduction

Risk and uncertainty are inherent in all projects. The size, complexity, location and speed of a project are all factors in risk assessment. The evolution of risk management has showed continuously more focus on the subject of project risk *(Birkeland, 2005)*. Clients and service contractors are aware of the consequences if work fails to succeed. Therefore a practical way of performing business is required to endure within the industry. In this section an introduction to risk theory, project risk management and analysis is given.

The methods considering risk and project risk analysis tend to have different approaches to what kind of risk considered. Project risk analysis mainly deals with risks related to parameters such as time, cost, quantity and quality. Risk analysis methods take into consideration risks related to *accidents, human loss and environmental* damage *(Walker, 2002)*. The main difference in the methods is that risk analysis tends to cover a broader perspective than project risk analysis.

4.2 Objectives of Project Risk Analysis

The overall goal of a project from a risk point of view is to identify and establish control of the risk factors. The primary goal of a risk analysis is to calculate and evaluate the risk associated with operations and compare it against acceptable criteria for risk. To execute this, it is essential that the purpose and scope of the analysis is clearly defined and is in accordance with the needs of the activity.

The purpose of a framework is to provide a consistent and systematic approach to risk handling in projects to allow project teams to proactively identify and prevent unwanted incidents before they occur or by reducing the impact of them if they occur. Risks need to be continuously assessed throughout the project as the nature, probability, and impact of risks change by phase and activity. The outcome of a project risk analysis shall give a picture of all critical situations and thereby make a better foundation for decision-making.

4.3 Guidelines for Project Risk Analysis

A framework for handling project risks is provided in DNV-RP-H101: *"Risk Management in Marine –and Subsea Operations,"* where detailed guidelines for planning and handling project risks are explained. This recommended practice provides a specific procedure for handling project risk in marine operations, giving a varied view of specific tools and processes in the core of the risk analysis. It can be applied to handle project risk analysis effectively.

The table below is presented based on the DNV recommended practice, DNV-RP-H101. It can be seen that use of the matrix involves making judgments of event likelihoods (in four categories covering remote to frequent) and event consequences (in four categories ranging from illness/slight injury to fatality. This matrix also includes the risk tolerability criteria (i.e. high – unacceptable risks, low – broadly acceptable risks, and the area in between - medium - the ALARP or tolerability region). The matrix is used as a tool for qualitatively screening the risk level posed by identified hazards.

Consequences			**Probability (Increasing Probability →)**			
Description	Environment	Reputation (Negative Exposure)	A Remote ($< 10^{-5}$/yr)	B Unlikely (10^{-5}-10^{-3}/yr)	C Likely (10^{-3}-10^{-2} /yr)	D Frequent (10^{-2}-10^{-1} /yr)
1 Extensive	Restoration time > 10 yrs	International	A1	B1	C1	D1
2 Severe	Restoration Time > 1 yr	Extensive National	A2	B2	C2	D2
3 Moderate	Restoration time > 1 mth	Limited National	A3	B3	C3	D3
4 Minor	Restoration time < 1 mth	Local	A4	B4	C4	D4

Low: The risk is considered tolerable and no further actions are required.

Medium: The risk should be reduced, if possible.

High: Unacceptable risk.

Figure 4-1: Risk Matrix According to DNV-RP-H101

The risk management process described in this recommended practice is applicable for each aspect of the business activity and focuses at each level of decision making.

4.4 Project Risk Analysis Process

Risk analysis can be performed through various methods. The choice of method depends on the end factors being analyzed, such as the projects' difficulty, schedule and budget. While some standards (such as BS 6079) recommend using a set of guide words for each step of the process of the risk analysis, DNV-RP-H101 recommends a guidance framework in the form of a series of steps describing how the analysis should be conducted. An adaptation of this framework is shown below:

Figure 4-2: Steps for Risk Analysis adapted from DNV-RP-H101

As apparent above, DNV recommends the following five steps for management of risks within marine operations:

Step 1: Establish a process plan. This includes defining the scope and context of what to be analyzed. This step specifies what is at risk and why the risk exists. DNV emphasizes that the risk analysis is planned in accordance with the development and conduct of the activity. This confirms that the risk studies are used actively in the design and implementation of the activity.

Step 2: Establish acceptance and screening criteria. This second step contains risk identification, determines the sources of risks and defines elements of the risk.

Step 3: Perform an overall risk assessment of the operations to define them within low (L), medium (M) or high (H) potential risk categories. This third step is the risk analysis itself. DNV lists several methods of risk analysis applicable under this step; FMECA is listed as applicable technique which will be explored later in this thesis.

Step 4: Based on concluded potential risk category a detailed risk identification program should be established. This step evaluates the risks.

Step 5: Based on risk category and findings from the risk identification program, the potential risk is reduced to an acceptable level through specific actions and risk reducing activities. This step defines how we treat the outcome of the risk analysis and identifies likelihood of occurrence and potential consequences of the risks, should they occur.

The above evaluation is thus suitable to determine which risks take the highest priority, which risks require further studies and which risks need less attention.

