Failure modes, reliability and integrity of floating storage unit (FPSO, FSU) turret and swivel systems

Prepared by
AEA Technology Engineering Solutions
for the Health and Safety Executive

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Failure modes, reliability and integrity of floating storage unit (FPSO, FSU) turret and swivel systems

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EXECUTIVE SUMMARY

During the 1990’s there has been an increasing move in the North Sea sector to subsea and deepwater production with the use of floating production and storage systems. A key technology is the use of Floating Production, Storage and Offloading (FPSO) vessels and other Floating Storage Units (FSUs). Such systems are either purpose built or converted from tankers or bulk carriers. The term FSUs may also encompass simpler systems such as storage and offloading buoys. An integral part of such systems is a turret system that keeps the vessel on station via single-point-mooring and allows the vessel to rotate in response to weather conditions. This technology has become established relatively quickly since the first FPSO (Petrojarl 1) entered UK waters in 1986 and previously there has been little historical information and guidance available to HSE inspectors on maintenance standards, best practice, risk and reliability. It is pertinent to note that most current FPSOs in UK waters were installed only in the late 1990s.

This document provides an independent assessment of established and emerging designs of turret and swivel systems for FPSOs and FSUs and has been undertaken as part of the HSE's Mainstream Research Programme. It provides an information source, guidance and practical handbook for HSE inspectors, both expert and with limited FPSO exposure. The report should prove useful to HSE inspectors; providing practical information in evaluating Safety Cases, assessing incident reports, prior to site visits, and to raise the level of awareness of safety issues in this rapidly evolving technology. The report addresses the full turret system including support structure and flexible riser attachments. The project has been undertaken in close consultation with HSE inspectors, operators and manufacturers of FPSOs and turret systems.

The basis for this report has been a thorough review of FPSO and FSU turret systems including consultation with turret and fluid transfer system manufacturers. A systems based approach has been used defining generic turret system types, the boundaries between systems, common systems and unique features for individual turret designs. This has produced a comprehensive guidance document on FPSO turret systems, their failure modes and inspection and maintenance practices. General issues such as ship structure and turret location are discussed as well as current regulatory and certifying requirements.

The present study has included site visits to a number of suppliers of FPSO turrets and swivel systems. It would be extremely valuable to extend the experience base with visits to other major suppliers including SBM and Bluewater. The experience of this study shows that such visits are an extremely valuable way of gaining first hand knowledge of maintenance practices and service history. It is strongly recommended that an HSE inspector should be present on such visits because of their unique perspective and the good contacts this establishes. It is also recommended that an electronic ‘Knowledge Base’ version is produced to make the information more widely accessible within HSE.
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ANNEX C Detailed information on individual Fluid Transfer Systems (FTS) and swivel systems
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ANNEX G Information on specific turret and FTS system manufacturers.
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Cross sections through Petrobras 31 and Petrobras 34 FPSO Turrets. 
*Courtesy Petrobras*

Multiple torroidal swivel stack. Cross Sections show flow annulus, bearings and seals. *Courtesy Brown Brothers*
1 INTRODUCTION

During the 1990’s there has been an increasing move in the North Sea sector to subsea and deepwater production with the use of floating production and storage systems. A key technology is the use of Floating Production, Storage and Offloading (FPSO) vessels and other Floating Storage Units (FSUs). These are generically referred to as Single Point Moored (SPM) systems.

Such systems are either purpose built or converted from tankers or bulk carriers. The term FSU may also encompass simpler systems such as storage and offloading buoys. An integral part of such systems is a turret that swivels to provide positive weathervaning and to maintain the system on station. This technology has become established relatively quickly. The first FPSOs World-wide were installed in the early 1980s, with the first in the UK sector of the North Sea being Petrojarl 1 in 1986. The majority of the FPSOs in the UK sector were installed only in the late 1990s. There has been considerable evolution in design to meet the specific environment needs of the North Sea. Much of the advances in turret design have come from Norway with innovative advances in swivel design from both the UK and Norway. Previously there has been little historical information and guidance available to HSE inspectors on maintenance standards, best practices, risk and reliability of FPSOs.

This report provides an independent assessment of established and emerging designs of turret systems for FPSOs and FSUs and has been undertaken as part of the HSE Mainstream Research Programme under contract HSE Ref E9/99/202. The document provides a comprehensive information source, guidance document and practical handbook for HSE inspectors, both expert and with limited FPSO exposure. This includes the full turret system including support structure and flexible riser attachments. The project has been undertaken in close consultation with HSE inspectors, operators and manufacturers of FPSOs and turret systems. The report is intended to provide practical information for HSE inspectors evaluating Safety Cases, reviewing incident reports, prior to site visits and more general information for those seeking to improve their knowledge of FPSO technology.

A Failure Modes and Effects Analysis (FMEA) has been conducted for standard turret designs and design variants to identify critical components, safety concerns and the relevance of safeguard strategies such as inspection, maintenance and condition monitoring employed to ensure integrity.

Detailed information on specific FPSO and FSU installations in UK waters and World-wide is included in the Annexes together with more detailed information on different turret and fluid transfer system designs.

