PSA – Norway

Un-bonded Flexible Risers – Recent Field Experience and Actions for Increased Robustness

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Executive Summary

The flexible risers, which are the focus of this report, have since 1986 been a component of increasing importance in Norwegian petroleum production. With the high number of new floaters on the Norwegian Continental Shelf (NCS) in the years 1993 to 2001, the number of flexible risers increased from about 50 to more than 250. In 2013 there are 326 flexible risers installed offshore. Several of these are operating in demanding conditions with high pressure, high temperature, large fluctuations in operating parameters and high dynamic loadings.

Field experiences clearly demonstrate that there are good reasons to be concerned about the robustness of flexible pipes:

- Updated Norwegian statistics for 2010-13 show at least 1.5% probability of failure per riser per operational year
- Internationally outside Norway there are also indications of high failure rates

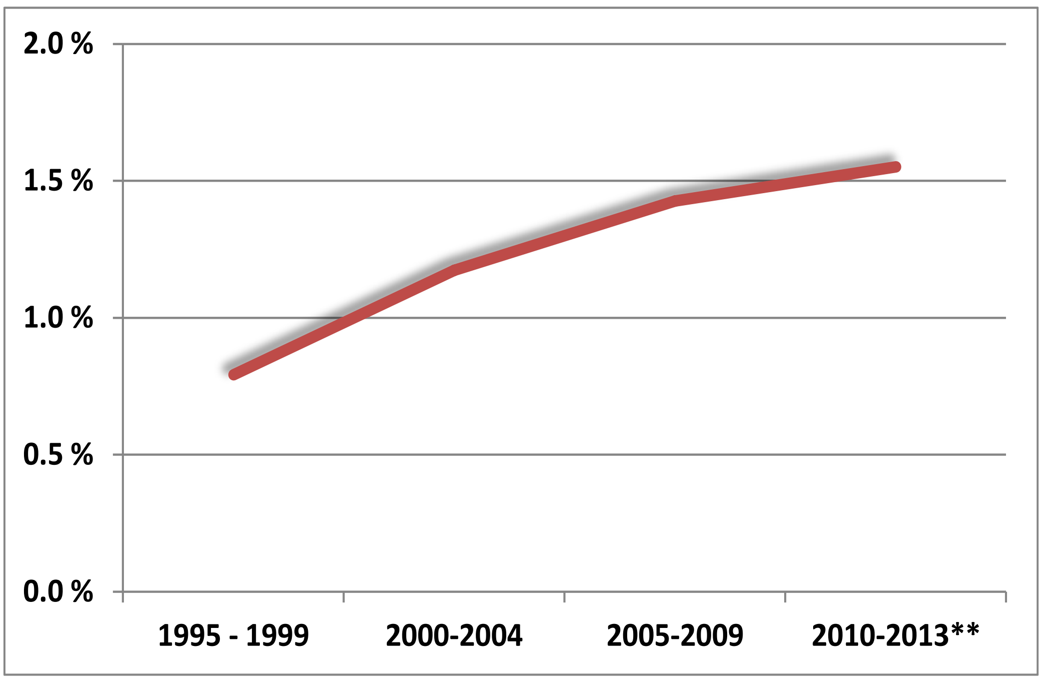


Figure 1: Major incident rate per riser operational year, as reported to PSA (not including all incidents, see section 3)

Historically, more than 25% of NCS risers have been replaced and only few risers have met their originally documented service life. This illustrates a significant reliability challenge facing the industry.

There are multiple causes for the high failure rate but the underlying factor is several years of inadequate appreciation of the complexity of flexible pipes and their possible failure mechanisms. The pipe structures and materials vary significantly between applications ranging from benign to very demanding. The basic technology is relatively new (compared to steel pipes), and it is still evolving to support more challenging applications.

Some design and material issues have been known for many years and are accommodated during design, resulting in a number of pipes operating safely and reliably over their intended service life and beyond. However, known failure modes sometimes appear unexpectedly due to aspects of the operating conditions being more severe than anticipated. Unfortunately other issues have resulted from preventable causes such as operation outside the design limits, mechanical damage due to handling errors, dropped objects, annulus vent system malfunction or inadequate maintenance. Assessment shows that a large number of failures have been caused by mechanisms where the knowledge and understanding have been inadequate to predict integrity issues. This means that several pipes have not been adequately qualified to meet the challenges of the intended service.

One of the challenges is to understand which pipes can operate well within safety limits and identify others that are less robust so that applicable Integrity Management programs can be put in place. The objective of the IM program shall ensure operation within design envelopes, tracking of degradation processes and detection of defects & damages in time, taking into account new knowledge over the operational period. A well prepared and executed IM program for flexible pipes should include the following activities:

- Perform risk rating of the individual riser to enable selection of appropriate IM activities
- Establish maintenance and operation plans and procedures that avoid damages, especially to the vent system and upper part of the external sheath
- Always keep operation well inside defined limits given by design or updated assessment
- When necessary, optimize the operational conditions to ensure sufficient life (e.g. restrict de-pressurization, limit pressure / temperatures, use compatible chemicals etc.)
- Implement condition and exposure monitoring and inspection to detect known or unanticipated failure / degradation symptoms and mechanisms
- Use monitoring equipment that can detect incipient failures to enable shut-down before loss of containment
- Establish strategies for repair and mitigations
- Ensure access to relevant flexible riser expertise

Even with rigorous IM, experience indicates likelihood for flexible pipe failures taking place in the future; alternatively operators must replace risers as a mitigating measure. In short term, the most cost effective solution would be to get as much life as possible out of risers through operational mitigations or optimization of the time for replacement maintaining adequate safety margins.

To ensure robust and cost effective operation of flexible pipes a number of knowledge gaps should be closed. All parties within the flexible pipe industry, including material suppliers, pipe manufacturers, operators and service providers should acknowledge their duty to contribute. From the perspective conveyed in this report the industry needs:

- Forums and arenas for sharing of information between manufacturers, operators, service providers and authorities
- More research and development to improve understanding and provide new and better technology
    - Improved understanding of how flexible pipes function (and fail) enabling identification of all possible failure mechanisms
    - Necessary understanding of degradation and failure mechanisms to enable lifetime prediction and better associated methods for condition assessment
    - Better methods and tools for inspection and monitoring
- More thorough and systematic investigation of incidents including extensive dissection of pipes retrieved from service
- Industry wide learning from each other and bench marking to identify best practices
- Continuous updating of industry standards, recommended practices and guidelines to reflect new knowledge and insight

I. Table of Contents

1 Summary & Introduction

1.1 Overview

Un-bonded flexible pipes have been used nearly 30 years on the Norwegian Continental Shelf (NCS), in static and dynamic applications. Conventional rigid pipe is essentially a solid material whereas a flexible pipe is a "machine" comprised of layers of different materials that each serve a different function while working together to contain and conduct fluids. Therefore, a flexible pipe is a far more complex technology than a rigid metallic pipe.

The use of flexible pipe has enabled development of a large number of fields and satellite tie-ins that could not have been accomplished, or would have been substantially more expensive if only rigid pipe was available. Unfortunately, with the added technical complexity of flexible pipes, there are additional vulnerabilities that have resulted in significantly higher failure rate than for simpler all steel pipelines and risers.

PSA Norway 2013:

"….flexible risers is an area where the industry still has a clear and pressing potential for improvement"

This higher failure rate is documented in PSA Norway's bi-yearly assessment of the risk level in the Norwegian oil and gas offshore industry, and has caused PSA to call for more robust (have sufficient capacity and margins to safely and reliably perform as specified) design and operation of flexible pipe systems with the following statements, ref [9]:

"The industry needs to address the following improvement areas:

- *Updating standards with the most recent experience*
- *Integrity management of flexible risers with continuous monitoring and systems for documenting operations history, which are actively used in follow-up*
- *Ensure good training and expertise throughout the organization responsible for following up integrity*
- *Clear and unambiguous responsibilities for safe operation and integrity management*
- *The industry must do a better job at sharing information between companies in order to ensure continuous improvement throughout the sector*
- *The industry must actively commit to research and development in order to increase knowledge about flexible risers*
- *Quick and precise incident reporting associated with pipelines, risers and subsea facilities"*

The objective of this report is to explore flexible pipe experience and the PSA concerns through an overview of the state of the art and recent experience for un-bonded flexible pipes. The report provides a brief introduction to un-bonded flexible pipe and its development history as a basis for the subsequent more in-depth discussion of performance experiences and current understanding of degradation, best practice integrity management, related uncertainties, and possible actions to achieve increased robustness. Focus is on the operational phase with the main attention on the Norwegian Continental Shelf.

Although the report is focused toward robustness of flexible risers, many of the descriptions and comments apply equally to flexible pipelines, flowlines and jumpers.

1.2 Flexible Riser Incidents

In the early years of flexible pipe operation on the Norwegian Continental Shelf, several incidents were encountered both with polymer ageing and insufficient anchoring of the PVDF pressure sheaths in end-fittings in high temperature applications. Installation damage to the external sheath was more the rule than the exception as equipment and procedures did not fully account for the vulnerability and importance of the external sheath. Improvements were made and the industry responded with new and improved un-bonded flexible pipe technology. It is important to recognize that the NCS flexible pipe applications were also rather challenging.

Figure 1-1 Varg FPSO offloading to a tanker, while a jack up drilling rig works at the wellhead platform – riser over an arch (NPD)

Development of Oil production on the Norwegian Continental Shelf has included a long series of floater developments, firstly by moored semisubmersibles (FPU), and then FPSOs. Water depths in the range of 300-350m were common for the FPUs while several of the FPSOs were moored in more shallow water, down to some 90m, see Figure 1-1.

In 1995 NPD started an incident reporting data base for flexible risers. As of October 2013 that database, now maintained by PSA Norway, contains in total of 85 reported incidents, of which 60 are in the category "Major". The number of reported major incidents increased rapidly, along with the increasing number of risers in operation from 1995 to 2004. A further increase in number of reported incidents continues to today.

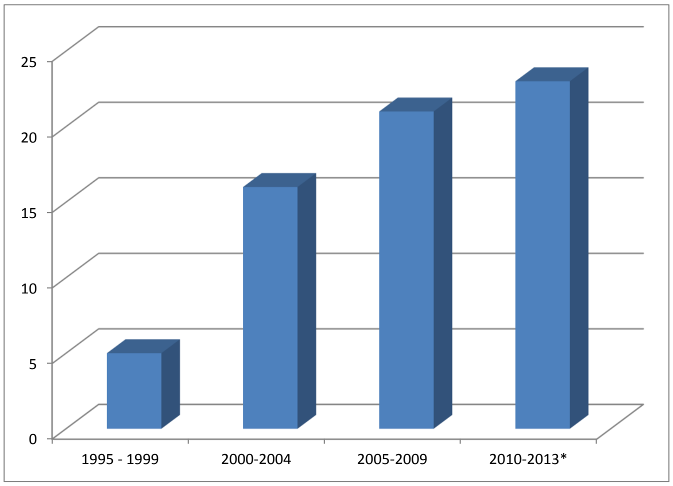


Figure 1-2 Major flexible riser incidents reported to PSA Norway (* last column normalized to 5 years)

Since year 2000 there has been a substantial increase in inspection, testing and monitoring activities, as well as improved life time assessment analyses. These activities are important elements in improving flexible riser integrity monitoring programs.

These activities have proven to be valuable in avoiding smaller incidents, loss of containment and accidents, however lack of experience sharing and inconsistencies in reporting have slowed the rate of improvements that would have been possible with a more pro-active approach.

For many years users of the flexible pipe believed the risers to be virtually inspection- and maintenance free, requiring only general visual inspection above and below water. More recently a philosophy of precautionary replacement of risers with suspected damage or higher risk of failure from known damage has been pursued by some operators. This is an expensive, however effective, way of reducing the number of time-driven incidents and may be reflected in the improving statistics since 2010.

Internationally, the lack of open incident reporting complicates the assembly of a complete picture. However, from the SureFlex JIP reports, ref [3], it is observed that external sheath failures, vent system anomalies, carcass and ancillaries failures are the most commonly reported incidents. Based on published papers from Brazil, there is reason to believe that external sheath failures in the upper part of the risers, corrosion issues and fatigue near the top end fitting, are important areas of concern.

Figure 1-3 Typical external sheath failure due to pressure increase in the annulus, double external sheath (4subsea)

There are several relevant Norwegian incidents that have not been reported, and there are also inaccuracies and lack of consistency in reported data. Still, the authors of this report believe that the reported incidents, public reports, technical papers and their experiences give a reasonable correct picture of today's reliability challenges and conditions for flexible risers.

With a high number of flexible pipe incidents worldwide the probability of severe accidents is present, and as far as the authors know, there have been at least 6 severe riser failures with rapid loss of large volumes of hydrocarbons. Only one of those 6 ignited, and tragically led to loss of lives. Of the 6 known severe accidents, 2 involved corrosion in the vicinity of the splash zone with no wave loading and 2 in similar positions with added dynamics. One related to brittle cracking and one to a gross station keeping problem. Only one of these 6 accidents was caused by a specific event. The rest were damage scenarios linked to service time.

Robust flexible risers…

….have ample capacity and margins to safely and reliable perform as specified

In addition a significant number of smaller un-ignited leaks have been observed. A wider range of known "close calls" support the picture of an increased probability of failure as flexible risers grow older. The risk of major accidents is the main reason for the required focus on increased reliability of flexible pipes; however the possible environmental and economic consequences will be of great importance when developing strategies for increased reliability of flexible riser.

Flexible Pipe Robustness

As discussed above, the frequency and significance of flexible pipe incidents have increased. PSA, in their 2012 report, "Risk Level in Norwegian Petroleum Activities" [9], acknowledged that the frequency and significance of flexible pipe incidents were rising and were higher than for steel risers and pipeline incidents. Therefore, they called for the industry to address specific areas of improvement.

It is required by the industry and operators to review this call for improvements and plan how they will contribute to improved flexible pipe robustness in the following areas.

Updating standards with the most recent experience
The standard for flexible pipe is API Spec 17J and the derivative standard ISO 13628-2. API Spec 17J 4th edition is in final revision editing. It includes new information about fatigue analysis and other topics. Additionally, API Spec 17L, Specification for Flexible Pipe Ancillary Equipment, 1st Edition was released in June of 2013. There is a lag between determination of the root cause of new failure scenarios and revision of the standards. However, the manufacturers and operators should be motivated, as they have been for many years, to agree on and implement appropriate new requirements to mitigate the experienced failure scenarios. A frequently used solution has been to prepare specific operator requirements in addition to the international standards. This may serve as a temporary solution; however there should be active participation by the operators to incorporate all relevant experiences in the standards.

Integrity management of flexible risers with continuous monitoring and systems for documenting operational history, which is actively used in follow-up
Integrity Management (IM) is a systematic process for periodic review of the condition and performance of flexible pipes on a given field to determine if any initiating events may have triggered or altered applicable degradation mechanisms for each layer of the flexible pipe or of ancillary equipment. IM includes the necessary follow-up and mitigations that are identified.


Figure 1-4 Flexible riser training

There are several approaches to integrity management available to the industry and all of them require information about both the original design and operational history to make the necessary assessments. Risk assessments based on probability and consequence assessments are an important part of integrity management and evaluation of responses to integrity threats that may be identified during IM reviews. Failure modes and integrity management are further addressed in sections 4, 5 and 6.

Ensure good training and expertise throughout the organization responsible for following up integrity

Training within operational organizations is the responsibility of management. However, it can be greatly facilitated by publication of reports such as this one, release of technical papers at local and international conferences and by training workshops conducted by the parent organization, equipment suppliers or contractors who are experts in the design, operation and failure analysis of flexible pipes.

Clear and unambiguous responsibilities for safe operation and integrity management

Operational safety and integrity management are the responsibilities of field operators. Safety of personnel, the environment and facilities are substantially enhanced by effective integrity management. Safety of operations has been greatly assisted by international guidelines and support by contractors with safety expertise. This type of assistance could also advance integrity. There are several established approaches to integrity management although some have not been mapped on to the specific technology of flexible pipes. Section 6 focuses on elements of integrity management for flexible pipes.

The industry must do a better job at sharing information between companies and stakeholders in order to ensure continuous improvement throughout the sector

In the past, industry communication has been substantially advanced by shared research, Joint Industry Projects and standardization activities. Unfortunately, shared research in the form of JIPs reduced significantly during the industry downturn a decade ago and has not recovered. CODAM and other similar data bases of field failures or incidents are an important start on information sharing, however, the information may be confusing, incomplete and sometimes misleading. Sharing of experience and research activities are discussed throughout this report.

The industry must actively commit to research and development in order to increase knowledge about flexible risers

As stated above, research and development activities greatly facilitate inter-company communication and alignment. A particularly urgent topic for research is polymer aging and related failure processes. Research and development is further discussed in Sections 2, 4, and 6. It is important that operators participate in the research not only to gain awareness of issues, but also to assure that manufacturers and other researchers fully understand how the pipe systems are used and operated. In the past, some important practical details have been ignored in research projects because they were not thought to be possible.

Quick and precise incident reporting associated with pipelines, risers and subsea facilities

The current PSA incident data base is effective in reporting riser incidents. It could easily be expanded. Section 7 and Appendix C discusses possible improvements for that system.

1.3 Acknowledgements

4Subsea and the authors appreciate the task assigned to them by PSA Norway. After their statements in, “Risk Level – Development Trends” report 2012, ref [9], translated to English in Appendix A, actions need to be taken by the industry. The authors are grateful for the opportunity to contribute by this report.

This report is written based on many years of flexible riser experiences from analysis, development of tools and methods, international standardization work, field operation, integrity assessments, as well as investigations of nearly 50 flexible pipes taken out of service. Totally, close to 30.000m of used flexible pipe has been inspected in detail, in a continuous effort by 4Subsea. Some pipes were leaking due to severe damages and others were intact serving as good references. Selected samples have been analyzed in detail, sometimes in cooperation with DNV-GL, Marintek, Sintef, IFE, riser manufacturers and operators, all with the clear objective of understanding more and contributing to more reliable flexible risers. The authors greatly appreciate the challenges offered by these assignments performed on behalf of operators, both nationally and internationally.

The primary authors of this report have been Jan Muren, Kent Caveny, Morten Eriksen, Nils Gunnar Viko, Joachim Müller-Allers, Knut Inge Engelbreth and Jørgen Eide with additional contributions from several of our 30 colleagues working with flexible riser integrity. The thoughts, conclusions and recommendations in this report are solely those of the authors.

During preparation of the report we received valuable input and comments, in particular from PSA Norway and Statoil. We are grateful for their contribution.

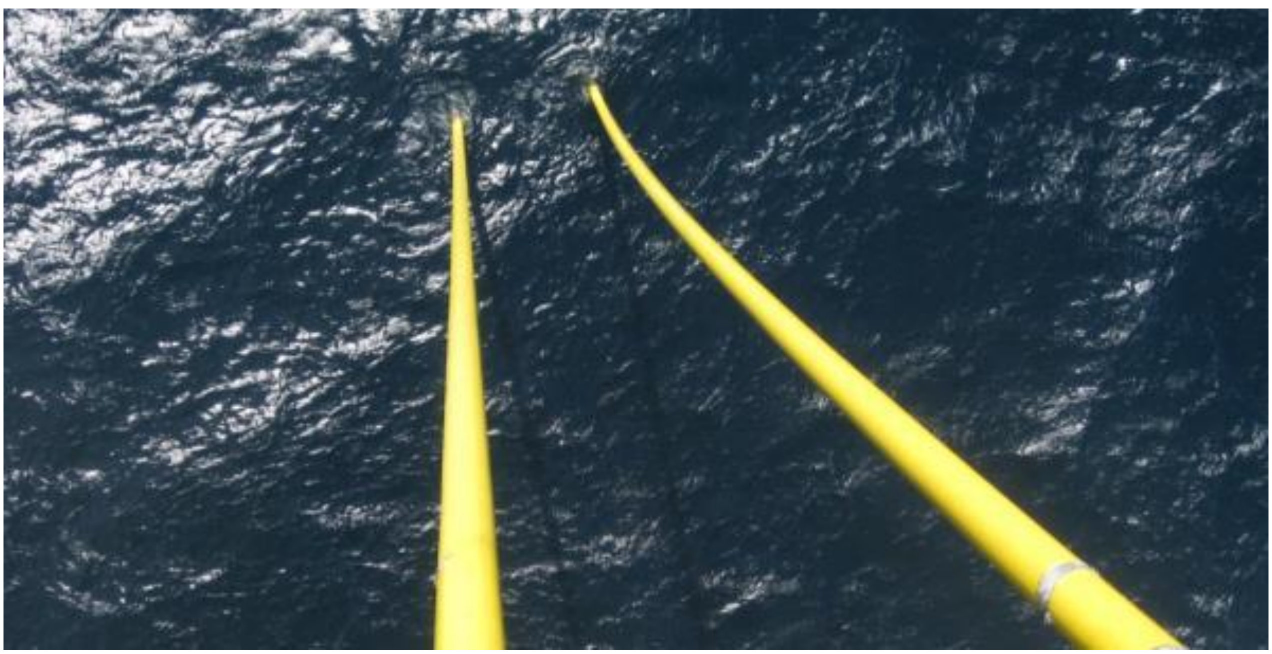


Figure 1-5 ….wonder how they are coping down there…..

2 Flexible Pipe History

2.1 Un-bonded Flexible Pipe History

In order to understand the challenges to developing robust flexible pipe designs and systems, it may be useful to consider how un-bonded flexible pipe has developed. In the early 1960s, IFP (Institut Français du Pétrole) began to develop what we now call "un-bonded" flexible pipe. The IFP, a French research organization, receives a small fraction of the tax on all road fuels sold in France and is to use that income to enhance research, development, education and awareness for sustainable developments in the area of energy, transport and the environment.

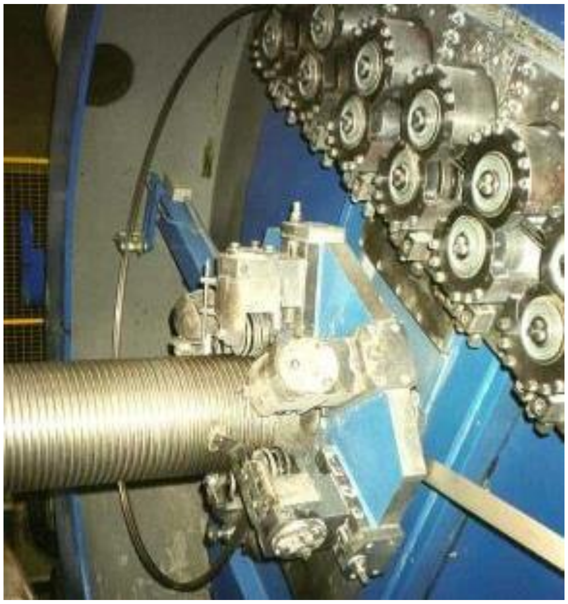
Their efforts to develop a high pressure hose, to replace drill pipe lead to a 1972 patent for un-bonded flexible pipe as we know it today. A unique characteristic of the new pipe was that it was not solid like conventional pipe, but composed of layers of both metal wires and polymer sheaths. That combination of materials facilitated the required flexure, but also has required a much broader range of technologies and design considerations and introduced new vulnerabilities. Coflexip, a consortium of IFP, ELF, ATO and a fourth investor, was created to commercialize the new technology and initially built a factory in Bordeaux. The first product was a 15,000psi Choke and Kill line. When 30km of flexible pipe was built for the Emeraude project, it became clear that better access for ocean transport of large reels was required. Therefore, the plant was moved to a former shipyard near Rouen on the Seine River where it remains today. In 1975 IFP formed a partnership called Flexservice with the Norwegian offshore contractor Ugland to transport and install flexible pipes. Over the balance of the 1970s Coflexip produced hundreds of kilometers of pipes from 2.5" to 10" with pressure ratings from 2000 to 10,000 psi. The primary applications were in Brazil and the North Sea.

Figure 2-1 An early day in the Bordeaux plant (Technip)

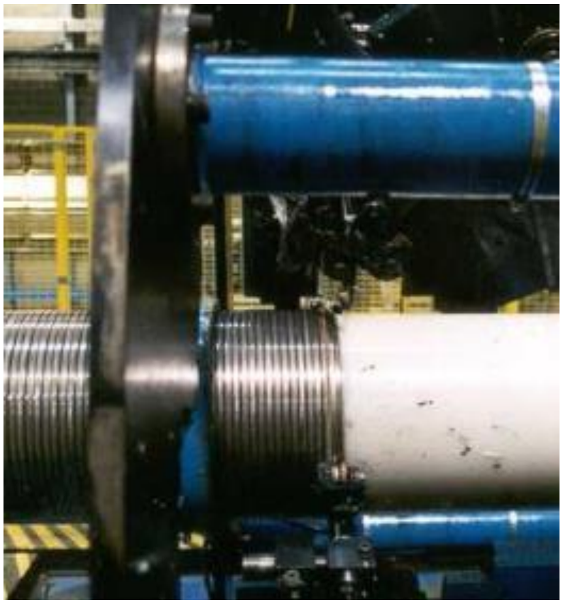
From that beginning an industry grew and facilitated a wide range of development concepts for oil and gas production systems where relative dynamic motion could not be accommodated by conventional rigid pipes. In particular flexible pipe was used as free hanging risers for floating production systems including semi-submersibles and moored ship systems. It was used for well-bay jumpers for developments like TLPs and guyed towers. It was also used in drag chains to accommodate heading changes on floating ship-shaped production systems.

2.2 Un-bonded Flexible Pipe Construction

The name "un-bonded" reflects the layer-by-layer manufacturing process for the pipe body. Prior to the introduction of carousels in the factories, pipe layers were applied as the partially complete body was spooled off of one reel, through a manufacturing station and onto another reel. The carcass was normally the first layer (some of the earliest pipes had smooth bores) and was made by feeding strip into roller dies that formed interlocking "S" profiles. The carcass winding machine and the hoop strength layer machines are frequently the pacing processes in manufacturing because of the tight pitch angle. However axial strength or tensile armors can also go slowly because of the need to change out wire bobbins in order to space out wire welds. Once the machines are set-up, the extrusion processes (which cannot be stopped or paused) run more rapidly than the winding processes. However, there are head and tail lengths of unusable pipe at each end of a typical finished pipe body segment. The end fittings are installed after the pipe body is complete and the head and tail lengths have been removed and the remaining good pipe has been cut to the desired length(s). Initially, it was expected that standard pipe designs could be stocked on reels to be cut to final lengths according to the customer's needs.