4.5 Qualitative Risk Assessment

Qualitative risk assessment deals with risk identification and serves as an initial risk assessment for a project. The objective of qualitative risk analysis is to identify the sources of risk and describe their potential consequences. Generally, this type of analysis is illustrated through risk matrices, where the probability of occurrence and consequences are represented as risk.

4.6 Quantitative Risk Assessment

Unlike qualitative risk assessment, quantitative analysis uses numerical scales to quantify the risks. Fault analysis is an example of a quantitative method. Access to reliable and current input information is required to be able to conduct this analysis. Offshore experience databases generally do not have the required information as input to risk analysis with regard to flexible pipelines, and therefore flexible pipeline risk analysis is more suitable for qualitative techniques.

4.7 Discussion

The approach for evaluation of project risk should be designated based on the nature of the project being analyzed. Therefore, risk evaluation and risk approximation is largely project specific. There are several approaches for dealing with risk components; both qualitative and quantitative methods may be used. For flexible pipe applications, qualitative methods are more appropriate due to the lack of detailed flexible pipeline historical operational information available in industry databases.

5 FMECA: Qualitative Project Risk Analysis for Flexible Pipelines

5.1 Introduction

The Failure Mode and Effects and Criticality Analysis (FMECA) method is the first step in a system reliability analysis. It involves review of components, assemblies and subsystems to discover failure modes, causes, and their effects *(Birkeland, 2005)*. Using FMECA, there is no need for advanced analytical skills to obtain satisfactory results *(Rausand et al., 2004)*. While the focus of a FMECA is exclusively on technical failures, its ease of use makes it an effective tool to analyze project risks as well.

5.2 FMECA Objectives:

The objectives of the FMECA are to:

- Identify potential failure modes that may lead to unwanted effects within the defined boundaries of the system being analyzed;
- Evaluate corresponding potential consequences on equipment and system considered;
- Rank each failure according to a criticality category of failure effect and occurrence,
- Establish mitigation actions to suppress or control the critical risks.

The installation phase is considered in the FMECA only when Failure Mode and / or Failure Mechanism are undetectable and may lead to failure during service life. Any failure, which could be repaired or detected during installation, is not considered in FMECA.

5.3 Methodology

FMECA is a systematic methodology to identify and help improve inherent reliability of a system. It is an iterative process of identifying historical or potential failure modes, assessing their probabilities of occurrence and their effects on safety / environment and assets, isolating the causes, and determining corrective actions or preventive measures. The method consists of several steps, which are recognizably consistent with the five steps outlined in DNV-RP-H101 for project risk analysis:

Step 1:

- System definition (function and component breakdown);
- Definition of boundaries of the studied system;

Step 2:

- Identification of risks, i.e. failure modes (including operational and environmental conditions at the moment of the failure);

Step 3:

- Assessment of the effect (local effect and global effect at system level);
- Identification of means of the failure;

Step 4:

- Classification of severity (see Table 5-1);
- Classification of probability of occurrence (see Table 5-2);

Step 5:

- Determination of the criticality (combining probability of occurrence and severity) based on the Risk Matrix defined hereafter (see Table 5-3);
- Determination of corrective actions, when necessary / appropriate.

5.4 FMECA Steps

This section applied the five steps defined above to the case of a flexible pipeline.

5.4.1 Step 1

The system definition must be given in this step. It is defined as follows for flexible pipelines:

The flexible structure for this case study is assumed to consist of all layers outlined below, including:

- Inner interlocked carcass
- Pressure sheath
- Pressure vaults and Armour Layers
- Anti-Wear Tapes
- High Strength Tapes
- External Sheaths

The function of these components of the flexible pipe has been explained previously in Section 3.1.1.

Definition of boundaries of the studied system is also required in this step. This case study for flexible pipelines is assumed terminated with end fittings of standard design. No other ancillary equipment will be considered.

5.4.2 Step 2

Identification of risks / failure modes should be evaluated for the entire life cycle of a flexible pipe. Below is a general discussion of hazard associated with flexible pipes during each stage of a flexible pipe's lifecycle. These hazards may be further translated to failure modes of the flexible pipes.

5.4.2.1 Design and Construction Stage

Design Uncertainty:

Discrepancies and neoconservative assumptions on operating conditions at the design stage may lead to failure of the pipeline through operation. Where unknown parameters exist, the design engineer should err on the side of conservatism in all cases. Of particular importance are design and operating pressures and temperatures, estimation of the sour gas components in the design fluid and the pipeline's required design life.

Design and Operating Pressures and Temperatures:

Design pressure and temperature define limits with respect to material selection, such as thermoplastic sheath and high-strength tape selection, while operating pressures and temperatures determine time-related effects on the flexible pipe throughout its design life.

Material Compatibility:

The metallic layers of a flexible pipe are qualified to resist certain levels of free oxygen, chloride, hydrogen sulfide and carbon dioxide. While there is some overlap in the qualification limits of the metallic materials, often, step changes between material grades are discrete and are particularly important in the steel annulus of the flexible pipe. Due to the effects of the confined environment created between the voids of the thermoplastic sheaths, the conditions of the annulus must be calculated with precision and confidence.