1.1 HOW TO USE THIS REPORT

The report is intended to provide practical information for HSE inspectors evaluating Safety Cases, reviewing incident reports and prior to site visits or routine investigations (RI). It also provides more general information for those seeking to improve their knowledge of FPSO technology. The emphasis in this document is on what to look for, what could go wrong, what questions to ask and what should be done in terms of inspection and maintenance.

In this report reference is made to a number of generic types of turret system. It should be recognised that the details may vary dependent on the manufacturer and that there is no such thing as a ‘standard turret’. Nevertheless this is a convenient way to categorize the different
systems. A systems-based approach has been used. Boundaries are defined between different
turret systems. Common and unique features are identified for individual turret designs.
Comment is made of specific features unique to a particular manufacturer or individual vessel
and principles of operation are described.

The key information is summarized in the main report.

A general overview of FPSO turret systems and how they operate is included in Section 2.

a) General issues including the location of the turret, mooring and construction standards are
discussed in Section 3.
b) Section 4 gives an overview of regulations that are applicable to FPSOs and floating
installations.
c) The main types of turret system and the components within those systems are
summarized in Section 5.
d) Historical and anecdotal information on failures, safety relevant components and
operational issues are discussed in Section 6.
e) The inspection and maintenance typically applied to turret and fluid management systems
is summarized in Section 7.
f) Finally, examples of good practice are given in Section 8

Extensive support information can be found in the Annexes to the report, in particular:

ANNEX A List of UK Installations
ANNEX B Detailed information on individual turret designs
ANNEX C Detailed information on individual Fluid Transfer Systems (FTS) and swivel
systems
ANNEX D Summary Look-up Tables on Failure Modes and FMEA Analysis
ANNEX E Information on specific UK and North Sea Installations
ANNEX F Information on other World-wide Installations
ANNEX G Information on specific turret and FTS system manufacturers.
ANNEX H Glossary of Terms

1.1.1 Approach to Safety Cases

In this instance the inspector may require information on a specific installation, or turret and
swivel design, but put this in the context of what is done for similar installations. The first step
would be to look in the list in Annex A to identify the generic Turret, Fluid Transfer System and
Main Bearing types relevant to that particular installation, as well as the suppliers.

The inspector may first want information on general issues such as turret location and
regulations that may apply. This can be found in Sections 2 to 4 inclusive. The subsequent
Sections of the report provide information on the generic type of turret system that has been
identified for the given installation.

A summary of the main types of turret system, the systems and components and how they work
is given in Section 5. The key information on safety critical components, what can go wrong,
what to look for, inspection and maintenance practices, and examples of good practice is given
in Sections 6 to 8 of this report. This information will provide most of what is required. Much
more detailed and specific support information can be found if required in the Annexes. Annex
B and C, in particular, provide comprehensive information on individual turret types and Fluid
Transfer System (FTS) types.
1.1.2 Approach to Incident Reports
The inspector may require information on a specific installation or turret and swivel design. The sequence of using the document would be as for Safety Cases above. More specific information may be sought on the particular systems or components under investigation using the support information in the Annexes. Section 6 and 7 are of particular relevance here; containing historical and anecdotal information on past failures and guidance on the inspection and maintenance typically applied to individual systems. Section 8 provides examples of good practice which may assist the inspector in his investigations.

1.1.3 Approach to Site Visits and Routine Investigations
As incident reports. By installation, turret type or manufacturer, as appropriate.

1.1.4 Accessing general information
The report sections are ordered to progressively drill down in the level of information and progress from general to more specific information. Information on specific UK and Worldwide installations can be found in the Annexes.

**EXAMPLE:**
Finding information for Anasuria FPSO

Annex A

--->

1. Look-up Table for *Anasuria* FPSO.
2. Identify Generic Turret type and manufacturer.
3. Identify Fluid Transfer System (FTS) type and manufacturer

*e.g.*

<table>
<thead>
<tr>
<th>UK FPSO &amp; FSU Installations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Anasuria</td>
<td>FPSO</td>
</tr>
<tr>
<td>Field Installation</td>
<td>New Build 1996</td>
</tr>
<tr>
<td>Operator</td>
<td>Shell UK</td>
</tr>
<tr>
<td>Field</td>
<td>Teal, Teal South, Guillemit A</td>
</tr>
<tr>
<td>Turret Type</td>
<td>ITP Internal Turret Permanent</td>
</tr>
<tr>
<td>Turret Supplier</td>
<td>SBM Inc.</td>
</tr>
<tr>
<td>Turret Diameter (m)</td>
<td>N/A</td>
</tr>
<tr>
<td>Turret Height (m)</td>
<td>N/A</td>
</tr>
<tr>
<td>Fluid Transfer System</td>
<td>Multipath Swivel</td>
</tr>
<tr>
<td>FTS Supplier</td>
<td>SBM Inc</td>
</tr>
<tr>
<td>Main Turret Bearing</td>
<td>SKF Bogey</td>
</tr>
<tr>
<td></td>
<td>Upper: 7m dia. triple race bearing -RKS</td>
</tr>
<tr>
<td></td>
<td>Main deck: radial bearings</td>
</tr>
</tbody>
</table>

This generic turret and FTS types are shown above in red. This enables the inspector to review the Sections in the main report to find the information on failure modes, safety relevant components and inspection practice for these generic types. More detailed information on the Anasuria FPSO can be found in Annex E, which summarises information on specific UK and North Sea Installations.

