UKOOA Guidance Note
on
Monitoring Methods and Integrity Assurance for
Unbonded Flexible Pipe

Prepared For

UKOOA
Oil and Gas for Britain

By

MCS International

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# UKOOA Guidance Note

**on**

Monitoring Methods and Integrity Assurance for Unbonded Flexible Pipe

## Guidance Note

Prepared for

[UKOOA Logo]

by

MCS International

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UKOOA & OLF
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1 ABBREVIATIONS

API .......................................................... AMERICAN PETROLEUM INSTITUTE
BS ............................................................. BRITISH STANDARD
CCTV .......................................................... CLOSED-CIRCUIT TELEVISION
CP ............................................................. CATHODIC POTENTIAL
CRA ............................................................. CORROSION RESISTANT ALLOY
FAT ............................................................. FACTORY ACCEPTANCE TEST
GVI/CVI ...................................................... GENERAL/CLOSE VISUAL INSPECTION
Hs ............................................................. SIGNIFICANT WAVE HEIGHT
HSE ............................................................. HEALTH AND SAFETY EXECUTIVE
MAOP ......................................................... MAXIMUM ALLOWABLE OPERATING PRESSURE
MAPD .......................................................... MAJOR ACCIDENT PREVENTION DOCUMENT
OLF .......................................................... OIL AND NATURAL GAS INDUSTRY
PA-11 .......................................................... POLYAMIDE 11 / NYLON-11 / ‘RILSAN’
PVDF .......................................................... POLYVINYLDENE FLUORIDE
QA/QC .......................................................... QUALITY ASSURANCE/QUALITY CONTROL
ROV .......................................................... REMOTELY OPERATED VEHICLE
SN ............................................................. STRESS/NO. OF CYCLES
SSC .......................................................... SULPHIDE STRESS CRACKING
Tz ............................................................. ZERO-UP CROSSING WAVE PERIOD
2 INTRODUCTION

2.1 REVISION HISTORY

This document is the fifth revision of the Guidance Note for final issue. This revision incorporates comments from the previous Task Group meeting held on the 21st of June, 2002 and latest feedback from flexible pipe suppliers, field operators, independent consultants and regulatory authorities from both the UK and Norwegian sectors of the North Sea.

Companies that have contributed to this Guidance Note in the form of either comment, provision of information or document review are acknowledged in Section 8.

2.2 GENERAL

This guideline applies to risers, flowlines, jumpers and drag chain jumpers constructed from unbonded flexible pipe and operated within the UK and Norwegian offshore sectors.

This document provides guidance on the integrity assurance and monitoring of a flexible pipe system. It is assumed that an Integrity Management Strategy is already in place, based on a risk assessment in accordance with the HSE “Guidelines for Integrity Monitoring of Unbonded Flexible Pipe”[1], or some other recognised guideline.

This document does not replace the need for a risk assessment to ensure compliance with the installation’s performance standard, or the pipelines major accident prevention document (MAPD). The relationship between the formal UK regulations and this Guidance Note is presented in Figure 1.1. Above the line are the legal regulations, which must be in place for oil field development in the UK sector. The Guidance Note is complimentary to the legally required regulations and provides specific guidance on current best practice integrity assurance for both existing and future flexible pipe systems. As illustrated in Figure 1.1, guidance is provided for all stages of a flexible pipe project, from concept definition through to detail design and manufacture, and into operation, based on lessons learned to date by the industry as a whole. Following the arrows around, the diagram shows that as experience is gained in the operation of flexible pipes, the industry develops an improved understanding of the various degradation and failure modes and the effectiveness of certain inspection / monitoring methods. In this respect, the fundamental objective of this Guidance Note is to highlight all integrity concerns that the industry has become aware of to date. By being aware of such issues, the industry can ensure that risks are continuously assessed and mitigated against. Finally, the knowledge gained can be fed back into future developments to avoid repetition of similar incidents.
This guideline is also intended to compliment other industry standards, specifications and recommended practices such as BS8010 [2], API 17J [3] and API RP 17B [4]. These latter documents specify requirements for the design, material selection, manufacture, testing and packaging of flexible pipe. However, it should be recognised that unbonded flexible pipe technology is continually evolving and a basic level of conformance with API 17J and API 17B may not be sufficient. This should be assessed at the project stage to capture recent industry experiences.

Project and operational managers or engineers would obtain the greatest benefit from this Guidance Note. The project engineer can use this Guidance Note to identify potential risks and provide integrity assurance through the development of a robust system design that incorporates adequate life of field monitoring capabilities. The operational engineer can also adopt the latest technical information and field experience from the guidance note to ensure that the system is monitored using viable inspection techniques. Both groups are important in providing overall system integrity.

In addition, this Guidance Note registers the fact that flexible pipe inspection / monitoring technologies are also evolving with the development of several new monitoring techniques in recent years. It is therefore recommended that interested parties regularly re-assess their flexible pipe risks and their assurance/monitoring programmes against the most recent experiences and technological developments.

The support of the Norwegian Oil Industry Association/ Oljeindustriens landsforening (OLF) in contributing to this Guidance Note is recognised in providing a wider operator experience base for the North Sea.

### 2.3 Guidance Note Layout

A route map of the Guidance Note is illustrated in Figure 1.2, and described below:

- Section 2 provides a series of technical assurance checks for the life cycle of the flexible pipe.

- Section 3 presents an overview of known failure modes. However, it should be noted that the failure data is not sufficient to enable a statistical analysis of failure probability for flexible pipe.

- Section 4 describes various degradation drivers and failure modes.

- Section 5 gives information on available inspection and monitoring techniques, describing the procedure, the current industry practice and a guideline recommendation.
Figure 1.1: Guidance Note Overview.

- Offshore Installations (Safety Case) Regulations (SI 1992/2885)
- Pipeline Safety Regulations (SI 1996/825)

Legally Binding Regulations

Best Practice Integrity Assurance

UKOOA Guidance Note 214221-GN01

Concept definition

Risk Assessment

Manufacture

Installation & commissioning

Project to operations

Operation

Degradation & failure

Guidance on inspection & monitoring techniques

Historical data

Detail design

Operational integrity assessment.

Project integrity assurance.
UKOOA Guidance Note on Monitoring Methods and Integrity Assurance for Unbonded Flexible Pipe

Figure 1.2: Route Map of Guidance Note

SECTION 2

Project

- Concept definition
- Detailed design
- Manufacture
- Installation & commissioning

Project/Operations

- Defines deliverables for project handover
- Check list of activities
- Safety management system

Operations

- Provides a system for identification and control of risks

SECTION 3

- Historical failure & damage data

SECTION 4

- Degradation & failure drivers

SECTION 5

- Guidance on inspection & monitoring techniques
3 LIFE CYCLE FLEXIBLE PIPE INTEGRITY ASSURANCE

This section of the document presents a list of integrity assurance checks that could be performed in an integrity review of the flexible pipe system. This list considers each stage of the pipe life cycle and incorporates field experience drawn from the Norwegian and UK sectors.

3.1 CONCEPT DEFINITION

The concept stage of a project is a significant opportunity to ensure that sufficient design assurance and monitoring capability will be incorporated into the flexible pipe system.

A summary list of checks is presented below:

- Ensure that sufficient engineering effort is given to develop the appropriate flexible riser configuration for the development. Past experience has consistently shown that a poor understanding of the riser configuration requirements leads to significant delay and cost overruns at the detail design phase of the project.

- Consider the purchase of a spare riser that is suitable for the service requirements of all the risers in the system.

- Consider the turret/deck layout and size for ease of riser installation and retrieval. This should review the potential clashing risks between adjacent risers and/or mooring lines. In addition, the turret/deck layout should assess the need for future inspection access of the riser-to-turret/deck interface and the bend stiffener.

- Consider the use of inspection hatches and CCTV to monitor the turret I tubes and bend stiffeners. Bend stiffeners are critical system components that are often difficult to inspect.

- Consider future pigging or line intervention requirements and the necessary facilities topsides and subsea.

- Consider the development of a process monitoring system to address:
  - Continuous bore pressure and temperature monitoring of each riser.
  - Annulus monitoring capability of each hydrocarbon riser.
  - In-line polymer coupon sampling (topsides and/or subsea).
  - Bore fluid composition monitoring, including bore density.

- Build redundancy into ancillary equipment, when possible.
3.2 **Detail Design**

The detail design stage should refine the concept definition and develop suitable operating envelopes. Several key aspects are listed below:

- Establish a design basis for the flexible pipe system that is complimentary to API 17J, thus enabling the operator to detail specific requirements for the particular application.
- Acceptance criteria for flexible riser clashing / interference should be defined. The type and thickness of marine growth should be established in this respect.
- Establish detailed operating envelopes that can be used for future anomaly limits. This should include lifetime predictions in terms of temperatures, pressures, CO₂ and H₂S content and maximum blowdown rates.
- Consider the need to monitor bore pressure and temperature for each riser.
- Consider fitting suitable polymer coupons in the flowline or the use of polymer spool pieces, to determine polymer integrity throughout the life of the pipe.
- Avoid a common annulus venting header system. This has the potential to flood all other riser annuli if a single riser is subject to damage, as has occurred on several North Sea dynamic risers.
- Consider a corrosion-fatigue assessment of armour wires within the annulus space to allow for a wetted annulus and to provide assurance that any additional fluid control procedure is effective in controlling the annulus environment. This forms an integral part of any assurance process for a flooded annulus in a riser system.
- Small scale fatigue testing can be employed to obtain armour wire fatigue characteristics in a corrosive environment. However, it is important to obtain sufficient test samples from the material batch employed in the manufacture of the flexible pipe so as to provide a design SN curve and to enable the use of an industry recognised safety factor to compute fatigue life.
- Consider prototype testing since it is an important part of the assurance process and is identified within API 17B. Prototype testing should be based on samples that follow the same manufacturing QA/QC process. High temperature application places a high level of importance to the end fitting sealing mechanisms.
- Consider the use of a secondary slack tether connection independently attached to the riser base to ensure a redundant load path in a tethered lazy wave riser configuration.
- The riser annulus venting system should be vented to a safe area, or a low pressure flare system. The use of a check valve should ensure a sufficiently low differential pressure to open the valve and to avoid bursting the riser outer sheath. In the event that a venting system is designed with no check valves, it should be confirmed that no back pressure is
generated from a low pressure flare system that increases the annulus pressure above 2 barg. Alternatively, the vent pipe should be vented to a safe area. The manufacturers guidance should be sought on the optimal solution.

- Ensure that the structural dynamic of the riser response to wave frequency is assessed. This can generate a greater number of fatigue cycles in the riser compared with a coarse \( T_{\text{min}} \) and \( T_{\text{max}} \) screening exercise, as is currently performed within the industry.

- Ensure the riser shut-in case is considered as a load case during an extreme event. This generally increases the loads acting on ancillary equipment, due to the increase in bend stiffener stiffness from cool down.

- Ensure suitable cathodic protection is offered to ancillary equipment for the field life.

- Design all ancillary equipment for non-inspection if based solely on GVI/CVI. This may require higher factors of safety on fatigue life to reduce the possibility of expensive field repair or replacement.

- Ensure the effect of large buoyancy elements is assessed during the design stage to avoid large riser curvatures and consider the use of smaller more uniformly distributed buoyancy elements to avoid large concentrated buoyancy loads.

- Drag chain flexible pipe design should not be classed as a static application.

- The use of shallow lay angle (15~20 degree) tensile armour wire should be carefully considered in dynamic applications or when subject to pressure fluctuations on a large radius of curvature due to its sensitivity to wire disorganisation with time.