Typical Carcass forming -- Narrow strips are formed into an open "S" by the rollers at the top and then clenched together on a stub mandrel to form a flexible, interlocked spiral.



Typical winding of hoop strength wires onto the pressure sheath.

Typical extrusion of external sheath -- but similar to extrusion of a pressure sheath. The extrusion process for the inner and outer sealing layers has to be continuous because the melt process depends on friction in the extruder screw. If the flow of material is stopped, so is the melt process. Even after a few seconds of stoppage cooler material in the extruder disrupts the process.

Typical armour wire winding station – Individual tensioned wires are carried on bobbins loaded on to the large rotating drum through which the pipe body is seen passing. The individual wires are lead onto the pipe body and spirally wound around it. The large drum may only rotate a few revolutions, making a few 10s of meters of pipe before it needs to be stopped so that a wire bobbin can be changed in order to stager wire welds so only one weld, or less, is included per wire pitch.
(Private photos from Kent Caveny and Wellstream International, Panama City, FL.)

Before the introduction of carousels in the factories and on lay vessels, the length of a given pipe was governed by how long a segment of the desired diameter could be loaded onto a reel while still respecting the minimum bending radius at which one or another of the pipe layers might be damaged. Pipes were available with inside diameters from 1" to 12". The upper diameter was limited by the size of the extruder head for the external sheath, number and dimension of wires and handling. Pressure ratings were from 500 to 15,000 psi (34 – 1034 bars) and roughly inverse to pipe ID. The temperature range was set at 0 to 90°C.

Pressure sheaths were made with Rilsan B (PA11) and external sheaths were either Rilsan A (PA12) or PE, and later also PA11. High pressure pipes used high strength steel wires that were only suitable for sweet service (low CO_2 and/or H_2S). Carcasses were firstly plain carbon steel in the expectation that they would not corrode in oil and gas service. Stainless steel was used for water service and became the material of choice. Most structures included an interlocking "Z" shaped hoop strength layer and tensile wires counter-wound at about 35 degrees from the pipe axis. Molded polyurethane bend stiffeners, with their own new technical challenges, were mounted directly to the end fittings which carried all bending loads through the end fittings structure and frequently also through the mounting flange.

It is interesting to compare the temperature exposure ranges of the polymer and steel components of flexible pipe. The preponderance of flexible pipes operates at a temperature of 70°C or below. The steel wires are exposed to slightly lower temperatures because the polymer pressure sheath is a good insulator. Carbon steel typically starts to loose significant strength at temperatures above 500 °C and melts at above 1400 °C. However the polymers used in flexible pipes may melt as low as 120 °C (HDPE) and all melt below 200 °C while they may be intended to operate continuously at temperatures as high as 80 °C (HDPE or XLPE), 90 °C (PA11) and 130 °C (PVDF). In spite of the high utilization temperatures of the polymers, exposure temperature alone has not been a reliability issue.

"Burst disks" to release permeated gases were an interesting design feature in early flexibles. They were thinned sections along the pipe external sheath where permeated gas could "escape". Anodes mounted to the end fittings were expected to protect the wires from corrosion if/when the annulus was flooded.

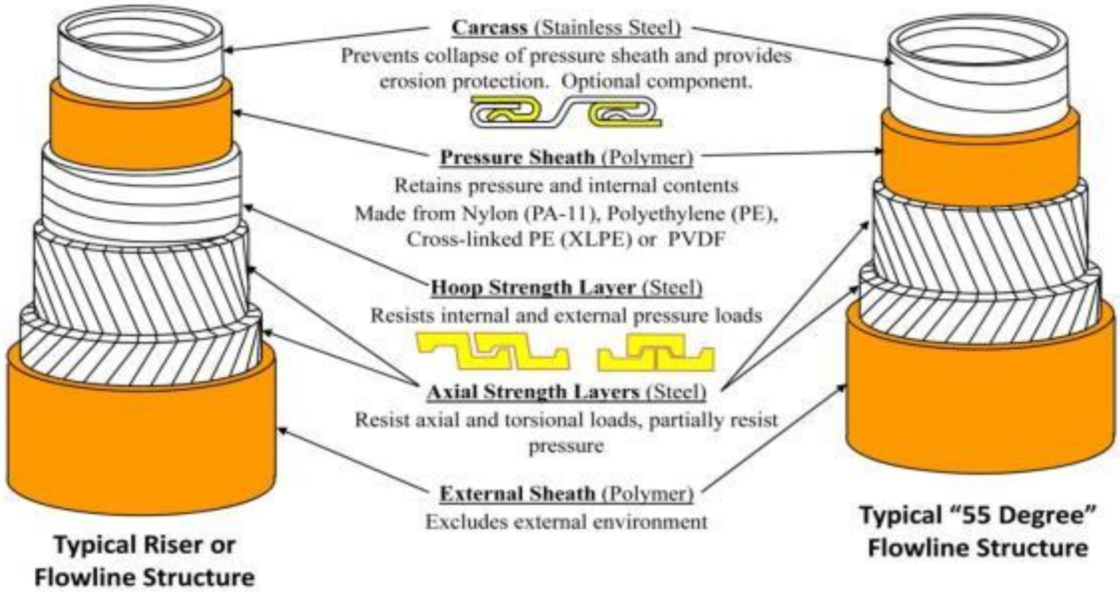


Figure 2-2 Typical flexible riser and flowline build-up's

In the very early days of flexible pipes some clients believed that it was maintenance free. The use of plastic inner and outer layers was thought to eliminate any concern for corrosion and others did not believe there was significant fatigue or aging risk. Those misunderstandings were eventually dispelled.

2.3 Technology Maturation

Initially the loading hose manufacturers, like Dunlop, Pirelli, Gates, PagoFlex, Manulli, Taurus and others tried to compete with Coflexip's long-length products. In the late '80s Dunlop built a long-length production line for bonded pipes, but they were not able to produce them with acceptable quality. Eventually it became apparent that the elastomers in bonded pipe were not sufficiently robust against blistering in high pressure gas and high GOR oil applications.

From 1968 to 1982, NKT, a Danish submarine cable manufacturer built subsea water pipes and chemical transport pipes using essentially submarine cable technology with the electrical conductors replaced by an HDPE tube. These were all static pipes, so hoop strength was provided by steel strips wound at a steep angle to the axis and axial strength was provided by counter-wound pairs of round wire layers.

One of the major oil companies was anxious to introduce price competition and encouraged submarine cable manufacturers, who used many of the same manufacturing processes as Coflexip, to offer un-bonded flexible pipes. In the early '80s, Furukawa, a Japanese cable manufacturer, developed an un-bonded flexible pipe that used dual "C" shaped interlocking hoop strength wires. They also offered both PA11 and PVDF lined pipes. For static pipes, they wound metal tapes at a shallow angle rather than using interlocked wires. All of their manufacturing was done in their submarine cable plant in Japan.

Figure 2-3 Rotating bending test of flexible riser, ref [12]

In 1983, Wellstream was established as a company and opened their first factory in the US, on the Gulf of Mexico in 1989. Later, in 1996, they opened a factory in the UK. By then Coflexip had additional factories in Australia and Brazil.

In 1996 NKT modified their cable factory in Denmark to produce flexible pipe under a license from Furukawa. In 2007, Wellstream also opened a factory in Brazil after closing their US plant.

When IFP developed un-bonded flexible pipe, they also developed some analysis tools and design requirements for it. However, the major oil companies wanted to know more about how flexible pipe worked and in particular how safe and reliable (robust) it was. There was a high ratio between the actual loads (working pressure) and capacities (design or burst pressure) verified by tests. This methodology did not address fatigue and other durability issues. Therefore fatigue testing was called for and many early projects were approved with contingency funds to replace the risers after 10 years of service.

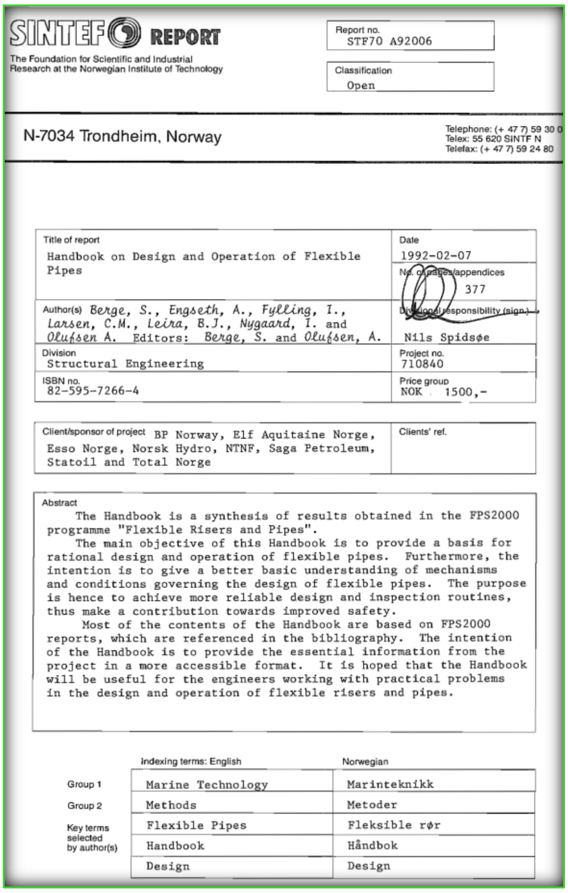
The fatigue tests in the late '70s were of the rotating bend test type, where a pipe was mounted in four bearings with a fixed curvature and subjected to rotation cycles while pressurized. Unfortunately, there was not a clear correlation between curvature change and stress level, so test results were difficult to interpret or extrapolate to specific installation conditions. By the early '80s Coflexip developed a test bench that ran pressurized pipe sections back and forth around a large sheave with a known axial tension. That provided a better representation of actual conditions although it was still hard to quantify the results. That test was actually quite severe because the radius goes from infinite to any fixed radius almost instantaneously. They also introduced a sag bend test rig that allowed natural change in curvature while pressurized but without axial tension.

In 1987 KSEPL built a test facility that could simulate operational conditions applying tension and a wide range of top angle movement to pressurized test sections. A number of qualification tests were then run for project-specific designs. Coflexip reproduced the KSEPL test rig in the mid '90s and Wellstream built similar rigs at their facilities. SINTEF built a horizontal rig in Norway and NKT eventually obtained the KSEPL test rig. Some full-scale sample testing is still done.

There were issues about how many cycles were sufficient (2 million became a frequent answer) and what to do about the many small waves. One common test strategy was to apply a few thousand average cycles to "bed in" the structure and then apply the maximum 3 hour storm cycles followed by about 10% of each significant bin. The bins were then repeated ten times before the maximum storm was again applied. A JIP was conducted that intended to test one or more samples to failure. Fatigue failure of the tensile wires was never achieved outside end fittings because of the conservatism in the analysis programs and the S-N data.

2.4 Industry Standards and Guidance

Initially, clients simply bought the products that were recommended by the suppliers for specific installations. Eventually, some operators began to write their own specifications that primarily specified the details of the applications and might include requirements for a fatigue qualification test. In the mid '80s, George Wolfe of SWRI volunteered to lead an attempt to prepare an API Recommended Practice for flexible pipe. That document was issued in 1987. API practice called for a Specification to be developed 5 years after an RP was issued. Therefore in 1993, a JIP was organized to have MCS develop an API Specification for flexible pipe and to update the RP. The JIP committee had many European and American members as is the case with the current API Flexible Pipe Task Group. That work culminated in the issuance of API Spec 17J 1st Edition and API RP17B 2nd Edition in 1996.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Abstract
The Handbook is a synthesis of results obtained in the FPS2000 programme "Flexible Risers and Pipes".
The main objective of this Handbook is to provide a basis for rational design and operation of flexible pipes. Furthermore, the intention is to give a better basic understanding of mechanisms and conditions governing the design of flexible pipes. The purpose is hence to achieve more reliable design and inspection routines, thus make a contribution towards improved safety.
Most of the contents of the Handbook are based on FPS2000 reports, which are referenced in the bibliography. The intention of the Handbook is to provide the essential information from the project in a more accessible format. It is hoped that the Handbook will be useful for the engineers working with practical problems in the design and operation of flexible risers and pipes.

	Indexing terms: English	Norwegian
Group 1	Marine Technology	Marinteknikk
Group 2	Methods	Metoder
Key terms selected by author(s)	Flexible Pipes	Fleksible rør
	Handbook	Håndbok
	Design	Design

Figure 2-4 The 1992 Flexible Riser Handbook, ref [13]

It is interesting to note that the API motivation for standards is, "To assure the wide availability of safe, reliable and interchangeable products". That is to say "robust and interchangeable products" and is aligned with PSA's goals.

In parallel with the API initiative DNV/Veritec ran a JIP project with the objective of standardizing the suppliers design rules and improve the industry understanding of flexible pipes. The DNV JIP was completed in 1987 and one of the outcomes was the Veritec JIP guidelines which was the most updated reference standard for flexible pipes at that point in time.

In the late '90s the API documents were reformatted and issued as ISO documents ISO 13628-2 and -11. That widened the availability of international standards for flexible pipe although the ISO documents are not supported by either standing committees or a quality program.

Subsequent JIP and the API task group work lead to the issuance of two API Technical Reports related to flexible pipes:

- API Technical Report 17TR1, 1st Edition, 3/01/2003, Evaluation Standard for Internal Pressure Sheath Polymers for High Temperature Flexible Pipes
- API Technical Report 17TR2, 1st Edition, 6/01/2003, The Aging of PA11 in Flexible Pipes

The first technical report was an attempt to identify the key parameters for high temperature liner materials, such as PVDF, in order to avoid future field failures due to insufficient understanding of material characteristics. The second technical report was intended to provide an understanding of hydrolysis aging of the most frequently used flexible pipe liner material. It also proposed an acceptance standard for aged material. A JIP has been proposed to update 17TR2 and possibly extend it to the other polyamide compounds that have been recently introduced into service.

In 2005 API Spec 17K was issued for bonded flexible pipes and the second edition was released in 2010. In 2013 API Spec 17L1 and RP17L2 were issued for Flexible Pipe Ancillary Equipment. API Spec 17J, 4th Edition and API RP 17B, 5th Edition are in final review in late 2013.

Not a public standard, however a significant contribution to improved and more consistent analysis and assessments of flexible risers was the handbook issued in 1992 by Marintek, after a JIP with Norwegian operators. The handbook has been widely used in all areas of the world, and is now being thoroughly updated through a JIP.

2.5 Early Field Experiences

No product is perfect and there has been important learning from field failures. Many of the more interesting failures have affected several pipes as a “common failure mode”. However, it is important to understand that the vast majority of pipes perform reliably throughout their design life. Many of the pipes that don’t complete their design life have sustained external damage (during transportation, installation or operation) or were operated outside of their intended design conditions. These are to large extent self-inflicted wounds by the operators and their contractors. In North Sea there have not been any tensile wire fatigue failures, likely due to intense focus on this failure mode over several years.

Early field issues included cracking of the PE and PA external sheaths at end fittings in very cold exposures. There were a few un-bonded pipe end fitting pull-outs before hooks, bends or welds were introduced at the end of the wires to better anchor them in the epoxy. Some bonded pipes failed because of exposure to high pressure gas and resultant “Rapid Decompression” tearing. There were also issues with “birdcage” bulging from torque or axial compression until high strength Kevlar outer tapes were introduced.

In 1988, an un-bonded flexible pipe leaked at the Castellon field in Spain. Investigation revealed that the PA11 liner had aged due to high temperature exposure in the presence of water. Although PA11 had long life in automotive and other industrial applications up to 90ºC, those applications did not include significant water that causes hydrolysis or reduction in chain lengths of the polymer molecules. After investigation, new curves were produced for service life with and without water exposure. With water exposure the PA11 was limited to 60 ºC for a 20 year life as opposed to the previously specified 90 ºC temperature limit.

Figure 2-5 External sheath cracking due to high temperature under bending stiffener, ref [14]

On Christmas Eve 1994, the first of a succession of flexible pipe end fitting failures occurred on Veslefrikk. Investigation by an ad-hoc industry group of operators, manufactures and materials suppliers, loosely called “The Friends of Flexibles”, determined that the innermost pressure sheath layer (in three-layer PVDF sheaths) was pulling out of the end fittings. The failure mechanism combined the effects of de-plasticizing of the polymer and high loadings in PVDF during cool down cycles. To enhance flexibility of the material, PVDF was highly plasticized (13% by volume) with DBS (dibutyl sebacate). The plasticizer would leach out of the PVDF due to exposure to production fluids. Water and gas exposure could completely remove all the plasticizer. Crude oil removed the DBS also, but some of the higher weight oil molecules around C18 could re-plasticize the material. Dissections and tests showed that after sufficient plasticizer loss had occurred, the carcass and inner sheath would withdraw a few millimeters during each cool-down cycle until they were no longer retained by the seal system. These findings lead to revised end fitting designs and re-development of the PVDF polymer compounds to minimize the volume shrinkage over the service life.

The Castellon field failure and the experience with the PVDF end fittings identified the desirability of finding another polymer for use in service with water exposure between 60°C and 90°C. Cross linked PE (XLPE) and PA-12 has subsequently been qualified for those applications. However, aging of polyamide compounds remains an area for research and evaluation.

The latest significant failures have been associated with carcasses. One failure mode is for the carcass in high pressure pipes with three-layer PVDF sheaths to be collapsed by radially inward pressure from permanent or temporarily trapped gas. A second carcass failure mode is tearing of the carcass by the combination of self-weight and PVDF shrinkage forces. Carcasses with increased thickness and strength have been used to overcome some of those issues. Carcass failure with other liner materials than PVDF has also been observed but then related to other issues like pigging and hydrate removal.

A third, recently encountered carcass failure mode, is related to manufacturing errors that result in a carcass that is very stiff when being fully extended or compressed so there is no freedom for adjacent interlocked wraps to slide within each other to accommodate dynamic changes in pipe curvature. Therefore, the carcass strip is exposed to fatigue and breaks up, especially in locations with high curvature variation like touch down zones, sag bends, hog bends and Mid Water Arch exits.

In the early 21st century there were some flexible pipe failures in deep water due to lateral buckling about the stiff axis of axial strength wires. This was primarily caused by heavy insulation layers causing high end cap loading on deep water pipes. If the external end cap load significantly exceeded the internal end cap load there could be a significant net axial buckling load on the wires.

There are recently observed flexible flowline failures due to designs with sweet service wire alloys being exposed to sour specie. Risers are also susceptible to this failure although they have an advantage if the annulus is not flooded and is freely vented.

Tension-tension fatigue failures of tensile wires are experienced in Brazil, probably on several occasions.

2.6 Norwegian Experience

The first successful applications of flexible risers in Norwegian North Sea were followed by a long series of floater developments, firstly by moored semisubmersibles (FPU), and then FPSOs. A water depth in the range of 300-350m was common for the FPUs while several of the FPSOs were moored in more shallow water, down to some 90m.

Figure 2-6 Veslefrikk A/B connected by flexible jumpers, bridge and utility lines in air suspension (Statoil)

Un-bonded flexible pipes have been used in Norway since 1986 first as static seabed lines and then as risers pulled in through guide tubes. The first challenging dynamic application in Norway was high pressure jumpers (bonded and un-bonded type) between the jacket Veslefrikk A and the thruster assisted moored FPU, Veslefrikk B. This was soon followed by the un-bonded flexible risers connecting the Snorre TLP with the, at that time, highly advanced Snorre subsea production unit in 1992. At that time flexible risers had already gained experience in the UK sector of the North Sea serving as a valuable reference.

2.7 Current Flexible Pipe Usage

More than 3500 pipes have been produced and deployed around the world in nearly 40 years. The pressure range is about the same as in the beginning, 500 to 15,000 psi, with most pipes between 3000 and 5000 psi. Although the pressure range has not changed significantly, the pressure rating for a given diameter has been moved up as required. Diameters have increased due to larger extruders and 1" pipes have been pretty much eliminated, so the range now is 2" to 18" (ID) with a few special low pressure pipes up to 20". Most pipes are between 4" and 12". The operating temperatures are between -10 and 130°C with over half the pipes operating at 60 °C and below, although about 5% operate above 120 °C.

The need for full scale fatigue testing has been largely replaced by the wide availability of reliable global load and cross-section fatigue analysis software.

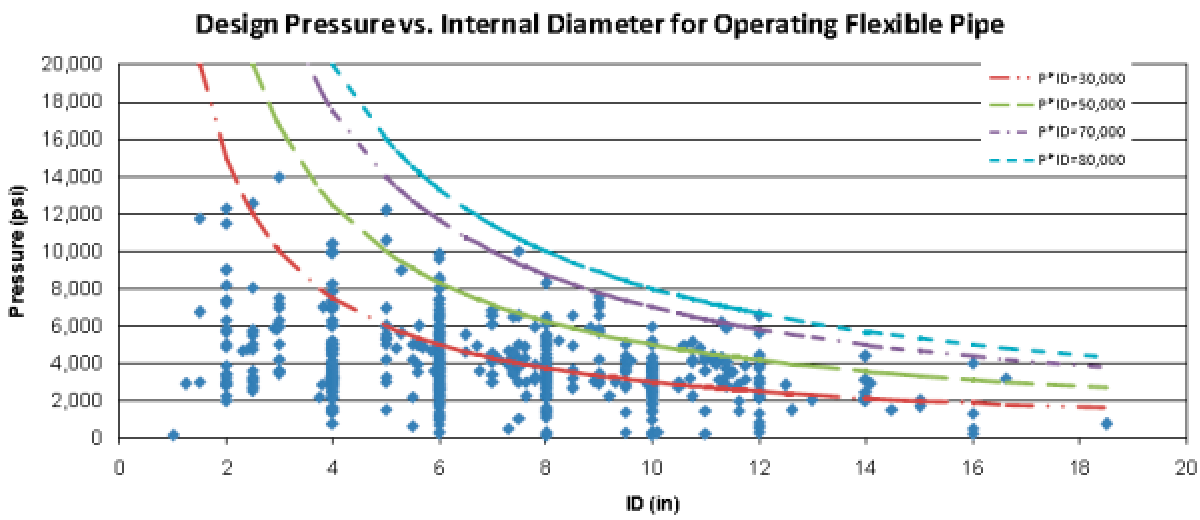

Figure 2-7 Overview of flexible pipes in use - pressure/diameter, ref [3]

Materials have changed too. There is still extensive use of PA11 for pressure sheaths and external sheaths, but there is also extensive use of PE, XLPE, PA-12, PVDF and some external sheaths are made of Thermo-Plastic Elastomers (TPE). There is a much wider array of reinforcing wires now as well with more sweet service wires and an increasing number of lower strength wires suitable for sour service. Carcass materials are almost all corrosion resistant and duplex stainless materials are widely used.

Perhaps the biggest change in flexible pipe applications is the operating water depth. Over half are in less than 500m although the other half are in greater depths and depth is increasing. About 7% of pipes are now in greater than 1500m water depth and a few have surpassed 1800m. Along with the increased water depths have come flow assurance issues that have required development of insulation and heating systems. Initiatives of replacing steel tensile armours with similar rods carbon fiber are pursued.

2.8 Joint Technology Development

As discussed earlier, IFP developed much of the original technology for the design and development of un-bonded flexible pipe and some technology was drawn from the cable industry. The manufacturers still conduct research and qualification programs for new materials, analysis methods, and applications. However, as is to be expected, they make every effort to hold their research results as proprietary knowledge that is frequently only shared with clients on a need-to-know basis.

Starting in the mid-1980s many operators, who were interested in using flexible pipes, were willing to propose or join Joint Industry Projects (JIPs) to investigate the capacity, performance, analysis and inspection of flexible pipes. The current good understanding of flexible pipe stress and fatigue analysis is a direct result of JIPs.

The Norwegian JIP “FPS 2000” developed and documented a substantial amount of flexible pipe design and technology. Similarly the information captured in API17TR2 is the direct result of several JIPs on aging of polyamides. The Industry standards have been developed and revised through JIPs.

Unfortunately, the weakness of oil prices in the late 80s and throughout the 90s substantially reduced new oil field development and the available support for the required flexible pipe JIPs. That support has not recovered in the first part of the 21st Century, even with crude prices 10 times higher than the low point in late 90s. Much of the continuing research has focused on fatigue analysis probably avoiding severe challenges. New research initiatives are required for topics such as polymer performance and corrosion that have caused major incidents because they are not sufficiently understood.

Figure 2-8 Recent PVDF testing (4Subsea)

3 Robustness Challenges

3.1 Introduction

The objective when starting operation of a newly designed, manufactured, installed and commissioned flexible pipeline or riser is obviously to continue operation with minimum downtime and risk of accidents until the associated field production is complete. The specification and design processes aim at delivering a robust, well-qualified product, with a lifetime well above the planned service life - rarely recommending replacement during the intended service life, followed by documentation fulfilling the service life requirements.

Figure 3-1 Flex riser replacement project (4subsea)

In practice, some operators have experienced the need for replacement of one or more risers before the predicted service life is met. The reasons for this are discussed in depth in this section looking at the incidents reported to Norwegian Authorities along with relevant national and international experiences. The objective is to provide an overview of the types of incidents that have been reported by flexible pipe operators around the world in order to understand the Robustness Challenges.

The reasons for failing to meet the desired service life may broadly be divided into 3 main areas.

- External or internal damage such as external sheath tears, flooded annuli and damage to carcasses or smooth bore liners e.g. from pigging or erosion
- Operation outside specified limits
- Shortcomings in design, fabrication or material qualifications

The first two items should be controlled by the operator and are avoidable with proper training, practices and attention to details. Unfortunately, the third category may produce "common mode of failures" that apply to a group of pipes that all use the same design features, material or manufacturing set-up to produce pipes at the more challenging end of the application range.