<table>
<thead>
<tr>
<th>Section 3</th>
<th>Section 4</th>
<th>Section 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examine general issues</td>
<td>General description of turret types, FTS and interfacing systems.</td>
<td>Examine for information on failure modes pertinent to given turret and FTS designs and interfacing systems. Look at summary look-up tables</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section 7</th>
<th>Section 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summary of inspection and maintenance practices</td>
<td>Applicable regulations</td>
</tr>
</tbody>
</table>
If additional information on the specific systems is required then drill down as appropriate in terms of Turret and FTS type by going to.

ANNEX B  Detailed information on turret
ANNEX C  Detailed information on FTS and swivel systems
ANNEX D  Summary Look-up Tables on Failure Modes. FMEA Analysis.
ANNEX E  Information on specific UK and North Sea Installations
ANNEX F  Information on other World-wide Installations
ANNEX G  Information on specific turret and FTS system manufacturers.
ANNEX H  Glossary of Terms

1.2  LAYOUT OF THE REPORT

The layout of the document is sequential and suitable for future adaptation as an electronic database. In the first part of the document the main FPSO and turret types are described including their functionality, key components and systems. This provides an introduction to the technology and a classification of key elements in the design. The second part of the document is systems-based and allows the inspector to drill down in increasing levels of detail on the maintenance practices and operational and safety risks associated with individual components and systems. Summary and Look-up Tables are included to guide inspectors on best practice for specific components and systems. Relevant pictures and diagrams are included to illustrate the technology.

Detailed information on specific FPSOs and FSUs in UK waters and World-wide is included in the Annexes with Summary Tables. This enables the inspector to source information on the specific installation they are visiting and guide them to information on the relevant turret type in the main document.
1.3 TERMS OF REFERENCE

The terms of reference for this study were as follows:

1. An in-depth study to provide more accurate information on the failure modes, and the reliability and integrity of the measures employed to ensure the continued effectiveness of FPSO vessel turret swivel bearings.

2. To address safety critical components already recognised by HSE as of potential concern including the securing bolts, bearings and seals. Safety critical securing bolts for swivel systems have been known to fail in the past with severe consequences. The potential for hydrocarbon release from bearing or seal failure is also of concern, as such releases continue to be a significant day to day risk offshore.

3. A practical guidance document and informed technical review relevant to HSE inspectors at all levels, from expert to those with limited exposure to FPSOs, to be presented in an accessible form.

4. To cover all available FPSO designs and turret designs, North Sea and World-wide. Include information on methods, manufacture, and types of design, different FPSO turret concepts, how these are used and identify generic and novel design features. Include full reference to manufacturers. To provide guidance on good/bad points of design.

5. Just the turret system but including the swivel, turret surround, flexible riser attachments and safety critical elements identified as of concern: for example the bearings, seals, securing bolts and other components identified as relevant to the study and the integrity of the system.

6. To identify what to look for, solutions, failure modes and reliability information, relevant inspection and maintenance practice and how to manage integrity, what guidance is available from manufacturers. Relate to maintenance standards. What are people doing, what should they be doing, is it adequate?

7. Identify risk areas and potential damage mechanisms. Include experience and historical information of failures and operation. To provide guidelines for HSE inspectors on factors that need to be considered in evaluating the Safety Case for FPSOs. To take on board the above reliability and failure issues, to ensure operation is safe and appropriate steps have been taken in terms of monitoring.

8. To address specific safety concerns raised by HSE. For example are there similarities to crane swivels which are maintained according to recognised standards. The loading of FPSO swivels is quite different and there are no similar standards yet for FPSOs. Identify differences and similarities for maintenance approach.

9. To identify other potential safety concerns regarding FPSO turret swivels and turret systems. Safety concerns relevant to FPSO operation in general and not affecting the turret systems lie outside the scope of the present study.

It is hoped the project will form the basis for future work leading to a British Standard and recommended practice. We understand access is likely to be available to relevant HSE past programme data and databases e.g. hydrocarbon releases database.

---

1 Failure Modes, Reliability and Integrity of Floating Storage Unit (FSU, FPSO) Turret Systems; AEA Technology Proposal HSE/E9/FPSO/99/202 October 1999 plus Addendum to proposal.
1.4 SOURCES OF INFORMATION
The sources of outside information consulted in putting together the guidance document include the following:

- Literature sources including journals, brochures, conference proceedings, databases and the World-wide Web
- HSE inspectors
- Safety Cases and DCR documentation
- Regulatory and Certifying Authorities
- Oil companies and FPSO, FSU operators
- Designers of FPSO vessels and turret systems
- Shipyards and manufacturers of FPSO vessels
- Manufacturers of FPSO turret systems (turret and swivel)
- Specialist component manufacturers e.g. bearing manufacturers
- Risk and safety assessments
- Relevant HSE programmes and databases
- Existing information held by AEA Technology, the National NDT Centre (NNDTC) and the National Centre of Tribology (NCT)
- Industry course information on FPSO technology
- Other regulators and certifying authorities
- Maintenance manuals where accessible
- Information from risk and safety assessments
- Relevant information from other current projects, taking account of client confidentiality

1.5 TECHNICAL APPROACH

FPSOs and FSUs have become established relatively quickly in North Sea operations. There are a number of generic turret design types, yet there is still considerable evolution in design and an increasing number of design and manufacturing companies involved in the market. There are specific challenges. First is the accessibility of information, some of which manufacturers may consider proprietary. Second there is a need to identify generic technology and features which are design specific. Finally HSE and offshore operators have little historical data on reliability, given the speed at which the technology has been exploited.