- Assess the suitability of end fitting coatings in terms of CRA weld overlay on all internal wetted surfaces with epoxy paint. Also establish the required CP on external surfaces.

- Assess the ability of the internal pressure sheath in smooth bore pipes to withstand collapse under all operational scenarios.

- Assess the FAT conditions with respect to the membrane and bending stress within the armour wires. This exceeds the present requirements of API 17J, which considers membrane stress alone. The FAT has the ability to exceed a yield magnitude stress level on the outer surface of the wires during a reeled hydrotest. In the event that wires do exceed the yield state on their outer surface, then the ductility of the wire and the possibility of weld repairs should be considered to avoid potential micro-cracks and fatigue initiation sites.

- Consider the use of strain gauges or other instruments attached to a dynamic riser, to measure deflections and verify the dynamic analyses. This is particularly important in regions with high extreme and fatigue loads such as the top bend stiffener region or subsea hold-down tethers.
3.3 MANUFACTURE

The QC/QA plays a significant role in the manufacture of flexible pipe and the ancillary equipment. The following points relate to integrity assurance in service and may be incorporated in the manufacturer’s build programme depending on the risk associated with the flexible pipe system:

- Establish a detailed manufacturing specification, setting out acceptable tolerances for the various pipe layers. These may include carcass ovality, weld qualification frequency, limiting notch radius on the pressure sheath and end fitting tolerances. The as-built documentation should include all manufacturing tolerances and ensure any non-conformances are documented, in accordance with API 17J.

- Establish critical areas on the flexible pipes, which should be free from welds in the armouring or carcass layers. Also, document weld locations for future inspection points.

- The pipe manufacturer should consider the supply of a metal insert marker for the inner sheath to end fittings for PVDF pipe. This will permit in-service monitoring for slippage using radiography, assuming access permits.

- The purchaser should review the level of QA/QC associated with the purchasing and inspection of the wires supplied to the pipe manufacturers.

- The pipe manufacturer should supply polymer coupons to be retained by the operator from the internal pressure sheath batch. The test coupons may form part of the in-service integrity management strategy, or for future testing.

- The pipe manufacturer should retain armour wire samples from the material batch employed in dynamic risers. The samples may be used for future fatigue testing and would be more representative than generic samples.

- The pipe manufacturer should consider a subsea closed venting port in the end fitting to permit future flushing of the annulus. This should be risk assessed, but is a desirable feature if a flushing programme is later applied in-service. Communication in the annulus may then be checked for outer sheath rupture in the hog region.

- Recommend that the pipe manufacturer perform an annulus volume test in the FAT programme to assess the integrity of the outer pressure sheath and the end fitting venting ports.

- Recommend that the pipe manufacturer perform an assessment of annulus flushing fluid compatibility with the annulus polymer layers for potential degradation effects and also any effect on anti-friction tape.

- Recommend that the bend stiffener manufacturer produce test coupons from the bend stiffener mould for verification against the design assumptions. The Buyer should assess the bend stiffener QA/QC for design and manufacture.
• Recommend that ancillary equipment be assessed for fatigue, and ensure that sufficient attention is paid to finishing details.

• Ensure that sufficient Cathodic Protection systems are in place on subsea infrastructure. In particular, determine the required anode sizes based on accurate calculation of surface area.

• All vent ports should be tested for flow in both directions to ensure that no restriction occurs.

3.4 INSTALLATION & COMMISSIONING

Historically, the installation phase has a relatively high risk of damaging the outer sheath of the flexible pipe. The following points reflect some basic measures:

• Installation analysis should be performed to determine allowable sea states and lay tables to aid installation. A record of the installation sea states should be retained and any sea state excursions assessed by competent persons. The potential for damage may drive the need for external protection of critical areas susceptible to impact damage.

• Records should be retained of offshore operational concessions for future assessment by the operational team.

• The use of management procedures should be reviewed to reduce the risk of damaging the outer sheath and flooding the annulus of the flexible pipe. A qualified offshore repair procedure should be developed as a contingency.

• The use of an approved bolt tensioning procedure should be adopted for the bend stiffener flange connections to reduce fatigue damage of the bolted assembly. The use of manual torque procedures is less accurate than tension tooling equipment during assembly.

• Ensure that the annulus venting system is not obstructed to avoid outer sheath rupture.

• On completion of installation, conduct a thorough GVI of the subsea infrastructure. This initial GVI forms the baseline for all future integrity management of the subsea systems.

• Annulus testing to determine the condition of the pipe external sheath should be performed as part of the commissioning process.

3.5 PROJECT HANDOVER TO OPERATIONS

The project-to-operations handover is a significant milestone in any project. The handover must ensure the following points are addressed to permit a seamless flow of information:

• Identification of project non-conformance reports related to the flexible pipe system.
• Project implementation of an integrity management strategy for the flexible pipe system, which is supported by operations.

• Supply of completed documentation. This should include as-built drawings of subsea ancillary equipment.

• Assurance that the system is verified and complies with legislation on handover.

• Establish and implement a ‘user manual’ for the flexible pipe system for use in operation.

• Establish operational envelopes of each flexible pipe at ‘handover’.

3.6 OPERATION

• Monitor and log the bore pressure and temperature.

• Establish alarm limits for key parameters and ensure all instances of operation in excess of this limit is logged.

• Monitor the annulus for potential flooding on hydrocarbon risers.

• Monitor the bore fluid characteristics in terms of CH\textsubscript{4}, CO\textsubscript{2} and H\textsubscript{2}S. Additionally, the use of inhibitors and other treatment fluids in the pipe (e.g. methanol, MEG) should be monitored and recorded.

• Assess the use of hot oil flushing to remove wax deposits in production lines for its duration at the elevated temperature and control the limits set for potential upper thermal excursions to avoid polymer degradation.

• Coupon sampling should be implemented for flexible pipes with a high risk of temperature degradation. It is proposed that the degradation of PA-11 be determined using the API Technical report on “the ageing of PA-11 in flexible pipes”, [6], with an inspection frequency driven by the pipe criticality from a risk assessment. The calculated polymer life would be reduced by an associated factor from the risk assessment to obtain an inspection frequency and to ensure sufficient polymer samples exist. Operating temperature, water cut and pH should be used to assess which coupons are retrieved.

• The use of potential annulus treatment fluids should be verified for compatibility with the pressure sheath polymer under relevant operational conditions for the design life. Compatibility with the external sheath and anti-wear layers should also be ensured.

• Repair a site of outer polymer damage on a flexible riser to minimise the exposure to oxygenated seawater and fatigue damage.

• Implement, maintain and review at regular intervals an integrity management strategy for the flexible pipe system.
4 HISTORICAL FAILURE / DAMAGE DATA

4.1 GENERAL

The objective of this section is to provide guidance on different types of failure / degradation modes that have occurred in flexible pipe systems, with a view to ensuring that known failure modes are mitigated against. Note that the failure statistics presented are not comprehensive and were originally collated during the preparation of a UKOOA report “State-of-the-Art Flexible Riser Integrity Issues”, [5]. Further failure incidents have been sourced during the course of preparing this Guideline Note are included in Tables 4.1 to 4.5.

MCS International insists that the failure data presented in this section is not used in any form of probabilistic analyses to attempt to determine a failure probability for flexible pipe. This recommendation is based on the following points:

- The lack of a comprehensive database of flexible pipe operational years in service.
- The lack of a comprehensive database of flexible pipe failure / damage incidents, and indeed failures for which the cause was never agreed between all parties.
- The fact that a number of failures are the result of operation outwith design limits.
- Some of the failure modes presented have been resolved by the industry.
- Flexible pipe system risks vary widely from field to field, and there is no replacement for a field specific risk assessment.

In addition, the failure modes described in the following sections include only those that have occurred in the UK and Norwegian sectors of the North Sea. Failure incidents that have only ever occurred outwith the North Sea include sour service corrosion and SSC of the metallic layers.

Note also that no fatigue failure of the metallic armouring has occurred to date. However, given that the majority of risers are still in the early stages of design life, this failure mode cannot be discounted.

4.2 FLEXIBLE RISER FAILURE / DAMAGE INCIDENTS – DURING OPERATION

A flexible riser is defined as a flexible pipe connecting a platform/buoy/ship to a flowline, seafloor installation, or another platform. The riser may be freely suspended (free, catenary), restrained to some extent (buoys, chains), totally restrained, or enclosed in a tube (I, or J tubes).
The majority of risers in both the UK and Norwegian Sectors have seen less than 5 years service. Table 4.1 presents a breakdown of the 49 operational failure / damage incidents that have occurred to date and whether the incident resulted in loss of containment. This lack of long term riser experience places great importance on performing a risk assessment to identify both historical and future failure/damage events, which may materialise with time. This requires that a suitable integrity monitoring strategy is developed to ensure that the potential risk is As Low As Reasonably Practicable (ALARP).

4.3 **Flexible Riser Failure / Damage Incidents – Installation & Commissioning**

In addition to the 49 recorded operational incidents, there have also been 26 of incidents that have occurred during installation and commissioning activities, in the UK and Norwegian sectors. Table 4.2 presents a breakdown of the installation and commissioning failure / damage incidents that have occurred to date.

4.4 **Flexible Flowline Failure/Damage Incidents**

A flexible flowline is defined as a flexible pipe, wholly or in part, resting on the seafloor or buried below the seafloor and used in a static application. In total, there have been 34 recorded failure / damage incidents of flexible flowlines identified by the UKOOA study [5] and this Guideline Note, for both the UK and Norwegian sectors. Table 4.3 provides a more detailed breakdown of these incidents.

4.5 **Flexible Jumper Failure/Damage Incidents**

A flexible jumper is defined as a short flexible pipe used in subsea and topside, static or dynamic applications. In total, there have been 7 recorded failure / damage incidents of flexible jumpers from the UKOOA sample for the UK and Norwegian sector. Table 4.4 provides a detailed breakdown of these incidents.

4.6 **Flexible Drag Chain Jumper Failure/Damage Incidents**

A flexible drag chain jumper is defined as a short (55 to 75m) flexible pipe used in a FPSO topside drag chain arrangement within a dynamic application. The drag chain may also be described as a Turret Transfer System and is an alternative to a turret swivel arrangement. In total, there have been 9 recorded failure / damage incidents of flexible drag chain jumpers from the UKOOA sample for the UK sector only. Table 4.5 presents a detailed breakdown of these incidents.
Table 4.1 UK & Norwegian Sector Riser Operational Failure / Damage Incidents.

<table>
<thead>
<tr>
<th>Failure / Damage Incident</th>
<th>No. of Occurrences</th>
<th>Loss of Containment</th>
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<tbody>
<tr>
<td>Degradation of PA-11 Internal Pressure Sheath</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Pull-out of PVDF Internal Pressure Sheath from end-fitting</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Ancillary Device Failure</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>External Sheath Damage</td>
<td>8</td>
<td>0</td>
</tr>
<tr>
<td>Armour wire corrosion</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>End-fitting vent valve blockage</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Flooded annulus</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>End-fitting leak</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pipe blockage</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>J-Tube Internal Pressure Sheath Collapse</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Carcass collapse</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

Notes:

1. PA-11 is limited to a maximum temperature of 65°C for water cut >5% based on a 20 year service life to API 17B 2nd Edtn. All failures were due to operating conditions out with design limits.