Internal or external damage is the greatest cause of premature flexible pipe failure. It is thus a paradox that this type of damage should also be the easiest to avoid by use of good plans and procedures and diligent execution of offshore activities.

The most common reason for operating outside specified limits is that operational conditions slowly change while the operators are not fully aware of exposure limits. Often the limits in the process control systems are set based on the maximum design pressure and temperature, while combinations of several factors define the border line, for example, limits on depressurization rates and minimum external exposure temperature at exposed topside end fittings. Also the instrument points reported in the control room may not be at the points of highest pressure or temperature, so the operator is misled into thinking he is obeying to the limits.

"Demanding application" when two or more of the following are true

- High temperature (>70 °C)
- High pressure (>200bara)
- Frequent fluctuations (P / T)
- High dynamics
- H_2S traces in sweet service pipes

There is also the challenge of inadequate information and knowledge transfer between the field development project and the operation. However, some improvements are seen through training programs staged for process operators. Still one of the key areas of suggested improvements is better education of all parties involved in design, procurement and operation of flexible risers. While operations and maintenance of flexible risers in earlier days were seen to be closer to a steel pipe, greater awareness is now emerging and approaches learnt from inspection and maintenance of complex machinery are more frequently considered.

The reliability challenges for flexible risers have been phased. Firstly, dominated by material issues coupled with fabrication and operation (PA11 aging / PVDF end fittings), then installation issues (external sheath breach / vent systems), and now approaching the time related deterioration phase (more complex polymer aging / corrosion / corrosion & fatigue).

So which risers are most exposed to the threats? In short we may say that risers in "demanding operation" are more vulnerable. These are error prone, and live a tough life out there.

3.2 Incidents and Reporting on the Norwegian Continental Shelf

The incidents reported to the Norwegian authorities, and stored in the CODAM database are the key basis for this evaluation. Our objective when analyzing the 85 reported incidents is to evaluate trends, and build competence on small and larger incidents, trying to avoid serious accidents.

Ref [8] provides an overview of the Norwegian flexible risers currently in operation. As the major operator on the Norwegian Continental Shelf, Statoil is also the major user of flexible risers. If static flexible flowlines are included the share would be even more dominant; however this overview is for risers only, and includes dynamic risers and risers pulled in through guide tubes on fixed platforms.

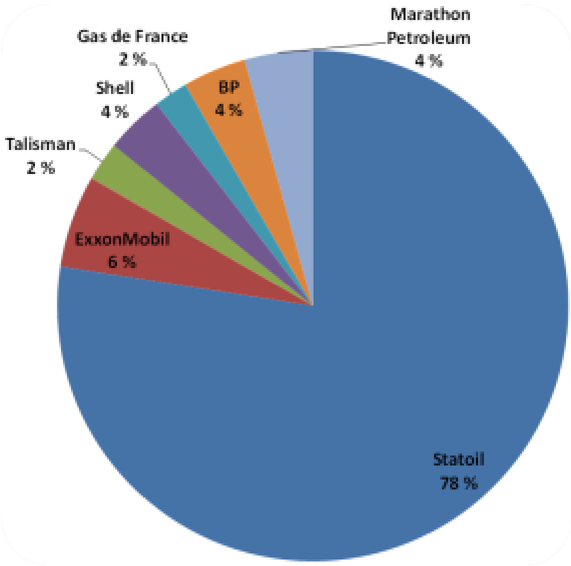

Figure 3-2 Flexible risers in Norway, by operator, ref [8]

At the beginning of 2013 there were 324 risers in this overview. In the coming years, new risers will be added, and some fields will be decommissioned keeping the number more or less stable.

The average age of the risers has over the last years declined as risers are replaced in relatively large numbers by several operators.

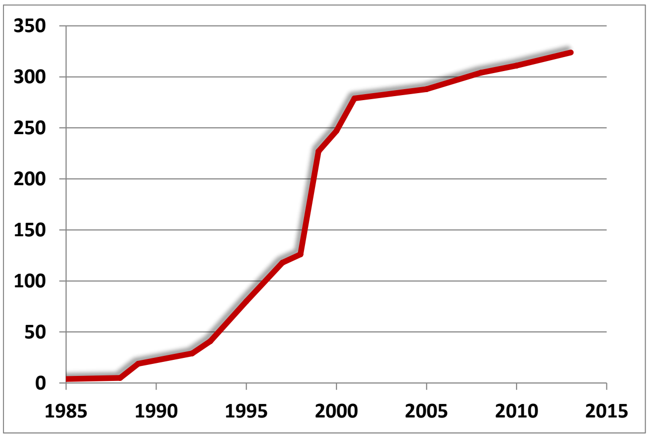

Figure 3-3 Accumulated number of installed flexible risers, ref [8]

The flexible riser incident database, being a part of CODAM, is a good initiative with large potential to promote learning and awareness of emerging incident trends. Unfortunately, some important incidents have not been reported that could have brought important learnings to the industry. One of PSA's seven areas for improvement is *"quick and precise incident reporting associated with pipelines, risers and subsea facilities".*

For CODAM to reach its full potential, specific guidelines are required as to what is to be reported and how. It is initially important to understand that there has been an incident, but that incident may only be understood superficially as a Loss of Containment (LOC) or blockage. As additional understanding is developed the incident reports (see Appendix C) should be updated to present a full understanding of:

- Initial failure mode
- The root cause of failure
- The initiating event
- The degradation mechanism
- Other technical details that could be used to make risk assessment of other flexible pipes.

Example Incident Scenario: *An Initial report may say an operator observed a riser leak as a sheen on the water and ROV investigation discovered a rupture in the external sheath at 90mWD. After investigation an update might report The Root Cause was operating outside the design envelope, the Initiating Event was increasing the production flow rate to a point that the measured riser-top arrival temperature reached the maximum allowable design temperature of 86^oC and the Degradation Mechanism was Rilsan Hydrolysis of the pressure sheath.*

Other technical data of interest would be the age of the riser, the exposure temperature, pressure and water cut histories at a measurement point and extrapolated to the failure location. Information characterizing the rupture in the pressure sheath and a profile of CIV through the pressure sheath near the rupture. The failure scenario would include the facts that the temperature in the riser before the riser top was everywhere higher than the maximum allowable and the rupture occurred where it did because that was where the differential pressure across the PS was sufficient to rupture the aged condition of the PS. Further below that water depth the aging was greater but the differential pressure was lower. Above the failure point the PA11 aging was less and so was the differential pressure. Rilsan aging had been monitored by coupons above the riser top.

It may be desirable to include near-miss cases in the incident data bases.

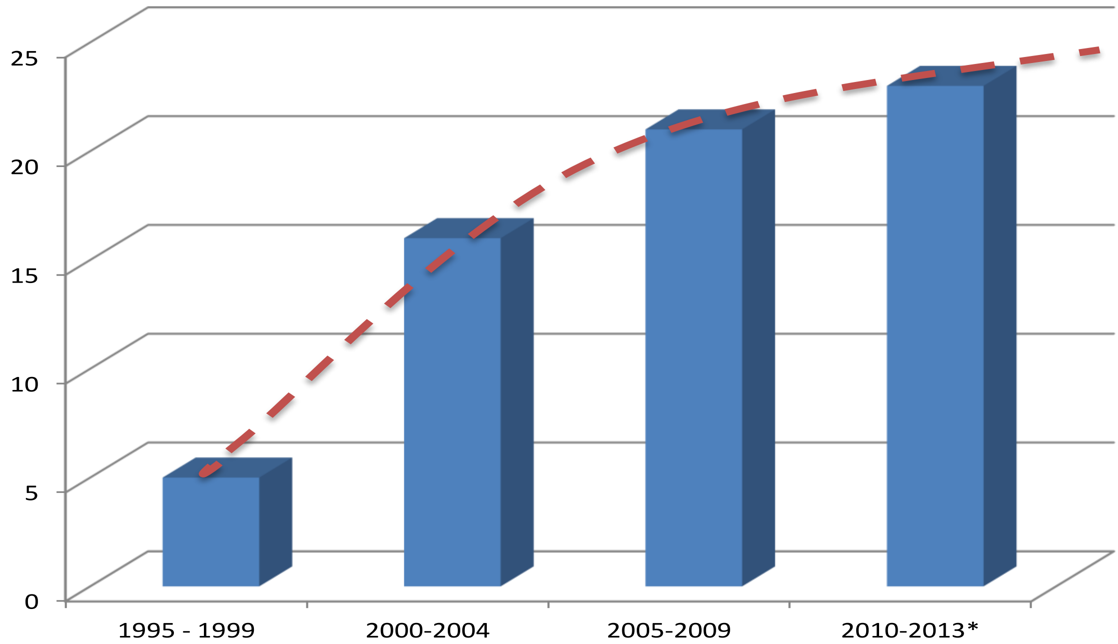

Figure 3-4 "Major" flexible riser incidents as reported to PSA Norway (1995-2013 Oct.) from CODAM (* last column normalized)

As seen in the above figure the number of reported major flexible riser incidents still increase, when five year blocks are used. The significant increase the first 10 years of the reporting period is attributed to the increase in number of risers being installed, augmented by higher reporting from competence build-up and increased awareness, i.e. what to look for and what to report. The continued increase in reported major incidents from

2005 is unexpected as larger integrity management and maintenance programs, training of offshore operators and major replacement programs are implemented (replaced risers without serious findings before recovery is not reported in CODAM).

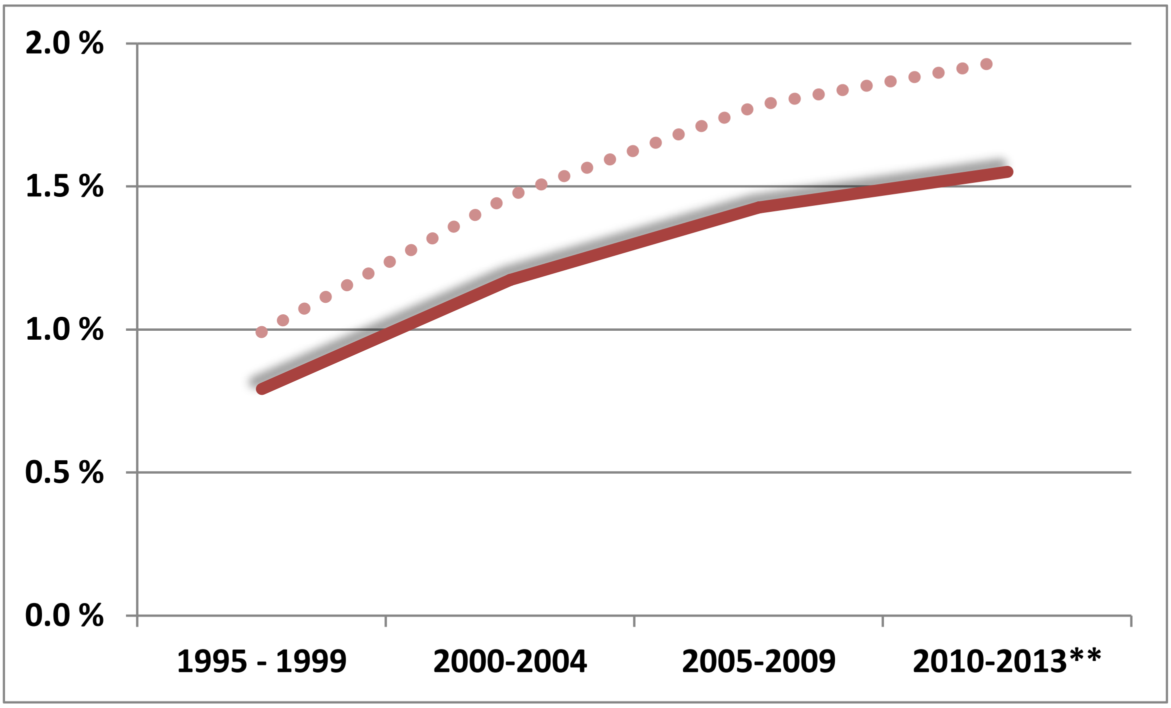

Figure 3-5 Flexible riser incident rate per riser operational year, major incidents as reported in CODAM, (* 2010-2013 scaled to 5 years) Dotted curve estimates total number of riser incidents, including unreported major issues

When taking number of risers in operation into account we confirm the trend commented above. The major incident rate increases from 0.8% to 1.5% over the ten years from 1995-99 to 2005-09. A slightly lower increase in incident rate after 2005-09 is observed.

Both 4Subsea and PSA Norway have information on incidents that should have been reported in CODAM. This underreporting is estimated at 20-25% hence a dotted curve is included to give a picture closer to reality.

When reviewing the incident statistics, Figure 3-6, carcass incidents dominate the statistics. These are caused by several failure modes related to the carcass; collapse, hydrates, pull-out, fatigue and sand erosion. The failure mechanisms associated with these carcass failures could include external over-pressurization, PVDF thermal shrinkage and erosion.

The most frequent collapse is caused by rapid pressure relief of the bore of risers with multiple pressure sheaths. The majority of the carcass incidents are related to multi-layer PVDF pressure sheaths. Some of these failure mechanisms may be relevant even for risers with single layer pressure sheaths. Several carcass sand erosion issues and vibration issues have been experienced, however not reported.

The second most frequent incidents are related to external sheath abrasion against bell mouth/guide tube, interfacing structures and seabed at riser touch down. Internal wear of tape layers are also observed at riser interface areas against structures, however these are not reported. Abrasion damage should have been considered as a possibility and mitigated during design.

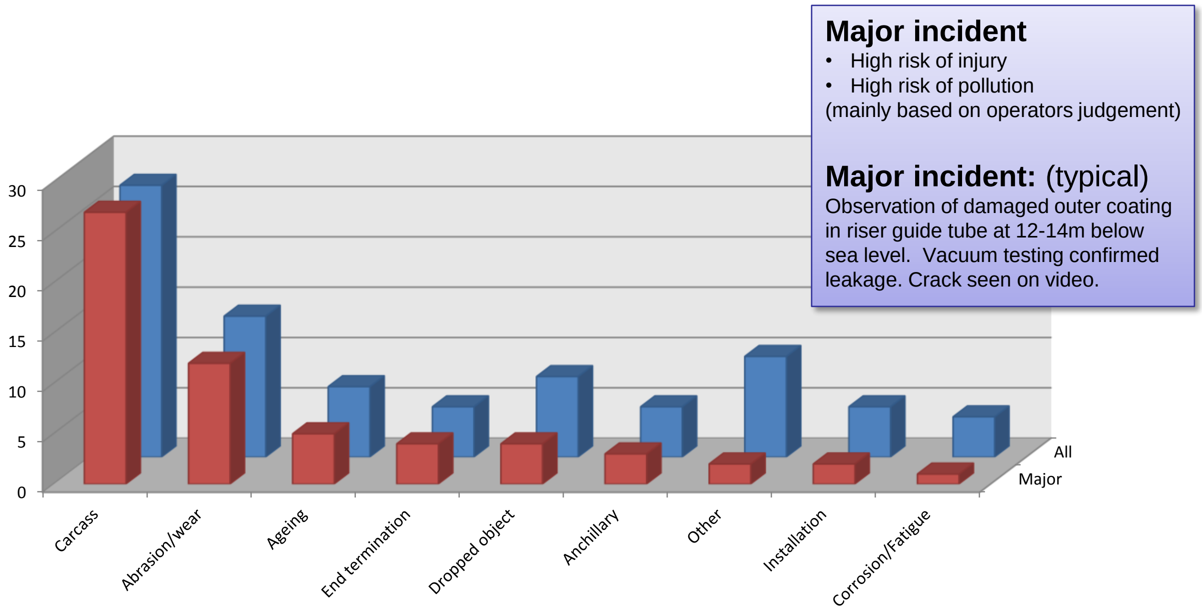

Figure 3-6 Flexible riser incidents as reported to PSA Norway (1995-2013 Oct.) from CODAM

Polymer ageing issues are emerging in the reported incident statistics, however not fully reflected in the statistics yet. This is partly due to non-reported findings on risers taken out of service for other reasons. The reported aging issues are mainly the early PA11 issues corrected by changes in the allowable operating window. There are observations that the external sheath and tape layers for high temperature risers do not sustain the continuous heat in areas of shielding / unintended insulation, even when the riser is operated inside design temperature. These observations are also supported by ref [3].

Figure 3-7 Severe corrosion lead to flexible pipe failure in Norway, however not reported as this is not a riser suspended overboard

The issues related to end terminations are both annulus vent issues in the end fittings, and the early PVDF pressure sheath pull-out. Some of the recent "Carcass issues" are related to carcass pull-out of the end fittings, ref [6]. Lack of sufficient annulus vent and lack of good arrangement of vent tubing / discharge system is a serious problem. Checking of vent systems and annulus testing, vacuum or positive pressure, as part of integrity management programs have revealed a large number of annulus vent issues, and thereby avoided escalation into more serious external sheath breakage and potential corrosion issues. As the industry is going towards to automatic annulus vent monitoring early discovery of vent issues will be a huge benefit. However when automated systems are used (a PSA robustness topic), a requirement for maintenance of vent tubes is expected to grow, as "clean-up" no longer will be performed by applied vacuum or rapid flow of nitrogen, as part of manual annulus tests.

Issues related to ancillary equipment are not the main focus in this report. Increased robustness is experienced due to experience build-up and increased focus as reflected in the recent API 17 L 1/L2 refs [15] and [16].

Damages to the external sheath from dropped objects are seen, however increased focus on marine growth removal for several risers in operation may result in an increase of such damage or it's reporting. This should be considered in the risk assessment, tool development and removal operation planning.

There are some incidents reported in CODAM related to corrosion and fatigue, however it is important to recognize that there are no reported failures due to fatigue. That may be a tribute to the work that has been put into developing fatigue analysis tools and S/N curves for the various alloys and exposure conditions. It may also reflect that the fatigue analysis tools, methods and assumptions are conservative and that the safety factor of 10 against fatigue failure is effective. There is no similar high factor of safety against corrosion, polymer degradation or other failure mechanisms.

As a warning against disregarding this failure mode, it is highlighted that increase in the allowable pressure armour utilization likely will be included in the coming revision of API 17J, ref [17] , increasing the importance of fatigue. Another important fact is that new and more accurate analysis tools and methods now exploit the previous conservatism in fatigue analysis during the growing number of life time extension assessments.

There have been several severe corrosion issues experienced that are not reported, as the corrosion damage was observed after retrieval of the line, and the cause for retrieval was not linked to corrosion. If such corrosion appears at dynamically loaded regions, failures will be experienced. This is a severe risk because corrosion mechanisms applicable to flexible riser steel armour in the annulus are not well understood. Therefore a significant joint industry research effort is needed to be able to agree and document the conditions under which corrosion would be expected or not expected, and what factor of safety to use in either case. Corrosion may often initiate at locations of damage to the external sheath, positions that are not accessible for inspection.

Much more care is required to avoid damage to flexible pipes that can aggravate fatigue, overload and corrosion of the flexible risers. In particular, as some reservoirs may start to sour, high strength wires, not rated for sour exposure, will be at risk for environmental attack that requires the presence of water. If the external sheath and GRV/vent system are working properly on dry gas lines there should be only limited risk. However, several gas injection flowlines outside of Norway have failed in sour exposures that required water to support the failure mechanism.

Corrosion processes in the annulus are complex and experience from inspection of about 40 decommissioned flexible risers the last years determined that only a few risers show the expected annulus conditions. Annuli that were expected, based on diffusion and condensation calculations to be fully or partially filled by water appears to be humid with only smaller water filled sections. Several risers appearing to be water filled in the annulus test reports are partly filled with oil from bore ref [28].

This indicates that annulus test methods may need improvement, and may need to be combined with other methods like annulus gas sampling to get reliable results, further the annulus environment analysis models, including temperature prediction models may need improvement

Several riser degradation mechanisms develop with exposure time, some linear, and some exponential. Most important are polymer ageing, corrosion, abrasion and fatigue. Fatigue in relation to corrosion processes and various H_2 embrittlement processes may develop rapidly.

Another highly important factor now confirmed to develop unfavorably over time, is the mean significant wave height in all North Atlantic, UN report on climate change ref [7]. An increase of 0.02m/year since 1950 is identified. Knowing that the <u>annual average significant wave height</u> on the Norwegian shelf is in the order of 2m, an increase of 0.5m over 25 years life time of a flexible riser is significant, and should be considered in future service life assessments. It is reasonable to assume that this increase will be applicable to at least some operating floaters in Norway, as identified also for extreme waves in [20]. (Yearly maximum and 100-year estimate shown in figure)

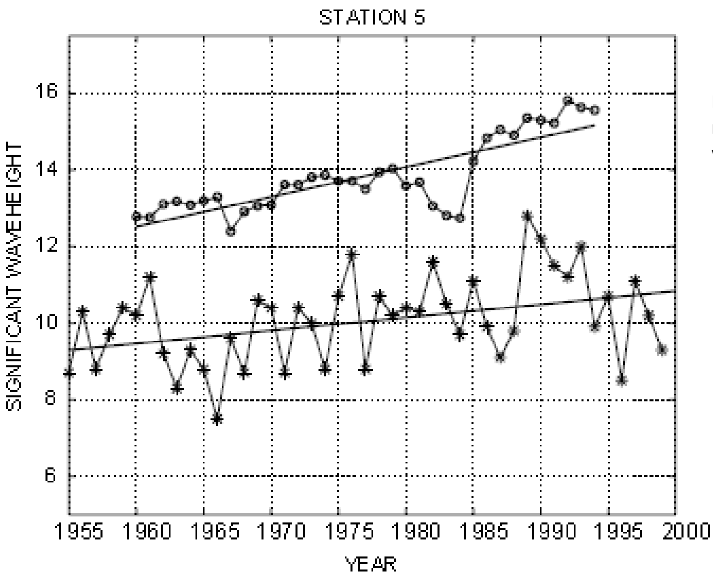

Figure 3-8 Mid-Norway, annual maximum Hs and estimated 100-year value, ref [20]

3.3 International Experience

Although this report is focused on the Norwegian Shelf, there is important reliability information available from other regions. The report from "SureFlex", [3] and published papers and articles are important sources for information on international experiences on flexible riser incidents and robustness. The data from CODAM as discussed above is included as a significant part of the SureFlex overview.

Generally the operators avoid publicity on their own experiences and possible flexible riser robustness challenges. However, in informal discussions at conferences or other meetings, there is significant interest in industry experiences and details. This perception is shared by other consultants and research labs, and indicates that there is a pressing need for broad and systematic sharing of experiences.

Based on anecdotal and published data one may say that external sheath breach, carcass, annulus gas vent and ancillary equipment incidents are the leading threats to flexible riser robustness, worldwide. Adding to that overview, it should be mentioned that several severe corrosion incidents were observed after external sheath breaches in the southern North Sea.

In Brazil there seems to be incidents of tensile armour wires breaking in operations when fully loaded. See Figure 3-9. From the published reports and status updates on inspection and monitoring tool developments there seems to be corrosion near the top end fitting in combination with dynamic tension variations that are at fault.

Figure 3-9 Severe armour wire corrosion / fatigue damage presented as Petrobras' experience, Ref [4]

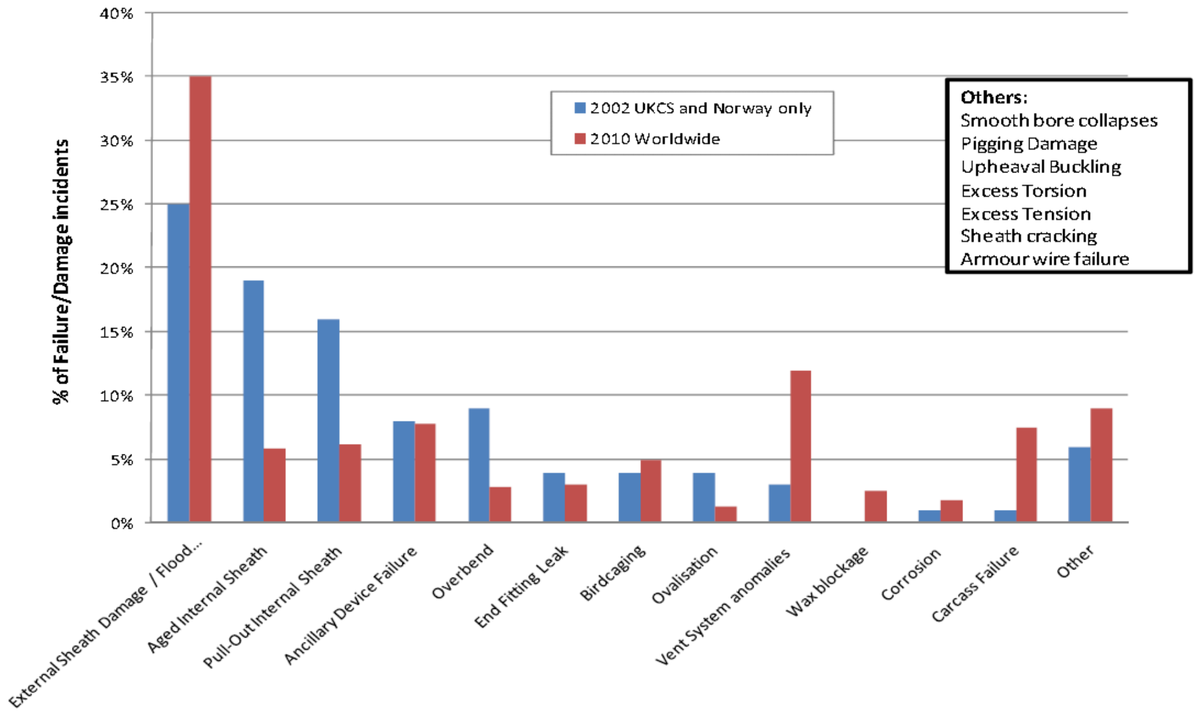

Figure 3-10 SureFlex incident overview, ref [3]

3.4 Serious Incidents

There have been only a few serious incidents with large release of hydrocarbons from flexible risers. To our knowledge only one of these "loss of containment" accidents ignited and lead to loss of life. Only sparse information is publicly available on these accidents. The below review do not give details on where and when, however some details are included to underline the potential consequences involved in the work with flexible riser integrity management, with the objective to contribute to increased awareness and safety.