This study has aimed to identify generic technology, considering existing designs as well as new developments and future trends. As the first stage, an initial design review was undertaken. This addressed all the issues identified in the requirements above with a focus on design and maintenance requirements. Information that is immediately accessible or could be collated from industry, HSE or other sources was included.

In parallel with the first stage contacts were made with industry, HSE inspectors and other relevant data sources identified above to access information relevant to the project. This has been an ongoing activity throughout the project. A variety of sources were accessed to ensure that information is representative and to gain information on maintenance practices and other data that may be considered proprietary.
The industrial companies and regulatory authorities consulted during the Project have included, but were not limited to, the following:

**Turret and swivel manufacturers**
- Maritime Tentech AS, Kristiansand
- Advanced Production and Loading (APL), Arendal
- Framo AS, Bergen
- Brown Brothers, Rolls Royce Marine, Edinburgh
- Bluewater, Holland
- SBM, Monaco
- SOFEC, Houston

**Oil companies:**
- Statoil, Petrobras, Shell International, BP, Amerada Hess, Norsk Hydro, Phillips Petroleum, Texaco

**Regulatory and certifying bodies**
- American Bureau of Shipping (ABS), Det Norske Veritas (DNV), Lloyd's Register, HSE

Specific site visits were made to Advanced Production and Loading (APL), Framo AS, Maritime Tentech AS and Brown Brothers Limited.

The design review included the following information and other relevant issues raised in the requirements above:

- Damage and failure modes
- Maintenance and inspection practices
- Risk and reliability data
- Operational and safety concerns
- Additional design information
- Ongoing consultation with industry and HSE
- The different types of FPSO turret design (North Sea and World-wide)
- Functionality of components, manufacture and design concepts
- Potential damage and failure mechanisms
- Safety and operational issues
- How to manage integrity
- What information is available from the manufacturers
- What to look for to ensure operation is safe and appropriate steps have been taken in terms of monitoring
- Identification of generic and novel design features
- Practical advice on good and bad points of the designs

The prime objective of this initial assessment was to classify the main design types and key components or structural elements. An evaluation was made of features that are generic and those that are novel or design specific. This formed the initial basis for the guidance document. Areas of omission in information or data were identified and an action plan established to access relevant data.

A more detailed assessment was made of key elements already raised by HSE and issues identified in the review including the integrity of the bearings, support bolts and elastomeric seals. Experts in the relevant technology undertook this, for example experts in damage mechanisms in large bearings from the National Centre of Tribology (NCT) and experts in
inspection methods from the National NDT Centre (NNDTC). Evaluation and assessment, leading to production of the draft guidance document followed this. Recommendations were included on areas requiring future research or development.

A key part of this evaluation was the Failure Modes, Effects Analysis (FMEA) for standard turret designs and design variants. This identified failure modes, safety concerns and the relevance of safeguard strategies employed to ensure integrity; such as inspection, maintenance and condition monitoring. This type of analysis is well established and universally accepted as being the most appropriate to the combination of moving and static components considered in this study.

1.6 SCOPE OF THE REPORT

This guidance document is limited to FPSO and FSU vessels that include a turret system for mooring, station management and fluid transfer. Mooring buoys such as CALM, SALM and SALS systems are excluded as well as FPSO designs, such as Spread-Moored and Riser-Porch which do not include a turret. A full description of types of FPSO turret systems can be found later in Section 5. The Glossary in Annex H gives fuller descriptions including other types of FSU.

The specific systems that are included and excluded are described later in Section 1.8 for the individual turret designs. In general all systems which lie within a cylindrical envelope above and below the turret are included as illustrated for conventional internal and external turret designs in Figure 1 and Figure 2.

Risers and mooring chains are excluded except for the connections and parts that run within the turret. The mooring spider where these join the turret is included. The ship structure to accommodate the turret is also excluded, as this will depend on whether the vessel is a new build or a conversion and will be vessel and shipyard specific. For external turrets the cantilever turret support structure is excluded.

For systems that lie outside these boundaries, high level comments are still included as a broader issue to aid inspectors, particularly where failure or damage to these systems may impact on the safe operation of the turret.
Figure 1
Pictures of conventional external turret FPSO showing the cylindrical envelope defining which systems are included within the scope of this guidance document. Comment on other systems is still included at high level where this may impact on the integrity or safety of the turret.

Figure 2
Pictures of conventional internal turret FPSO showing the cylindrical envelope defining which systems are included within the scope of this guidance document.
1.7 DEFINITIONS

1.7.1 FPSO
Floating Production, Storage and Offloading Vessel. A marine vessel single-point moored to the seabed allowing direct production, storage and offloading of process fluids from subsea installations - usually via an internal or external turret system.