2. PVDF pull-out from the end-fitting crimping arrangement caused several failures worldwide from 1992-1996. PVDF is used for high temperature applications (up to 130°C for water cut 0–100%) and has a high thermal expansion coefficient. Therefore, expansion and contraction of the sheath, due to temperature cycling, resulted in gradual pull-out and leakage. Note that the crimping arrangement has since been re-designed and no failures have occurred to date. The potential for another failure mode to occur is not discounted.

3. Venting valves on the end-fitting are designed to allow diffused gas in the annulus to escape without overpressuring the external sheath. In the case of the 3 smooth-bore pipe failures noted above, pressure build-up in the annulus resulted in collapse of the internal pressure sheath and leakage. This is also the case for the collapse in the J-Tube. However, the possibility of external sheath failure may drive another failure mode, such as corrosion-fatigue of the armour wires.

4. Failure caused by a leak path within the end-fitting.

5. Recent carcass collapse in 2001 of a high pressure gas riser during depressurisation. Designed involved a multi-layer PVDF internal pressure sheath. Investigation into these failures is still ongoing.

Table 4.2 UK & Norwegian Sector Riser Installation & Commissioning Failure / Damage Incidents.

<table>
<thead>
<tr>
<th>Failure / Damage Incident</th>
<th>No. of Occurrences</th>
<th>Loss of Containment</th>
</tr>
</thead>
<tbody>
<tr>
<td>External Sheath Damage</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Overbending</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Vent plug missing</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Overtwisting</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>Flooded Annulus</td>
<td>5</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 4.3   UK & Norwegian Sector Flowline Failure / Damage Incidents

<table>
<thead>
<tr>
<th>Failure / Damage Incident</th>
<th>No. of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradation of PA-11 Internal Pressure Sheath</td>
<td>6</td>
</tr>
<tr>
<td>Crack propagation through Internal Pressure Sheath</td>
<td></td>
</tr>
<tr>
<td>PA-11</td>
<td>1</td>
</tr>
<tr>
<td>PVDF</td>
<td>3</td>
</tr>
<tr>
<td>PE</td>
<td>1</td>
</tr>
<tr>
<td>Overbend (Installation)</td>
<td>1</td>
</tr>
<tr>
<td>Overbend/vibration</td>
<td>1</td>
</tr>
<tr>
<td>External Sheath Damage (Installation events)</td>
<td>6</td>
</tr>
<tr>
<td>Ovalisation (accident event)</td>
<td>1</td>
</tr>
<tr>
<td>Upheaval buckling</td>
<td>1</td>
</tr>
<tr>
<td>End-fitting leak</td>
<td>3</td>
</tr>
<tr>
<td>Annulus flooding</td>
<td>7</td>
</tr>
<tr>
<td>Birdcaging</td>
<td>1</td>
</tr>
<tr>
<td>Pressure Sheath brittle fracture during offshore hydrotest</td>
<td>1</td>
</tr>
<tr>
<td>Pressure Sheath failure due to extrusion fault</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4.4   UK & Norwegian Sector Jumper Failure / Damage Incidents

<table>
<thead>
<tr>
<th>Failure / Damage Incident</th>
<th>No. of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Degradation of PA-11 Internal Pressure Sheath</td>
<td>1</td>
</tr>
<tr>
<td>Pull-out of PVDF Internal Pressure Sheath from end-fitting</td>
<td>1</td>
</tr>
<tr>
<td>Overbend (Installation)</td>
<td>2</td>
</tr>
<tr>
<td>Excessive torsion (installation)</td>
<td>1</td>
</tr>
<tr>
<td>End-fitting leak</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.5   UK & Norwegian Sector Drag Chain Jumper Failure / Damage Incidents

<table>
<thead>
<tr>
<th>Failure / Damage Incident</th>
<th>No. of Occurrences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Armour wire dis-organisation</td>
<td>3</td>
</tr>
<tr>
<td>3-layer PVDF pull-out of internal sheath from end-fitting</td>
<td>1</td>
</tr>
<tr>
<td>Overbend (Installation)</td>
<td>1</td>
</tr>
<tr>
<td>MDPE internal sheath collapse</td>
<td>2</td>
</tr>
<tr>
<td>3-layer PVDF internal sheath fatigue cracking</td>
<td>1</td>
</tr>
<tr>
<td>PVDF internal sheath creep and cracking within end-fitting</td>
<td>1</td>
</tr>
</tbody>
</table>
5 SOURCES OF POTENTIAL FLEXIBLE PIPE DAMAGE & FAILURE

This section presents the potential sources of damage and failure that could occur in a flexible pipe system. The section presents degradation drivers that evolve with time until failure occurs. In addition, single events generally associated with abnormal events are also considered.

Each damage or failure mode is listed below with its recommended monitoring technique(s) in underlined italics. Reference should be made to Section 6 for a detailed description of each monitoring technique and its limitations.

The purpose of the monitoring technique is to obtain sufficient information on the amount of damage or degradation to the pipe and implement remedial action to avoid failure. The time period between inspection and the specific degradation mode then influences the integrity management strategy of the flexible pipe system and possible re-evaluation within the risk assessment.

5.1 FLEXIBLE PIPE DEGRADATION AND FAILURE DRIVERS

The degradation mode and failure driver approach identifies those operating conditions that provide a significant degradation mechanism for a flexible pipe. The most significant factors being:

- Temperature.
- Pressure
- Production fluid composition.
- Fatigue (pressure related) and collapse (multi-layer pressure sheath)

The scale of the failure can vary from a small leak to full bore failure (e.g. end connection failure) depending on the nature of the degradation mechanism within the flexible pipe system. In the event of pipe failure, the above operational parameters will form the key input into the subsequent failure investigation.

5.1.1 Temperature

A significant degradation driver for flexible pipe is the time that the flexible pipe operates at “high” temperature. The acceptable temperature range is relatively low for a flexible pipe compared with steel pipe. It is also important to consider locations where the flexible pipe is
externally insulated from the local environment since this can increase the polymer temperature, for example, end fittings, those areas under fire or thermal insulation, or within a conductor or bend stiffener.

Sections 5.1.1.1 to 5.1.1.3 below discuss the various available polymer materials typically used for the internal pressure sheath of a flexible pipe.

5.1.1.1 Polyamide 11 (PA-11)

The majority (circa. 60%) of dynamic flexible risers employed in the UK sector have a PA-11 internal pressure sheath. It is also considered the main polymer sheath within the Norwegian sector. This polymer is subject to hydrolysis at elevated temperatures and has been the cause of several failures, although not catastrophic in nature.

This polymer is sensitive to both a free water phase and a dissolved water phase if greater than 80% saturation in a liquid/gas stream for prolonged periods at high temperature. In addition, water content with a low pH level increases the rate of ageing as does the use of acids and chemical treatment which can adversely affect this polymer. However, this is dependant on the concentration and period of treatment. The effects of various fluids and gases on PA-11 has formed the basis of recent work performed by the API Technical Group on “The ageing of PA-11 in flexible pipe” [6].

5.1.1.2 Polyvinylidenedi Fluoride (PVDF)

PVDF is widely used (circa. 35%) as an internal pressure sheath for risers within the UK sector. The polymer is not sensitive to water cut and offers good resistance to most oilfield chemicals at elevated temperature. PVDF has a higher thermal expansion coefficient than PA-11, and hence is more susceptible to notch / crack propagation as a result of thermal cycling stresses. For dynamic applications, API 17J specifies a maximum allowable strain of 3.5% for PVDF.

PVDF is available in either plasticised or unplasticised form, as described below. Note that API 17J does not distinguish between the two products.

Plasticiser is often added to the PVDF to aid the polymer extrusion process during manufacture. However, during operation the plasticiser molecules tend to ‘leech’ out of the polymer, causing embrittlement. Although hydrocarbon molecules may replace some of the lost plasticiser, eventually the material degrades over time, increasing susceptibility to crack propagation due to thermal cycling stresses.
Unplasticised PVDF is generally accepted to be a more stable polymer, since there is no plasticiser present that can leech out over time. However, unplasticised PVDF has a higher elastic modulus than the plasticised form, reducing the yield and ultimate strain and increasing the yield stress.

Note that for all polymers, the allowable strain should be based on one third of true yield of the material in its equilibrated and aged state.

5.1.1.3 High Density Polyethylene (HDPE) & Cross Linked Polyethylene (XLPE)

Temperature is important for High Density Polyethylene (HDPE) in combination with high pressures due to the possibility of rapid depressurisation and blistering when in the presence of hydrocarbon gases. The use of cross-linked polyethylene (XLPE) is similar to HDPE with an improved temperature range and improved blistering resistance when compared to HDPE.

HDPE is not widely employed as a pressure sheath with hydrocarbon products. Its use is normally associated with water injection pipe and low pressure/temperature production fluid. The polymer is sensitive to oxidation and may exhibit environmental stress cracking based on the polymer strain and temperature. HDPE has good resistance to acids (depending on concentration) and water.

XLPE is HDPE after crosslinking. The polymer is employed for higher temperature service and has a similar mechanical behaviour to HDPE. The polymer is used as an alternative to PA-11 in high water cut service.

Guideline on Inspection/Monitoring:

- Bore temperature at hottest location should be continuously monitored, logged and assessed, or an extrapolation technique employed. Temperature should be monitored across the system to achieve an effective management strategy.
- Number and range of thermal cycles should be monitored for a PVDF pipe.
- The degradation of PA-11 should be assessed if operated above 40°C.
- PA-11 coupon sampling should be performed for all new flexible pipe developments if temperatures are expected to exceed 60°C during the operational life. By periodically sampling coupon samples, the degradation over time can be monitored and thus prevent leakage through the polymer.
5.1.2 Pressure

The greater the nominal operating pressure of the system, the greater the potential degradation damage from fatigue or from depressurisation. Overload from greater utilisation of the armour wires is unlikely unless gross local wastage of the wires is experienced.

Static flexible pipe

A static pipe can accommodate greater corrosion damage to the carbon steel armour layers and degradation from polymer ageing compared to a dynamic pipe.

Dynamic flexible pipe

Pressure increases the damaging effects from wear and corrosion-fatigue in an aggressive annulus environment for dynamic pipes. This aggressive annulus environment may be oxygenated or de-oxygenated seawater with permeated gases/fluid migrating from the bore.

The fatigue service life of the armour wires is proportional to the operating bore pressure (inverse power law). This and the nature of the annulus environment at the most dynamic location is an important consideration in assessing the most critical risers in an inspection monitoring strategy. Refer to “Fatigue” as a degradation mechanism and failure driver. Operating internal pressure drives fatigue by inducing high contact pressures between the various layers of the flexible pipe structure, causing significant increases in wire stress. A full description of the fatigue mechanism for a flexible pipe is presented in [8].

Guideline on Inspection/Monitoring:

- Monitor and log the pressure range and frequency based on ½ hour sampling initially to confirm stability of the operational system. This can then be relaxed to assess the nominal pressure readings based on a risk assessment. A daily basis is recommended if no operator guidance is provided based on a risk assessment.

- Monitor the number and duration of shut-ins and the shut-down rates. This can adversely affect the fatigue life of the riser system.

5.1.3 Production Fluid

Both the acidic nature and the saturated water content of the bore fluid has a detrimental influence on both the degradation of the carbon steel armour wires in a flooded annulus and the ageing of the PA-11 pressure sheath.
PA-11

A low pH is detrimental to PA-11 (pH < 5.5). Reference should be made to the API Technical Group’s work on PA-11 [6].

CO₂, H₂S & O₂ levels

Both dynamic risers and static flowlines may be subjected to a wet aggressive annulus environment. The static pipe is subject to potential carbon steel wire corrosion and the PA-11 polymer to ageing in an acid solution. However, the dynamic pipe is also subject to a significant reduction in fatigue life of the carbon steel armour wires from the corrosive environment generated by CO₂ or H₂S gases in an aqueous solution.