Transported Fluid and Annulus Environment Determination:

Determination of the annulus environment involves completion of a number of key steps. First, the fluid which is transported through the bore of the flexible pipe must be accurately represented. Typically, fluids compositions are provided by operators at standard conditions (temperatures and pressures) or at maximum operating conditions, represented in molar percentages. The definition of the souring gas components (H_2S and CO_2) may be presented within the global fluid or in required design levels outside of the global fluid (either percentages or ppm), which must be then worked into the global fluid composition at the maximum operating temperatures and pressures. If the fluid involves a design level of H_2S, it is important to see if that level should be treated in its gaseous composition. These points are required in order to accurately represent the working fluid.

Once the global composition of the fluid is determined, the PVT (pressure, volume, temperature) calculations should be completed to represent the gaseous constituents in partial pressures or fugacities. Fugacities are corrected partial pressures, which are applicable to non-ideal gases.

Diffusion analysis is then completed taking the partial pressures or fugacities as inputs. Diffusion considers how the gases diffuse across the pressure sheath of the structure and into its annulus, creating a unique environment, with a separate pH than that of the bore.

The results of diffusion analysis can then be used to ensure materials are selected which are compatible to the environment and to gauge corrosion behavior of the flexible pipe.

Definition of External Environmental Parameters:

The environmental effects on flexible pipe design are important and should be clearly defined prior to the design stage. A profile of the temperature gradient through the water column is important for thermal analysis of the pipe; typically, a specific overall heat transfer coefficient is targeted to ensure flow assurance. Temperatures of the external environment are particularly important in this context.

The maximum water depth and a representative wave scatter diagram of the area are needed to calculate the potential of hydrostatic collapse of the flexible pipe and to properly size the carcass to resist this collapse. These parameters, in addition to wave particle-motion velocities and seabed current, are needed in the determination of on-bottom stability.

5.4.2.2 *Installation Risks*

Installation must be considered an essential part of a flexible pipeline's life cycle. "Installation phase is critical for flexible pipes. They are vulnerable for external loads, and must be handled with care." (PASN, 2008). Pipelines may be optimised to accommodate in-place design and operating conditions but be difficult to install, rendering it not a feasible solution for operators. The following considerations are required for a successful installation campaign:

Choice of Installation Equipment:

Installation equipment selection depends on water depth and the required laying tension. For deeper water or when high tensions are needed, a Vertical Lay System (VLS) is often preferred to installation over a chute.

Vessel deck space and capacity should be investigated prior to decision whether the flexible product should be supplied on reels or for larger supplies, on a carousel. Ancillary equipment to be installed (stiffeners, etc.) should be worked into the offshore procedures and schedules; often, handing of ancillary equipment requires adherence to special procedures in additional to those related to strictly the flexible pipe and requires extra offshore time.

Mechanical Properties of the Flexible Pipe:

The flexible pipe crushing resistance should be evaluated in order to set installation tensions related to the capacity of the flexible pipe to resist deformation. If the pipe has a low tolerance to crushing, special installation equipment may be required.

A series of lay steps should be identified through detailed installation analysis in order to specify flexible pipeline payout at a specific tension, vessel movements and handling operating such that the mechanical properties of the flexible pipe, namely MBR, are adhered to during the lay sequence. This type of analysis is generally conducted for a range of seastates specific to the field.

Pipeline Protection Required:

Additional offshore time related to installation of pipeline protection (weak links), rock dumping or trenching needs to be considered in the offshore budget and schedule.

5.4.2.3 Operational Risks

During operation, the most crucial considerations are related to how closely operation in the field relates to what was specified as expected operation at the design stage.

As previously stated, the following data should be collected on a routine basis and analyzed for design specification adherence:

- Pressure
- Temperature
- Flow rate
- Pressure test history
- Storm frequency and durations
- Chemical injection records
- Pipeline movements

Increasing or decreasing temperatures, pressures and flow rates will have an effect on the integrity of the flexible pipeline, in terms of the rate of corrosion, thermoplastic and sheath ageing.

Changing the chemical injection profile from what was prescribed at the time of design may have a negative effect on the flexible pipe; each wetted surface of the flexible (namely the carcass and pressure sheath) should be evaluated for compatibility with the injected chemical prior to its use.

5.4.2.4 Risks during Inspection and Maintenance of Flexible Pipelines

The frequency of inspection campaigns is seen as critical in maintaining flexible pipeline integrity. Any anomalies identified should be rectified promptly in order to ensure that degradation of the pipeline does not occur.

5.4.3 Step 3

This step requires "identification of means of the failure." This is relevant to the failure causes for flexible pipes. Flexible pipe potential failure causes are listed below.