1.7.2 FSO
Floating Storage and Offloading Vessel: As FPSO but no production capability. Stores oil products that can be offloaded to pipelines or shuttle tankers.

1.7.3 FSU
Floating Storage Unit. Generic term for floating installations including FPSOs and FSOs.

1.7.4 Single Point Mooring (SPM)
Mooring to the seabed from a single location on a Floating Production Unit, usually via catenary mooring and involving a number of anchor chains, buoyancy aids and flexible risers. Single location in this context refers to the turret.

1.7.5 Turret
A cylindrical single point mooring system geo-stationary with the seabed allowing rotation of the FPSO or FSO vessel in response to wave and wind conditions (weathervaning).

1.7.6 Fluid Transfer System
Method of transfer of fluid from the turret (geo-stationary) to the process plant on the vessel.

1.7.7 Weathervaning
Rotation of the ship about the turret in response to wind, sea and climatic conditions.
## 1.8 SYSTEMS INCLUDED AND EXCLUDED

The following systems are included and excluded from the scope of the document.

### Table 1 Systems included and excluded from scope of guidance document

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>Major Component</th>
<th>Included</th>
<th>Excluded</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLUID TRANSFER</td>
<td>Swivel Stack</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drag Chain Assembly</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Flexible Riser connections</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Swivel Maintenance Structure (Scaffolding)</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cranes and Winches</td>
<td>○</td>
<td></td>
<td>Within Turret only</td>
</tr>
<tr>
<td></td>
<td>ESDV Tower</td>
<td>●</td>
<td></td>
<td>Drag chain systems only</td>
</tr>
<tr>
<td>TURRET</td>
<td>Turret Shaft</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Support Bearings</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turret Casing</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Turret Rotation Mechanism</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mooring Spider</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mooring Buoy (Disconnectable)</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risers and Umbilicals</td>
<td>○</td>
<td></td>
<td>Within turret only</td>
</tr>
<tr>
<td></td>
<td>Ship Structure and Turret Cavity</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Systems within turret casing and cavity</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>STP Buoy</td>
<td>●</td>
<td></td>
<td>STP System only</td>
</tr>
<tr>
<td></td>
<td>STP Room and Locking Mechanism</td>
<td>●</td>
<td></td>
<td>STP Systems only</td>
</tr>
<tr>
<td>MOORING</td>
<td>Mooring Chains and Connections</td>
<td>●</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Risers below turret level</td>
<td>●</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Included**
- ○ Higher level comment only

A more detailed description of individual turret components can be found later in this report.
2 BACKGROUND TO FPSO AND FSU TURRET SYSTEMS

There is an increasing move in the North Sea sector to subsea and deepwater production and the exploitation of marginal fields. A key technology is the use of Floating Production, Storage and Offloading (FPSO) vessels and other Floating Storage Units (FSUs) in place of conventional oil platforms. The first FPSO World-wide was installed in 1981 with the first in the UK sector (Petrojarl 1) in 1986. There are currently 14 FPSOs operating in UK waters most of which were installed in the late 1990s.

FPSOs are either purpose built or converted from tankers or bulk carriers. These comprise a vessel with integral process plant, moored to the seabed and attached to risers from subsea wells. Production fluids flow up the flexible risers to the turret system where they are transferred to the process plant on the vessel by a swivel or other Fluid Transfer System. Here they are processed and the products stored in tanks or exported. The vessel will usually have the facility to offload oil products to subsea installations, pipelines, storage buoys or storage vessels. The term FSUs may also encompass simpler systems such as storage and offloading vessels or buoys which have no production capability. The FPSO is an adaptation of simpler storage vessel technology and the use of mooring buoys for transferring production fluids from wells and installations subsea.

Figure 3
Example of a Floating Production Storage and Offloading vessel (FPSO) moored to the seabed via a conventional turret single-point mooring. BP Foinavon FPSO, Courtesy BP
The first FPSOs came into service in the Far East and South America in the early 1980s as a cost-effective solution to the exploitation of small and marginal fields, to extend production in existing fields or allow early production in new fields. These operated in shallow water commonly less than 150m deep and in good climatic conditions. The 1990s saw considerable advances in application of FPSOs with more than 60 FPSO vessels now operational Worldwide, many in severe climates and water depths up to and exceeding 1000m. There are particular advantages in using FPSOs in fields with short field lives where the cost of investment in pipelines, structures and field abandonment would be high.

These early vessels were spread-moored with the risers feeding into a simple porch at mid-ship. In most locations spread-mooring is not practicable and a single point mooring is desirable to allow the vessel to weathervane, adjusting to wave and climate conditions. An integral part of most modern FPSO systems, and the method of providing single-point-mooring, is a Turret System. This swivels to provide positive weathervaning, maintain the system on station and allow fluid transfer from the risers to the process plant onboard.