This typical adverse effect on fatigue life for a dynamic pipe is illustrated in Figure 5.1 below. This shows that an annulus partial pressure of 10mbar CO₂ has a recognised adverse effect on the armour wires that increases in severity with an increase in partial pressure. Note that partial pressures are typically higher for static flowlines than for risers, as the riser annulus can be vented at the topsides.

Figure 5.1: Illustration of aggressive nature of annulus environment on fatigue.

![Stress range vs No. of Cycles](image)

The potential to draw oxygen into the annulus space, in small quantities, requires consideration because of its detrimental effect on corrosion rates. This is generally associated with riser shutdowns and may have implications for armour wires near the top of the riser in the turret (a largely static area). The possibility of oxygen in the upper riser annulus space should be considered as a possibility for a prolonged shutdown period. This assumes that the riser has an open venting system (no check valves).
Guideline on Inspection/Monitoring:

- Monitor production bore fluids and their molar percentage of aggressive gases. Obtain analytical models that predict the annulus environment.
- Assess check valve settings to avoid high levels of CO$_2$ and H$_2$S partial pressure in the annulus for risers.
- Assess fatigue damage from small scale testing and calculate the service life of the risers for inclusion in the risk assessment with appropriate factors of safety. The use of annulus treatment may be a consideration depending on risk assessment results.

5.1.4 Fatigue

Fatigue is a degradation issue for dynamic pipe and especially risers. The sensitive locations on the risers correspond to: the bend stiffener or bellmouth region, the touch down location, the mid-water arch, the sagbend and possibly the hog region, depending on water depth and system design. The fatigue life of the riser is significantly reduced when the annulus space has a wet aggressive environment. This wet environment can occur from outer sheath damage, flooding via end connections, flooding from venting system, or potentially condensed water vapour permeation from the bore (depending on operating conditions and amount of water vapour exiting the vent system). This reduces the fatigue life of risers as a result of the corrosion-fatigue mechanism that may act on the unprotected carbon steel armour wire. The operation of the riser at high pressure, when subject to high partial pressures of CO$_2$ and H$_2$S and higher mean stress in the wire accelerates this particular degradation mechanism for carbon steel armour wires.

The fatigue resistance of the PA-11 internal sheath polymer also reduces as it degrades under the effect of high temperature and water cut. Similarly, PVDF is susceptible to notch propagation under the influence of surface imperfections combined with a high number of repeat bending cycles.

Guideline on Inspection/Monitoring:

- Monitor the pipe bore fluids/pressure/annulus volume.
- It is also desirable to record environmental loading in terms of Hs and Tz.
- Future flexible pipe technology currently under development includes the use of fibre optic sensors incorporated into the armour wire. The objective of these sensors is to monitor operational strains to determine remnant fatigue life.
5.1.5 Corrosion

In general, corrosion alone is not usually a significant degradation mechanism for flexible pipe. The corrosion rate of a flexible pipe carcass or armour wire is governed by the local environment and is governed by material selection and the materials compatibility with the bore fluids.

The reliance on the cathodic protection from end fitting anodes should be carefully assessed based on the anticipated corrosion mechanism against the manufacturers original design assumptions and verification programme. The ability of the end fitting anodes to protect the armour wires in a flooded annulus should be verified.

Guideline on Inspection/Monitoring.
- GVI to monitor any gross breach of the pipe and check for annulus venting in the subsea ports.
- CP surveys of damaged risers.

5.1.6 Erosion

The erosion of the internal carcass is a concern at pipe bends, as the smaller the bending radius the greater the potential erosion level. This potential erosion level is a direct function of the fluid velocity, sand content and whether the fluid is a gas, or liquid. A dry gas exhibits greater erosion rates than a liquid. The quantity of sand produced is the primary concern for erosion. Local loss of the carcass material is considered to be the failure point for the flexible pipe. The limiting bend radius for the polymer from API 17J generally sets the minimum bend radius possible in the flexible pipe and therefore the point of greatest erosion.

Guideline on Monitoring measures:
- Monitor sand production rates and bore fluid/gas velocities and compare with original limits from the design premise.

5.1.7 Scale / Wax formation

The formation of scale within the flexible pipe may create a blockage and affect the pipe flexibility characteristics, mass and its ultimate burst condition. In addition, scale may have a beneficial effect by acting as an insulator for the polymer pressure sheath and reduce the rate of ageing of the polymer.

Guideline on Monitoring measures:
- Monitor topsides for scale formation and apply scale inhibitors (check for polymer compatibility).
Monitor topsides for wax formation and apply inhibitors accordingly. Hot oil flushing can also be used to prevent waxing issues. Again, the effect on the polymer needs to be evaluated.

5.1.8 Flow induced vibrations

A relatively recent concern relating to high-pressure gas service flexible pipe application is that of high frequency flow induced vibrations. In a number of cases, these vibrations have resulted in audible high frequency noise at the FPSO topsides, and have been termed ‘singing risers’ by the industry.

The likely cause of the vibrations is due to flow over the ridges in the internal carcass, which generates vortices. It is plausible that for a particular pipe diameter, the frequencies at which vortices are shed is flowrate dependent. At certain flowrates, the shedding frequency approaches natural frequencies of the pipe structure and a form of resonance arises.

Operators have experienced this phenomenon in a number of dynamic risers, and concluded that the effect is solely dependent on the flowrate. Although no failures of dynamic risers have occurred as a result of these vibrations, this issue represents a concern that is presently a focus for the industry.

Guideline on Monitoring measures:

- Monitor topsides flowrates and determine the range of flowrates, which induce high frequency vibrations. If feasible, operate the riser at flowrates outwith this range.

5.2 Service Loads

Overbending of the pipe can occur during installation or operation from poor installation procedures and controls, or it can occur operationally from ancillary equipment failure. In addition, inaccuracy in the design assessment during extreme loading events may not detect the potential for overbending to occur. Overbending of the pipe can also develop from pressure fluctuations in a trench flowline resulting in upheaval buckling. The significance of such events relates to their ability to unlock the pressure armour wires, or generate sufficient wire gaps to permit polymer extrusion and failure of the pressure sheath. This situation may arise after overbending has occurred.

Allowable pipe crushing loads should also be determined. This is usually an important consideration for riser installation.

Monitoring Measures:
- Hydrotating (more representative for a static pipe to check that the pressure armour layer has not unlocked).
- Installation procedures to reduce the potential for overbending.
- GVI and/or sonar to establish revised configuration.
- Option of radiography in topside applications (e.g. dragchain application) to monitor wire gap size.

5.3 **ANCILLARY EQUIPMENT**

The ancillary equipment used with flexible pipe is an integral part of the integrity of the system and warrants attention as part of the integrity management strategy.

5.3.1 **Buoyancy Elements**

The loss or slippage of a buoyancy element is more likely to occur during installation than in operation from insufficient clamping of the buoyancy elements to the pipe. However, loss of buoyancy elements in service may also occur and the robustness of the riser system configuration design dictates the significance of such an event. In general, the configuration designer should perform analysis sensitivities to determine the effect of losing a single buoyancy module.

*Guideline on Inspection/Monitoring:*

- General/Close Visual Inspection (GVI/CVI).

5.3.2 **Bend Stiffener to Turret/Deck Interface**

The bend stiffener interface with the floater or fixed structure is a critical area of the flexible pipe and is worthy of detailed examination as part of an integrity management strategy. Generally, the bend stiffener is in a location that is difficult to access and to perform a detailed inspection. Hence, the basic level of inspection of the bend stiffener and the turret/deck interface assembly is limited.

The cathodic protection (CP) of the bend stiffener and turret/deck connecting structure requires monitoring. A low level of protection causes concerns associated with corrosion and fatigue. An overly high level of cathodic protection may cause concerns with hydrogen embrittlement.

For field developments with high fatigue or extreme seatstates, a series of dynamic load tests for the riser and bend stiffener is normally required to demonstrate fitness-for-purpose of the design.
Guideline on Inspection/Monitoring:
- GVI/CVI and CP monitoring

5.3.3 Riser Base

The riser base restrains the flexible riser in certain riser configurations and requires monitoring for indications of base overturning, bearing loads, etc. from previous storm events. The riser base loads may be sensitive to the offset location and the as-installed geometric location should be checked against the design installation tolerances.

Access to inspect the sub-sea base for load/fatigue sensitive locations should be addressed. Alternatively, a case for building redundancy into the design should be considered.

Guideline on Inspection/Monitoring:
- GVI/CVI and CP

5.3.4 Tether Base/Connections

The tether connections restraining the riser in various configurations should be assessed for redundancy, or possess sufficient design robustness to minimise the potential for failure.

Guideline on Inspection/Monitoring:
- GVI/CVI and CP

5.3.5 Mid-Water Arch (MWA)

The MWA is a critical component for riser configurations. The corrosion/fatigue/extreme event assessment is a primary failure driver within this assembly and to any component in the critical load path.

Guideline on Inspection/Monitoring:
- GVI/CVI and CP

5.4 ACCIDENTAL (INCLUDES INSTALLATION, COMMISSIONING AND OPERATION)

Accident events from dropped objects, trawl boards, subsea collision, anchor dragging, clump weight descents, etc. can produce varying levels of damage to a flexible pipe depending on the severity of the impact and the level of protection offered to the pipe.

Installation/commissioning is included within this section due to the large number of damage or failures that have occurred during this stage of the pipe life cycle.
It is recommended that operational procedures and/or protective measures, such as external protection at critical locations, be in place to minimise the possibility and consequence of an accidental event during installation, commissioning or operation. However, monitoring methods can assist in the early detection of potential damage in dynamic pipe. This may range from gross damage detection, or near miss information established from General Visual Inspection (GVI), or annulus monitoring to indicate potential flooding.

The presence of impact damage in the form of a gouge, or notch type defect in the polymer material is a weakness in the design of a flexible pipe and bend stiffener. This requires careful assessment beyond the immediate consequences of such a defect. This form of damage generally represents a site of potential crack growth.

The fire resistance of flexible pipe shall be in accordance with specified requirements. The design of a flexible pipe for fire resistance is contained within API 17J and should be referenced to obtain a recognised test procedure. Loss of pressure integrity would be rapid if an unprotected flexible pipe is exposed to a jet or pool fire depending on the fire intensity. This is based on the time to degrade the inner pressure sheath polymer with subsequent loss of the pipe’s pressure integrity. The melting point for PA-11 is approximately +180°C and +120°C for HDPE. This indicates the general susceptibility of flexible pipe to fire damage.

**Guideline on Inspection/Monitoring:**

- GVI
- Management procedures limiting known dropped object hazards.
- Consideration of fire protection based on a risk assessment.

5.5 **Manufacturing Defects**

Manufacturing defects within this section addresses only those known defects that can contribute to a failure within the pipe system. This does not address defects from accidents or design omissions.
Ancillary equipment

Poor welding and poor weld features on ancillary equipment may shorten the field life of subsea equipment. The ancillary equipment should be fabricated to a recognised standard and a suitable inspection performed in areas vulnerable to fatigue damage. The use of local weld grinding to a recognised standard should be considered to improve fatigue life during the fabrication phase.

Any paint coating protection system or cathodic protection system should be designed to a recognised standard or guideline (DNV RPB401). Particular attention should be given to the ballast coating protection, if any, to avoid accelerated wastage of the anodes.