- Collapse of carcass and/or pressure armour due to excessive tension
- Collapse of carcass and/or pressure armour due to external pressure
- Collapse of carcass and/or pressure armour due to installation loads or ovalizing due to installation loads
- Collapse of carcass due to trapped gases during rapid depressurization
- Dropped object impact
- Erosion or corrosion of carcass profile due to transported fluid
- Violation of MBR during installation
- Damage to carcass caused by through flowline tool
- Rupture of pressure armours due to excess internal pressure

- Rupture of tensile armours due to excess internal pressure
- Rupture of pressure sheath due to inadequate thickness, high and low temperature or loss of supporting layers
- Bore fluid not compatible with pressure sheath polymer
- Rupture of tensile armours due to excess tension
- Excessive marine growth giving rise to increased top tension
- Incorrect lay-angle / tolerance
- High reverse end cap loads (note that this is mostly significant in deep water application)
- Excessive bending in riser configuration
- Incorrect handling / mechanical damage during installation
- Failure of tensile armour wires
- Collapse of carcass and / or internal pressure vault
- Bird-caging of tensile armour wires
- Excessive sand level and transported fluid velocity
- Corrosion of carcass
- Aggressive production fluids
- Corrosion of pressure or tensile armour exposed to sea water
- Corrosion of pressure or tensile armour exposed to diffused product
- Abrasion
- ROV contact during inspection operations
- Wear at the exit of the J-tube
- Damage during pull-in in the J-tube

- Topside incident resulting in loss of load overside to subsea
- Internal damage due to through flowline tool

Additionally, this step requires "assessment of the effect." This is relevant to the failure modes for flexible pipes. Failure modes resulting from the above failure causes are listed below.

- Carcass and pressure armour collapse
- Pipeline burst and pressure sheath rupture
- Tensile failure of armour wires
- Compressive failure of tensile armour
- Overbending
- Torsional failure of armour wires
- Erosion of carcass
- Corrosion of carcass
- Corrosion of pressure armour and tensile armour
- Damage to the external sheath
- Damage due to dropped object impacts
- Damage to the end fitting

5.4.4 Step 4

This step requires classification of the severity. Classification of severity for the purposes of the FMECA is defined in Table 5-1:

Severity Criteria	Harm to People	Environment	Damage
1: Negligible	First Aid Injury	Within site boundary. No significant environmental impact. Easily controlled / recovered by worksite.	Insignificant damage to plant & equipment
2: Moderate	Medical Treatment / Restricted Work Case	Within site boundary. Short-term environmental impact.	Limited damage to plant & equipment
3: Significant	Day-away-from-work Case / Temporary or permanent partial disability	Outside the site boundary. Localized pollution giving rise to significant environmental impact but unlikely to last beyond 1 month. Recovery/rehabilitation may require external assistance.	Significant damage to local area or essential plant & equipment
4: Severe	Single Fatality / Injury resulting in permanent and severe disability. May prevent Operational Safety Case acceptance.	Extended the exceeding of license conditions & / or uncontrolled release. Significant environmental impact beyond the site boundary unlikely to last beyond 12 months. Recovery/rehabilitation requires external assistance	Damage extending to several areas/significant impairment of installation /equipment integrity
5: Catastrophic	Multiple Fatalities / Multiple serious injuries Likely to prevent operational Safety Case acceptance.	Massive & uncontrolled release with significant environmental impact extending well beyond site boundary. Chronic pollution resulting in damage lasting more than 12 months.	Extensive damage (multiple fires/explosions) or loss of installation

Table 5-1: Severity Classes

For each failure mode, the most critical criterion is considered between harm to people, environment and damage, and it is ranked highest in the severity ranking.

Classification of probability of occurrence (see Table 5-2);

	Pre-Mitigation (Existing control measures)
A: Very Unlikely	To the best knowledge of the risk assessment team the hazard has not occurred within industry.
B: Unlikely	To the best knowledge of the risk assessment team the hazard has occurred within industry at least once
C: Possible	To the best knowledge of the risk assessment team the hazard occurs annually within industry.
D: Likely	To the best knowledge of risk assessment team the hazard regularly occurs more than once a year.
E: Very Likely	To the best knowledge of risk assessment team the hazard is predicted to occur at least once during course of the work unless changes are made.

Table 5-2: Probability Classes

5.4.5 Step 5:

This step involves determination of the criticality (combining probability of occurrence and severity) and can be based on the Risk Matrix defined hereafter (see Table 5-3):

Severity	A	B	C	D	E
1	1A	1B	[illegible]	[illegible]	1E
2	2A	2B	[illegible]	2D	2E
3	3A	3B	3C	3D	3E
4	[illegible]	4B	4C	4D	4E
5	5A	5B	5C	5D	5E

Table 5-3: Risk Matrix

[illegible]: Tolerable but reasonable mitigation measures should not be ignored.

Medium (M): Tolerable but ALARP Principles must be demonstrated.

High (H): Action plan is mandatory for risk identified as high.

Determination of corrective actions, when necessary / appropriate, is also required of this step. Mitigating actions are specific to each failure mode of the flexible pipe. This is further explained in the case study, below.