Advances in FPSO technology have allowed vessels to operate in increasingly severe environments, deeper water and to handle higher pressures and more wells. Initial FPSO designs had an external turret with a simple swivel connected to a flexible riser. More recent designs have used complex multiple swivel assemblies with turrets internal to the ship; in some cases, handling production fluids from 30 or more wells. Such designs of turret system are complex and may include multiple flexible riser connections, pipes for process fluid and well injection, multiple seals, valves, initial separation assemblies, pig launchers and securing bolts. The consequences of failure here are clearly more severe than for a simple swivel joint. Many
FPSOs have a design life of 25 years or more and there are strong cost incentives to the operator to maintain the FPSO on station.

The technology is relatively new in the UK and Norwegian sectors although more extensive information exists in Brazil where much of the present deepwater technology was pioneered. Most UK operators now have at least one FPSO in operation and they have gone through somewhat of a learning curve on reliability during initial operation. Experience is more extensive in simple swivel joints in buoys; these have been used in the UK sector for a many years and formed the initial basis for conventional 'Bluewater' turret designs as opposed to the 'Tentech' central turret designs, which originated later in Norway. The limited number of generic Turret System designs is advantageous in allowing experience and improvements to be passed on to future developments; but disadvantageous in that problems may become generic across FPSO operations.

2.1 FUNCTION OF THE TURRET SYSTEM

The Turret System performs four main functions in an FPSO:

- maintaining the vessel on station through single point mooring
- allowing weathervaning or rotation of the vessel to adjust to climatic conditions
- fluid transfer from the risers to the process plant
- transfer of electrical, hydraulic and other control signals

An FPSO turret system contains three main systems: the turret itself, a fluid transfer system (FTS) -usually a multi-path swivel to transfer the production fluids to the process plant on the vessel, and intermediate manifolding known as the turret transfer system (TTS) which provides
a link between the turret and the FTS. The TTS is often referred to more generally as the turntable or turntable manifolding.

2.2 WEATHERVANING

An advantage of a turret system over other options for floating installations such as spread-mooring is that it allows the vessel to rotate and adopt the optimum orientation in response to weather and current conditions. This rotation of the vessel about the turret is known as Weathervaning.

In most cases the vessel can freely rotate through 360°; known as free weathervaning. If the rotation is restricted this is described as partial weathervaning. The latter is the case for turrets with a drag chain for fluid transfer, which can only rotate +/- 270° in either direction.

2.3 PARTS OF A TURRET SYSTEM

In the context of this report the turret system is considered in four parts:

**Turret (T)** This provides the single-point mooring and allows weathervaning of the vessel. Includes the turret shaft, turret casing, main and lower bearings and the mooring spider.

**Fluid transfer system (FTS)** This is typically a multiple swivel assembly. Transfers the process fluids and other signals from the turret to the process plant on the vessel. Positioned above the turret and linked via the turret transfer system (TTS)

**Turret transfer system (TTS)** This refers to the intermediate manifolding linking the turret and the FTS. Positioned on a turntable on top of the turret this rotates with the turret. Otherwise referred to as the turntable or turntable manifolding.

**Interfacing Systems (IS)** including, swivel access structure, mooring lines and flexibles below the turret and other ancillary equipment.

This delineation is illustrated in Figure 6 and Figure 7 for an internal turret with a swivel and for a drag-chain, respectively, as fluid transfer systems (FTS). The systems and components within each of these is discussed later in Section 5.
Figure 6
Cross-section through an internal turret with a swivel as the fluid transfer system, showing the delineation used in this report for sub-systems within the turret system.
Figure 7
Cross-section through an internal turret with a drag chain as the fluid transfer system, showing the delineation used in this report for sub-systems within the turret system.
2.4 INTERFACES

There are four main external boundaries separating the turret system from the vessel. These are important from a safety and operational standpoint as they are all points of load and/or hydrocarbon transfer:

- Fluid Transfer System to ship (to process plant)
- Main turret bearing
- Lower turret bearing and cavity containing moonpool
- Mooring spider or mooring buoy (disconnectable) to mooring lines and flexible risers

The interface between the FTS and the process plant on the vessel is known as the FPSO/Turret interface.

In addition there are internal interfaces within the turret system:

- FTS to Turret Transfer System
- Turret to Turret Transfer System
- Turret shaft to mooring buoy or spider

Usually flexible risers connect the swivel to the FPSO/Turret interface.

Another important interface on an FPSO from a safety standpoint is between the marine and offshore structures. This is usually considered to be at deck level. For the purposes of this report the turret system is considered to be part of the offshore structures.

2.5 LOAD TRANSFER FOR A TURRET SYSTEM

The Turret will encounter significant loading from the single point mooring, from waves and current and from the weathervaning FPSO vessel. The external interfaces represent the areas of load transfer. For a typical turret system the areas of load transfer are as follows:

- Torque arms to Swivel
- Main Turret bearing
- Lower bearing pads
- Connections to single point mooring
- Bend-stiffeners on flexible risers

Where the turret includes a separate mooring spider, or mooring buoy in the case of disconnectable systems, then there will be significant load transfer across this internal interface. The main bearing is the main area of load transfer from the turret to the vessel including both axial and radial loads. The lower bearings, usually pads, take much lower loading. The vessel structure adjacent to the turret cavity can encounter significant ovality and loads and is a common area for development of cracking.
2.6 EVOLUTION IN TURRET SYSTEM DESIGN

The main distinctions for a turret system are between internal and external turrets, in the type of fluid transfer system adopted (swivel or drag chain), whether the turret connection is permanent or disconnectable, whether active or passive weathervaning, and in the location of internal turrets.