The use of high strength bolts or studs may be susceptible to hydrogen embrittlement in a cathodically protected system. The studs employed in critical components should be screened for CP compatibility prior to use.

Improper stud tensioning of critical flanged connections associated with the bend stiffener to turret assembly may result in greater fatigue loads onto the connections. On this basis manual torquing is not preferred for critical components. The design of such equipment should cater for tension tooling equipment.

The improper tensioning of the buoyancy elements on the pipe may result in slippage during the installation phase and should be monitored and recorded.

Bend stiffener

The bend stiffener is susceptible to manufacturing defects in the polyurethane and the metallic insert. Particular attention should be made to those fatigue sensitive areas of the bend stiffener and the application of protective coatings.

It is recommended that highly stressed welds within the bend stiffener fabrication be protected from seawater exposure to avoid potential corrosion fatigue issues. The ability of the coating system to protect the fabricated assembly should be verified.

The bonding of the polyurethane to the metallic insert is important and forms an integral phase of the bend stiffener assembly. The metallic bonding surface should be inspected within the manufacturer’s quality plan to ensure a sufficient bond surface is achieved. The improper bonding of the metallic parts to the polymer may result in premature failure of the bend stiffener.

A cut or tear in the polyurethane bend stiffener, especially at the tip, would be cause to reject the bend stiffener. The repair of such defects by local grinding should be assessed based on the location of damage, since it represents a location of a stress raiser and a site of weakness.
Flexible pipe

Wire defects from weld repairs, or the cold forming process can introduce susceptible areas into the pipe construction, especially at dynamic locations. It is important to ensure tensile armour wire repairs are staggered along the pipe length and the weld procedures are compatible with the fluid environment.

Pressure sheath defects can occur from the extrusion process and variations in the wall thickness or surface imperfections.

The end fitting is a critical stage in the build of a flexible pipe and should be witnessed by interested parties within the manufacturers quality plan. The tolerances applied to the end-fitting components used should be documented in the as-built records.

The QC provided by the manufacturer should record the location of welds within the pipe. Welding of tensile wires should be assessed and located away from a future dynamic location on the riser.

The potential for thickness fluctuations, surface imperfections and poor surface finish in the polymer from the manufacturing process should be monitored and supplied within the manufacturer’s dossier. This has implications on the polymer properties from the extrusion process. There is the possibility that the polymer may enter the pipe as a slug of degraded material and may exist as a discontinuity and locally raise the stress in the sheath when in dynamic service.

Guideline on Inspection/Monitoring

- Ensure that a detailed manufacturing specification is with the supplier prior to manufacturing, and is enforced by a competent third party.

- Access to manufacturing non-conformances should be according to an agreed quality plan, and be witnessed or assessed by the customer and a competent third party in the design and manufacture stage of a flexible pipe.

- The thickness fluctuations within the polymer should be locally assessed to determine the possibility of a stress discontinuity effect within the polymer. This is a particular issue in dynamic applications. A limiting notch radius should be applied to the internal and external surfaces of the pressure sheath.

- Perform detailed assessment of the manufacturers QA/QC to ensure that critical defects are found.
6 GUIDANCE ON INSPECTION & MONITORING TECHNIQUES

6.1 GENERAL

This section presents the experience gained within the UK and Norwegian sectors of the inspection and monitoring techniques listed below.

It is important to recognise that no single inspection technique will ensure the integrity of a flexible pipe system. A raft of monitoring measures and inspection techniques is required to demonstrate integrity and ensure that the system risk is ALARP.

The most widely used inspection and monitoring technique involves General Visual Inspection (GVI). This is supported by Close Visual Inspection (CVI) and Cathodic Potential measurements within the typical inspection programme. The use of annulus monitoring techniques is a developing area that is gaining wider acceptance within the Norwegian and UK sectors.

6.2 VISUAL INSPECTION

6.2.1 General or Close Visual Inspection (GVI/CVI)

Procedure

Flexible pipe and its ancillary equipment requires inspection by diver or ROV. The subsea operation is weather limited to the ROV diver capability in terms of wave height, current and visibility. Inspection of ancillary equipment generally considers visual assessment for gross damage.

Industry Practice

This inspection approach is widely adopted within the UK sector. The visual examination considers the general layout and configuration monitoring of the riser, jumpers, flowline, etc. The frequency is based on a risk assessment and is generally annual.

As part of the General Visual Inspection (GVI) technique, a benchmark survey is usually undertaken of the general layout and configuration after installation and commissioning. The GVI programme determines the location of riser bases, mid-water arch, tether locations, manifolds, drill centres, etc. In-service monitoring also considers the extent of soft or hard marine growth and the need for riser cleaning. However, the riser cleaning operation is not widely performed. Close Visual Inspection usually identifies specific tasks within the GVI
programme. CVI involves undertaking cathodic potential measurements to determine the rate of anode wastage and indications of venting from end fittings, primarily on gas service pipes.

Guideline Note

GVI or CVI is recommended after installation and commissioning to detect damage and gross deviations from the design basis. In addition, CVI is recommended to monitor the effectiveness of the riser and ancillary equipment(s) cathodic protection (CP) system.

The GVI interval should be established from the risk assessment, unless specific knowledge indicates otherwise to warrant a shorter inspection period. The frequency of GVI is determined based on the operational severity of the system and the time in-service.

The GVI technique is opportunistic in nature and limited to detection of gross damage and oil or gas seepage. It is unlikely that GVI will detect a small outer sheath defect and potential annulus flooding, especially on a system with light to heavy marine growth or when subject to vessel heave motion.

The GVI of the bend stiffener and buoyancy locations is generally limited due to poor access within the majority of dynamic riser systems. GVI may directly detect damage to the bend stiffener body or the loss of studs, or indirectly from uncharacteristic motions of the riser with close ROV or diver inspection. However, any damage would have to be significant to detect gross uncharacteristic motions in the low sea states associated with diver or ROV operation. The turret I-tube section is not generally accessible and the condition of the turret connector may be an area of uncertainty. Again, this is dependent on the accessibility of the diver or ROV survey.

The use of supplementary techniques in support of GVI is possible to assess the integrity of critical steel structural components with respect to surface cracking, if access permits. Alternating Current Field Measurement (ACFM) is a potential tool with a subsea capability.

6.2.2 Internal Visual Inspection

Procedure

This technique involves the use of an internal inspection camera and crawler device to gain access to a greater length of pipe. The procedure requires an inspection opening in addition to flushing and cleaning treatments that can result in a disruption to operations.
Industry Practice

The internal inspection technique is not widely adopted within the UK sector as part of an integrity monitoring strategy. Its use is limited to the upper section of risers to assess the PVDF pressure sheath bond to the end fitting. A possible explanation for this low usage is the difficulty in accessing the flexible pipe topsides and the incorrect perception of limited coverage to straight lengths of flexible pipe with the carrier tool. This perceived limitation is considered too restrictive in gaining only a limited amount of information. The internal inspection to date involves the use of CCTV and requires pipe access.

This technique has been used successfully to detect collapse of the internal pressure sheath and/or internal carcass.

Guideline Note

This option is available in the event of potential damage to the pipe, or suspected leakage from the end fitting pressure sheath. However, the technique is not part of a routine inspection programme. The inspection requires access to piping and the use of crawler devices, which could be developed for greater coverage beyond straight lengths.

6.3 PRESSURE, TEMPERATURE & BORE FLUID TESTING/MONITORING

6.3.1 Pressure Testing (Hydro testing)

Procedure

Offshore pressure testing is performed to demonstrate the leak integrity of the flexible pipe in compliance with industry standards and specifications (BS8010, API17J). A leak test is normally performed at 110% of the Maximum Allowable Operating Pressure (MAOP) of the system. An easily visible, non-toxic dye is usually employed during the test for leak detection. However, there is a possibility that small leaks can be missed by the ROV or a diver.

Industry Practice

This technique is applied to all systems to demonstrate leak integrity after installation and commissioning. The previous regulatory requirement to perform testing on a six yearly basis is no longer applicable and a risk approach is now widely adopted by the industry.
Guideline Note

Flexible pipe leak testing is a mandatory requirement during installation and commissioning. The requirement for future leak testing depends on the service conditions and the ability of a test to detect inherent weakness in the flexible pipe.

The hydrotest should be applied on-shore to demonstrate suitability for re-use. The test pressure should reflect the original FAT criteria with a pressure of 150% of the “new” system’s maximum allowable operating pressure and held for 24 hours. This forms a basic test on-shore to measure the pipe integrity and should be considered as part of a pipe re-evaluation test programme. On-shore testing of retrieved pipe should consider the safety issue associated with annulus gases diffusing from the retrieved pipe. This may take several days or weeks to de-gas.

The benefit of in-situ pressure testing of a dynamic riser is limited in proving its integrity. Such a “static” test would impose a sea state restriction on the test, which may then only register failure with gross wire disorganisation, corrosion, polymer embrittlement and may fail to detect any weakness in the pipe associated with dynamic loading.

Hydrotesting of a static flowline is more appropriate in determining the general condition of the pipe because it applies loads in the principle directions of the in-service loads. The nature of the static test is better reflected in the static operating condition of the pipe. In this instance the hydrostatic test then provides a measure of confidence that the flexible has an operating life beyond the test period assuming a reduced operating pressure from that of the test.

In choosing the hydrostatic test fluid, the potential to fail the test and lose pressure integrity should be recognised. Therefore the use of well bore fluids is not recommended.

The use of Nitrogen gas is recommended for high temperature gas risers employing PA-11, if viable, to avoid the need to dry the riser as would be the case with a more conventional hydrotest. Of course, consideration must be given to safety and also to acceptance criteria before recommending the use of Nitrogen.

6.3.2 Internal Pressure

Procedure

Monitoring of bore pressure occurs in the topside facilities, or infrequently from well tests.
Industry Practice

Bore pressure is monitored and is generally recorded on an excursion basis. The pressure trip setting is set against the system MAOP. This approach is limited and does not necessarily indicate the “nominal” pressure of the pipe, which is useful information for future life assessment calculations. The increased operating pressure is an important parameter in the measurement of potential PA-11 degradation and in wire fatigue damage for a flooded riser. The present industry practice records the data topsides for each riser, or group of risers, but the data is not fed back into the integrity management strategy for the flexible pipe system.

Guideline Note

Bore pressure is a basic monitoring requirement. Data should reflect each individual pipe, if possible. If pressure is monitored from the separator vessel and no direct pipe pressure monitoring is performed, then a basic assessment should be made on wellhead pressure to obtain some form of correlation for each flowline or riser. It is recommended that continuous monitoring of the pressure should be performed topsides to provide detail on the “normal” operating conditions. Any aberrations outside a stated limit should be recorded at suitable intervals (daily is recommended if no pressure pulsation effect occurs and no alternative guidance is available based on a risk study).

6.3.3 Internal Temperature

Procedure

Temperature monitoring is performed to varying degrees; the quality of the data is dependent on the source of the temperature sampling points. The majority of the monitoring performed is from topside equipment. In this event a correlation has to be established linking the topside measurements to subsea conditions for the flexible pipe or wellhead temperatures. This is difficult to perform for wellhead jumpers due to the co-mingling of fluids from several wells into a common manifold. The use of more infrequent down hole tubing temperature measurement could be used as a conservative temperature measure for the wellhead jumpers.

Industry Practice

Temperature monitoring is predominately performed from the topside process pipework and is based on an excursion limit. The temperature data is not regularly recorded or logged for each riser. Wellhead temperature is infrequently monitored and is not widely employed to assess subsea flowlines.
Guideline Note

The bore temperature is a basic monitoring requirement. Monitoring of this temperature should be continuous and recorded on a suitable basis. Daily temperature monitoring is recommended if no other guidance is available from a risk study. The temperature logging should record both magnitude and range.