5.5 Case Study

This case study evaluates the main failure modes of a flexible pipeline used for subsea production, evaluates the effect of these failure modes and lists mitigating measures which may be introduced during each stage of the flexible's life cycle to prevent the failure mode from occurring. Within this case study, the five steps outlined above for conduction of a risk analysis will be used in order to complete the FMECA:

5.5.1 Failure Mode – Carcass and Pressure Armour Collapse

5.5.1.1 Failure Causes

- Collapse of carcass and/or pressure armour due to excessive tension
- Collapse of carcass and/or pressure armour due to external pressure
- Collapse of carcass and/or pressure armour due to installation loads or ovalizing due to installation loads
- Collapse of carcass due to trapped gases during rapid depressurization
- Dropped object impact
- Erosion or corrosion of carcass profile due to transported fluid
- Violation of MBR during installation
- Damage to carcass caused by through flowline tool

5.5.1.2 Failure Effects

- Pipe blockage
- Damage of pressure sheath layer and loss of containment

5.5.1.3 Mitigating Actions and Controls

5.5.1.3.1 Design and Construction Stage

- Selection of carcass / pressure vault materials and sizes and material qualification
- Hydrostatic collapse analysis
- Crushing resistance analysis

5.5.1.3.2 Installation Stage

- Reel drum / chute radius specification such that the flexible's MBR is not breached
- Limitations on installation environmental conditions and consequently installation tensions

5.5.1.3.3 Operation Stage

- Limits on depressurization rates

5.5.1.3.4 Inspection and Maintenance Stage

- Limit the activities within riser layout sector of the platform to minimize risk of dropped object
- Provision of guidelines relating to the use of pigs and other through flowline tools.

5.5.1.4 Summary

- Since the failure causes are plentiful and have been seen in industry yearly (i.e. dropped objects), the probability is classified as C.
- Since the severity of the failure mode may be significant, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.2 Failure Mode – Pipeline Burst and Pressure Sheath Rupture

5.5.2.1 Failure Causes

- Rupture of pressure armours due to excess internal pressure
- Rupture of tensile armours due to excess internal pressure
- Rupture of pressure sheath due to inadequate thickness, high and low temperature or loss of supporting layers
- Bore fluid not compatible with pressure sheath polymer
- Violation of MBR (pressure armour unlocking)

5.5.2.2 Failure Effects

- Pipe failure / leak

5.5.2.3 Mitigating Actions /Controls

5.5.2.3.1 Design and Construction Stage

- Selection of pressure vault material and sizes and material qualification
- Stress analysis under operating, design and factory acceptance test conditions

- Manufacturing tolerances

5.5.2.3.2 Installation Stage

- Installation analysis ensuring MBR is not compromised during installation operations

5.5.2.3.3 Operation Stage

- Limits on operating pressures and temperatures and MBR
- Chemical compatibility assessment of pressure sheath polymers

5.5.2.4 Summary

- Since the failure causes are plentiful and have been seen in industry, the probability is classified as B.
- Since the severity of the failure mode may be significant, it is given a severity rating of 3.
- Together, B3 translate to a risk ra[redacted]

5.5.3 Failure Mode – Tensile Failure of Armour Wires

5.5.3.1 Failure Causes

- Rupture of tensile armours due to excess tension / pressure
- Excessive marine growth giving rise to increased top tension
- Incorrect lay-angle / tolerance
- Corrosion of tensile armours

5.5.3.2 Failure Effects

- Pipe failure

5.5.3.3 Mitigating Actions and Controls

5.5.3.3.1 Design and Construction Stage

- Selection of armour wire material and thickness and qualification
- Stress analysis under operating, design, installation and factory acceptance test conditions
- Control of manufacturing tolerance on lay angle and gap

5.5.3.3.2 Operation Stage

- Cathodic protection by aluminium anodes

5.5.3.4 Summary

- Since the failure causes are not typically seen in industry, the probability is classified as A.
- Since the severity of the failure mode can be localized to just the one pipeline, it is given a severity rating of 2.
- Together, A2 translate to a risk rating of Low (L).

5.5.4 Failure Mode – Compressive Failure of Tensile Armour

5.5.4.1 Failure Causes

- High reverse end cap loads (note that this is mostly significant in deep water application)

5.5.4.2 Failure Effects

- Bird-caging of tensile armour wires
- Lateral buckling of armour wires
- Rupture of external sheath
- Damage to pressure sheath layer and loss of containment

5.5.4.3 Mitigating Actions and Controls

5.5.4.3.1 Design and Construction Stage

- Selection of high strength tape composition to restrain armour bird-caging
- Reverse end cap analysis

5.5.4.4 Summary

- Since the failure cause is unlikely, the probability is classified as B.
- Since the severity of the failure mode may be significant, it is given a severity rating of 3.
- [redacted]

5.5.5 Failure Mode – Overbending

5.5.5.1 Failure Causes

- Excessive bending in riser configuration
- Incorrect handling during installation

5.5.5.2 Failure Effects

- High strain of external sheath
- Cracking of the external sheath
- Unlocking of interlocked pressure or tensile armour layer
- Rupture of internal pressure sheath due to excessive creep through unlocked pressure armour
- Pipe failure / leak

5.5.5.3 Mitigating Actions and Controls

5.5.5.3.1 Installation Stage

- Limits on bend radius
- Drum / chute radius greater than MBR
- Simulation of installation operation to assess the bend radius and review of installation procedure
- Adherence to MBR

5.5.5.4 Summary

- Since the failure causes been seen in industry, the probability is classified as C.