Figure 3-11 Passive fire protection test (Trelleborg)

The following are 6 reports shortly describing serious incidents with tragic outcome or near misses that could have become fatal accidents under slightly different conditions.

West Africa, large diameter production jumper
Closed annulus vent on one side lead to external sheath failure above water. Sheath damage carefully repaired. Large second external sheath breach just below water line, undiscovered, likely covered by marine growth. Gas filled annulus from damage and up to end fitting. Functioning CP-system. Water dump line in the vicinity mixing air in the water. Heavy wire corrosion. Wire failure and parting of riser during production. Gas release and ignition. Multiple casualties. (Similar incidents without gas release in North Sea South)

North Sea South, large diameter gas riser (2 similar incidents)
Riser in guide tube. Annulus gas vent clogged up during operation. Large external sheath breach in water line area. Undiscovered. Annulus testing did not discover breach, probably due to lack of flow through vent ports. Heavy wire corrosion. Wire failure and parting of riser during production. Significant gas release.

North Sea South, large diameter gas flowline
Rock dumped crossing with gas flowline on top. 55deg structure i.e. no pressure armour. Multiple hit by trawling equipment. External sheath breach. Sheath repaired by clamp. Rock berm re-installed. Continued trawling and/or breach overlooked during first repair. Anodes in the vicinity, high strength wire, seawater ingress. Small plastic deformation in armour wires leading to localized high stress with normal operation pressure. Multiple wire brittle failures initiating parting of flowline and large gas release.

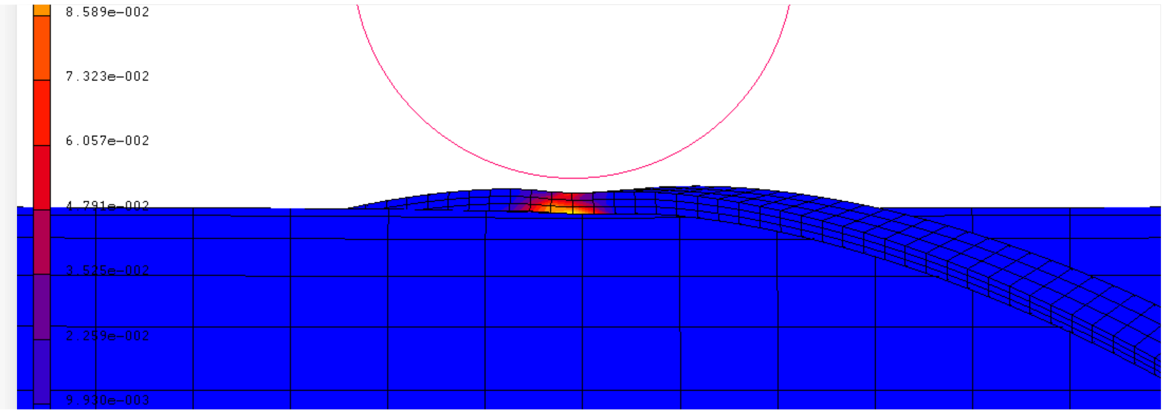

Figure 3-12 Plastic deformation of wire after simulated impact (4Subsea)

North Sea South, large diameter gas export
Riser in guide tube. Annulus gas vent not connected. Large external sheath breach in water line area. Undiscovered. Heavy wire corrosion. Wire failure and parting of riser during production. Significant gas release.

North Sea South, multiple risers
Risers in guide tubes. Position loss of vessel. Heavy overload of risers. Turret piping failures. Significant gas release.

North Sea North, production riser (2 similar incidents)
High temperature risers. Carcass pull-out from topside end fitting due to PVDF shrinking. Ref [6]. Failure of pressure sheath after carcass being removed from the top. Small gas release.

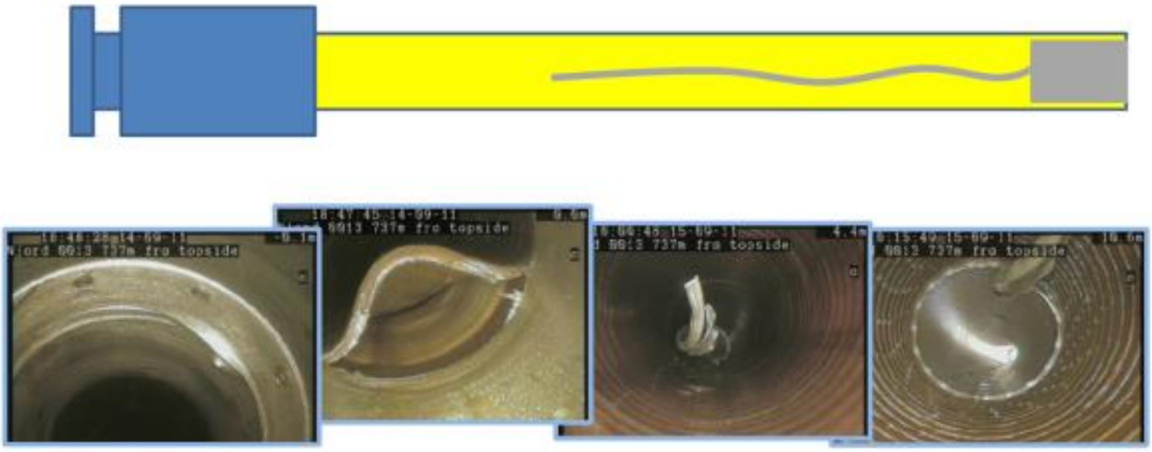

Figure 3-13 Internal inspection of the top of a riser after carcass pull-out, ref [6]

Summarizing the learning from these serious incidents all except the one caused by vessel loss of position could have been avoided with better insight in the possible failure mechanisms and careful inspection, monitoring and testing activities.

Normal safety thinking often concludes that fighting the “minor incidents” is a good way of avoiding less frequent but more serious “major incidents”, and the rare but tragic accidents. This approach will likely be a way to reduce the probability of flexible riser “loss of containment” accidents, as many incidents are related to non-functioning annulus gas vent, and this problem is frequently seen offshore. Ensuring a functional annulus vent is not complicated and will efficiently contribute to reduced risk.

The last serious incidents mentioned above caused by carcass pull-out is much more complex and is a good illustration of the challenge the industry needs to address. One of these risers had continuous annulus vent monitoring, and both risers were closely followed in a well-engineered and executed integrity management program. This failure could have been detected and possibly prevented, but early warning signals were not understood and no inspection program was in place to reveal what was going on. Later such programs were initiated and several similar potential incidents have been avoided by riser replacement.

After working a long period with one particular case, it’s very easy to believe that all weaknesses have been found in this particular area. History has proven that wrong, to some extent, through incidents of PA11 ageing due to organic acids and PVDF-pull out and carcass collapse issues that result from the same mechanisms as the end fitting issues in the mid ‘90s.

Figure 3-14 Typical small carcass collapse

When problems appear to be solved, and time goes by, the failure mode may reappear in a new and challenging setting. This may be related to the” half-life” of industry experience as older troops are replaced by younger ones with insufficient knowledge transfer processes both within and between operators.
As production applications impose more challenging environments (higher pressures, temperatures, water depths or fatigue environments) it may be that previously established safeguards are no longer adequate and require re-evaluation for fitness.

3.5 Dissection and damage investigation

Figure 3-15 Investigation of PVDF shrinkage in a decommissioned flexible riser (4Subsea)

Investigations of used flexible pipes are bringing new and valuable knowledge to the industry. This is often performed for pipes that have suffered severe damage during operation, however much could also be learnt from investigation of decommissioned pipes that are taken out of service without any damages.

Such dissections and detailed material and fracture investigations have to be carefully planned, executed and documented to gain the maximum from the activity.

Characteristics of the polymer materials may change significantly over time and information on e.g. ageing in relation to operational parameters may provide very useful information for further reference and life time assessments.

Investigation of corrosion products and e.g. pitting may provide concrete information on the relevant corrosion processes for the materials used, along with the time scales involved. Likewise, thorough investigation of fracture surfaces may give accurate information on how the cracks have developed, brittle, ductile or fatigue.

When bringing together all the information from fabrication, installation, operation, de-installation, dissection and lab investigations one may gain in depth knowledge of the important degradation processes, or events leading to the riser change-out. The more accurate information available for the whole life of the riser the more value may be gained from the investigations. As the time spans involved from fabrication to dissection may be several decades, high focus should be put on the gathering of relevant information early in the dissection project.

Figure 3-16 Removal of tensile armour wires for corrosion investigations (4Subsea)

Based on experience from investigation of more than 50 risers over the last 15 years the importance of documentation, marking and preservation during recovery should be highlighted. Even more important is the HSE focus during all work with used and/or damaged flexibles, involving everything from radioactive scale in the bore to toxic gases when cutting PVDF.

See: http://youtu.be/AMTlWTwSNio

4 Damage and Degradation Mechanisms

4.1 Introduction

As described in Section 2, flexible pipes used in offshore oil and gas production were developed in the 1960s and taken into use in the 1970s. Applications have become more challenging with time in terms of harsher environments, increasing water depths and more severe production conditions. Flexible pipes are complex multilayer structures with challenging combinations of steel and polymers.

Compared to steel pipes used, for similar service, the number of potential damage and degradation mechanisms is much higher including several issues that are unique to flexible pipes. This means that understanding of vulnerability, long term integrity and field performance had, to a large extent, to be built from scratch.

Integrity issues that were discovered early in the use of flexible pipes have been solved adequately by the industry. However, recent field experience history shows that other and newer issues still remain. To minimize costs and HSE impacts the industry need to develop methods and knowledge to identify pipes at risk and implement mitigations.

This section presents and discusses damage and degradation mechanisms that are known to have either led to pipe failure or required premature replacement or repair. The intention is to identify vulnerability in terms of:

- pipe designs & configurations
- service condition
- operational aspects

4.2 Overview of Origin of Degradation Issues

A key attraction of flexible pipes for the offshore industry has been their use as dynamic risers. This has required ensuring and demonstrating adequate wear and fatiguing life. Therefore flexible pipe technology has utilized the vast knowledge and experience from fatigue of steel component in the offshore and other industries. This includes well established design standards and criteria that typically require the calculated fatigue life to be a minimum of 10 times the required service life for details that cannot be inspected.

There are, however, several flexible pipe integrity issues that have not been encountered by other industry before or have been dealt with in ways that are not practical for flexible pipes in service offshore. To better understand the origins of the integrity challenges they are grouped as follows:

4.2.1 Use of Polymers

Polymers may have inherent compatibility issues in the exposure environments but may also create significant problems in interaction with contacting steel layers.

- Compatibility with the physical conditions and properties of conveyed fluids – physical and chemical ageing (loss/gain of plasticizer, creep, change in Mw, swelling, change in properties with temperature, etc.)
- Absorption and Diffusion of gases
- Significant differences in thermal expansion coefficient compared to neighboring steel layers
    - Anchoring and sealing in the end fittings
    - Forces developed internally and transmitted to the Carcass

4.2.2 Annulus

Un-bonded flexible pipes rely on the structural reinforcing wires being protected within an annulus. However, the annulus design and materials produce the following challenges:

- Gas permeates from the bore through the pressure sheath leading to
  - requirement for reliable arrangement for venting of the annulus to avoid pressure build–up
  - acid gases such as CO_2 and H_2S accumulating in the annulus whenever they are present in the bore
- A vulnerable outside polymer sheath provides sealing against the outside environment. Breaches to the external sheath will change the annulus environment.
- Both with intact and with damaged external sheaths there will be a range of possible annulus environments that may lead to both corrosion and fatigue challenges for the structural wires. Several of these challenges are unique to flexible pipes and require special attention.

4.2.3 End Fittings

End fittings on flexible pipes represent complex solutions integrating suitable sealing, termination of load carrying wires and arrangements for venting of permeating gases from the annulus. A number of integrity issues can arise.

4.2.4 Ancillary Components

Flexible risers rely on ancillary components to limit curvature, provide buoyancy and anchoring. Ancillary components have contributed to integrity issues, such as excessive heating under bend stiffeners, external sheath wear, inadequate fixation, anchoring failures etc.

4.2.5 Miscellaneous Issues

Examples are corrosion and erosion issues for carcass; however these are issues that should be dealt with adequately based on industry experience with the same materials exposed in identical ways. Riser singing is a special topic for dry gas lines that is mainly related to the internal carcass structure.

4.3 Polymer Related Failure Modes

Polymers have vastly different properties than steel:

- The thermal expansion coefficients for relevant polymers are more than 10 times higher than steel.
- Plasticized polymers may lose plasticizer and reduce volume
- Polymers absorb, to very different degrees, hydrocarbon components (both gas and fluid) and water. For some polymers this leads to swelling and enhanced susceptibility to blistering. Of relevant materials Polyethylene has the highest solubility for hydrocarbons
- Polymers are viscoelastic resulting in creep and stress relaxation which is fast at high temperatures and slower at low temperatures
- Time dependent response – ductile under slow strain rates / brittle at high rates
- Polymers are made by chemical reactions and can suffer chemical attack. In particular Polyamides will suffer hydrolysis which may lead to embrittlement at high temperature and in acidic environments

4.3.1 Multilayer PVDF Pressure Sheaths

PVDF is the high temperature pressure sheath material and will therefore see the largest temperature variations. During rapid cool down the much higher thermal expansion coefficient compared to steel will lead to high strain levels in the PVDF liners relative to the steel layers. Stresses generated by residual strain will transfer loads, in particular to the Carcass if the friction to outside layers is low.

The first PVDF material used in flexible pipes was Coflon, which was highly plasticized. Loss of plasticizer leads to reduction in volume. The material was also susceptible to fatigue and creep. The solution was 3 layer pressure sheaths with an inner sacrificial layer and an outer anti-creep layer inside the pressure armour.

<u>Early End-fitting pull-outs</u>
One of the first problems that manifested itself with PVDF Coflon was pull-out of the pressure sheath from the end fitting in late 1994. This problem was solved by better end fitting design and is not considered a problem today.

<u>Pressure sheath induced Carcass Collapse</u>
Around 2002, carcass collapse in 3 layer PVDF pressure sheaths appeared as a problem in high temperature high pressure gas applications. The explanation has been that during depressurization of the pipe bore, gas dissolved in the polymer layer at high temperature, moved from the polymer into the narrow space between two outer polymer layers potentially generating high pressures. If the evolved gas could not escape to vents at the end fittings where the bore pressure was reduced, sufficient differential pressure could be produced to collapse the carcass locally. In some cases hydrates may form between polymer layers during operation, and release the required gas volumes and differential pressure when the hydrates boil off. Controlling the depressurization rates to stay below specified limits has allowed operators to limit the carcass collapses.

<u>Pressure sheath induced Carcass tear-out</u>
A recently experienced failure mode involving 3 layer Coflon layers is pullout and/or rupture of the Carcass. The mechanism is believed to be the combined loads on the carcass from self-weight and thermal contraction of the sacrificial sheath when friction between the sacrificial sheath and the main pressure layer has been lost due to loss of plasticizer. Several failures have taken place over the last 3-4 years in Norway and several risers suspected to be at risk for the same mechanism have been taken out of service for replacement. The susceptibility to this type of failure depends on operating conditions: high T and high P combined with many and rapid P and T cycles lead to the highest susceptibility.

This failure mechanism has in recent years probably been the most costly in terms of investigations, replacements and lost or delayed production. Significant efforts have been invested by Statoil to develop understanding and modeling capabilities for this failure mode.

The cause of this mechanism seems to be similar to what created the pull-out of pressure sheath from the end fitting in the 1990's. It is an example of a physical mechanism that was tied to one failure mode but other potential consequences were not addressed adequately.

<u>Related issues</u>

- Two-layer pressure sheath are in service with PVDF materials using less plasticizers. There are some concerns for collapse issues
- There are some concerns in the industry that single layer Coflon (highly plasticized PVDF) in flow lines may pull out of the end fitting for certain operating conditions
- Single layer PVDF pressure sheaths with low levels of plasticization could potentially under unfavorable operational conditions produce similar pull-out loads

4.3.2 Chemical Ageing

<u>Background</u>
Chemical ageing is a potential integrity issue with polymers. Many polymers exhibit good compatibility with several chemicals but there will often be some *achilles heals*. When compatibility issues exist the degree of incompatibility tends to increase with temperature. The ageing mechanisms of highest concern in flexible pipes are:

- Hydrolysis caused by water, increasing with rising temperature and enhanced by acids, is the primary concern of Polyamides but may also be a problem for Polyester tapes. The mechanism leads to reduction of polymer chain lengths (proportional to molecular weight (M_w)) and may lead to embrittlement

- Oxygen degradation is highly temperature dependent and would primarily be of concern for Polyamides and Polyethylenes. The polymers normally include antioxidants to provide protection against oxygen unless it is fully consumed. Production environments are normally considered oxygen-depleted but repeated batch chemical injection can carry sufficient oxygen to be a long term threat. The largest concern for oxygen degradation is for external sheaths in applications with high bore temperature and insulating effects from, for instance, bend stiffeners
- Injection chemicals can also inflict degradation directly as for the following pairings:
  - Methanol for PA
  - Amines for PVDF
  - Acidic injection fluids

Ageing of Polyamide pressure sheaths

PA11 is the pressure sheath material with the most ageing concerns. There have been several failures of PA11 pressure sheaths in both risers and flow lines.

In early days the upper use limit was believed to be 90 °C; however due to in-service failures of pressure sheaths, the API 17TR2 was developed. It was issued in 2003 providing guidance for use of PA11 in flexible pipes. Corrected Inherent Viscosity (CIV) reflecting the size/length of the PA11 molecules (indication of M_w) was introduced as the measure of degradation and CIV=1.2 dl/g was defined as the "initial acceptance level" (CIV=1.1 for static pipes). For new PA11 extrusions the CIV is typically in the range of 1.7 to 2.4.

API 17TR2 incorporates service life curves for the time to reach the CIV acceptance level as function of temperature and pH. The upper use range is limited to temperatures in the region of 60 °C to 70 °C depending on fluid chemistry and 15 to 20 year service lives. The lower the pH in the produced water the shorter the useful service life and exposure to methanol further limits the service life. The impact of Oxygen is not covered by the API 17TR2.

After TR2 was issued the rate of PA11 pressure sheath failures seems to have gone down. At least no failures have been reported in Norwegian sector after TR2. However, the field experience gives a mixed picture. There are cases where Coupons and analysis for pressure sheaths from retrieved risers exhibit properties that suggest that the service life curves in API 17TR2 is over-conservative. On the other hand there are cases in Norway where coupons recently have indicated that PA11 is degrading significantly faster than predicted by the model. These are relatively low temperature applications (55°C – 65°C) and the pipes have been in service for relatively long times. It is suspected that organic acids in produced water or in the crude oil, that were not included in the TR2 studies, may have a stronger impact than allowed for in the TR2 service life models.

Figure 4-1 Inside of aged PA11 pressure sheath

Figure 4-2 External sheath cracking

Hydrolysis of PA11 is expected to reach a CIV plateau at a level that depends on the exposure conditions. This has been shown theoretically and demonstrated by some laboratories and also seen in a few cases offshore. The question is whether the plateau in some situations can be high enough to give the required life and even allow life extension. It is also worth reflecting on the CIV acceptance criterion, which is partly defined based on one riser failure in the 1990's. There is very limited knowledge about how and at which level of degradation PA11 pressure sheaths will fail. It is also worthwhile to consider that the factor of safety against PA11 aging for the TR2 initial acceptance level is thought to be about 2.0. That is far lower than the more precisely understood fatigue factor of safety of 10 for steel. In addition, some PA11 liners are known to be operating at CIV levels below the initial acceptance level and below the associated factor of safety.

There has been one case in Norway where special grease used in the swivel has caused severe degradation of a PA11 pressure sheath. This was not common swivel grease and it leaked into the lift gas. The issue was identified on coupons and subsequent dissection of a riser confirmed severe degradation of the pressure sheath. The issue was detected before failure and adequate actions were taken.

Several challenges clearly exist for integrity assessment of PA11 pressure sheaths. Significant knowledge gaps remain if we want to ensure optimum, safe and cost effective exploitation of flexible pipes with PA11 pressure sheaths. Nevertheless, the industry has made limited investment in the required research for these issues over the last years.

Ageing of PA11 external sheath

In recent years there have also been several incidents in Norway where PA11 external sheaths, on pipes with liners rated for higher temperature service, have failed, under bend stiffeners or on buried subsea riser sections or flow lines. The bend stiffener cases have been in air above the sea level. External insulation (e.g. bend stiffener) combined with high fluid/gas temperatures in the bore can lead to high temperatures in the external sheaths. Rupture of external sheaths will lead to ingress of water and air and the two can have a significant impact on corrosion of armour wires.

The insides of external sheaths are exposed to that annulus environment (possibly including acid gases), that should be anaerobic and may range from relatively dry to condensed water/oil phase. On the outside, air (oxygen and ozone) will be in contact with the surface of the sheath.

If the fixation arrangement between the bend stiffener and the end fitting allow water (rain or sea-spray) to enter, the environment on the outside of the sheath under the bend stiffener may vary between 100% humidity and relatively dry. With a design that does not allow water to enter, the environment will be relatively dry since the temperature will be well above the dew point of the ambient atmosphere.

Thus the exposures of external sheaths under bend stiffeners can vary considerably from case to case and it is difficult to say when and if the API prediction curves are valid. Retrospectively, one can say that it is not unexpected that the sheath ruptures have taken place after relatively few years; however it is difficult to derive predictive models from the field experiences. Further investigation of failure cases and experimental studies are necessary to establish credible models that can be used predictively for integrity management. Key challenges are to understand the actual exposure environments and the combination of hydrolysis and oxygen degradation. It is worth noting that oxygen degradation will not lead to a CIV plateau as mentioned previously for hydrolysis.

Degradation of external sheaths in buried sections of subsea flow lines requires other considerations. Oxygen dissolved in seawater may play a role but it is reasonable to assume that the oxygen concentration well into mud and silt on the sea floor will be low. Thus hydrolysis may be the dominating mechanism but the impact of acidic components is unclear.

It is essential to note that ageing of outside PA11 sheaths depend on temperature and is therefore only relevant for cases with sufficiently high temperature of fluids and gases in the bore of the pipe. (Or in exposures with high external temperature such as a pencil buoy near the equator with a riser passing through)

4.3.3 Other Relevant Issues for Polymers

- Anti-wear layers in many pipes are made from Polyamides, and will suffer from hydrolysis depending on exposure. In pipes operating at high temperatures and with insulation around the pipe the anti-wear layer may become brittle and disintegrate. Or in worst case may soften and increase friction between the layers and accelerate fatigue

- PVDF has much lower fracture toughness than PA11 or PE and therefore is more susceptible to fatigue at any surface imperfections such as may be produced during extrusion or during operation.
  Some fatigue and fracture toughness failures have been reported in the field

Figure 4-3 Fatigue growth in PVDF (secondary failure) after notch made by carcass failure (Talisman)

4.4 Annulus Related Integrity Issues

4.4.1 Overview - Issues and Field Experience

Over the last 10-15 years there has been increasing focus on corrosion of armour wires in flexible pipe annuli. In early days of flexible pipes it was assumed that the annulus environment in a pipe with intact external sheath would stay dry. There would be no corrosion issues and the SN-curves for fatigue in dry environments could be used. It was eventually recognized that water vapor permeating through the pressure sheath can condense and build up a water phase in the annulus in many pipes. In addition it has turned out that external sheath breaches take place relatively often leading to ingress of seawater or air (or both) from the outside.

The most serious failure of a flexible riser was caused by corrosion of armour wires. That and other potentially high consequence failures have been found on pipes with breaches in the external sheath close to the splash zone or above the sea level. Based on available information, corrosion failures or near misses for flexible pipes can be summarized in the following:

- At least 4 risers have failed with loss of containment – 1 in Africa and 3 in the North Sea region outside Norwegian Shelf
- At least 3 near misses on risers – 2 in Norway and 1 in Africa, including one near miss after abrasion of external sheath

Figure 4-4 Corroded armour wire after breach of external sheath, ref [12]

- At least 7 flexible flow lines with high strength steel wires have failed through mechanisms that are believed to be driven by H_2S. None of these have been in Norway but have taken place in the North Sea region, West Africa and Arabian Gulf.
- At least 1 flow line has failed in a location where impact damage had resulted in deformation of high strength axial armours with subsequent HIC probably caused by cathodic protection.

Many of these incidents represent cases with unacceptable high personnel risks and all have resulted in significant cost to operating companies. All the riser issues are related to external sheath damages and the best way to avoid this would be to prevent sheath breaches. However, it is unlikely that the industry will manage to eradicate external sheath damages completely. It is therefore important to develop better understanding of the corrosion mechanisms and influencing parameters to enable prediction capabilities. It is also important to proactively assure that installation and other offshore work is planned and executed to minimize the risk of damage to flexible pipes.

There are examples where risers have survived long periods with breaches in the external sheath but we do not have the required knowledge to reliably distinguish between detrimental and harmless external sheath damages. There are, however, indicators such as breach location, type of damage and pipe configuration that would lead to higher probability of corrosion.

All the corrosion failures of flexible flow lines have come as surprises to operating companies. Retrospectively some of them seem to relate to H_2S but it has not been possible for any of the cases to explain the full sequence of events and detailed mechanisms. Knowledge gaps clearly exist that can only be filled if operators fund adequate research programs.

Although available information indicates that there have been no incidents related to corrosion inside intact annuli (or far from holes in seawater flooded annuli) it is premature to assume that issues will not appear. Dissections of retrieved risers have shown some limited corrosion damage on armour wires in intact annuli. The primary concern would be reduced fatigue resistance from surface irregularities. It is known from other areas of research into fatigue of steel components that corrosion pits/grooves as small as a fraction of 1mm leads to significant reduction (as much as one order of magnitude) of the fatigue life.