The magnitude of the bore temperature is important to establish the degree of ageing for PA-11. The temperature cycle range is important for establishing damage to the PVDF pressure sheaths. The most appropriate data should come from the hottest location of the flexible pipe system, if possible. This invariably requires a temperature monitoring facility nearest the wellhead for the production riser, or subsea flowline system. A gas injection system would require sampling topsides. Extrapolation of monitoring data from locations remote from the high temperature source requires a degree of caution, and a tolerance should be applied to the predictions to gauge the sensitivity in the polymer degradation result. This extrapolation of data can be affected by different flow conditions, or co-mingling of produced fluids in a subsea manifold.

The use of a temperature monitoring system should attempt to incorporate polymer coupons in the bore fluid from the manufacturing batch at installation to provide a thumb-print of the flexible pipe integrity. This requires future access for retrieval after a suitable period of operation for coupon analysis.

The number of coupons used plays an important part in the future sampling requirements. Refer to test coupon sampling within Section 6.4.1.

The potential for ancillary equipment or the local environment to increase the polymer temperature requires consideration. This may represent locations with stagnant flow conditions above the water line. This may involve end fittings, pipe in caissons, pipe in turret I-tubes, bend stiffeners and pipe with fire insulation, etc.

6.3.4 Bore Fluid Characteristics

Procedure

All operators monitor the bore fluid characteristics. However, the frequency and use of this data varies considerably across the industry and not all monitoring is related to the integrity of the flexible pipe.
Industry Practice

Bore fluid monitoring is largely performed from the topside separators. This provides an averaging of the riser fluid characteristics and represents a smeared data set, especially for the aggressive gases in the production fluid.

Guideline Note

Water cut monitoring is required. The water chemistry should also be assessed.

*Bore fluid pH* monitoring assesses the acidic nature of bore fluids, since this is a known degradation driver for PA-11. This is not generally performed and would require sampling from the separator. As an alternative, the pH may be calculated based on water chemistry and contributing detrimental factors, e.g., CO$_2$ and H$_2$S. This suffers from the averaging effect of multiple risers running into a single source. However, it is indicative in developing a general trend, which is more easily monitored. The use of a wellhead test is opportunistic in nature and provides more accurate measurements of specific increases in CO$_2$ levels. This may assist in predicting local flowline or riser degradation for use in pH calculations on the associated pipe system.

*TAN (Total Acid Number)* requires monitoring for the organic acids in the bore fluids due to its potential adverse effect on a PA-11 pressure sheath.

*Treatment Chemicals* with concentration and duration of treatment require monitoring and approval from the manufacturers for polymer compatibility. Refer to API technical group DRAFT guidance on PA-11 [6].

*Bore gases* require monitoring for H$_2$S, CO$_2$ and CH$_4$ levels. However, this is not generally performed. If separator gas sampling is performed then a correlation or trend should be established linking the sampled results to each riser. The separator gas characteristics should be recorded for use in the gas injection or gas export pipe risk assessment.

*Sand production* requires monitoring from wellhead tests, or topsides information. The amount of sand produced in the system is important due to its erosion characteristics.

*Slugging*. The degree of slugging should be monitored due to its effect on the potential fatigue life of the risers or jumpers.
6.4 **IN-LINE COUPON MONITORING & DI-ELECTRIC SENSING (FDEMS)**

6.4.1 **In-Line Coupons**

**Procedure**

This method involves periodic removal and sampling of test material coupons that have been placed in the product stream to assess the state of polymer degradation. The samples are commonly placed in a rack system either directly or indirectly in the process stream.

**Industry Practice**

The use of polymer coupons is not widely adopted within the UK sector and possibly relates to a lack of topside facilities to cater for their use. This infers some reliance on more indirect measurements of the bore temperature and water cut in the process facilities for PA-11 degradation calculations. In many cases, even these are not always performed, which suggests that some operators consider that their specific pipe operating characteristics are relatively benign in terms of temperature and bore fluids. This assumption has, however, resulted in several PA-11 degradation failures as a result of long-term operation outwith pipe design limits.

Coupon sampling is normally performed at the topside facility using ladder rack holders, and involves destructive testing of the samples. A major disadvantage of topside sampling is that the internal fluid in the pipe is normally much cooler at the topside location than it would be at the subsea wellhead. Hence, the results from any topsides coupon sampling is likely to underestimate the amount of polymer degradation in the flexible pipe. Furthermore, it is not always easy to extrapolate results from topside sampling to predict subsea polymer degradation because of co-mingling of flow at the subsea manifold. These detailed issues should be assessed in performing polymer life calculations.

**Guideline Note**

PA-11 is a sensitive polymer to ageing and should be assessed for degradation. This assessment should reflect the bore fluid composition and temperature profiles based on a basic calculation approach. If the use of in-line coupons is adopted then the frequency of monitoring the coupons needs to be set on a suitable safety factor associated with the uncertainty of the polymer life and the service condition of the flexible based on topside sampling. The testing of the PA-11 coupons should be gauged against the corrected inherent viscosity based on the recent findings of the API working group [6]. The use of alternative pressure sheath materials should be considered in the coupon samples for future integrity monitoring.
6.4.2 On-Line Di-Electric Sensing of Coupons (FDEMS)

Procedure

Frequency Dependent Electro-Magnetic Sensing (FDEMS) involves in-line electrical analysis of material coupons placed in the product stream. The measured electrical response is directly related to the polymer viscosity, which is a measure of the state of polymer degradation. Testing of the polymer samples is non-destructive and may be installed at the surface or subsea.

Industry Practice

This technique is not widely adopted. The technique employs an in-line sensor system for use topside and/or sub-sea and has the potential advantage of placing polymer coupons within the hottest section of a subsea system. This technique addresses some of the concerns associated with topside sampling of coupons. However, the system is still in the development stage and is the subject of a current joint industry project. Very little feedback of the system capability and its reliability exists.

Guideline Note

The system is still in the development stage and awaits assessment. If proven, the system may work well in targeting individual lines for coupon degradation. It can provide for sampling of data at remote subsea locations but requires planning at the conceptual design stage to accommodate the equipment. In addition, the system is sensitive to certain inhibitor injection chemicals, such as methanol, and this can result in spurious life predictions. The data is usually downloaded sub-sea to an ROV based on a suitable sampling interval.

6.5 RISER ANNULUS INTEGRITY MONITORING BY GAS SAMPLING AND ANALYSIS

Procedure

The gas sampling and analysis procedure requires that the vented gas from the riser annulus is analysed via a flowmeter system, and then disposed in the low pressure flare system or a safe area. This procedure measures the polymer gas permeability, the adverse gas constituents (CO$_2$, H$_2$S, water vapour) and hydrogen gas formation from CO$_2$ corrosion. The procedure can also detect breach of the outer or inner polymer sheaths to fluid ingress.

Industry Practice

The use of gas sampling and analysis from the end termination vent is problematic to date and is not widely adopted within the industry. This difficulty arises from the low flow rates actually monitored and the accuracy of the sampled results [approximately 0.1 litres/day}
depending on the riser size and the partial gas pressures]. The use of annulus volume monitoring has been applied as an alternative to flowrate monitoring or gas sampling, due to the low flowrates experienced in operation.

However, it is possible to collect a sample of annulus gas using a Pressure Build-Up Test, as described below. Subsequent analysis of annulus gas is being implemented by some operators to determine the annulus water content or hydrogen concentration. These measurements are then used in conjunction with the calculated annulus flowrate to assess the total amount of corrosion.

The use of annulus volume prediction techniques has not found wide acceptance in monitoring the integrity of the annulus space. However, annulus volume measurement is beneficial in establishing the general condition of the dynamic riser. For most recent procedures, the annulus volume is measured by its ability to hold a pressure or partial vacuum. These techniques are used to identify trends and the possibility of annulus flooding based on a reduction in the annulus volume with time. It is good practice to perform an annulus volume measurement on the flexible pipe once it has been installed and then compare the results of this test with future annulus volume measurements to be performed during the life of the field.

Outline procedures for performing an Annulus Vacuum Test and Pressure Build-Up Test are presented below:

i) Annulus Vacuum Test.

The vacuum test procedure isolates the annulus vent system to draw a partial vacuum in the annulus space. The vacuum in the annulus is then filled with a known quantity of Nitrogen to determine the free or unflooded annulus volume. The vacuum is achieved using a water driven vacuum pump. A pressure gauge is fitted into the isolated section and the Nitrogen bottles should be carefully monitored to ensure over-pressurisation of the annulus is not possible. A relief valve should be considered and set at 1.0~1.5 barg (riser manufacturer should be consulted). The volume of nitrogen used to replace the vacuum is a measure of the free annulus space and the potential level of flooding. This test procedure takes approximately 12 hours to perform. The test layout is illustrated in Figure 6.1.

The outline procedure is described below for information. It is acknowledged that these procedures do merit separate examination and review:

1. Evaluate the risks of performing the Vacuum Test Procedure offshore.
2. Rig up equipment in accordance with Figure 6.1.
3. Review previous annulus results.
4. Record riser bore condition during test. This should involve pressure and temperature and environmental temperature.

5. Raise permit to work in accordance with standard offshore procedures.

6. Pressure test equipment to 110% of the operating pressure and hold for 15 mins.

7. Check the vent ports for flow. Flow greater than 0.5 litres/day should be assessed and test suspended.

8. Verify isolation valve integrity.

9. Isolate vent system and begin to evacuate the annulus while recording the annulus pressure with time.

10. Reduce the annulus pressure to 200mbar and then isolate from the vacuum pump. Allow the annulus pressure to stabilise.

11. Release the vacuum in the annulus using bottled nitrogen, noting the pressures in the nitrogen bottles both before and after testing.

12. Reposition all valves to normal operating condition.

13. Calculate the annulus volume from the amount of nitrogen required to fill the partial vacuum in the annulus.

An illustration of a typical vacuum test plot is shown in Figure 6.2 below:

**Figure 6.2. Illustration of Vacuum Test Result (Courtesy of BP).**
Figure 6.1 Illustration of Vacuum Test Layout (Courtesy of BP)
ii) Annulus Pressure Build Up Test.

The pressure build up test assesses the annulus free volume from the time to build up the annulus pressure to a stated maximum value. A relief valve should be included in the isolated section with a low pressure setting of 2 barg. A flowmeter is necessary to measure the volume of gas vented from the annulus space after the upper pressure level is achieved. The amount of permeated gas is dependent on the operating conditions of the riser and its construction. Records should be retained every 4 hours to obtain a plot of pressure versus volume. However, the test may take several days to perform. On reaching a pressure of 1.5 barg the pressure is released to 0.5 barg and then to 0 barg with the time and volume of gas exhausted monitored. An example result plot for the Pressure Build-Up Test is shown in Table 6.1 below.

The annulus volume can be assessed based on the pressure build up rate and measurements of the pressure and gas volume exhausted. The test procedure takes approximately 4~5 days to perform. The advantage of this prolonged test is the availability of annulus gas for analysis.