- Since the severity of the failure mode may be significant, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.6 Failure Mode – Torsional Failure of Armour Wires

5.5.6.1 Failure Casues

- Failure of tensile armour wires
- Collapse of carcass and / or internal pressure vault
- Bird-caging of tensile armour wires

5.5.6.2 Failure Effects

- Pipe loops during installation

5.5.6.3 Mitigating Actions and Controls

5.5.6.3.1 Design and Construction Stage

- Torque balance design (2 tensile armour wires cross wound in opposite direction)

5.5.6.3.2 Installation Stage

- Installation analysis / procedure

5.5.6.4 Summary

- Since the failure cause isn't typically seen in industry, the probability is classified as B.

- Since the severity of the failure mode is not seen as detrimental to the pipe, it is given a severity rating of 2.
- Together, B3 translate to a risk rating of Low (L).

5.5.7 Failure Mode – Erosion of Carcass

5.5.7.1 Failure Causes

- Excessive sand level and transported fluid velocity

5.5.7.2 Failure Effects

- Thinning and collapse of carcass

5.5.7.3 Mitigating Actions and Controls

5.5.7.3.1 Design and Construction Stage

- Selection of carcass material and size
- Erosion due to sand taken into account in the design

5.5.7.3.2 Operation Stage

- Use of sand screens

5.5.7.4 Summary

- Since the failure causes been seen in industry, the probability is classified as C.
- Since the severity of the failure mode may be significant, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.8 Failure Mode – Corrosion of Carcass

5.5.8.1 Failure Causes

- Corrosion of carcass
- Aggressive production fluids

5.5.8.2 Failure Effects

- Collapse of carcass
- Pipe failure

5.5.8.3 Mitigating Actions and Controls

5.5.8.4 Design and Construction Stage

- Selection of carcass material and size

5.5.8.4.1 Operation Stage

- Corrosion inhibitor

5.5.8.5 Summary

- Since the failure cause is seen in industry, the probability is classified as C.
- Since the severity of the failure mode may be detrimental to the pipe, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.9 Failure Mode – Corrosion of Pressure Amrour and Tensile Armour

5.5.9.1 Failure Causes

- Corrosion of pressure or tensile armour exposed to sea water
- Corrosion of pressure or tensile armour exposed to diffused product

5.5.9.2 Failure Effects

- Failure of pressure vault and tensile wire
- Pipe failure

5.5.9.3 Mitigating Actions and Controls

5.5.9.3.1 Design and Construction Stage

- Cathodic protection system
- Selection of wire material
- CO_2 Corrosion analysis of armours in damaged condition (flooded annulus)

5.5.9.4 Summary

- Since the failure cause is seen in industry, the probability is classified as C.
- Since the severity of the failure mode may be detrimental to the pipe, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.10 Failure Mode – Damage to the External Sheath

5.5.10.1 Failure Causes

- Abrasion
- Dropped Object
- Mechanical damage during installation
- ROV contact during inspection operations
- Wear at the exit of the J-tube
- Damage during pull-in in the J-tube

5.5.10.2 Failure Effects

- Ingress of sea water in annulus due to external sheath damage
- External sheath becomes brittle and weak

5.5.10.3 Mitigating Actions and Controls

5.5.10.3.1 Design and Construction Stage

- Selection of abrasive resistance material
- Addition of a protective sheath

5.5.10.3.2 Installation Stage

- Adherence to installation procedures
- External sheath repair personnel and kit present on board during installation

5.5.10.3.3 Operating Stage

- Platform operating procedures and competence assurance schemes

5.5.10.4 Summary

- Since the failure cause is seen in industry, the probability is classified as C.
- Since the severity of the failure mode isn't seen as completely detrimental to the pipe, it is given a severity rating of 2.
- [redacted].

5.5.11 Failure Mode – Damage due to Dropped Object Impacts

5.5.11.1 Failure Causes

- Topside incident resulting in loss of load overside to subsea

5.5.11.2 Failure Effects

- Damage to flexible pipe external sheath
- Damage to end fitting
- Flexible pipe or end fitting failure
- Damage to pressure armour and tensile armour

5.5.11.3 Mitigating Actions and Controls

5.5.11.3.1 Design and Construction Stage

- Crushing impact resistance analysis

5.5.11.3.2 Operational Stage

- Operational controls and restrictions from Platform procedures / permits to work.
- Dropped Object Impact Protection

5.5.11.4 Summary

- Since the failure cause is seen in industry, the probability is classified as C.
- Since the severity of the failure mode may be detrimental to the pipe, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.5.12 Failure Mode – Damage to the End Fitting

5.5.12.1 Failure Causes

- Abrasion
- Dropped Object
- Mechanical damage during installation
- ROV contact during inspection operations
- Internal damage due to through flowline tool