4.4.2 Annulus Environments and Corrosion Mechanism

Multitude of possible environments
It can be difficult to predict the local annulus environment adequately for corrosion and corrosion fatigue assessment.

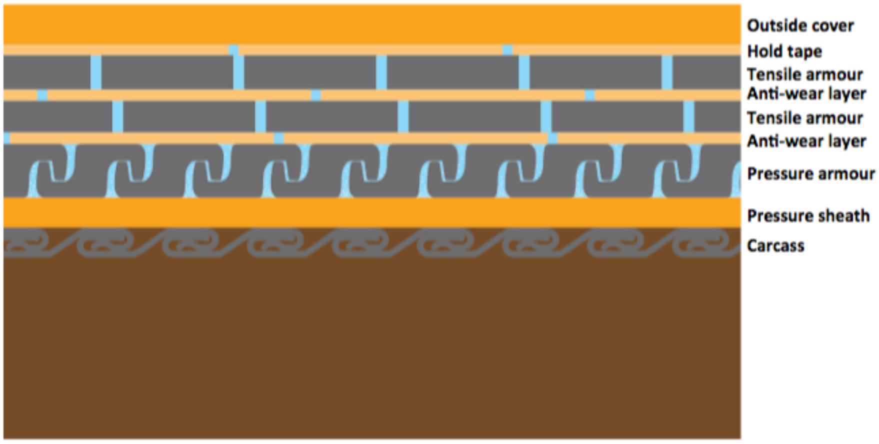

Figure 4-5 Annulus of flexible riser

A range of different conditions can exist in an annulus. It may vary along the pipe and depends on the configuration of the pipe, service conditions and whether the external sheath is intact:

- Gas phase with varying concentrations of water vapor below the dew point
- Liquid water, filling all available free space in the annulus
- Mainly gas phase with condensed moisture or water films on the armour wires
- Sections which may vary between dry and wet

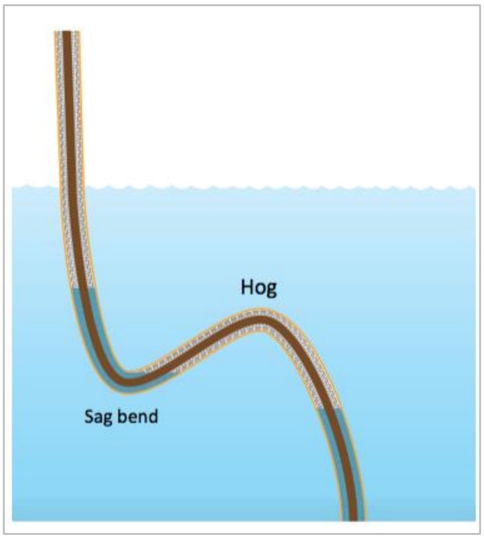

Figure 4-6 Partly liquid filled annulus

The gases diffusing from the bore will partly dissolve in and thus influence the conditions of any liquid water. If the annulus is flooded with seawater, dissolved oxygen in the seawater will be consumed partly through corrosion but the total metal loss from oxygen will be negligible unless the water/oxygen is regularly renewed. In the vicinity of a hole there may be renewal of oxygen from fresh seawater or air. Gas pockets trapped in high points, such as the hog on a riser, may introduce pumping actions when large temperature changes take place as for instance during shut down.

CO_2 corrosion

Flexible Pipe manufacturers have from around 2000 made extensive investigations of corrosion of armour wires in some relevant annuli conditions as required by API Spec 17J. There is strong evidence that CO_2 corrosion rates on steel armours in anaerobic water in flexible pipe annuli are low – typically below 0.01 mm/year. The reason for this is the low ratio between available water volume and the steel surface area in a confined annuls. This will be the case for both condensed water and ingress of seawater in regions of the annulus where the seawater would not be renewed. Oversaturation of iron ions in the water leads to high pH levels and strong films of iron carbonate on the steel surfaces that protect efficiently against corrosion.

Freshly condensed water will become acidic from absorption of CO_2 and it will take some time to develop oversaturation of Iron ions. In this period the water will be more corrosive than stagnant water that has reach high pH levels. Wires recurrently exposed to freshly condensed water “running” down into the annulus through vent tubes, may suffer much higher corrosion rates than predicted for fully submerged armour wires.

Impact of oxygen

It has been suggested that Oxygen ingress into an environment dominated by CO_2 corrosion may destroy protective iron carbonate films and significantly increase the corrosion rate. This is a possible explanation of the apparently high corrosion rates observed in some risers with breaches in the external sheath. However, testing of this and other hypotheses will be necessary to close knowledge gaps and thus enable predictive capabilities and improved risk assessment associated with external sheath damage. Industry funded research is needed.

Figure 4-7 Armour wire corrosion (Statoil)

Protective films forming on steel surfaces often limit corrosion rates. Mechanisms that damage these films may therefore promote enhanced corrosion. In addition to chemical attack, mechanical abrasion may also damage protective surface films. Any mechanism wearing holes in an external sheath may therefor also create high corrosion rates when the steel armours have been exposed directly to the same wear mechanism.

Cathodic protection

Cathodic protection may protect steel directly under holes that are exposed to the sea. The reach of the protection to steel wires away from a hole, under the external sheath, will be limited due to screening effects. In situation with renewal of oxygenated seawater due to circulation or pumping effects unprotected corrosion may take place due to oxygen penetrating into the annulus beyond the reach of the CP potential.

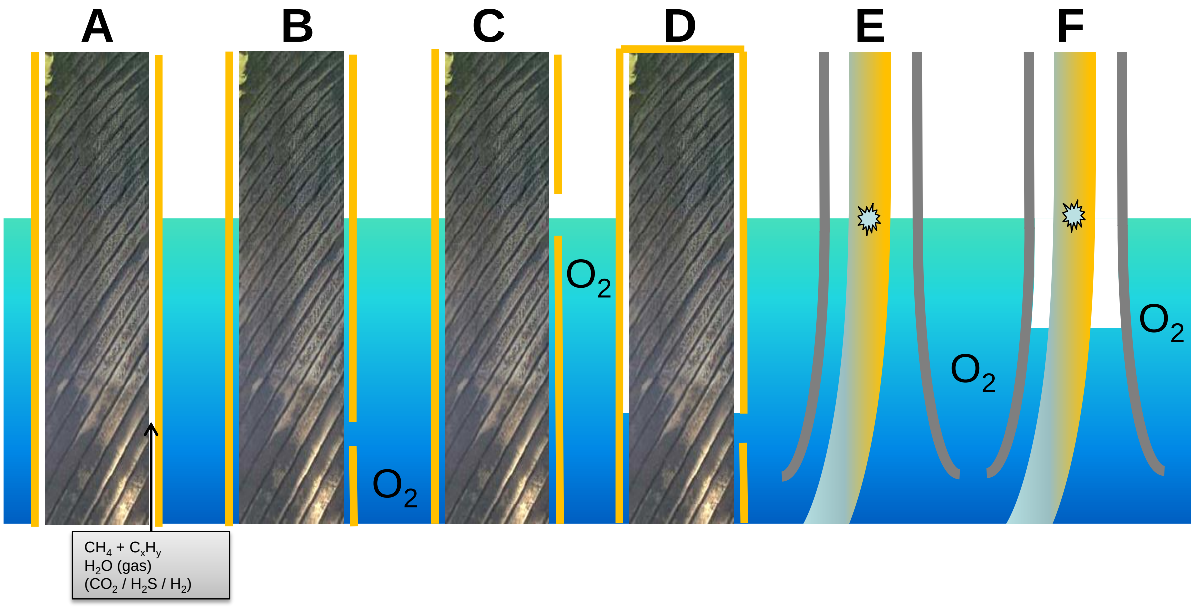

Figure 4-8 Variations in external sheath breach locations (B - F)

H_2S related issues

Technip has published results from full scale testing with bore environments with high concentrations of CO_2 and H_2S. The test included both long-term exposure under pressure and fatigue. The corrosion rates were low and the test did not provoke any SCC or HIC related failures of high strength steel wires. On the other hand the industry has experienced H_2S related failures at lower partial pressures of H_2S than used in the reported tests. This demonstrates that the mechanisms and conditions creating vulnerability are far from adequately understood. To enable identification of cases that are at risk an industry funded research program is required to close the knowledge gaps.

Representative fatigue environment

Adequate fatigue life of tensile armour wires has always been a design requirement for flexible risers. Procedures for calculating fatigue and acceptance criteria have been adopted from fatigue assessment of other un-inspectable critical steel components used on offshore installations. One of the challenges with fatigue calculations of armour wires in the annulus is to predict the environment that the wires are exposed to in the fatigue hot spots and generate representative SN curves. Possible environment are:

- Dry environment – assumed to be relevant for operational phases only when the flow in the bore consists of very dry gas
- Armour wires fully submerged in anaerobic condensed water or seawater. Typically found in fatigue hot spot when annulus is flooded in risers where the bend stiffener or bell mouth is subsea or at the touchdown point
- Anaerobic gas including CO_2 and water vapor where the temperature varies below and above the dew point or where “freshly” condensed water recurrently runs down from the vent tubes. This can create a range of scenarios
- Any of the last conditions above with oxygen ingress

The last two types of environments are difficult to predict and simulate in detail and worst-case assumptions may be necessary.

An issue with long-term fatigue is that the SN curves used in the analysis, in potentially corrosive environments, are generated over a few days, weeks or months and will normally be completed before corrosion processes would be able to generate significant surface irregularities such as pitting. If there were slow corrosion processes taking place surface irregularities would be generated over time eventually creating notch factors or stress concentrations that could substantially reduce the fatigue life. It is known from the literature that surface irregularities or pitting smaller than 0.1mm in depth cause significant reduction in fatigue life. This should be an area of concern and the industry should seek to close knowledge gaps.

4.4.3 Causes for external sheath Breaches

The most dramatic corrosion damages on risers have been the result of external sheath breaches. Prevention of these breaches would reduce the number of major corrosion related incidents. Some causes for sheath breaches are discussed below:

Figure 4-9 Blocked vent leading to breach in external cover, ref [12]

Blocked vent system

Blocked vent system (clogging of vent tubes/ports, vent ports not connected, valves unintentionally left closed) lead to excessive pressure build-up in the annulus. Eventually the sheath will breach in a location where the breach resistance is lowest. It is worth noting that available information indicates that all the cases of corrosion that have led to riser failure (loss of containment) have been linked to sheath breaches caused by over-pressure in the annulus. It may be that holes generated by over-pressure have features (exposed area, rupture of tape layers, size of hole etc.) that create conditions with high susceptibility to corrosion. Comprehensive vent system management procedures that include annulus monitoring and vent flow testing should prevent this sheath damage mechanism.

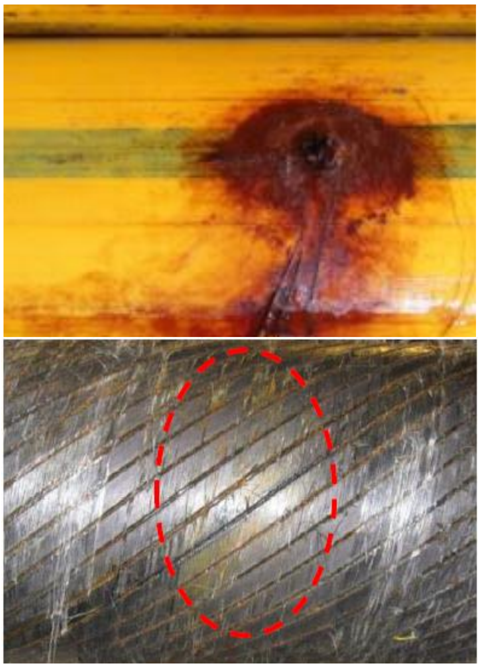

Figure 4-10 Typical external sheath cut with corrosion products on the surface, including wire inspection under the same damage, ref [28]

Cracking of external sheaths

One cause of sheath breach that has become more frequent over recent years is embrittlement and cracking of PA11 sheaths due to high temperatures under insulating bend stiffeners (in particular in air) or in buried pipes sections on the sea floor. Several incidents have been reported over the last years in Norway. Investigation of one of the cases revealed significant corrosion of tensile armours. Cracking under bend stiffeners can be detected and located by annulus vent testing.

Abrasion

Wear of external sheaths have led to several cases of sheath breaches in Norway. Typical locations have been at touch down and in bell mouths. Significant corrosion damage on tensile armours was found in at least one incident. When the external sheath has been worn through the abrasion will act on exposed armour wires. This may promote enhanced corrosion if the abrasion destroys protective films that form from corrosion processes.

Impact damage

Impacts with “sharp” objects have, in many instances, created holes in the external sheath on risers and flow lines. Experience shows that many of the holes are relatively small. There are cases where several corroded wires (but not extensive) have been found under such holes located in or above the splash zone.

A limited number of dissections indicate that no significant corrosion damage was found under or in the vicinity of holes in riser external sheaths well below the sea surface and above the mud line.

It is important to be aware that impacts with objects can plastically deform the tensile armour layers. This will leave residual stresses making high strength materials sensitive to HIC in connection to cathodic protection. It is believed that there is at least 1 reported case where this has caused failure of a flow line (outside Norway).

Damage from installation
Experience shows that many external sheath breaches are created during installation. Most of these will be repaired if discovered before overboarding, or during as-installed inspections but there is always a risk that external sheath damages remain undetected.

Vent maintenance and breach detection
Continuous vent monitoring will be the best approach to ensure early detection of non-functioning or deteriorating venting systems. Monitoring systems are available today and their benefits should outweigh the cost.

Regular annulus testing has been taken into wider use recently and is an essential method for detecting external sheath breaches in the upper parts of risers (from well below the sea level and up to the top of risers). This will also provide information about functionality of the vent system. Corrosion rates can become high after sheath breaches. This should be reflected in the frequency of annulus vent testing to ensure that breaches will be detected and repaired before excessive corrosion could take place.

The vent monitoring system should be able to:
- Track vent rate
- Detect the onset of corrosion by sensing Hydrogen produced by corrosion
- Quantify the corrosion rates by sensing Hydrogen production rate
- Detect and quantify significant changes in the corrosion processes
- Detect leakages from the bore that indicate the onset of pressure sheath / end fitting seal failure

These are targets that the industry could reach through adequate investment in development of knowledge and technology. The potential is great however the lack of knowledge is significant.

Early detection and repair
Early detection of breaches to the external sheath and immediate repair is the best way to minimize associated integrity risks.

4.5 Other Integrity Issues

4.5.1 End Fitting Issues

Relevant integrity issues for the end fitting are:
- Blockage of vent tubes (discussed under external sheath breaches)
- Maintaining all required sealing (to avoid leakage from the bore and ingress of air and water from the outside) under all operating conditions
- Termination of tensile armour wires. This is becoming a problem for deep-water risers where high loads in the tensile wires are transferred directly into the wire terminations in the end fitting. The forming process from manufacturing may leave residual stresses and the wire geometry in the transition from pipe to end fitting may create stress concentrations

4.5.2 Ancillaries

All flexible risers, and several flexible flowlines, are dependent upon various ancillary equipment components, like clamps, buoyancy elements, bend restrictors or various support structures. The integrity of the flexibles requires well functional ancillary equipment. This is discussed further in ref [16].

In practice there have been several issues experienced related to ancillary equipment, seldom leading to loss of flexible pipe integrity, however there have been close calls at several occasions. The most serious have been loss of Mid-Water Arch vertical mooring, bending stiffener attachment failure, vertical tether wear and clamp failure.

Figure 4-11 Mid-water arch with marine growth (pipe dynamics seen as white areas) (Talisman)

Several clamp failures have been experienced due to erroneous use of high strength bolts in contact with anodes at the clamp, leading to brittle failure. Early discovery of these failures enabled repair before dynamics in bad weather exposed the flexible riser to unacceptable curvature and tension.

Several cases of tether wear due to unfavorable (outside design envelopes) clamp exit angles, and dynamics have been discovered due to inspection of recovered ancillary equipment during riser replacements, and subsequent revised ROV inspection plans.

4.6 How Do Flexible Risers Fail?

Different damage and degradation mechanisms will lead to different modes of the ultimate pipe failure. The consequences may be vastly different and have significant impacts on the risk assessment. Loss of containment is the most serious ultimate failure since this may create risk to life, environment and other equipment.

Failure modes caused by full rupture of armour wires carrying the tensile load may lead to full opening of the bore to the environment. This can lead to large gas fires and significant release of pollutants.

Figure 4-12 Testing of carcass radial leak rate (4Subsea)

Penetrating cracks in the pressure sheath will cause leakages that to some extent will be limited by intact carcass and pressure armour layers. The leakage rate may initially be limited and it may be possible to detect the leakage by vent monitoring systems before the external sheath will breach. The pressure in the bore and the gas content in the flow will govern the leakage rates and consequences.

Carcass collapse and carcass pull-out may initially cause flow restrictions in the bore that may be detected. However, if the carcass failure goes undetected the pressure sheath may be damaged through different mechanisms and develop leakages. In such cases the pressure armour will contribute to limiting the leakage but clearly less so than if the Carcass was intact. If there are mechanisms where the pressure armour layer is pulled out of the end fitting the leakage potential would be significant.

Operators often request predictions of leakage scenarios. Some insight is available but there is a need for developing systematic knowledge that would make it possible to better predict leakage scenarios for different pipe structures, configurations and services for different failure mechanisms.

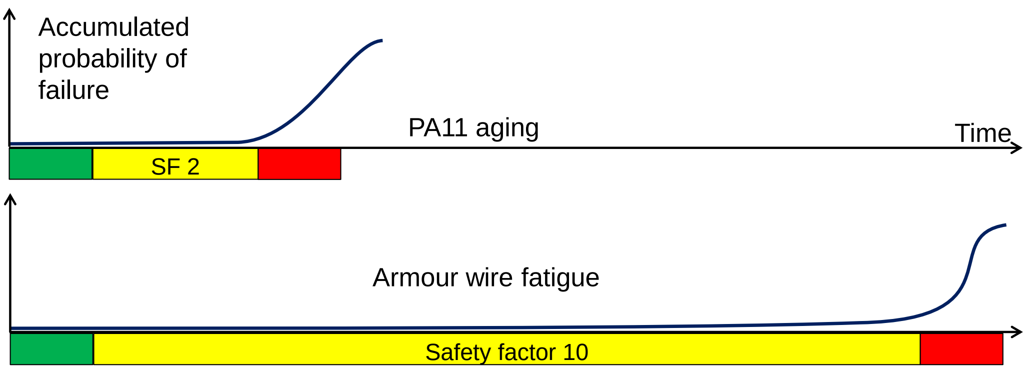

Figure 4-13 Differences in applied safety factor on service lives related to polymer aging and armour fatigue

5 Inspection, Monitoring and Condition Assessment

5.1 Introduction

5.1.1 Topics Covered

Inspection, monitoring and condition assessment are essential elements in managing the integrity of flexible pipes. This section addresses needs and availability of methods and tools for Inspection, Monitoring and Condition Assessment of flexible pipes. Challenges related to qualification of inspection and monitoring equipment are discussed and available tools for selected integrity issues are considered. By Condition Assessment we mean procedures and software for determining the safe service life, safe operating conditions or consequence of damage scenarios. The topics covered here are necessities for integrity management, which is covered in Section 6.

5.1.2 Inspection Challenges

The complex structure of flexible pipes combined with their configuration makes inspection and monitoring challenging. Several degradation mechanisms are unique to flexible pipes limiting the chance of finding available tools. Should suitable inspection equipment exist, access difficulties in remote and subsea locations would limit their use.

The dream is a tool that could measure the condition of all elements through the pipe wall to verify that they all are within their design requirements. Reality shows that many degradation mechanisms can only be assessed indirectly by modeling or through material coupons outside the flexible riser. Adequate quantification of degradation or damage inside the pipe wall is demanding.

End fittings that form integral parts of flexible pipes represent additional challenges on top of those found in the main pipe body while bend stiffeners and other externally mounted ancillary devices limit substantially the access for inspection. Many flexible risers are installed inside I-tubes that completely prevent normal access for most inspection methods. Further, the most exposed part of a flexible riser might be dynamic in the wave zone, neither accessible for ROV inspection nor by scaffolding or abseilers from the vessel.

One of the biggest challenges with flexible pipe operation has been that “now and then” new “surprising” failure mechanisms have appeared. Inspection and monitoring normally target well-defined defects or specific changes in property and performance of materials. If lucky, the deployed inspection and monitoring methods may detect symptoms of degradation mechanisms that have not been anticipated or previously experienced.

However, in general, inspection and monitoring programs are directed at known issues that constitute identified integrity risks. The purpose can be predictive to verify service life or detective to catch incipient pipe failure in time to avoid serious loss of containment.

Development of new inspection and monitoring solutions would typically be directed at specific degradation and damage mechanisms hand in hand with modeling and analysis tools for condition assessment. The principle should be:

- Make structural assessment to determine acceptance criteria for property changes or defects that need to be detected and quantified:
- Specify inspection requirements in terms of
  - defect types or changes in property or performance to be measured
  - requirements for measurement sensitivity and confidence
- Select and qualify methods for the specific requirement and application

The purposes of inspection and monitoring of flexible pipes can be grouped in the following ways:

- Verification of operation within design limits (typically Temperature & Pressure, chemical exposure and Metocean conditions etc.)
- General inspection to detect anomalies
- Inspection and monitoring to quantify known potential degradation for verification against service life predictions
- Quantification of known or suspected damages
- Monitor to catch incipient failures enabling shut down in time to limit consequences of failure (consequence reduction only)

The latter is intended to provide reduced consequential risk for failure processes that have not been detected and should be considered if there are significant uncertainties. This type of monitoring requires well defined alarm criteria and clear procedures for actions to be taken when positive detections are made.

5.2 Discussion of Tools and Methods

Available inspection and monitoring methods were reviewed in "Guidance Note on Monitoring Methods and Integrity Assurance for Un-bonded Flexible Pipes", ref [29]. This subsection discuss issues relating to methods and equipment that are relevant for some of the most critical integrity challenges identified in this report for PSA Norway.

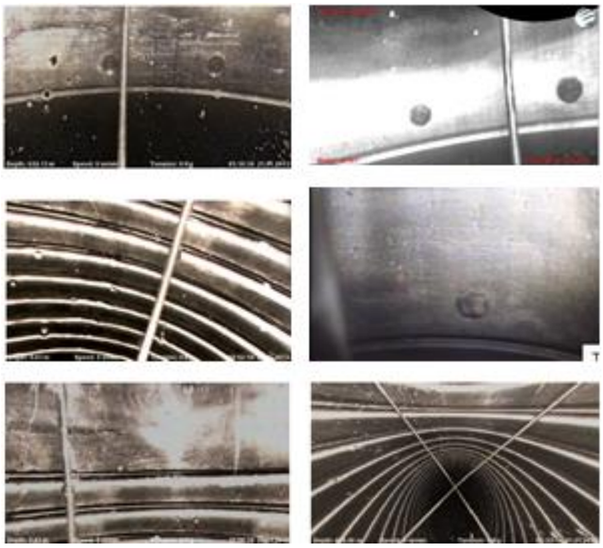

Figure 5-1 Internal inspection examples (Statoil)

Monitoring and Internal inspection tools for Carcass Collapse and pullout

Statoil has carried out extensive internal inspection in risers at risk for Carcass pull-out. Wire line tools have been adapted for the required tasks:

- Internal visual camera inspection. Camera units can be used both in gas and in water filled sections of risers and can reach to the bottom of risers. The picture quality has been good and allowed detection of relatively small deformations
- Close video inspection and laser scanning has been deployed for measurement of Carcass pitch in the top end of risers in a Nitrogen atmosphere. This has provided good quality measurements of pitch length with a resolution of 0.1mm.

Deployment of these tools requires access to the inside of the pipes during shut down. The pipes have to be either water filled or inerted with Nitrogen.

To detect potential pull-out events Statoil has installed Acoustic Emission monitoring units to pick up the sound generated by a pull-out.

Figure 5-2 PA11 coupon extracted for analysis (Statoil), ref [28]

Monitoring for PA11 pressure sheath ageing

The best way to monitor the degradation of Polyamide pressure sheaths is through coupons exposed to the same flow as the risers and flow lines to be assessed. Today the most common arrangement is to use cylindrical coupons installed in holders exposed directly to the flow through 2'' access fittings. The access fitting is installed on steel pipes topside. Equipment is available today to pull coupons during live production.

The challenges with this kind of coupon systems are:

- To exploit the full value of the coupon monitoring it is essential to have good temperature records for the flow close to the coupon location
- The coupons are normally located in the cold end of the flow for production risers. It is necessary to compensate for a lower temperature to estimate the condition in the warmest end of a riser or a flow-line.
- There is limited knowledge about how well the material properties measured in a coupon correlates with the pressure sheath

Experience shows that PA11 coupons have allowed detection of ageing issues that would not otherwise have been detected. This is in particular valid for cases where the aging mechanism was not anticipated by previous testing and therefore was not accounted for by the model in API 17TR2, as well as for cases where temperature records were insufficient to show that aging was being significantly accelerated by temperatures above those predicted during design.

Pressure sheath acceptance criteria in terms of CIV are defined in API 17TR2. If the coupons are located in a part of the flow path where the temperature is lower than in the riser or flow line being monitored it is necessary to compensate for this temperature difference. This would lead to different acceptance criteria for the coupons and can in principle be deduced from the service life model in API 17TR2 if the temperatures are known at both the coupon location and the hottest exposure location.

Annulus vent testing and continuous vent monitoring

It has been recognized more and more over recent years that annulus testing and monitoring is a valuable contribution to integrity management. Annulus testing as a regular service enables:

- Measurement of the flow impedance in the vent paths allowing detection of gradual blockage
- Reliable detection of breaches in the external sheath in the upper part of the riser down to well below the sea level
- Estimation of the free gas volume in the upper part of the riser (plus the combined effect of gas pockets below)
- Sampling of the vent gas

Figure 5-3 Less successful annulus vent backup system

Several companies provide annulus vent testing services. There are indications of inconsistencies between the results reported by different service providers when tests have been performed on the same riser fairly close to each other in time. This suggests that there is a need to develop standardized testing and reporting procedures to ensure consistency.