Initial FPSO vessels had external turrets cantilevered on the bow of the vessel. Such designs are not suitable for the adverse conditions experienced in the North Sea. Without exception all the FPSOs in the North Sea have internal turrets: that is the turret is integral to the vessel. The turret drops down in this case into a cylindrical cavity introduced into the ship structure and rotates around a large main bearing. Most FPSOs are passive, allowing the vessel to freely rotate about the turret. In some turret designs, the turret position is controlled with an active drive mechanism: this is known as an active turret. Most FPSOs are permanently moored to the seabed. There has been a recent trend to disconnectable turrets where the mooring spider with associated mooring and flexible riser connections can be disconnected to leave a mooring buoy which floats submerged about 50m below the sea surface. The most elegant examples of this are in the Submerged Turret Loading (STL) and Submerged Turret Production (STP) systems developed by APL in Norway where the whole turret itself disconnects to float under neutral buoyancy below the sea surface.

Initial external turret system designs had a single axial swivel connected to a flexible riser. More recent designs have used complex multiple swivel assemblies for fluid transfer bringing production fluids from 30 or more wells and these are generally internal to the vessel. Such designs are extremely complex. As well as the swivel itself the turret may include turret transfer systems, multiple flexible riser connections, axial and radial bearings, pipes for process fluid and well injection, multiple seals, valves, initial separation assemblies, mooring attachments and securing bolts. The probability of failure here is clearly more severe than for a single swivel joint.
Since the first FPSO was installed in the UK sector in 1986 there has been considerable evolution in design. Swivels have evolved from simple axial swivels, to toroidal swivels, to multiple swivel assemblies to compact swivels with a solid internal core. There has been an increase in pressure rating to handle the more difficult conditions of marginal and High Pressure High temperature (HTHP) fields. A fluid transfer design developed in Norway has used a drag chain system as an alternative to the swivel: this provides only partial weathervaning but removes the need for rotating swivel components and dynamic seals. Advanced Production Loading (APL) in Norway have developed the STP system, an elegant alternative to the conventional turret with a disconnectable turret buoy. Turrets have become larger and handle an increasing number of wells. This has introduced considerable complexity in the turret transfer systems: which initially were simple manifolding, but are now more complex structures that fully enclose the swivel, such as in the recent Terranova FPSO. Disconnectable versions of conventional turret designs have also evolved which have been designed for operation in more severe climatic conditions.

2.7 CONNECTION AND DISCONNECTION

All FPSOs in UK waters are permanently installed with the exception of those with STL and STP disconnectable turret systems. In conventional turrets the FPSO is brought to station and connected to the catenary moorings. The flexible risers are pulled through the turret using the crane and then connected usually at above deck level. Installation and connection can take several days or weeks and disconnection is not straightforward. The cost to mobilize the installation system for a conventional FPSO was quoted by one contact as close to $50M.

World-wide there are several FPSOs with disconnectable versions of conventional turrets; more common in external than internal turrets. In these cases the moorings and flexible risers are attached to a disconnectable mooring buoy, held under tension at the bottom of the turret. The mooring buoy can be simply disconnected and float about 30-50m below the sea surface under its own buoyancy, allowing the FPSO to sail off. To reconnect, the mooring buoy is pulled up using the crane and winch on board the vessel. This is illustrated below in Figure 9. For the STP and STL systems found in the North Sea the whole conical shaped turret can disconnect from the FPSO and float subsea; this is described as a turret-buoy.
Figure 9
Illustrations of an SBM disconnectable internal turret. Left illustration-Connected. Right illustration – mooring buoy disconnected and floating subsea still attached to the catenary moorings and flexible risers

Courtesy SBM
3 GENERAL ISSUES

3.1 SHIP STRUCTURE

Each type of turret places a different burden on the surrounding structure, once in operation. For this reason the interface between turret and ship structures is an area requiring considerable analysis. The method of analysis is laid down by the Classification Societies and is detailed in a later section of this document.

The motion of a vessel in a seaway depends on a very large number of factors that includes the following:

- Hull form (position of centre of buoyancy and in particular the shape of the waterplane)
- Position of the centre of gravity (which is variable depending on loading condition)
- Windage profile
- Mooring line tension

As a result, each vessel will have a unique character with respect to motions. This in turn produces a unique loading profile on the turret and the surrounding structure. Each designer/building yard will, therefore, develop a unique structural arrangement for each vessel. Thus the vessel’s structural detail is not dependent upon the type of turret system and will vary from vessel to vessel. The vessel’s structural detail is not, therefore, included in the scope of this document.

3.2 GENERAL SYSTEMS AND ARRANGEMENTS AFFECTING THE TURRET

One of the first concerns of the designer is the minimising of the vessel’s motions when moored. A key consideration in this respect is the ease and speed with which the vessel will weathervane around the mooring. Some vessels weathervane “freely” while others, such as those fitted with the Drag Link system, will not. Clearly free movement offers reduced thruster fuel consumption as well as the associated monitoring and maintenance effort.