5.5.12.2 Failure Effects

- Damage to internal / external corrosion coating and excessive corrosion of end fitting
- Release of bore fluids due to end fitting failure
- Structural failure of end fitting body
- Ingress of sea water into annulus due to external sheath crimping failure

5.5.12.3 Mitigating Actions and Controls

5.5.12.3.1 Design and Construction Stage

- Selection of appropriate end fitting steel

5.5.12.3.2 Installation Stage

- Adherence to installation / handling procedures

5.5.12.3.3 Operating Stage

- Platform operating procedures and competence assurance schemes

5.5.12.4 Inspection and Maintenance Stage

- Provision of guidance relating to the use of through flowline tools

5.5.12.5 Summary

- Since the failure cause is seen in industry, the probability is classified as C.
- Since the severity of the failure mode may be detrimental to the pipe, it is given a severity rating of 3.
- Together, C3 translate to a risk rating of Medium (M).

5.6 Discussions of Results

Through the FMECA approach to risk analysis, failure modes for flexible pipes were identified and the level of risk associated with each failure mode was ranked. To rank the risks, Table 5-1 to Table 5-3 have been used, which define levels of severity and probability. These matrices follow guidelines presented in DNV-RP-H101 for project risk analysis and have been adapted to suitably assess risk in the context of flexible pipelines.

This case study has identified twelve failure modes for flexible pipelines. From these twelve failure modes, 58% represent medium risk scenarios and 42% represent low risk scenarios. No high risks have been identified. These results are presented in Figure 5-1.

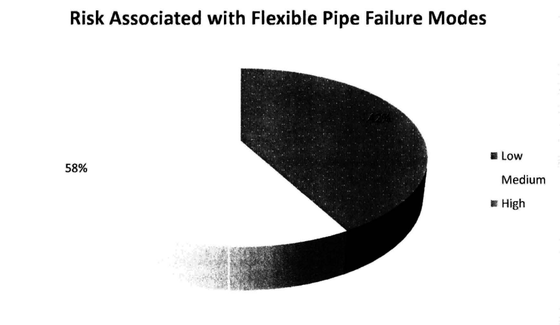

Figure 5-1: FMECA Study Results Summary

Since risks associated with all failure modes have been classified as "Low" or "Medium," the use of flexible pipelines and ancillary equipment does not present any unacceptable risk, as analyzed in the context of this case study. According to this risk ranking, no action plan is *mandatory*, however, actions / recommendations have been defined when possible to further mitigate the risk.

This case study supports the use of flexible pipes, such as in FPSO applications, but recognizes that risk mitigation actions must be evaluated at each stage of the flexible pipes' lifecycle. Controls available at these stages should be implemented to reduce risk.

Current risk mitigation measures place particular focus on adherence to operational guidelines and their contributions to the prevention of flexible pipeline risks. Future trending in flexible pipeline engineering suggests technological advances may aid in further reduction of the risks identified in this case study. Such future trends will be discussed in the following chapter.

6 Future Trends for Flexible Pipe

6.1 General

As existing oil and gas fields become depleted, oil companies move into deeper waters, expand existing offshore fields with satellite wells and try extracting more oil from existing fields by using enhanced oil recovery technologies *(NKT, 2011)*.

The market is also approaching an age when the design and guaranteed life of existing offshore installations are wearing out and there is a growing need to replace existing pipes. All these factors indicate a rising market for flexible pipes *(NKT, 2011)*.

The progression of material engineering and the advancement of the understanding of the structural action of subsea pipes have led to an increasing use of flexible pipeline systems which is predicted to expand the limits of future subsea engineering.

The below figure, Figure 6-1, indicates the current and anticipated future capabilities in flexible pipe applications, showing a trend towards to ultra-deep water applications.

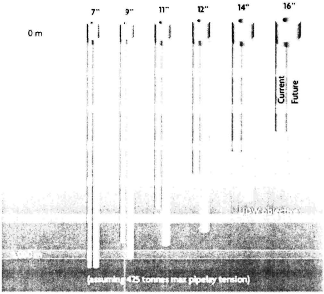

Figure 6-1: Flexible pipeline trends (Technip, 2011)

6.2 Risk Reduction Technologies

New technologies are being employed to deal with the risks posed by flexible pipes. Heat tracing is being incorporated in to the walls of the flexible pipe structures to ensure that operational temperatures are being controlled and recorded properly. This will help in the reduction of pipe blockages due to hydrates.

Similarly, carbon fibers are being explored rather than steel fires to allow for stronger and lighter armour wires, which help in the reduction of the armour wire failures. Such advances in technology improve the performance of flexible pipes and will aid in expansion of this technology.

Additional emerging technologies are presented below, which will aid in the reduction of flexible pipe failures. Each of the twelve failure modes for flexible pipes, which have been identified in the case study, are listed in the table, and an emerging technology or advancement in flexible pipeline engineering which will aid in reduction of associated risk, is presented in Table 6-1.