There is an increasing interest in continuous vent monitoring and equipment has been installed on many production units. Equipment from several suppliers is available in the market. The main benefits from continuous online vent monitoring are:

- Potential for detecting increase in vent flow from small or incipient leakages through the pressure sheath
- Detect abrupt blockages of the vent paths
- Quantification of the normal gas venting rates and detection of anomalies

Different suppliers employ different measurement principles that may influence how the output should be interpreted. There is a need for consistent and robust procedures and criteria for use in the control room. This would include procedures for riser-specific calibration in relation to type of service, pressure, temperature and configuration.

There is a potential for enhancing the value of annulus testing and monitoring. The variability between risers and response to changes in operating conditions are not well understood. This may limit the exploitation of a potentially very valuable "health" monitoring capability. To close this knowledge gap the industry should initiate a program to collect data systematically and through comparison and statistical assessment develop quantifiable correlations and uncertainty limits.

Figure 5-4 MAPS riser inspection inside guide tube, ref [31]

External inspection to detect and quantify corrosion damage on axial armours

To the knowledge of the authors no available methods have either demonstrated or proven capabilities for detection and quantification of corrosion damage on tensile armour wires in flexible pipes. Some service companies have promoted scanning Eddy Current but no credible qualification results have been published. It is also claimed that Radiography, in particular with digital imaging, should have the required capabilities. Comprehensive optimization and qualification is still needed and the industry should also become better at defining detection and sizing requirements and provide realistic pipe samples for testing and qualification.

Methods to detect ruptures in axial armours

A number of methods have been developed or adapted for detection of wire ruptures

- Petrobras has installed strain gauges directly on tensile armours in the outer layer
- Non-contacting stress measurement system, MAPS from GE, has been tested offshore as inspection device and can be installed for permanent monitoring
- Acoustic emission monitoring to the detect the sound emission from wire ruptures have been tested (carcass pull-out systems is in use)
- NOV Flexibles offer risers with integrated optical fibers in the axial armours including optical strain (and temperature) gauges

5.3 Qualification Challenges

Figure 5-5 How small pits should be detected? Ref [30]

Within the inspection industry it is common to define inspection requirements in terms of sensitivity and confidence. Detection and defect characterization capabilities of inspection methods for critical components are normally verified on objects with controlled defects. Such objects are also used for calibration purposes.

Inspection methods for flexible pipes are often required on short notice and without adequate definition of how the inspection results shall be used. On short notice it is difficult to define the detection and sizing requirements and there is often not sufficient time to prepare suitable test objects. The industry would benefit from more extensive general qualification of selected inspection methods to be much better prepared when requirements appear.

As an example several methods have been promoted and adapted for inspection of armour wires in the annulus. Methods include radiography and electromagnetic methods such as eddy current. We suggest that the industry would benefit from the following:

- Define relevant inspection needs in terms of types of degradation and required defect sizing
- Prepare and offer pipe sections for optimization of the inspection methods and for general qualification
- Develop guidance for how to qualify methods and equipment for specific inspection tasks including
    - How to calculate minimum required capacity of armour layers to continue operation, which is necessary for determination of detection and sizing requirements
    - How to use existing or develop new "pipe sample objects" for qualification for the required inspection tasks

5.4 Methods for Condition Assessment

Determination of structural utilization or the safe service life for flexible pipes requires the use of several analysis and modeling tools. During the design phase capacity and service life assessments are based on design requirements in terms of loads and other exposure parameters over time. The purpose of inspection and monitoring during the operational phase is, for many integrity issues, to provide the best possible input to analysis tools required to determine the margins against failure or whether e.g. the pipe stresses respond according to assumptions and calculations. These analysis tools are essential elements in the integrity assessment.

Significant advancements have been made over recent years to the analysis of some integrity issues while for others only limited progress has been made.

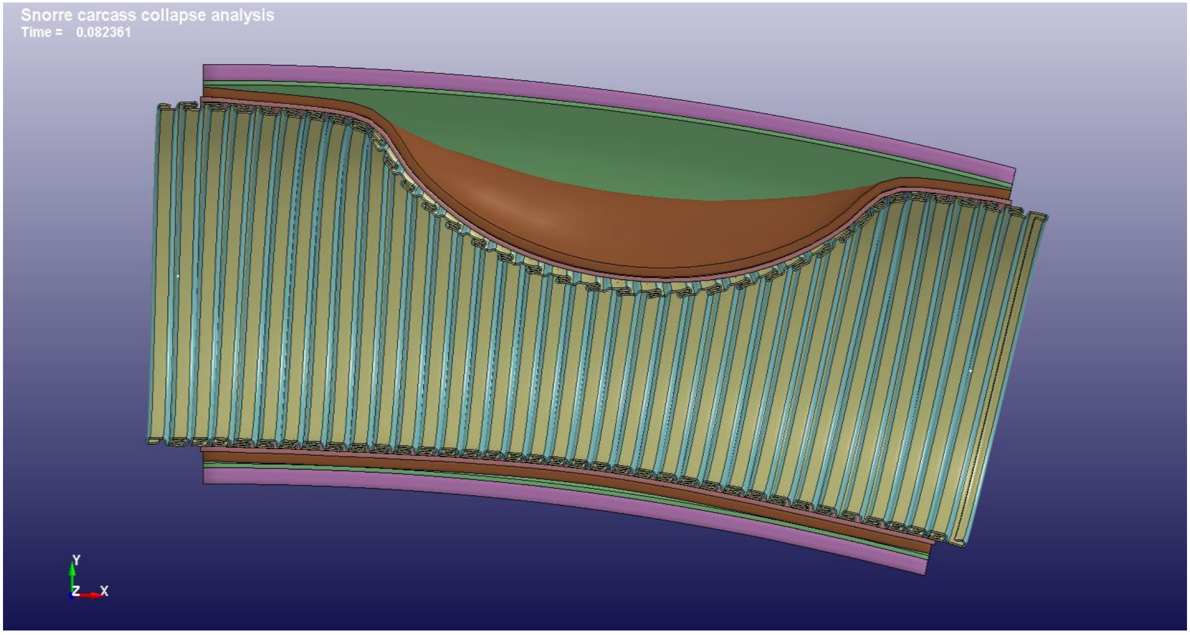

Figure 5-6 Prediction of carcass collapse pressure for a multi-layer PVDF pressure sheath flexible during bending (4Subsea)

5.4.1 Modeling to Assess Time Based Degradation Mechanisms

Fatigue of steel components

Fatigue assessment of reinforcement wires is building on methodology developed for fatigue of other steel components used offshore. The main challenges with flexible pipes are:

- Load transfer from environmental forces and movement of the vessel (wave- and low-frequency motion)
- Stress distribution between wires and in particular the choice of friction factor and the possible presence and impacts from residual stresses
- The corrosivity of the local environment at the fatigue hot spot and selection/generation of representative SN curves. Substantial efforts have been made by the manufacturers and within Joint Industry Projects to generate SN curves in representative environments. Most of the results are proprietary to the individual companies or to closed groups of companies making it difficult to make independent assessment of the approach and relevance
- Fatigue tests to generate SN-curves are generated over durations that are very short compared to the required service lives for flexible pipes. The surface damage (in terms of surface irregularity) created by corrosion processes that many tests are designed to replicate may be negligible in the limited test period compared to what may take place over the service life. Thus if corrosion processes take place over long term the SN curves will not capture the impact the generation of surface irregularities from corrosion may have on the fatigue life
- In most low to medium water depth facilities the main driver for fatigue is bending which is now designed to be located well away from the end fitting through the shape of the bend stiffener. In deep water applications the fatigue is driven more by tensional loads and the highest stresses are transferred to the termination of the tensile wires in the end fitting. Stress concentration introduced by the shape of the wires at their entry into the end fitting and possible residual stresses, create new challenges for fatigue analysis
- Several flexible pipe experts have suggested that the conservatism in the overall methodology used to calculate fatigue life might be unduly high. In addition to the safety margin for fatigue in relation to the SN curves there may also be conservatism in the load input and the stress predictions for the reinforcement wires in the pipe. In this context it is important to note that the safety margins used for fatigue of steel components are intended to avoid failures

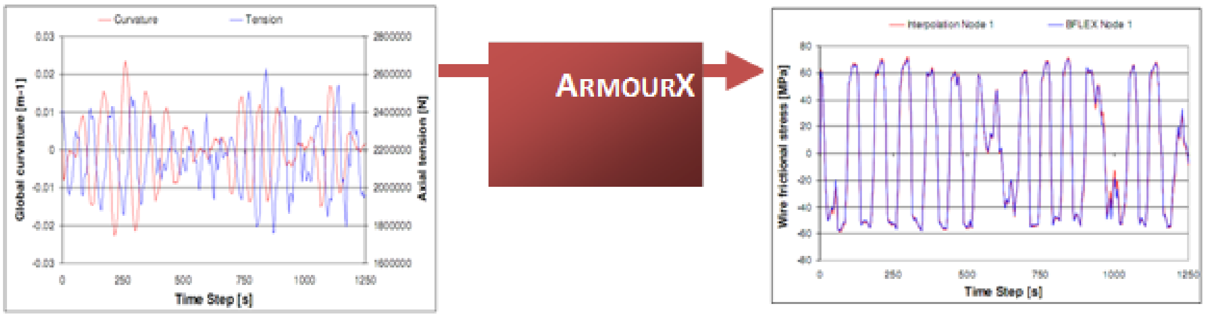

Figure 5-7 State of the art flexible riser fatigue analysis, going from global ir-regular riser response to local wire stress time series

Polymer ageing

As discussed in chapter 4, hydrolysis is believed to drive the ageing of PA11 and recommendations regarding assessment of ageing of PA11 in flexible pipe pressure sheaths are provided in API 17TR2, ref [19]. A service life model is specified for assessment of the ageing of PA11 as function of temperature and pH in the produced water. The model was provided by Coflexip (now Technip Flexifrance) and was developed based on testing during 1990's.

As described in Section 4 field experience shows a mixed picture where some cases indicate that the model is over-conservative while in other cases coupons indicate a higher degradation rate than predicted by the model. A possible explanation is that some organic acids have a larger impact on ageing than predicted by the pH dependence in the model. It has also turned out that laboratory testing in nominally similar environments have given significantly different results between laboratories. This generates uncertainties regarding the model in API 17TR2. How can we know that the model is right when reputable laboratories are not able to reproduce each other's results?

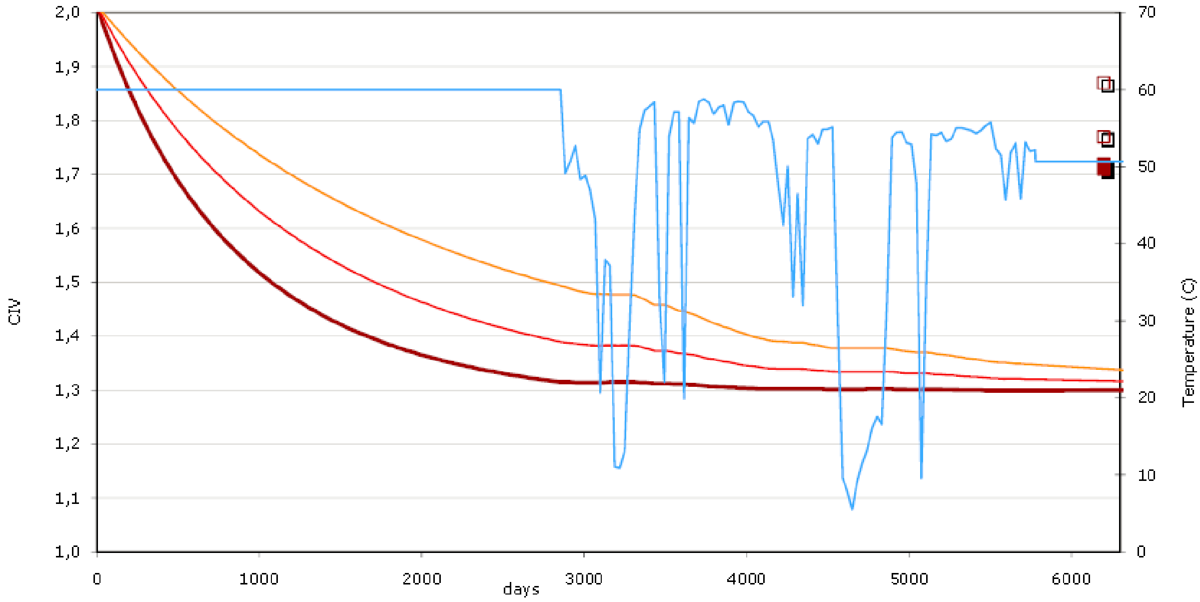

Figure 5-8 Ageing sensitivities compared to measured results, example showing conservative model results (Force)

Several players in the industry have expressed the need to understand the discrepancies and to improve the model to provide reliable predictions for conditions where significant deviations have been found. Nevertheless it has been difficult to generate sufficient support for Joint Industry initiatives to address the issues systematically. Over the last years individual operators facing specific issues have had to find their own solutions on how to deal with the issues since industry accepted guidance is lacking.

Manufacturers have introduced new alternative Polyamides over recent years. Wellstream has delivered pipes with PA12 for several years and Technip has published a new "high performance" Polyamide. The manufacturers show that these materials perform better than PA11 but so far only through testing they have been a part of themselves. Independent testing would enhance the credibility.

It is essential to note that API 17TR2 only apply to PA11 and only indirectly gives guidance on issues to be aware of for qualification of other Polyamide materials.

<u>Corrosion models CO_2</u>
In early days the rule was considered to be that the annulus would stay dry and corrosion in the annulus was only considered an issue when the annulus got flooded through damage of the external sheath. When it was realized that the annuli in many cases have to be considered to be water filled it was necessary to establish suitable models for corrosion. The main corrosion threat for wet annuli has been considered to be CO_2 permeating from the bore since CO_2 is present in most hydrocarbon production environments.

There are several prediction models available for CO_2 corrosion as for instance the NORSOK M-506 model, ref [34]. The challenge for prediction of corrosion rates in the annulus is the prediction of the pH in the water. The module for calculation of pH in the NORSOK model does not cover confined environments with high ratio between steel surface and water volume as found in water filled annuli. This produces over-saturation of Iron ions, with correspondingly high pH, in the water and correspondingly low corrosion rates. Laboratory investigations by the flexible pipe manufacturers, in particular Technip, have demonstrated corrosion rates in simulated water filled annulus environments well below 0.01mm/year. There seems like a consensus has emerged within the industry that corrosion in representative confined water filled annuli is sufficiently low to be negligible. No general prediction model for CO_2 corrosion in flexible pipe annulus is available in public domain.

However, there is a range of scenarios for environments in flexible pipe annuli that deviate from the confined water-filled environment as discussed in section 4 of this report. No models exist today for predicting corrosion rates for scenarios with ingress of oxygen or situations where "freshly" condensed water may run into the annulus from vent tubes or on steel surfaces where water recurrently condenses. There are in particular significant uncertainties for the corrosion rates under external sheath breaches in the splash zone or above the sea level.

Corrosion models H_2S

H_2S can cause cracking (SSCC or HIC) in high strength armour wires and contribute as an acid to the overall corrosion process on any steel.

Armour wires used in H_2S containing environments should either be made from steels that have been defined suitable for sour service or be specifically qualified through testing as defined in NACE MR O175/ ISO 15156. In particular very high strength material (exceeding 900 MPa) should be qualified through testing.

To our knowledge there are no relevant prediction models for the corrosion contribution from H_2S in annulus environments.

Erosion

To our knowledge erosion assessment in flexible pipe carcasses is based on general erosion modeling developed for rigid pipes and small scale rough bore tests at DNV. One source of guidance is DNV RP O501. A significant program for full scale carcass erosion tests are scheduled for 2014.

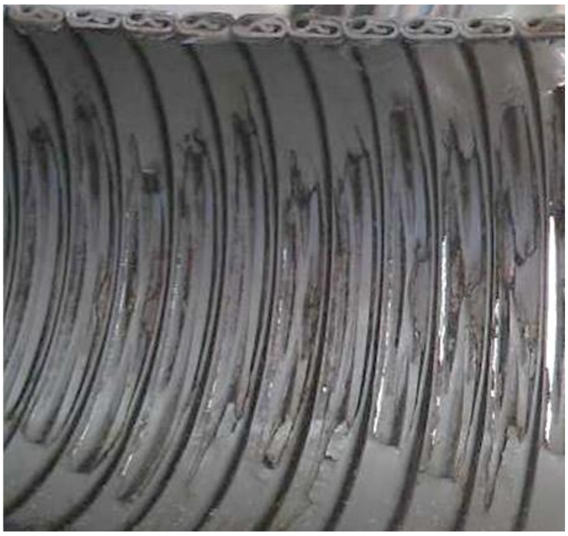

Figure 5-9 Carcass erosion, ref[12]

5.4.2 Capacity and Load Interaction

Status for design and load assessment tools

Most load and response analysis of flexible risers are performed by a combination of global and local cross section analysis. The global analysis may now take into account short crested seas, and more accurate vessel motions including low-, wave- and possibly high-frequency (TLPs) components. Design analysis are often performed in long crested seas which may give realistic results for extreme seastates, however for lower seastates realistic wave spectra and short crested seas are required for e.g. fatigue analysis, ref [35].

Other important factors contributing to more realistic global response of the flexible risers are non-linear bending hysteresis for the correct bore pressure, and accurate modelling of ancillaries like bend stiffeners, including correct material characteristics, geometry, gaps etc., guide tube structures and mid water arches (MWA).

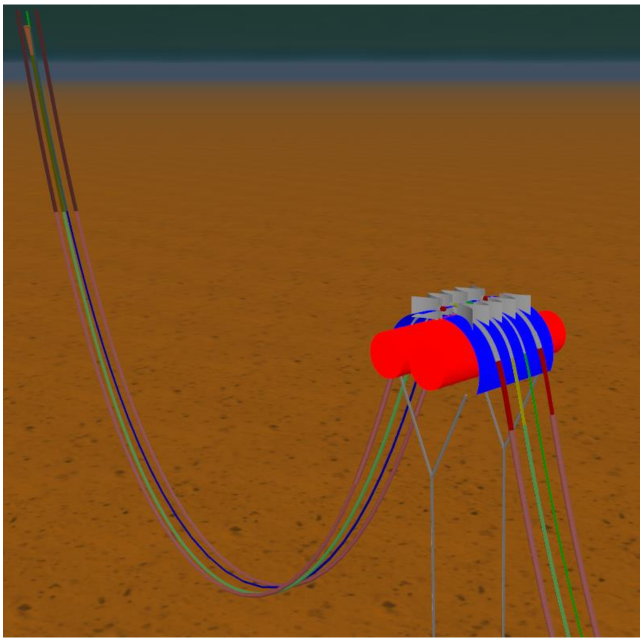

Figure 5-10 Accyrate model of MWA, including all risers and umbilicals (4Subsea)

With the modern time domain global analysis tools and clusters of multi-core PCs there are no real practical limit for how many seastates and sensitivities that can be run during design and life time assessment projects for a flexible riser system. The key is to keep overview and understand, key drivers and the interaction of various parameters.

Local analysis

Significant advancements have been made within local analysis of flexible risers over the last 5 years. Dedicated tools like BFLEX from Marintek may be used for prediction of steel armour stresses and fatigue, and may be combined with global analysis in special post processing routines to provide stress time series in ir-regular seastates to be used for fatigue analysis by Rain flow counting.

For more advanced analysis and damage assessment to determine stress levels after damage events or interaction with ancillaries, non-linear finite element tools like MSC-MARC are used. With detailed knowledge of geometry and materials, and possible changes over time, very accurate models may be made. When all layers are modelled the results may give detailed insight in layer interaction, stresses and deformations including effects of damages or ir-regularities.

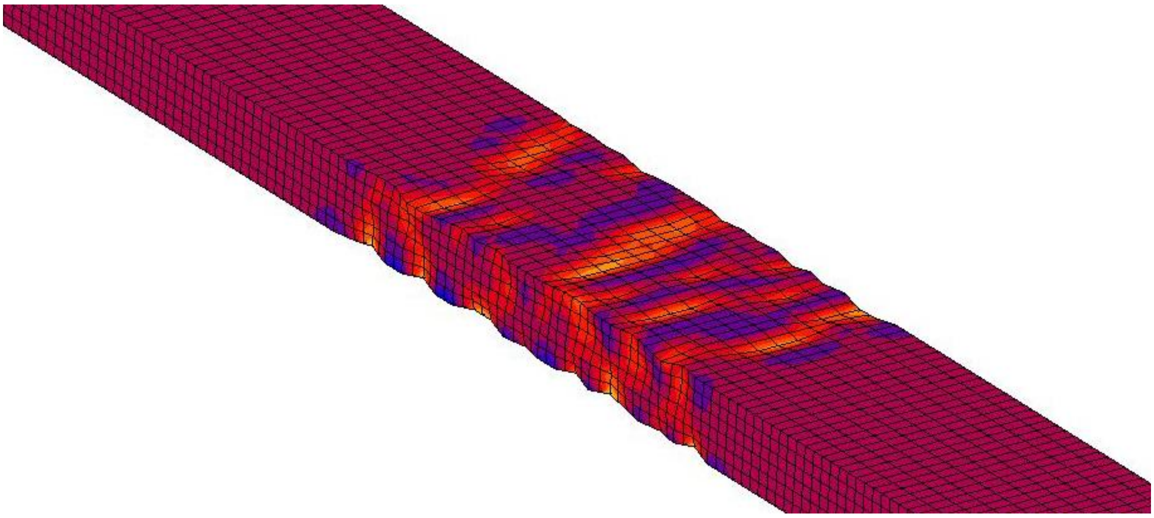

Figure 5-11 Investigation of local stress in corroded wire (4Subsea)

The issue of Carcass pull-out has been investigated in detail in 2D and 3D finite element models, ref [6]. Finite element models have been developed to investigate in detail the load transfer between polymer layers and the carcass and the stresses induced have been assessed for different realistic operational conditions. In particular to study effects that takes place during cool down. The modeling has included strain, time and temperature dependent material properties and has generated results that have given plausible explanations of observed failures and therefore also predictive capabilities.

5.5 Inspection and Assessment Example Case

The purpose of this sub-section is to illustrate how calculation tools interact with inspection and monitoring in addressing an integrity issue.

Consider a riser where an external sheath breach has been found in a location above the water level. The event causing the breach could have occurred as much as 2 years before the time of detection and there is a danger that substantial corrosion could have developed. The challenge is to find out whether the riser could be kept in operation after repair of the outer breach.

It is then necessary to determine the maximum corrosion damage that can be allowed and still maintain adequate margins against rupture and fatigue, if relevant. This would include simulation to identify the maximum allowable damage for different realistic distributions of metal loss in the armour layers.

Based on determination of the maximum allowable corrosion damage the detection requirements must be determined for inspection to quantify the damage. In principle uncertainties in detection and defect sizing for the selected inspection method must be taken into consideration to ensure adequate confidence.

Following this an inspection method must be selected and a suitable verification/qualification/calibration program must be carried out. This would include:

- Specification and preparation of representative pipe sections with a range of simulated damages.
- Define conditions under which the verification shall be carried out
- Definition of parameters to be reported from the inspection
- Prepare all necessary facilities
- Perform testing
- Reporting

The reported results must be assessed in relation to the detection and defect sizing requirements. If the inspection method is required to detect a specific flaw type or size, detailed procedures for inspection offshore should be prepared.

To supplement the inspection or to provide a safety barrier against failure it may be worth considering deployment of a wire stress monitoring system. The purposes would be to verify that all wires are carrying loads and to ensure detection of wire breakages at least until successful inspection has been performed. Wire stress monitoring systems also require qualification to verify detection capabilities for the pipe configuration under question.

In connection with monitoring to detect wire breakages it is also necessary to determine by calculation/modeling the consequence of one or several wire ruptures. This is necessary to establish response procedures for situations where wire breakages should be detected.

5.6 Critical Selection of Inspection and Monitoring Activities

All inspection and monitoring applied for flexible pipes have to serve a purpose. Monitoring equipment installed during construction must be followed up during the operation phase. As an example: coupons installed must be retrieved and analyzed and assessed against expectations to serve its purpose within integrity management.

It is also essential that procedures and criteria for how to act on signals from monitoring systems have been defined: If a continuous online vent monitoring system has been installed it is necessary that the system is calibrated and checked regularly and that control room operators have clear instructions on how to respond if the vent rate exceeds thresholds. Response would typically cover consultation to onshore experts and/or shut-down the riser if excessive vent rate is detected.

It is important that the selection of inspection activities actually serve the defined purpose. For instance the primary concerned with a water filled annulus is external sheath breach in locations with high risk of corrosion. Thus if an external tool is used to determine that the annulus is water filled it is still necessary to find out if this has been caused by a breach or whether the water has built up from condensation in the annulus. If there is a breach the challenge is to locate it.

Operators should avoid deploying inspection equipment that has not been adequately qualified for a required purpose unless the purpose is to gain experience under field conditions.

5.7 Maintenance and Repair

When comparing to other "machinery" with similar level of complexity there are few maintenance options for the flexible riser - no oil to change and no wear out parts to replace. A few repair options do exist and some maintenance tasks needs to be carefully followed up.

The single most important maintenance task is to keep the annulus vents free at all times giving good opportunity for the gas diffused out to the annulus to vent out to a safe area, low pressure flare or similar, without any possibility of blocking, backflow of oxygen or water condensing in the vent tubes to find its way down to the steel armour wires.