The outline procedure for this test is as follows:

1. Perform risk assessment for performing the offshore test procedure.
2. Rig up equipment per Figure 6.3.
3. Review previous annulus results.
4. Record riser bore conditions during the test. This should measure pressure and temperature.
5. Raise permit to work in accordance with standard offshore procedures.
6. Pressure test the equipment to 110% of the operating pressure and hold for 15 mins.
7. Check vent ports for flow. Flow greater than 0.5 litres/day should be assessed and test suspended.
8. Verify isolation integrity.
9. Isolate the vent system and permit pressure build up.
10. A flowmeter should be positioned to measure the volume build up gas while it is exhausted. Continuity of vent ports and the annulus should be checked from the FAT.
11. Monitor and record pressure every 4 hours until the reading approaches 1.5 barg, typically several days.
12. Take gas sample if required, then release pressure slowly, recording time taken for pressure to drop to 1.0 barg, 0.5 barg and ambient. The volumes of gas exhausted should be recorded during this process.
13. Reposition all valves to normal settings.

14. Calculate annulus free volume from the pressure and volume of exhausted gas.

15. Gas sample may indicate a wet annulus from water vapour.

Table 6.1: Extracts from a Pressure Build Up Test (Courtesy of BP).

<table>
<thead>
<tr>
<th>Gauge Reading at end Of</th>
<th>Date</th>
<th>Time</th>
<th>barg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1 after 4 Hours</td>
<td>21/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 1 after 8 Hours</td>
<td>21/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 1 after 12 Hours</td>
<td>21/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 1 after 24 Hours</td>
<td>21/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 2 after 4 Hours</td>
<td>22/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 2 after 8 Hours</td>
<td>22/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 2 after 12 Hours</td>
<td>22/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
<tr>
<td>Day 2 after 24 Hours</td>
<td>22/11/2000</td>
<td>9:00</td>
<td>0</td>
</tr>
</tbody>
</table>

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iii) Annulus Pressure Test

This test will not provide an absolute result but it will trend the annulus free volume. The method involves slowly charging the vent ports in the top end fitting with Nitrogen to a pressure of 1 barg. The volume of gas injected from the high pressure Nitrogen bottle is then recorded to calculate the free volume in the annulus. The test should allow for stabilisation of the riser annulus which should be achieved within 20-30 minutes. The annulus volume is predicted based on the pressure/volume differences. The pressure test should have a low pressure relief valve setting of 1.0~1.5 barg and a flowmeter to measure the vented gas to atmosphere. This test should be shorter in duration than option (ii). In addition, the test should be performed three times to assess repeatability of results. The HP Nitrogen bottle should employ a 10” pressure gauge to ensure greater accuracy in measuring
the pressure drop. This test takes approximately 12 hours to perform. The test layout is illustrated in Figure 6.3.

An outline procedure is given as follows:

1. Perform risk assessment.
2. Rig up equipment per Figure 6.3.
3. Review previous annulus results.
4. Record riser bore condition during test. This should involve pressure and temperature and environmental temperature.
5. Raise permit to work.
6. Pressure test equipment to 110% of the operating pressure and hold for 15 minutes.
7. Check the vent ports for flow. Flow greater than 0.5 litres/day should be assessed and test suspended.
8. Verify isolation valve integrity.
9. Set the low pressure relief valve to 1.2 barg.
10. Record initial bottle pressure.
11. Set HP regulator to 2 barg (consult manufacturer for guidance).
12. Introduce nitrogen to the annulus. A smooth build up of pressure is required. The HP regulator can be used to control the rate of pressure build up in the annulus.
13. Close the isolation valve when the annulus pressure achieves 1.0 barg.
14. Record the HP gauge pressure.
15. Blowdown annulus in a controlled manner.
16. Repeat test twice for repeatability.
17. Record and verify results.

Guideline Note

Annulus testing is recommended on hydrocarbon risers to assess the annulus condition. A flooded riser is much more susceptible to fatigue damage than a pipe with a dry annulus. The level of damage is a function of the operating conditions of the riser.

The possibility of a partially flooded riser from produced water trapped in the sag bend should be considered against the particular risers operating conditions. This may involve the potential permeation of water vapour across the pressure sheath, which is related to the operating conditions of the bore and the annulus.
Flexible Riser Annulus Testing

0 - 250 bar Gauge (bottle pressure) 0–10 bar (regulated)

16 x 50Litre Nitroge Quad

Figure 6.3: Illustration of Riser Annulus Test (Courtesy of PGS Production)
6.6  **Radiography, Eddy Current & Tomography**

6.6.1  **Radiography**

**Procedure**

This method provides local integrity monitoring checks and is generally applied externally to an on-line system using a double wall shot technique. The single wall shot technique requires access to the bore and involves pipe access.

**Industry Practice**

The industry does not generally perform radiographic examination of pipe unless an anomaly has been identified or is suspected. The main limitation of this technique is that it can only be applied topsides. The technique requires suitable access for the film and source, a specified exposure time and the normal area restrictions associated with a radioactive source. The technique is adopted for riser end fittings to monitor wire pull-out, or to monitor the degree of wire disorganisation in dragchain flexible jumpers. The technique can detect wire failure, but is open to interpretation from the multiple layer construction of a flexible pipe and the shot angle. The preference is to adopt the double wall shot technique, which requires a greater degree of operator interpretation of the film to assess the multiple armour layers (6 layers) than the single wall shot technique (3 layers). An important advantage of the technique is that no pipeline intervention is required.

Radiography has also been used to assess the degree of scale formation within a pipe using a gamma ray source and a detector to measure the intensity of the transmitted radiation. This technique is dependent on relative changes in density (i.e. metallic and polymer pipe layers, and scale density) to ascertain the level of scaling. This technique requires trials on an equivalent pipe to calibrate the system.

**Guideline Note**

This inspection technique is employed to monitor armour layer movement and the potential for armour wire disorganisation, wire failure, or wire pull out from end fittings (if fitted with a metal insert). This type of data provides permanent records, which assesses future trends and can be used to develop a potential monitoring or replacement pipe programme.

The use of a gamma source subsea to monitor the degree of scaling in a flowline is possible, but has not seen wide acceptance within the UK sector to date. This may be related to the age of the system under review.
Radiography is also a basic technique used in assessing the “fitness for purpose” case for re-instating a flexible pipe. However, it is difficult to detect defects such as pits in armour wires with the method and the method is only suitable for detecting significant material wastage in the wires or wire failure, depending on the shot angle. The radiography technique cannot be used to support the case that a pipe has not seen any pitting damage beyond a minimum depth detection level of 0.4mm ~1.1mm deep pits.

6.6.2 Eddy Current Methods

Procedure

This procedure permits the inspection of the outer layer of tensile armours for anomalies and for transverse ruptures in the outer layer of tensile armours. The procedure is suitable for incident monitoring and is locally applied to an area of the pipe, access permitting. External cleaning of marine growth is required to deploy this inspection tool externally. The tool can also be applied internally provided suitable topside access exits.

Industry Practice

This technique is not widely adopted, although several operators have applied the technique. The main technical issue is the perceived low reliability in detecting wire breakage beyond the first metallic layer. Generally it is found that inspected results are open to wide interpretation.

Guideline Note

Because of the difficulty in interpreting results beyond the first metallic layer, the eddy current method is limited to the inspection to the first tensile armour layer from external inspection, or the internal carcass from internal inspection. The depth of penetration is therefore an issue and is the subject of further development work. Topside application with both external and internal access is the best possible application of the system. The system has not been applied widely subsea, due to accessibility difficulties at critical areas of a riser system, in particular, the fatigue sensitive topside bend stiffener location, and hogbend of the distributed buoyancy regions. The technique could be applied internally but is again restricted by the depth of penetration to the carcass layer and possibly the pressure armour layer, subject to operator interpretation.
6.6.3 **X-Ray Computed Tomography**

**Procedure**

This non-destructive technique inspects the full cross section of a flexible pipe including the polymer layers. Although still in the development phase, cross-sectional images of flexible pipes have been produced using a technique based on medical technology.

The components of an X-ray CT system are the x-ray source, the object to be inspected, a detector array and a motion control system, as illustrated in Figure 6.4. X-rays (i.e. photons within a certain frequency range), generated by the source, are sent through the test object in a linear path and detected by scintillator crystals on the other side. A low density area gives a larger signal in the detector than a high density area. After collecting enough views for one cross section, the sample data are processed by computer, which employs various filtering techniques to generate a digital image.

Example CT images are presented in Figures 6.5 and 6.6. The metallic layers are shown as light areas, whilst lower density regions are presented as darker areas on the CT image.

The quality (resolution and contrast) of the CT image is dependent on several factors, including, alignment of detector and source, number of detectors, detector electronics, computer software, x-ray path (should be as linear as possible), signal / noise ratio, dose rate, x-ray energy and test object (thickness and density).

**Industry Practice**

The monitoring tool is a relatively new development with no field experience in the UK or Norwegian sectors. The tool was initially developed for topsides application (detection of PVDF pull-out from the end-fitting) and is planned to be available to the market by the end of 2003. Future effort shall be aimed at FAT’s, pipe re-certification and subsea inspections.

**Guideline Note**

The inspection technique is still in development and is not field proven to date. However, the quality of the CT image is impressive, clearly indicating the condition and configuration of the internal polymer and metallic layers. The initial development is focused on topsides end-fitting inspection.
Figure 6.4: Layout of X-ray Computed Tomography (CT) System (Figures Courtesy of TomX AS)

Figure 6.5: Magnified CT-Image of a Flexible Pipe Cross-Section

Figure 6.6: CT-Image of Flexible Pipe End-Fitting with 2-layer PVDF Internal Sheath

Note that the steel end-fitting has been subtracted from the image. The focus is on the 3-layer PVDF internal pressure sheath.
6.6.4 Electromagnetic and Radiographic In-Situ Inspection Techniques

Electromagnetic and radiographic technology presently under development for in-situ inspection of flexible pipe is described in [7]. These methods are focussed on determining the condition of the pressure and tensile armour wires, such that the existing API fatigue factor of safety requirement (for non-inspectable components) can be justifiably reduced.

The priority detection area for new inspection techniques is the bend stiffener region, since this is where fatigue loading is at a maximum. Also, the consequence of a failure in this area represents the highest possible safety risk.

Procedure

The proposed procedure for assessing the condition of the metallic armours in the bend stiffener region is to send an internal tool, equipped with various radioscopic and electromagnetic equipment, into the pipe bore. This equipment detects the armour condition through the use of an external radiation source attached to an external carrier on the outside of the pipe. To date, initial prototypes have been tested in laboratory conditions.

Industry Practice

This initiative is still under development and is not commercially available to the industry.

Guideline Note

In summary, the industry is well aware that such an inspection tool would offer significant benefits to flexible pipe operators. The next phase in the development of the tool is to perform extensive field testing to ascertain the capability of this novel technique, [7].

6.7 LOAD, CONFIGURATION & EXTERNAL ENVIRONMENT MONITORING

6.7.1 Load and Configuration Monitoring

Procedure

Load monitoring involves the use of top tensioning equipment to measure the actual dynamic loading on the pipe versus the predicted loads from the environmental loading for the riser configuration. The monitoring device may involve a pre-installed external load cell or in-line load ring. Alternatively, an external strain sensor can be employed after installation.
Industry Practice

The industry practice to date does not implement top tension monitoring. A minority of operators employ the strain sensor technique. This may be due to the requirement to cater for load cells at the design stage.

Guideline Note

Very little field experience exists on the ability of strain sensors to accurately correlate the motion of the riser against the predicted model behaviour. This is still considered to be in the development stage.

6.7.2 External Environment

Procedure

This method measures the true environmental loading on the pipe system for comparison against the design assumptions. Several methods exist for measuring waves, current and wind. The vessel excursions should also be monitored within the external environment to ensure the vessel operates within its design excursion envelope.