<table>
<tr><th>Failure Mode</th><th>Risk Reducing Technology</th></tr>
<tr><td>Carcass and Pressure Armour Collapse</td><td>Eddy current internal inspection probes are being developed by a company called Force for inspecting the inner carcass and to monitor carcass condition for pipe collapse reduction.</td></tr>
<tr><td>Pipeline Burst and Pressure Sheath Rupture</td><td>Through advanced material engineering research, Technip has been developing new pressure sheath materials which display superior properties such as decreased potential for deplastification to prevent issues with pressure sheath degradation.</td></tr>
<tr><td>Tensile Failure of Armour Wire</td><td rowspan="3">New analytical prediction methods for the numerical evaluation of tensile armour wires behavior are under development by MCS Kenney, based on detailed 3D FEA modeling.</td></tr>
<tr><td>Compressive Failure of Tensile Armour</td></tr>
<tr><td>Torsional Failure of Armour Wire</td></tr>
<tr><td>Overbending</td><td>Fugro Structural Monitoring is to develop an on-board riser management software system for planning and monitoring operations in real-time. Overbending can be closely controlled offshore.</td></tr>
<tr><td>Erosion of Carcass</td><td rowspan="2">Development of a helically wound pipe with a hydrogen-induced crack growth and general corrosion resistant liner by manufacturer Pipestream.</td></tr>
<tr><td>Corrosion of Carcass</td></tr>
<tr><td>Corrosion of Pressure Armour and Tensile Armour</td><td>TOTAL and Schlumberger have developed annulus monitoring systems which eliminate the need for vacuum tests and provide real-time alarms in the case of flooding in the annulus (which leads to corrosion of pressure and tensile armours).</td></tr>
<tr><td>Damage to the External Sheath</td><td>Vertical Strategic Anchoring Systems are under development by JP Kenny to help mitigate geo-hazards which may lead to external pipeline damage.</td></tr>
<tr><td>Damage due to Dropped Objects</td><td>SPS Marine Technologies is developing a lightweight alternative to conventional stiffened steel that provides exceptional energy absorption characteristics.</td></tr>
<tr><td>Damage to the End Fitting</td><td>Radiographic tools for inspection of topside end fittings on flexible risers are under development by Tom-X.</td></tr>
</table>

Table 6-1: Flexible Pipeline Risk Reducing Technologies

Although the technologies listed in Table 6-1 are still under development and are not currently considered mainstream in flexible pipeline engineering, such advancements, once refined and commercialized, will likely promote risk reduction in flexible pipeline operations.

7 Conclusions and Recommendations

7.1 Conclusions

Flexible pipelines are used offshore Newfoundland for both static and dynamic oil and gas applications. They have long history of use throughout the North Sea and Australia. With advances in flexible pipeline engineering, their presence is broadening to more complex environments.

The increased use of flexible pipelines has prompted the need for a consolidated set of rules for flexible pipeline design, installation and operation. Industry has adopted the guidelines and recommended practices set forth by the American Petroleum Institute as the standard for flexible pipelines. Operators, flexible pipeline manufacturers, and construction companies follow API-17J and API-RP-17B to ensure the integrity of the flexible pipelines assets.

At each step in the flexible pipeline's life cycle, specific measures are undertaken to ensure pipeline integrity. Factors that affect a pipeline's integrity are recognized, monitored and controlled throughout each phase of its lifecycle, namely Design, Construction, Installation, Operation and Maintenance.

In a framework for Project Risk Analysis, methods for risk analysis of flexible pipelines are suggested. The scope of analysis depends on complexity, time and costs of operation. For risk analysis of flexible pipeline systems, a FMECA identifies and qualifies the involved risk.

A case study is presented for which a FMECA is conducted on flexible pipelines to identify and qualify risks. Failure causes and mitigating measures are identified for each failure mode. Mitigating measures are recommended for each stage of a flexible pipe's lifecycle. Should these not be realized, there is a possibility of pipeline failure. It is therefore important to recognize the possible failure modes for flexible pipelines and perform mitigating actions and controls such that pipeline failure is avoided.

All risks identified and qualified through the FMECA for flexible pipes have been found to be tolerable, thus encouraging the use of flexible pipelines. Through future works and expansion of flexible pipeline engineering and technology, these risks may be further minimized.

7.2 Recommendations

For systems using flexible pipelines, an integrity monitoring and inspection program needs to be established. API-RP-17B, Section 13.2.1.1, states that for flexible pipelines: "...a detailed integrity and condition monitoring program should be established, based on an evaluation of the failure modes to which flexible pipe are exposed and the risk attributed to failure from each source."

The objectives of flexible pipeline integrity monitoring should address the following:

- Early degradation detection to allow for remedial actions;
- Demonstrated fitness for purpose;
- Compliance with statutory / regulatory requirements;
- Provision of a service record of data.

To have an effective measure of the use of a flexible pipe throughout its lifecycle, a detailed quantitative risk analysis should be conducted. The outcome of such analysis should provide technical and commercial justification of flexible pipe use. In addition, it would also help improve safety and integrity of the pipe system throughout its lifecycle.

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