Maintenance options:

- Keep annulus vent open
- Removal of marine growth
- Pigging / chemical injection to remove internal deposits

Repair options:

- Repair external sheath breaches, severe dents or scratches
  - Polymer welding
  - Clamps (dry or ROV installed subsea)
- Re-establish annulus vent in case of clogging
  - Vent clamp with new drilled hole in the external sheath
  - Chemical cleaning (compatible with polymers)
- Ancillary equipment
  - Repair or replace buoyancy elements
  - Repair or replace clamps
  - Repair or replace bend restrictors (split half shells)
  - Replace bend stiffeners (require re-termination)
- Re-termination of end fitting cutting away damaged pipe

Figure 5-12 ROV installable clamp stop oxygen ingress to armour wires (4Subsea)

6 Integrity Management

6.1 Objective

The overall scope of the integrity management (IM) program is to ensure that the flexible pipe system is able to fulfill its function with sufficient regularity, by structured follow–up and review of the operational condition. At specified intervals, an IM Review should be made to determine if all inspection and monitoring data (process data, CP surveys, vent tests, coupon measurements, GVI etc.) is within expected ranges and that there are no indications that the system could have been damaged.

The integrity of a flexible riser is to a large extent determined in its design and fabrication phase through material selection and dimensions of components suitable for the required service. The integrity, by adequate margins against failure, is built into the system. Degradation mechanisms may over the lifespan of the system threaten the system integrity by any of the mechanisms described in Section 4.

The IM activity is a continuous, cyclic effort performed during the whole lifespan of the system. To accomplish this, operators should develop integrity management programs and perform both routine- and event based integrity assessments, the latter often triggered by anomalies identified through the integrity management program.

A framework for the lifetime assessment can be based on the existing guidelines for lifetime extension NORSOK Y-002, ref [32] and ISO TS 12747 ref [33]. Both of these consider the overall process and tasks to be accomplished.

A high-quality, "living" IM systems is required to ensure that the target reliability level is being met and maintained. The importance of available documentation, recording of operational data and knowledge by personnel involved are highlighted. Upon identifying anomalies, new hazards or due to major modifications, a failure event tree could be utilized – documenting that the current risk level is acceptable.

As offshore oil and gas facilities are frequently modified It is required to maintain a quantitative measure on the probability of failure, showing that the total risk remains at acceptable level. The frequently used ALARP (As Low As Reasonably Practicable) process does not maintain this over time.

6.2 Challenges

The following main challenges are experienced in relation to integrity management of flexible pipes:

1. Establishment of an Integrity Management Plan during design / procurement / installation / commissioning.
2. Installation of the necessary Inspection and Monitoring systems prior to start-up
3. Management acknowledgment of risk level
4. Incident Reporting Flow - Time between incident detection and close out
5. Research gaps including quantification of degradation mechanisms and applicable statistics.
6. Acceptance criteria
7. Condition Assessment methods
8. Information management
9. Information sharing

6.2.1 Establishment of Integrity Management Plans

The life-cycle of a flexible pipe system is typically 20-25 years from installation to end-of design life. During this time a multitude of persons and companies are involved, with responsibilities ranging from design, fabrication, installation, operation, modifications or repair and inspection or testing work. Documenting all these phases and work tasks with the required detail and quality level, from the perspective of integrity assessment, is a key for successful IM.

Integrity Management Plans must be established during design and modified and updated to capture relevant information through commissioning and operation. That way all of the design criteria and expectations for system elements will be captured and maintained. If events occur in manufacturing, transportation, installation and commissioning that warrant specific monitoring or altered acceptance criteria, they will be captured.

The plan needs to capture all of the design requirements, limiting conditions, acceptance criteria and the performance expectations and margins for each flexible pipe in the system. The plan should identify the specific inspection and monitoring functions and the frequency with which they should be accomplished. Responsibilities should be assigned for the planned activities along with the required level of training. The plan should include an explanation of the importance of each activity and the potential consequences of not meeting the acceptance criteria.

6.2.2 Installation of Necessary Inspection and Monitoring Systems

Monitoring required for the full operational life of the flexible pipe systems must be defined during design and necessary equipment and procedures must be in place before production start-up, or adapted to existing systems when relevant. Typical monitoring requirements for flexible pipes are:

- Annulus vent monitoring allow continuous verification of a functioning vent system (detection of incipient blockage), possible detection of incipient leakage from the bore of the pipe and breaches of external sheaths. In addition it will verify healthy function of gas permeation and vent arrangement.
- Polymer coupons to be retrieved during operation for analysis to monitor the performance of the pressure sheath material. This is in particular relevant for materials that may suffer time based degradation such as polyamides. There are several examples where operators have wished that they had installed coupon systems or more of them.
- Production conditions and parameters: Pressure and Temperature and how they change with time (number of shut-downs and rate of change) are necessary for integrity assessment of flexible pipes. They are essential to verify that pipes are operated within the design specifications and several degradation mechanisms can only be assessed when adequate pressure, temperature and fluid composition data are available for the full operational period. There are many examples where lack of suitable data has prevented adequate assessment. It is important to make sure that production and process sensors provide data for the location of each riser.
- Vessel motion and riser response, see: http://youtu.be/Q5VZX9HmO4k)

Figure 6-1 Riser response measurement sensor (4Subsea)

Baseline data for inspection and monitoring should be taken at commissioning or within the first year of operation. Data should include riser vent system volume and flow data, CP system potentials, process system temperatures at critical points and any other data identified for regular inspection or monitoring in the IM Plan.

6.2.3 Management's acknowledgement of Risk Level

All stake holders involved in flexible risers needs to accept that flexible pipes still is new (at least in some applications) and complex technology, and need to take advantage of the few high-quality monitoring options existing for "challenging applications".

Operations management should sign off the Integrity Management plan and commit the necessary resources to conducting the annual inspection and monitoring as well as the regular evaluations. The evaluation report including a discussion of any changes in risk level from that planned during design should be submitted to Operations management for agreement and approval. Management is required to approve any incident reports (initial, interim, final) and the associated actions.

6.2.4 Incident reporting Flow – Time between incident detection and close out

Handling of incidents should be defined in the IM plan and should include guidance on how to handle any loss of containment, loss of function or failure of any flexible pipe system element (e.g. loss of buoyancy, vent blockage, external sheath breach, insulation damage, bend stiffener failure etc.).

Shortly after all appropriate safety and process actions have been completed (typically within a day); an initial Incident Report should be prepared describing the known facts and conditions of the incident (see Appendix C) and submitted to management and the appropriate authorities. When it is safe to do so, a root-cause evaluation of the incident should be conducted by a team with expertise in flexible pipes, material sciences, process operations and safety.

The supplier of the damaged or failed equipment should be notified of the incident and asked to provide input to the investigation. The team may determine that testing, measurements, analysis or other work must be done to identify the root-cause. An interim report may be prepared to warn other fields and operators of potential risks that are being further investigated.

When all investigations are complete and there is consensus on the root cause, a final report should be issued along with the operator's internal recommendations for additional actions. The necessary time must be allowed for to ensure proper investigation, identification of the root cause and recommendations for corrective action. Unnecessary delays may allow similar events to occur with potentially greater consequences.

Figure 6-2 Investigation of used risers giving new knowledge

6.2.5 Research Gaps

The successful implementation and execution of an integrity management program is highly dependent on the understanding and knowledge of flexible pipe science and technology. That understanding and knowledge has been developed over the past decades by the manufacturers and through Joint Industry Projects (JIPs) with participation for operators, manufacturers, regulators and academic. However, incidents and root-cause evaluation have in many cases identified the need for improved understandings and new technology or for more precise data for specific materials or damage mechanisms requiring additional research and development. Other research may be required to develop analytical models and tools or to collect the appropriate statistical information to support risk assessments.

The development of analytical models for known failure mechanisms, qualified inspection tools and reliable data for estimating Probability of Failure (and thus risk level) is considered as key necessities to improve reliability level of flexible pipes. The latter is perhaps the most important as it would enable targeting the analytical models and inspection tool at those failure modes being significant contributors and driving the failure probability.

6.2.6 Acceptance Criteria

The flexible pipe integrity is established in the design and manufacturing phases. Any flexible pipe designed and manufactured according to API 17J, ref [17] ensures that a minimum level of integrity is inherent in the system. The specification includes acceptance criteria for major analysis parameters but leaves detailed dimensional tolerances and some performance parameters to the manufacturers or specifications from the buyer. For the purpose of performing an integrity assessment during the service lifetime there is no guideline commonly accepted covering all the challenges presented in sections 3 to 5.

As stated in NORSOK Y-002, ref [32] the integrity of flexible pipes, due to the composite structure of layers with differing materials, is currently lacking inspection methods qualified to accurately quantify the pipe condition: “As a consequence, a life extension of flexible pipes may mainly be based on design data and monitoring data”. Similar consideration applies to the integrity assessment during intended design life.

API 17B, ref [18] is the main recommended practice for flexible pipes. The document presents an inspection/ monitoring philosophy and states the recommended objectives. A generic framework for developing the IM plan, performing inspection/monitoring actions and reviewing the results is included.

6.2.7 Condition Assessment Methods

A primary output of the IM System is periodic (6 / 12 months) Condition Assessments. The intent is to reconfirm, on the basis of recently updated inspection, monitoring and testing results that the flexible pipes continue to conform to the design requirements and performance expectation. However, if the results indicate that the flexible pipes have been damaged or degraded, then it is necessary to use other means to assure that the flexibles continue to be fit for service. Similar assessments may also be required if the type of service, for a flexible is to be changed or if life extension is intended.

Performing the lifetime assessment is based on a similar approach as for service life documentation in the design phase. Where analytical models exist these should be used, although consideration must be given to the uncertainties in input and models. This applies for instance to fatigue damage accumulation, corrosion of steel components, cathodic protection systems or polyamide degradation.

Condition assessment tools have been described and discussed in section 5 “Methods for Condition Assessment”.

6.2.8 Information Management

The quality and availability of information captured during design, manufacturing, installation and operational service are vital for successful demonstration and verification of the flexible pipe integrity.

Past experience shows that the information from design and manufacturing life phase has not been captured properly and must be reconstructed from inadequate records. A disproportional amount of time may be spent on search for documentation and data acquisition compared to actual integrity assessment and engineering work.

The information management system is part of the overall integrity management system, and may easily be made an enabler when undertaking any type of integrity assessment. If the necessary data for life extension had been adequately captured during design, both Integrity Management and Life Extension could be much easier.

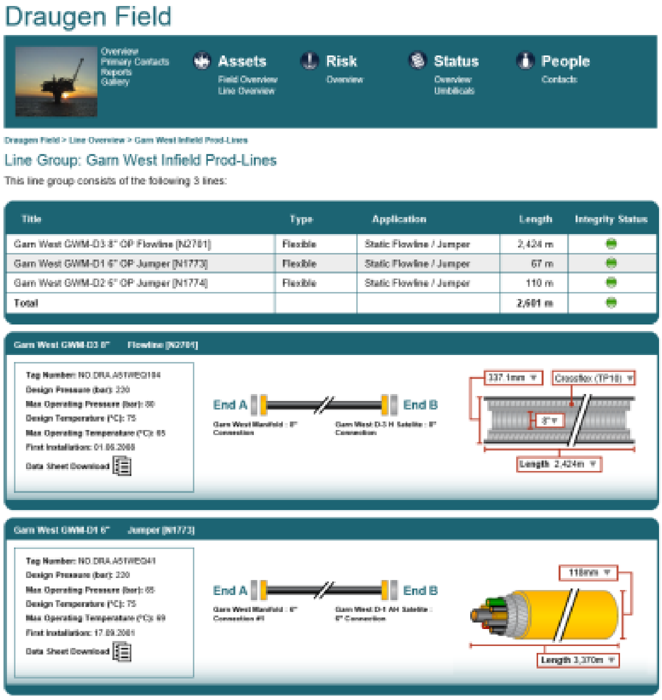

Figure 6-3 Information management system in use for Shell

6.2.9 Information Sharing

Currently, technical conferences, dedicated workshops and the industry standards and guidelines are the main interface scenes for shearing information on flexible risers.

Industry standards are far from a live system, with 5-10 years turnover from new experiences to updated specifications. Collecting operators own experiences in separate technical requirements often done, however in a long-term perspective this should be avoided for reliability, safety and financial reasons. Separate company requirements should as far as possible be incorporated in revised international standards.

The exchanges of information through published papers in technical conferences like OMAE, OTC, UTC and Rio Pipelines shows willingness to share experiences and new achievements, however a more specific and systematic

Figure 6-4 Practical knowledge sharing (4Subsea)

knowledge exchange will be beneficial to operators, manufacturers and contractors involved in flexible riser IM. Everyone working with flexible riser integrity issues knows that detailed knowledge and experience are needed to understand and develop solutions and avoid incidents.

The recent carcass pull-outs experienced by Statoil that were described in some detail at OMAE, ref [6] are an example of a functioning Incident reporting and sharing system. Further information and data on the topic, in several additional papers, will allow IM-engineers to understand, and extrapolate to the common features to their field conditions and equipment. Most of the underlying technology was developed, by the informal

"Friends of Flexibles" group during their investigations of the PVDF end fitting failures. Unfortunately, because it was not formally documented in the literature, its relevance or existence was not apparent to those being confronted with the more recent carcass issues. Unfortunately, the "Friends of Flexibles" group came together in the appropriate spirit of cooperation and sharing, conducted the studies, resolved, by that time, the most pressing issue and then disbanded.

Alternative examples of how important research data can be captured and disseminated are provided by Joint Industry Projects (JIPs) and standardization groups like API. API17TR2, the technical report on aging of Rilsan, was developed by an API Task Group, The Rilsan Users Group based on the information and learnings from a series of JIPs that are still ongoing. Another long-running JIP is Marintek's activity on "Corrosion fatigue testing, ref [22] started in 2001 and still providing valuable information and advances.

Conferences and JIPs are two of the best forums for sharing technical information, common research and development activities in open or semi-open settings. An initiative to assemble and maintain a list of flexible riser publications and JIP invitations would be welcome, all indexed in a way to assist the search for technical information within a particular subject.

A fully open worldwide incident database for flexible risers would be a highly appreciated and very useful contribution to improved risk assessments, and enable prioritizing the most significant risks. Because many operators may be concerned about being associated with incident data, the data base would need to be operated by an independent organization, supported by the operators, both financially and with data. The operators will benefit from a wide information database when developing and maintaining a risk based integrity management program and should therefore be incentivized to contribute financially to maintaining the data base.


PARLOC re-launches database

BY ROBERT PATERSON, HEALTH AND SAFETY DIRECTOR, OIL & GAS UK, ABERDEEN, UK
Pipelines International — December 2012

The protection of people, the natural environment and physical assets is a key priority for the United Kingdom offshore oil and gas industry, and a determining factor in its overall success. With that as a consistent, high-level objective, the Pipeline Riser Loss of Containment (PARLOC) database is a dynamic online tool

Figure 6-5 PARLOC database, for riser and pipeline leaks in UK ref [24]

With the Norwegian database CODAM experience, the authors have suggested a reporting format providing anonymity and at the same time providing sufficient information, see appendix B for details.

A starting point may be seen at the CODAM summary, ref [23]. A similar overview may come from UK's update of incident statistics through the Pipeline and Riser Loss of Containment (PARLOC) database (the PARLOC database does not only contain loss of containment incidents), and the planned report in 2014.

By combining these two databases, a comprehensive overview of UK's and Norway's offshore experiences may be established, if other areas or operators will contribute remain to be seen. The experience with voluntary contributions is not very good as observed through the SureFlex work, ref [3]. Anyway, some sort of informed review and conformity checks need to be implemented to assure that the important aspects are captured and correct assessments are reported.

A final concept for capturing information and training the next generation of flexible pipe engineers and operators would be seminar or training courses conducted by the more senior people in the industry who have acquired many years of experience and relevant information.

To maintain the reputation or competitive position, flexible riser manufacturers and operators have sometimes selected to retain some information. However, when safety and environmental concerns are present, with potential significant consequences openness should be an obvious obligation. When a possible safety hazard is identified it will potentially affect several other operators. Mutual exchange of information can ensure that the safety hazard will be prevented from developing into a critical situation.

7 Strategies for Improved Robustness

7.1 Review of Failure Statistics

7.1.1 Assessment of flexible pipe failures

The following Table is a subjective summary of why a number of in service failure mechanisms have not been adequately predicted.

Table 7-1 Overview over possible reasons for failure of flexible pipes

Type of failure	Stage of detection	Number of cases	Reason for inadequate prediction or mitigation: Knowledge gap	Inadequate IM & maintenance	Lack of information sharing	Insufficient training	Manufacturing & installation defects	How should degradation mechanism / failure mode have been avoided
Carcass Collapse - multi-layer pressure sheaths	After LOC	4	Dominating	Non or limited relevance	Non or limited relevance	Non or limited relevance	Non or limited relevance	Different design / different material
	Before LOC	20+	Dominating	Non or limited relevance	Non or limited relevance	Non or limited relevance	Non or limited relevance	
Carcass pull-out	After LOC	2	Dominating	Non or limited relevance	Non or limited relevance	Non or limited relevance	Non or limited relevance	
	Before LOC	4+	Dominating	Non or limited relevance	Non or limited relevance	Non or limited relevance	Non or limited relevance	
Annulus Armour Wire Corrosion	After LOC	4	Contributing	Significant	Significant	Contributing	Non or limited relevance	Better Maintenance, Monitoring and Testing
	Before LOC	3	Contributing	Significant	Contributing	Contributing	Non or limited relevance	
Armour Wire Cracking (H2S)	After LOC	5	Significant	Significant	Non or limited relevance	Non or limited relevance	Non or limited relevance	Material selection
PA11 pressure sheath failure	After LOC	6	Significant	Contributing	Non or limited relevance	Non or limited relevance	Non or limited relevance	Material selection
PA11 pressure sheath excessive ageing	Before layer failure	3+	Dominating	Non or limited relevance	Non or limited relevance	Non or limited relevance	Non or limited relevance	Material selection
PA11 outer sheath cracking	After layer failure	3+	Significant	Significant	Contributing	Contributing	Non or limited relevance	Material selection / design & ageing prediction
Carcass fatigue failure	After LOC	1	Significant	Non or limited relevance	Non or limited relevance	Non or limited relevance	Significant	Improved manufacturing procedures

LOC = Loss of Containment	Colour coding	Dominating (dark green)
IM = Integrity Management		Significant (medium green)
		Contributing (light green)
		Non or limited relevance (very light green)

The failure mechanisms included in the table are those given the strongest focus through this report and the indicated number of incidents is based on available knowledge to the authors. We are primarily incorporating mechanisms that have led to Loss of Containment or serious degradation.

The category Knowledge Gap would include

- Mechanisms that were not understood
- Inadequate knowledge about the operating limits that would lead to unacceptable degradation for known mechanisms
- Insufficient knowledge about the exposure conditions both chemically and physically

The category Lack of information sharing would cover cases where the issue was understood within some parts of the industry but not adequately shared to enable operators to take mitigations before failure.

Our assessment of how the degradation mechanism should be avoided assumes that the operating conditions are given and cannot be significantly changed to reduce the damaging impacts.

It is worth making some notes regarding some of the Failure mechanisms:

- Based on today's knowledge a large part of the Carcass Collapses in pipes with multi-layer pressure sheaths can be avoided by limiting the depressurization rates. In many cases it may be difficult to comply with such limitations and in that perspective a different design avoiding possibility for pressure differences over multilayer pressure sheaths would be the preferred solution
- Carcass pull-outs may be caused by a mechanism similar to what caused pressure sheath pull-out from end-fittings in the 90's. However, the fact that the carcass pull-outs were not predicted must be related to knowledge gaps regarding layer interactions and changes in PVDF stiffness over time
- Issues related to ageing of Polyamides will primarily be related to knowledge gaps on the effects of acids, injection chemicals and uncertainties for the ageing models. For an exposure condition where the margins are inadequate with respect to failure it may in some cases be possible to make the exposure less harsh but in most cases the fundamental solution would have been another material. Better knowledge would enable operators to decide how long such pipes can operate with adequate margins as part of the IM system.
- Annulus Wire Corrosion stands clearly out as an integrity issue that can be avoided through adequate maintenance and IM

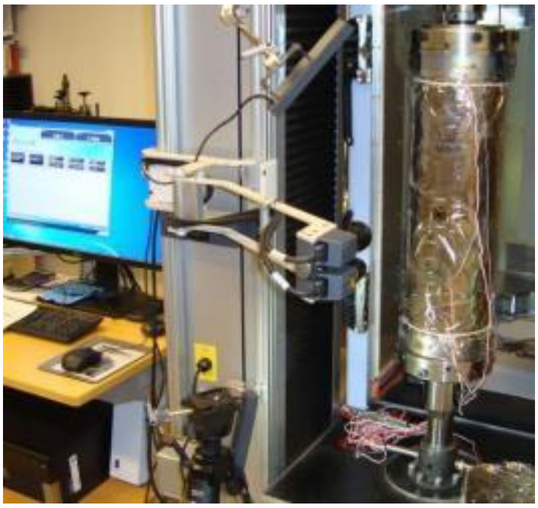

Figure 7-1 Temperature induced loads being tested on a PVDF riser section (DNV)

7.1.2 Lessons from Failure Statistics

Important lessons to be taken from Table 7.1 are:

- Knowledge gaps have resulted in inadequate qualification of many flexible pipes
- Experts with in depth insight are essential for integrity assessment
- Several knowledge gaps must be closed
- Systematic Integrity Management is Essential
  - Make use of best practices
  - Make use of new knowledge when available
  - Be prepared for new integrity issue

7.2 Review of Possible Approaches

PSA has stated the following expectations to make flexible pipe designs and usage more robust

- *Updating standards with the most recent experience*
- *Integrity management of flexible risers with continuous monitoring and systems for documenting operations history, which are actively used in follow-up*
- *Ensure good training and expertise throughout the organization responsible for following up integrity*
- *Clear and unambiguous responsibilities for safe operation and integrity management*
- *The industry must do a better job at sharing information between companies in order to ensure continuous improvement throughout the sector*
- *The industry must actively commit to research and development in order to increase knowledge about flexible risers*
- *Quick and precise incident reporting associated with pipelines, risers and subsea facilities*

The following graphic interpretation depicts how the expectations could be implemented for idealized flexible pipe integrity management of a field operation.

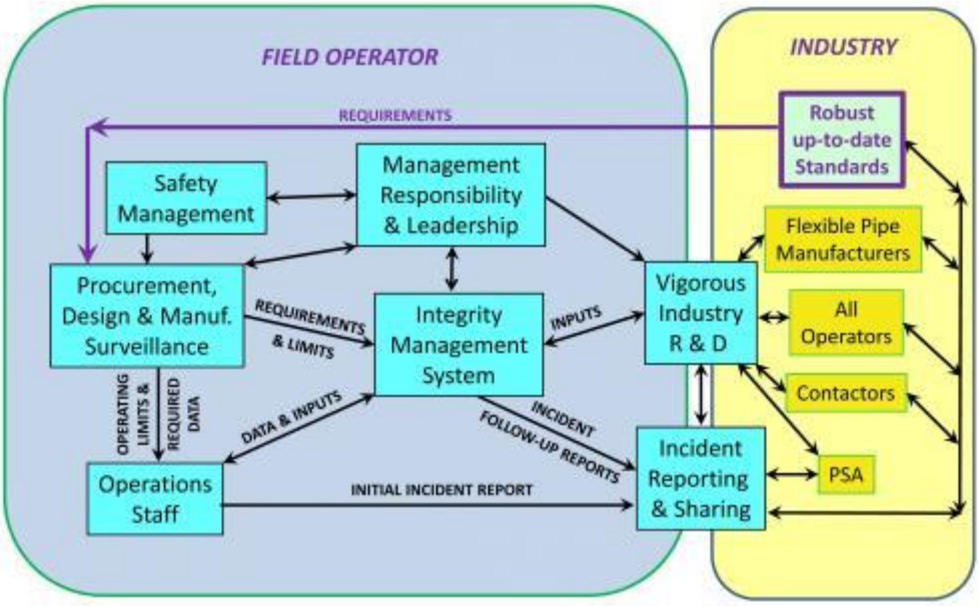

Figure 7-2 Idealized expectations for robust operation of flexible risers

The primary stake holders within flexible risers are the **Field Operator** and the **Industry** which includes regulatory agencies like PSA, other operators, manufacturers and contractors. The two groups share the need for Incident **Reporting & Sharing** and **Vigorous Industry R&D** to advance their mutual understanding of flexible pipe technology, issues and performance. The Industry also has the responsibility to establish and maintain **Robust, up-to-date Standards** for Field Operators to use in procurement and operation of flexible pipes and related systems.

However, the heart of robust flexible pipe operation is the **Integrity Management (I/M) System** developed in conjunction with the **Procurement, Design and Manufacturing** of the flexible pipe system in order to assure that the key design limits and operational requirements are captured and that the necessary process system functionality, instrumentation and analysis systems are provided. The most cost efficient and successful integrity management is initiated early in the design phase and procurement process, and carried into the operational phase by training offshore personnel and onshore technical support resources.

Some obstacles against achieving better robustness are believed to be:

- Insufficient quantitative knowledge about service life issues

  It is necessary to learn more details, and ensure the basis for quantitative assessments related to the degradation mechanisms, compensating measures and probabilities of occurrences. Better understanding of design features and conditions that can initiate damage and failure needs to be developed. These can't be achieved without a renewed emphasis on industry sharing of information and a vigorous research program.

- Inadequate inspection, monitoring and testing solutions to prevent and discover anomalies

  The industry needs to continue the improvements of inspection, monitoring and testing regimes to enable real condition based follow-up. Furthermore, it is becoming evident that in challenging applications, flexible risers, which are complex multi-component systems, need close monitoring. Planning of monitoring and inspection systems during design, as well as development of new monitoring systems is required.

- Reluctance to accept that flexible risers are very complex and in challenging applications need close follow-up

Operators need to move away from the curse of "install and forget", which has led to accidents, loss of revenue and expensive recovery/replacement activities. The desired robustness can only be achieved through active planning and implementation of IM programs that may require significant investment of time, funds and labor. Robustness starts during the design phase but it must be actively maintained throughout each Field's life cycle.