Industry Practice

The industry practice to date makes use of general weather monitoring systems on the installation. The majority of data is not actively monitored but available to review retrospectively. Similarly, the use of vessel excursion monitoring may not be actively assessed by all the operators but is subject to review, if required. Wind monitoring is not normally relevant unless it is considered to impart significant load on the pipe, which is normally not the case.

Guideline Note

The environmental data for the North Sea region is well established and hence environmental monitoring is not considered important for flexible pipe field developments in this area. However, in the case of field developments in regions with either more severe extreme or fatigue environments or with increased water depths, an onboard monitoring system is recommended to validate design assumptions, in particular with respect fatigue loading.

Current monitoring is potentially an issue for vortex induced vibration (VIV) of subsea flowlines subject to the presence of spanning anomalies. The use of GVI should monitor spanning lengths to ensure overbending of the pipe does not occur. Vessel excursions should be monitored using some form of DGPS system, or alternative technique, to monitor the motion response of the vessel, to verify any model testing. This should be assessed
during operation to ensure the vessel and dynamic riser system remains within its design envelope.

6.7.3 **Sidescan Sonar**

**Procedure**

This procedure involves towing a sonar survey vehicle along the length of the pipe to confirm the configuration for buried or unburied pipe. This is a technique intended for detecting upheaval buckling, loss of cover, loops in pipe and pipe free spans in flowlines and jumpers.

**Industry Practice**

This technique is not widely used in the UK sector. Sidescan sonar is generally used to identify anomalies that may be formed directly by the pipe or indirectly by the pipe generating a seabed disturbance. This anomaly is then assessed in detail using the GVI technique.

**Guideline Note**

This technique is available to identify anomalies in flowline configurations, or upheaval buckling with the support of GVI. The market development of multi-beam side scan sonar in place of a single beam acoustic sonar offers improvements in beam spreading, resolution, speed of advance and focus issues. The length of pipe being examined may limit the use of this inspection technique.

6.7.4 **Survey of Buried Pipe (Pulsed Induction System)**

**Procedure**

A pulsed induction system is an option employed with an ROV to monitor the depth of burial for upheaval buckling detection.

**Industry Practice**

The pulsed induction system is not used. Instead, the use of GVI by ROV to detect upheaval buckling from loss of coverage is more common. Alternatively, the use of sonar is possible over a greater area to monitor flowlines and potential seabed disturbance. The last two options indicate that the inspection is more reactive to a change in seabed condition rather than a more predictive system associated with the pulsed induction system.

**Guideline Note**
6.7.5 Internal Configuration Monitoring

Procedure

This procedure monitors the longitudinal profile of the pipeline and employs a pig with an onboard sensor package to detect upheaval buckling, pipe loops and changes in previous profile histories.

Industry Practice

The UK sector is not adopting this technique. This may be due to the lack of suitable topside or subsea pigging facilities to permit such an operation or the perceived poor return on information for pipeline intervention. Reliance is therefore placed on the use of GVI by ROV to detect gross disturbance to the pipe.

Guideline Note

No Operator field experience available to date.

6.7.6 Fibre Optic Monitoring within the Flexible Pipe

Procedure

This is a relatively new development involving the use of an optical fibre within the tensile armour construction to monitor the real time dynamic response of the riser, and to obtain detailed knowledge of fatigue and extreme wire stresses and the annulus condition of the flexible pipe. Furthermore, future development work is geared towards optical fibres which can detect corrosion.

Industry Practice

The technique is still in the development stage and is not field proven to date.

Guideline Note

No Operator field experience available to date.
6.8 **INTERNAL GAUGING**

**Procedure**

The procedure requires a pig to run in the flexible pipe system and requires a pre-designed pigging facility. The pigging run is initiated on detection of an incident to the flexible or rigid pipe.

**Industry Practice**

The running of a conventional intelligent pig to obtain degradation information on the flexible pipe is not viable. The use of gauging pigs is an option to detect flow restrictions in the pipe. Gauging pigs with metallic parts should be treated with caution and manufacturers advice sought to avoid potential damage to the flexible pipe. In general, no pigging of smooth bore pipes is performed due to concerns with the internal polymer liner.

**Guideline Note**

The running of a gauging pig can be used to identify a collapsed inner carcass, or lack of ovality and any flow restrictions in the flexible pipe. However, potential concerns exist in damaging the pipe by running a pig and manufacturers advice should be sought. It is recommended that an initial assessment should be made from external observation or measurements (GVI), assuming access permits such an examination.

6.9 **OUTER SHEATH REPAIR PROCEDURES**

**Procedures**

Several repair procedures exist to repair the outer sheath of a locally damaged flexible pipe. The outer sheath repairs can be separated into dry or wet repairs.

**Industry practice**

In-service damage to a pipe generally results in repair or replacement, depending on the extent of damage, time of detection and the replacement schedule. The decision to repair or replace is based on a design assessment with the manufacturer and relevant interested parties. The next decision is whether to perform a wet or dry repair. The dry repair allows more control and involves retrieval of the pipe to shore.
Guideline Note

i) Dry repair of outer sheath.

External visual examination should be performed of the entire pipe and possibly radiographic examination if any damage is suspected in a fatigue sensitive location.

The use of polymer patch repair welding may be considered but this is not a robust repair solution. The patch weld repair may prove extremely difficult due to the water saturation levels within the polymer and the difficulty in drying successfully. The polymer weld repair may fail to survive any subsequent strain loading from reeling performed during dispatch and re-installation. The local polymer weld repair is not recommended as the only barrier repair procedure based on its poor reliability. The repair technique should be verified prior to use.

The use of a conventional mechanical clamp repair offers a more robust solution. The clamp is placed over the damage site and an environmental barrier seal is normally applied with either a single or double sealing arrangement. The ability of any clamp repair to retain its sealing integrity when subject to future annulus treatments should be assessed. This may place future restrictions on the type of annulus monitoring techniques applied. The location of the clamp should consider the flexure of the pipe in determining the size of the clamp and any curvature restrictions imposed on the flexible. The repair technique should be verified prior to use.

The development of a pressure retaining repair technique utilising existing lightweight pipe repair clamps is ongoing. These units are already qualified for use on a wide range of surface and splash zone pipe repairs and are capable of retaining an internal annulus pressure.

Prior to repair, fluid samples should be taken from the annulus to assess for pH levels, ferrous oxides, etc, as this information is valuable in any future life assessment.

The annulus should be pressure tested to an agreed limit to demonstrate the repair integrity. It is recommended that the manufacturer’s advice be sought but if no other guidance is available, the test should set at a 1.5 barg maximum limit on the annulus pressure.

After completing the repair, a bore pressure test to 150% of MAOP should be performed to demonstrate pipe integrity.

ii) Wet repair.

A seal should be placed over the damaged section of outer sheath in order to isolate the annulus from the seawater environment. The seawater flooded annulus space may then be flushed with an inhibitor fluid to mitigate the effect of the seawater breach on the carbon steel armour wires. Alternatively, based on a risk assessment of the pipe, the early detection of the
damage site may provide sufficient justification for clamping. The repair task will require diver or ROV activities, which may be complicated by dynamic riser motion.

A two-part Epoxy Adhesive, developed for underwater application should be utilised for sheath repairs. This process provides a barrier seal with no pressure retaining ability.

The principle advantage of this method is that the repair is lightweight, and has no effect on riser buoyancy. See Figure 6.7.

However, disadvantages for the epoxy repair method are:

- The epoxy curing timescale places restrictions on underwater procedures.
- Epoxy handling and preparation requires approved procedures and trained personnel.
- Surface preparation of the sheath surrounding the damaged area is required. This may be difficult to achieve in areas of extensive damage or high marine growth.
- The quality of the repair is not quantifiable.
- The repair patches have a history of being dislodged following impact from inspection by ROV’s or by riser dynamic motion.

The alternative wet repair technique requires a mechanical clamp to be installed over the damaged area, as shown in Figure 6.8.

Traditional steel pipeline repair clamps have been successfully installed by WROVs over damaged sections. These clamps can be fitted with pipework to allow routine monitoring of the riser annulus inhibiting fluid. This type of clamp provides a full pressure repair to the sheath. The disadvantages of traditional pipeline repair clamps are:

- The weight of the installed clamp with anodes, which may require separate deployment to the seabed for the WROV to dock onto.
- The complexity of the WROV tooling requires a specially trained ROV crew.

An alternative lightweight and low profile clamp which is pressure retaining and includes fasteners suitable for rapid installation by WROV is shown in Figure 6.9. The clamp is designed to accommodate fittings suitable for routine monitoring of the riser annulus inhibiting fluid alongside the development of a range of clamp installation tooling that can be rapidly installed to any WROV. The lightweight clamp requires further development to demonstrate a proven field track record.
As with all mechanical clamp repairs, an accurate measurement of the outer diameter of the riser at the damaged location is required prior to the manufacture and installation of the repair clamp.

On completion of the repair, a pipe bore pressure test to 110% MAOP should be performed to demonstrate pipe integrity, if damage to the armour layers is suspected.

The repair technique should be verified prior to use.

6.10 **RISER DISSECTION**

**Procedure**

Dissection of a flexible pipe may be performed to determine its mode of failure or to assess degradation of a non-failed retrieved pipe. This is typically performed by the pipe supplier under the supervision of an operator representative familiar with the pipe construction.

The detailed procedure for failure inspection and dissection is dependent on the actual pipe design but should include the following standard stages:

- If unknown, perform an assessment of the most likely failure location.
- Remove all pipe layers in a layer-by-layer fashion, noting and marking distance from the end-fitting or other reference point.
- Take photographs during each layer removal, performing relevant observations.
- Measure and record relevant dimensions, such diameter, pitch length and wire gaps.
- Measure and record pipe anomalies, e.g. wire disorganisation or damage, unlocking of pressure armour, cracking, collapse or extrusion of the polymer.

If relevant, further laboratory analysis of the polymer or metallic component may be required to determine cause of failure. This may include checking that steel wires are within specification (UTS, hardness, elongation, profile) or microscopic polymer examination.

Detailed pipe dissection is time-consuming and hence a review of the in-service pipe loading should be performed to assess the most probable failure location. Typically, detailed dissection of an entire cross section is limited to around 8m per day for a standard 10-inch pipe, depending on the pipe design.

The dissection of an end-fitting may be required to determine the pipe mode of failure. This requires an intimate knowledge of the end-fitting design and involves detailed examination of the polymer crimping rings.
Industry Practice

This procedure is widely employed by the industry to determine mode of failure and to prevent similar failure occurrences elsewhere. In a small number of cases, non-failed retrieved risers have been examined for armour wire corrosion in order to justify re-use.

Guidance Note

In the event of failure of a perceived low risk pipe, then detailed dissection should be performed as a priority. Pipe dissection is particularly important if similar pipe designs are also operating in the same environment as the failed pipe. Furthermore, in harsh operating conditions where limited previous experience exists, operators should consider retiring a riser for detailed dissection and integrity assessment. This may demonstrate that the remaining risers are fit for ongoing use, through the provision of a new benchmark in riser experience.

Figure 6.7: GRP clip is used to deploy the Epoxy Adhesive.
Figure 6.8: A typical steel pipeline repair clamp.

Figure 6.9: A lightweight repair clamp under development.
7 REFERENCES


8 ACKNOWLEDGEMENTS

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**Regulatory Authorities:** UK Health & Safety Executive, Department of Trade & Industry, Oljedirektoratet (OLF)

**Consultants / Specialist Inspection Providers:** BPP Technical Services, Galactic Salvage, TomX AS.