Unfortunately, history indicates that Operators have been unwilling to invest in robustness through well planned and executed Integrity management systems at the outset and have used "alternatives" as described below when confronted with the results of that decision. Most operators will use elements from the listed "alternatives".

1. **Learn to live with challenges**
    - Exploit opportunities and understand weaknesses
    - Use industry experience to modify operational restrictions
    - Close knowledge gaps
    - Increase margins in new designs or retrofits
    - Train personnel and provide good procedures

2. **Replacement based on experience and risk assessment**
    - Replace riser at failure, and/or
    - Schedule replacement based on experience, analysis and risk assessment
    - Step-vise technology improvements

7.3 Ways forward

7.3.1 Learn to Live with Challenges

The simplest actions a field operator could take to improve flexible pipe robustness might include:

- Analyze own and industry experiences to find how probability of incidents could be reduced
- Modify operational procedures adapting ample margins based on collected experience and insight
- Perform regular technology training of operational staff working with flexible pipes
- Follow-up status and adherence to procedures and regular Integrity Assessment Reviews of all flexible assets and interfacing systems
- Fill the technology gaps by industry funded research and feed experiences back to industry and own organization

In the short term, it is possible to take better advantage of existing information through broader distribution and sharing of issues and related knowledge. A gap analysis of that information would point the way to high priority research topics that needs to be launched.

Although there are common flexible riser challenges independent of geographical location, experiences from the North Sea, West Africa, and Brazil show significant differences in Integrity Management (IM) urgency in addressing specific challenges. However; clearly open exchange of information about incidents, findings and solutions is called for. For instance the reservoir souring experienced in West Africa is now becoming an increasing concern also in the North Sea. Fatigue challenges experienced in Brazil are now becoming more important in West Africa and the North Sea.

It's fairly obvious that increased margins in design are likely to give increased robustness in operation. The qualification programs performed does not fully cover all configurations and interfaces experienced by the riser, and the limitations and assumed conditions of the qualification tests are not conveyed to the users in sufficient detail to prevent incidents. Larger margins on temperature, pressure, tension, dynamics and fluid composition will improve reliability, but will challenge ground breaking developments in deep waters, HT/HP fields or reservoirs requiring special chemical treatments.

Based on experiences it is advisable to include higher margins between present design limits and maximum operational limits on temperature, pressure, flow assurance issues and bore fluid. In practice this will mean that all risers should be designed with:

- Sour service armor wires
- Good margin against aging of pressure-, external-sheath and tape layers, even for the best insulated areas
- Increased margin on pressure from previous design practice (burst & fatigue)
- Well within change rate guidance given by previous design practice
- Double external sheath in all critical sections, typically top 2-300m
- Vent-system with confirmed flow capacity well over max diffusion rate, with redundancy
- CP system with ample reserve capacity

To be able to defend higher margins, all involved have to sit down and learn from the experiences and recognize that riser, ancillary equipment and interfaces is complex and unfavorable combinations are easily overlooked, even by experienced people.

7.3.2 Replacement Based on Experience and Risk Assessment

Recently, some operators have replaced risers before an incident or serious findings from inspection or monitoring activities because of risk assessment of recent incidents and characteristics of similar pipes. These preventive replacements may be producing improvements in the incident statistics, however at a significant cost. They are certainly one short termed path to improving robustness.

Well prepared and scheduled preemptive replacements, after 8-10 years operation, may be more cost effective than disrupting a field in full operation. This is particularly true in North Sea and other areas where seasonal weather patterns prevent efficient replacement work in 6-8 months per year, in addition to long lead time on riser deliveries.

Figure 7-3 Onshore activity during a major riser replacement program

For particularly productive wells, satellite fields or export risers, scheduled replacement may be cost effective compared to stop in production or export for 1-2 years (delivery time + waiting on weather). With the probability of major riser incidents in the order of 2% per riser per year on average, as shown previously in this report, the risk and cost assessments may result in favor of scheduled replacement.

Existing Integrity Management programs and associated Risk Assessments have identified several North Sea risers as candidates for replacement. But operators may be reluctant to replace a riser because of the high cost (roughly costing 100 Million NOK or $16Million) and the perception that the Risk Assessment probabilities are not justified.

For bonded flexible pipes used for crude loading scheduled pipe replacements together with external inspection is a common integrity management strategy, ref [1]. This has been effective in reducing the risk of incidents. However, it has not prevented some of Norway's most severe oil spills. On very rare occasions such replacements have also been planned for un-bonded flexible risers during the development phase, most often due to insufficient fatigue or aging lifetime, predicted by analysis during design.

7.4 Condition Based Integrity Management

Integrity management of flexible risers is moving closer to a condition based activity. Today, some risers are equipped with annulus gas vent monitoring, others with movement sensors tracking possible interference with structures, cables or risers in the vicinity. Some risers are equipped with optical fiber sensors continuously monitoring strain, temperatures and possible wire failures. See ref [26] & [27].

Implementing online monitoring giving an overview of "everything" that can be measured on the riser in an IM program with scheduled inspection, monitoring and testing activities followed by an office assessment phase and status reporting with suggested actions are challenging. The main reason for this is the change from an offline assessment system to an online operational support system.

Figure 7-4 Typical online riser annulus vent monitoring cabinet (4Subsea)

Online monitoring will give many opportunities both for long term condition follow up, improved life time assessment, and may also provide instant warning of emerging failures. The latter will require intelligent data processing/filtering and thoughtfully set alarm limits. Further, online systems being part of an offshore operational decision process will require good procedures and available onshore expert support, all based on good insight in degradation processes, damage root causes and progression to loss of integrity.

All activities within integrity management of flexible risers is based on an understanding of how various degradation mechanisms may affect the inspected areas, monitored parameters, or tested performances, however this understanding is still far from complete. An example may be the analysis of vented gas from riser annulus. Hydrogen is known to be produced in the corrosion reaction between H_2O and Fe, and it is detectable in the annulus vent gas. However, there is more research needed to relate the rate of hydrogen production to rates of metal loss, even if it is assumed to be uniform throughout a riser.

Clear objectives are needed for what to monitor and why. There is a need for good procedures and tools for how measurements shall be analyzed and assessed including relevant acceptance levels and required actions. The more experience built into the procedures and analysis, the safer and more efficient. Presently there are high demands for operational advisory due to several reliability challenges with the flexible risers. The offshore operational personnel need to get clear advice on what to do when, with basis in the condition monitoring, hence regularly updated procedures and training is needed.

The best way of implementing condition based integrity management of flexible risers may be to centralize the data collection and assessment. Some important aspects should be considered:

- Challenges and benefits by centralized onshore follow-up (integrated operation)
- Support on riser issues when demanding situations occur offshore
- Possibility for cross referencing data between the operator's installations, maximize learning
- Increased volume of consistent measurements overcomes large variability
- Generally increased awareness and attention to flexible riser integrity

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[31] PSA Norway Seminar on Flexible pipes November 2013, MAPS/GE presentation "MAPS-FR: Inspection and Monitoring"
[32] NORSOK STANDARD Y-002, Edition 1, December 2010 Life extension for transportation systems
[33] ISO/TS 12747:2011 Petroleum and natural gas industries -- Pipeline transportation systems -- Recommended practice for pipeline life extension
[34] NORSOK M-506 CO2 corrosion rate calculation model (Rev. 2, June 2005)
[35] 2013 TPC 0711. Wellhead Fatigue Analysis Method: Steps for Improving the Quality of the Global Riser Analyses, Heidi Gryteland Holm, Harald Holden 4Subsea AS, Massimiliano Russo Statoil

Appendix A Translation of PSA Risk Report 2012 (extract)

As PSA Norway's bi-yearly risk assessment report is issued in Norwegian only, PSA translated the section, 5.3.3 regarding flexible risers, ref [9].

5.3.3 Leaks from and damage to risers, pipelines and subsea production facilities

Leaks from risers and pipelines constitute a substantial potential for major accidents. This has previously been demonstrated e.g. by the Piper Alpha accident in 1988. Such events are therefore a major focus area. This is due to;

- the large volume of hydrocarbons in the actual riser and in the pipeline that will feed a potential leak
- the high pressures and large dimensions used on the Norwegian shelf
- new technology in the form of flexible risers that are introduced in connection with development of floating production facilities
- the leak may rise up underneath the facility and thus entail a more substantial risk of ignition than other leaks on the facility

No leaks from risers to manned facilities were reported in 2012. Neither were any leaks from pipelines reported in 2012. In the previous year, two leaks were reported from flexible risers to manned facilities.

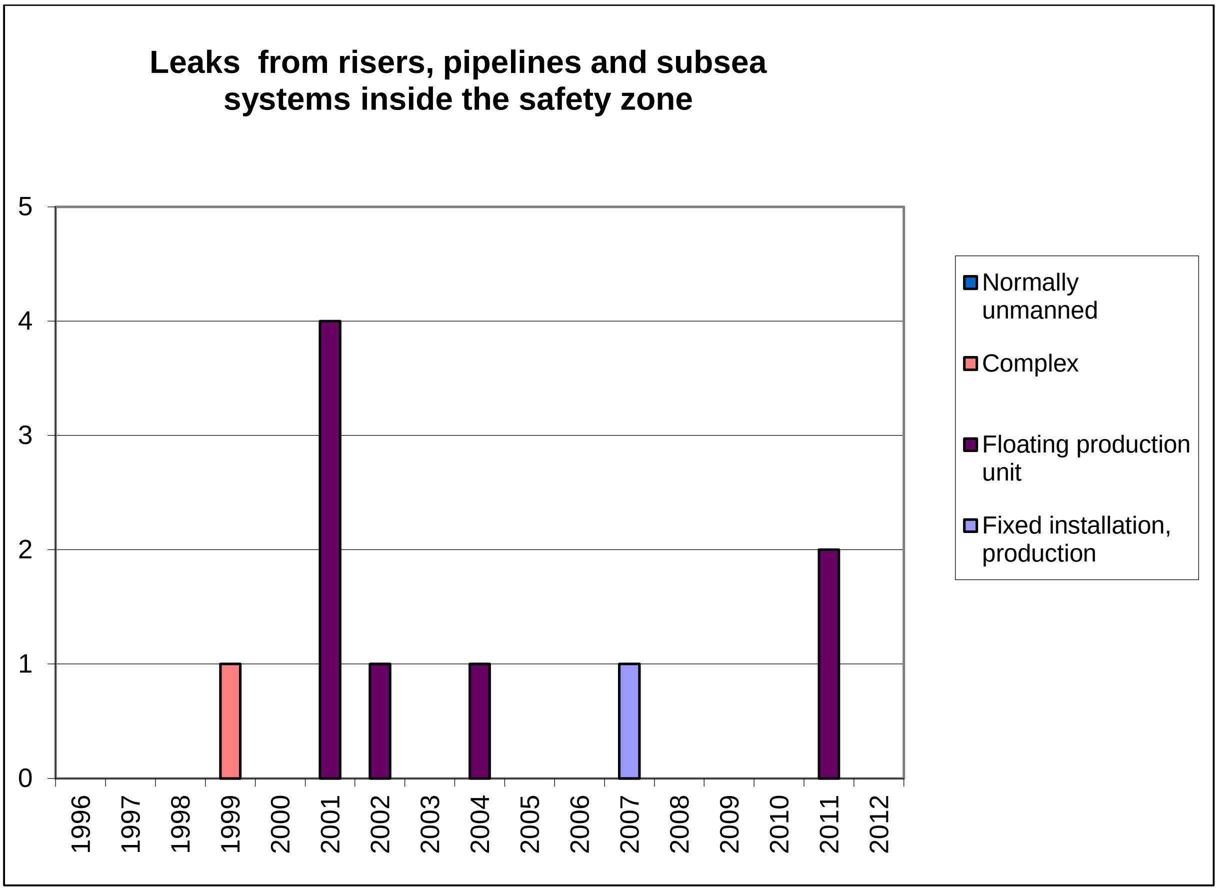

Figure 55 Number of leaks from risers and pipelines within the safety zone, 1996-2012

In 2012, six incidents were reported involving serious damage to risers and pipelines within the safety zone. The most severe incidents had the following pipe diameters: one 2'', two 8'' and three 9'', and the damage, as in previous years, was a combination of damaged external sheath and collapse/tear of carcass on flexible risers. The data for previous years has also been updated with a basis in new information. We have added 21 incidents that are deemed to be serious from the year 2000 to 2011. This means that the data and overviews have been adjusted correspondingly. These incidents are also primarily associated with flexible pipelines and risers.

The overview for 2012 and the update of previous years' data show that leaks from and damage to flexible risers is an area where the industry still has a clear and pressing potential for improvement. As in previous years, we can conclude that the trend shows that the failure rate (faults per year in operation) is still substantially higher for flexible risers than for rigid steel risers. Several of the reported discoveries in 2012 are still linked to challenges identified in 2010 and 2011 in connection with a special type of design for flexible risers.

The industry, and especially Statoil and its sub-suppliers, has devoted major and systematic efforts to reviewing each individual incident associated with flexible risers, with dissections of risers and detailed analyses. Over many years of engineering and operation of flexible pipelines and risers and a high degree of technological development in the area, Norway has developed world-leading expertise.
In order to realize this expertise through increasing the quality of new flexible pipelines and better follow-up of existing ones, operators and suppliers should work in a more goal-oriented and deliberate manner to spread their experience - first internally in their own company, then the industry at large. Industry associations, such as the Norwegian Oil and Gas Association, must elevate this topic on their agenda and ensure that their experience is used to benefit the entire industry.

It is an invariable regulatory requirement (Section 57 of the Facilities Regulations concerning pipelines) that *'for flexible pipeline systems and pipeline systems of other materials than steel, utilization factors and any load/action and material factors shall be stipulated so that the safety level for such systems is not lower than for steel pipelines and steel risers'*. Looking at the incident frequency for flexible risers, one could question whether this requirement has been met and whether the complexity of safely operating flexible risers has been adequately communicated in the organizations. There are also grounds for questioning whether the industry does a good enough job in handling the challenges associated with operating existing flexible risers and pipelines that are continuously ageing, in addition to designing and installing new ones.

The industry needs to address the following improvement areas:

- Updating standards with the most recent experience
- integrity management of flexible risers with continuous monitoring and systems for documenting operations history, which are actively used in follow-up
- ensure good training and expertise throughout the organization responsible for following up integrity
- clear and unambiguous responsibilities for safe operation and integrity management
- the industry must do a better job at sharing information between companies in order to ensure continuous improvement throughout the sector
- the industry must actively commit to research and development in order to increase knowledge about flexible risers
- quick and precise incident reporting associated with pipelines, risers and subsea facilities

There have been a few small leaks from subsea facilities both within and outside the safety zone in 2012. The leaks were mostly hydraulic fluid and methanol, as well as some gas. Due to their location, rates and leak types, these leaks posed little or no risk for personnel and negligible environmental risk, and therefore do not affect statistics of serious leaks. No serious damage to subsea facilities was reported in 2012.
Serious damage is also included in the calculation of the overall indicator, but with lower weight than for leaks. There were six reported incidents with serious damage to pipelines and risers in 2012. Figure 56 shows an overview of the most serious incidents involving damage during the period 1996-2012.

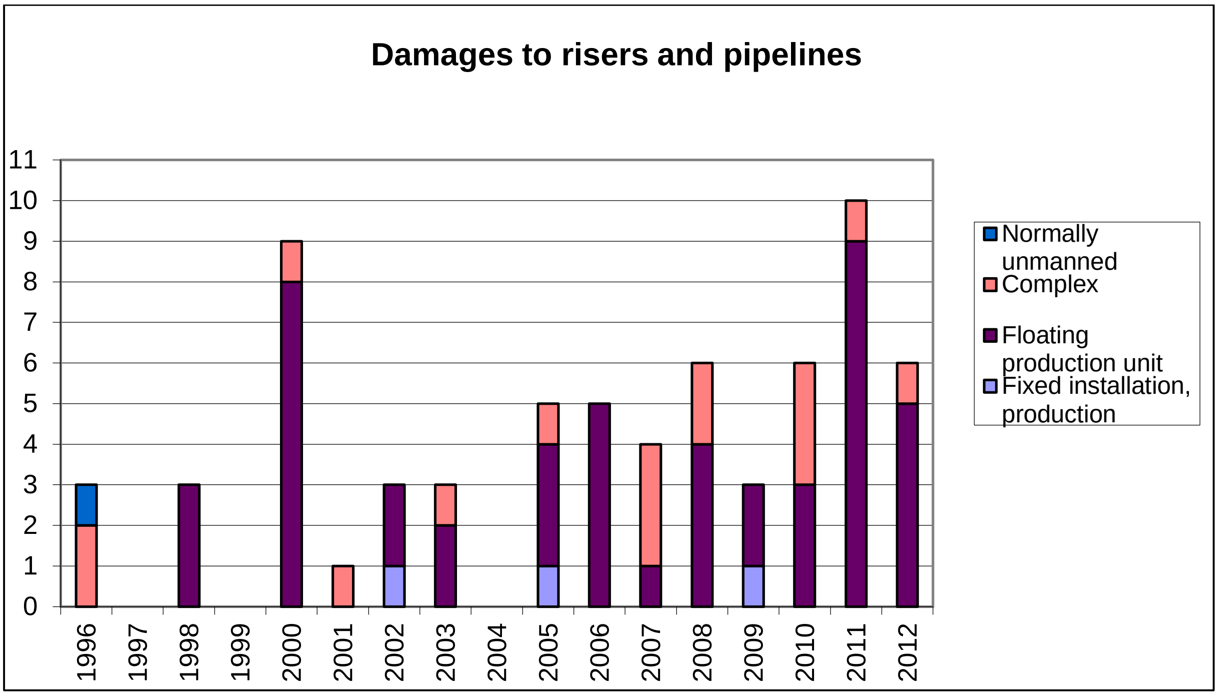

Figure 56 Number of incidents with serious damage to risers and pipelines, 1996-2012

Appendix B CODAM Data Used in This Report (from PSA)

incident_date	severity	dimension	medium	cause
17.04.1995	Major	8	Oil/gas	Coflon layer shrinkage
11.07.1995	Major	10	Water	Micro leakage
29.10.1995	Major	8	Oil/gas	Coflon layer shrinkage
25.11.1995	Minor	16	Oil	Unknown
01.09.1997	Major	9	Water	Bending
01.09.1998	Insignificant	16	Oil	Not reported
26.08.1999	Major	8	Water	Unlocked Zeta wires
26.06.2000	Minor	6	Oil	Unknown
26.06.2000	Minor	6	Oil	Blockage of gas release valve
26.06.2000	Major	6	Oil	Unknown
26.06.2000	Major	6	Injection	Unknown
26.06.2000	Major	6	Injection	Unknown
26.06.2000	Minor	6	Injection	Unknown
26.06.2000	Minor	6	Oil	Unknown
26.06.2000	Major	6	Oil	Unknown
01.09.2000	Minor	6	Oil	Unknown
01.09.2000	Minor	6	Oil	Unknown
01.09.2000	Major	6	Injection	Unknown
01.09.2000	Minor	6	Oil	Unknown
01.09.2000	Major	6	Oil	Unknown
01.10.2000	Minor	6	Injection	Not reported

26.02.2001	Minor	9	Oil/gas	Unknown
08.03.2001	Major	6	Injection	Collapse of coflon layer
04.10.2001	Major	11	Water	Hole in outer coating
08.01.2002	Major	6	Injection	Bursted outer coating
01.03.2002	Major	6	Injection	Collapse of carcass
01.03.2002	Major	6	Injection	Collapse of carcass
01.03.2002	Major	6	Oil	Collapse of carcass
15.05.2003	Minor	8	Oil	Fallen off MWA
15.05.2003	Minor	6	WATER	Fallen off MWA
01.07.2003	Major	6	Injection	Hydrogen induced cracking.
01.07.2003	Minor	11	Water	Unknown
11.08.2003	Major	6	Injection	Hydrogen induced cracking
11.08.2003	Major	6	Injection	Hydrogen induced cracking
31.10.2003	Minor	8	Oil	Not reported
05.11.2004	Major	10	Oil/gas	Fabrication/desig n
01.01.2005	Minor	2.875	Gas	Lack of vent and pressure build-up in the annulus.
01.05.2005	Minor	8	Injection	Unknown
01.06.2005	Major	6	Oil	Unknown
01.06.2005	Major	6	Injection	Unknown
01.07.2005	Minor	6	Oil	Unknown
16.09.2005	Major	6	Oil	Not reported
01.01.2006	Major	2	Gas lift	Unknown
05.11.2006	Major	10	Oil/gas	N/A

19.11.2006	Major	10	Oil/gas	N/A
25.11.2006	Major	10	Oil/gas	N/A
16.12.2006	Major	11.6	Condensate	N/A
11.05.2007	Major	10	Oil/gas	N/A
01.07.2007	Major	8	Oil	Hydrate plug
31.03.2008	Major	16	Gas	N/A
30.09.2008	Major	5	Service	Collapse of carcass
04.10.2008	Major	5	Service	Collapse of carcass
26.10.2008	Major	8	Oil/gas	Collapse of carcass
01.01.2009	Minor	2	Gas lift	Believed to be damaged during installation
02.01.2009	Major	12	Oil/gas	Abrasive wear
28.01.2009	Major	12	Water	Abrasive wear.
20.02.2009	Major	16	Gas	Wear.
01.06.2009	Major	6	Injection	Lacking end termination plug
01.06.2009	Major	6	Oil	Unknown.
01.06.2009	Major	6	Oil	Unknown
01.06.2009	Minor	6	Oil	
01.06.2009	Major	6	Oil/gas	Lacking end termination plug.
01.06.2009	Minor	6	Oil	Unknown
24.07.2010	Major	6	Oil	Collapse of carcass
16.11.2010	Major	6	Oil	Collapse of carcass
30.11.2010	Major	6	Oil	Collapse of carcass
31.03.2011	Major	6	Oil	Collapse of carcass.

01.04.2011	Major	2	Gas	Unknown
01.04.2011	Major	6	Oil	Carcass tear.
05.04.2011	Major	6	Oil	Carcass tear.
07.04.2011	Major	6	Oil	Collapse of carcass.
09.04.2011	Major	6	Oil	Carcass collapse
18.04.2011	Major	6	Oil	Carcass tear
24.04.2011	Major	6	Oil	Carcass tear off
24.04.2011	Major	6	Injection	Collapse of carcass
28.04.2011	Major	6	Oil	Overload or fatigue
01.01.2012	Major	8	Gas	
01.03.2012	Minor	2	Gas	Corrosion fatigue
15.03.2012	Major	9	Gas	Carcass collapse
29.4.2012	Minor	5	Gas	Wear of the outer sheeting
19.05.2012	Insignificant	11	Water	Foreign object.
22.08.2012	Major	9	Oil	Unknown
28.09.2012	Minor	8	Oil	Anchor replacement.
05.11.2012	Major	9	Oil	Carcass collapse
17.04.2013	Major	6	Gas	Over pressurized annulus

Appendix C Suggested Common Flex-riser Incident Format

Required information for the data base:

1. Installation date
2. Failure discovery date
3. Name of field (may be omitted for anonymity)
4. Type of service
5. Pressure and temperature data at time of observed failure
6. Basic structure information
    a. Design temp / press
    b. Internal diameter
    c. Rough / smooth bore
    d. Pressure sheath material and number of layers
    e. 35 or 55 degree structure

7. Description of first observed indications (5 or 10 sentences)
8. Clear differentiation of later observations and findings
9. Follow-up description of subsequent evaluations and findings
10. Final resolutions and determination
11. Specific list of expected root failure causes
12. Differentiation between observed failure characteristic and actual root cause
13. Other safety critical information / experience

Appendix D Abbreviations

Acronym	Definition
ALARP	As Low As Reasonably Practicable
API	American Petroleum Institute
CIV	Corrected Inherent Viscosity
CO2	Carbon Dioxide
CODAM	Corrosion Damage (PSA database)
CP	Corrosion protection
DBS	Dibutyl Sebacate
DNV	Det Norske Veritas
DNV-GL	Det Norske Veritas – Germanischer Lloyd
FE	Finite element
FPS	Floating Production System
FPSO	Floating Production Staorage and Offloading
FPU	Floating production Unit
GE	General Electric
GOR	Gas/Oil Ratio
GVI	general visual inspection
H2	Hydrogen
H2O	Water
H2S	Hydrogen Sulfide
HDPE	High-Density Polyethylene
HIC	Hydrogen-Induced Cracking
HSE	Health Safety Environment
HT/HP	high temperature high pressure
I/M	Integrity Management
ID	Inside Diameter
IFE	Institiutt for Energiteknikk
IFP	French Petroleum Institute
IM	Integrity Management
IPCC	Intergovernmental Panel On Climate Change
ISBN	International Standard Book Number
ISO	International Standardization Organizations
JIP	Joint Industry Projects
LOC	loss of containment
MAPS	Magnetic strain measurement system
MPa	Mega Pascals
MWA	mid water arches
N/A	Not Applicable
NACE	National Association Of Corrosion Engineers
NCS	Norwegian Contineltal Shelf
NKT	Cable (and riser fabricator) Nordiske Kabel og Traadfabriker
NOK	Norwegian Kroner
NORSOK	Norwegian Standardization for Offshore Oil & Gas (Norsk sokkels konkurranseposisjon)
NOV	National Oilwell Varco
NPD	Norwegian petroleum Directorate
OMAE	International Conference on Ocean, Offshore and Arctic Engineering
OTC	Offshore Technology Conference
PA11	Polyamide 11
PA12	Polyamide 12
PARLOC	Pipeline and Riser Loss of Containment
PE	Population Equivalent (In Wastewater Treatment)
PSA	Petroleum Safety Authority

Acronym	Definition
PVDF	Polyvinylidene Difluoride
R&D	Research And Development
ROV	Remotely Operated Vehicle
RP	Recommended Practice
S-N	Stress Number
SCC	Stress corrosion cracking
TLP	Tension Leg Platform
UK	United Kingdom
UN	United Nations
US	United States
UTC	Under water Technology Conference
XLPE	Cross linked Polyethylene