The weathervaning or aligning moment on the vessel is the product of the elements’ force on the vessel side and the longitudinal distance of this force from the turret mooring. Thus the longitudinal position of the turret is related to the weathervaning action. If a turret is placed at the centre of the weather’s lateral effort, the vessel may not weathervane at all.

In order to facilitate weathervaning the designer is keen to locate the turret as far forward as possible and in this respect the external turret systems have an advantage over the internal systems. In addition, external turrets do not require any internal volume of the vessel, leaving a higher proportion of vessel volume to cargo storage or other revenue related activities.

There are, however, adverse effects in having the turret located at the forward extremity of the ship. Firstly, if the turret is very close to, or beyond the vessel’s bow, the accommodation block must be located aft and downwind of the swivel stack: the stack being a potential critical item for leakage. Secondly, with waves striking at the bow which is a long way forward of the centre of gravity, the motions of a vessel are the most severe at the bow. When moored in deep water these motions can produce a “dynamic amplification” of the loading in the risers.

The turret location and the vessel’s arrangement require a bargain to be struck between these effects. For many North Sea vessels the turret mooring is located forward of all the cargo tanks. In the case of the Schielhallion FPSO, which was designed for deep water, the turret was located aft of the first pair of cargo tanks in order to reduce the dynamic effects on the risers.
3.3 MOORING SYSTEMS AND TURRET LOADING

If one ignores their own static weight, the loads in the mooring lines depend only upon the vessel’s motion. The motion, in turn, depends on a multitude of factors which naval architects find difficult to evaluate. The previous section discussed the effects on motion of the longitudinal location of the turret and the depth of water/length of risers. The vessel’s hull form and stability characteristics also play an important role on motions: not to mention the weather and sea conditions. This document does not propose to discuss these meteorological, statistical and naval architectural issues. The cable to turret connection, however, lies on the boundary of inclusion in the scope of this document and being a safety critical element, is afforded a degree of attention.

Given that the motions of the vessel cannot be precisely calculated even for specified climatic conditions, it is clear that in a real, unpredictable seaway the loading in each cable attachment must also be difficult to forecast. Even predictions resulting from model tests are limited by the imprecision of inexact non-dimensional factors.

The cyclical effects of waves means that, even if the actual loads are only marginally larger than those anticipated at design time, the effects of fatigue in the cable to turret attachments can be critical. Those turrets in which the mooring lines are brought within the body of the turret before being connected would tend to endure less movement at the point of connection and therefore tend to suffer less from abrasion and fatigue than those where the connection is made at the turret exterior. In either case, however, there are no generic means of attachment that can be related to turret types.

3.4 SCAFFOLDING AND SUPPORT STRUCTURES

Not all of the structure is provided to resist motion induced loading. Some of the structure is provided to allow access to equipment and to protect personnel and the equipment from the elements. Such issues are to be considered at the design stage, but there is no detailed requirement for how the access and protection is to be provided. Once again, each designer and yard will have it’s own methods.

It is a fact, however, that the better a vessel weathervanes, the more predictable is the direction of attack from wind, rain and greenwater on the deck. Thus the structure provided for protection from the elements on the better weathervaning vessels can be more “focused” and thus less plentiful.

3.5 PERSONNEL ON BOARD

There are typically 30-40 people on board a modern FPSO compared to a larger number on a conventional offshore oil installation. Some of these will be involved in ship related activities and not specifically with oil production. This dual role as a marine vessel and oil production unit with personnel from both backgrounds has safety implications. Modern practice is to incorporate both as a single team.

Very few of these personnel will be present in and around the turret. This would be, for example, if they were involved in visual inspection and maintenance procedures on the turret system, installation or aspects of turret operation. For modern FPSOs, personnel may also be present during disconnection and reconnection of turret buoys. A dedicated team of 3-4 people is not uncommon for swivel and turret system maintenance.
3.6 CONSTRUCTION STANDARDS

Most early FPSOs are based on tanker conversions. Indeed this is favoured by the surplus of such vessels World-wide. The way in which the specific structural requirements for the turret cavity are met is shipyard and design dependent. As the technology has evolved, there have been practical advantages in using new-build FPSOs constructed to specific designs. This design can take account of the dynamics and stress environment of a single-point moored FPSO, which are different to those of a marine vessel. This may include double hull construction, stabilisers and dynamic positioning devices.

It is desirable, but not always the case, that above deck structures and process plant on FPSOs should be properly constructed in accordance with offshore standards. This should also be the case for the turret system. We believe this to be the case in modern new-build FPSOs in the UK and Norwegian sectors. Construction of FPSOs, however, is often subcontracted out, for example to shipyards in the Far East. There have been instances where process plant fabrication has followed shipyard rather than offshore standards. The practical consequence of this is reduced wall thickness in piping and poorer weld quality, which becomes evident on field inspection. The operator should specify the standards to which the plant has been designed and if ‘off the shelf’ components are used, should modify or reject any substandard systems. There are cases where offshore standards may also be inadequate, for example in tank over/under pressure devices. These are issues that should be considered in the context of the Design and Construction Regulations (DCR) requirements.
Figure 10
Captain FPSO under construction. Drag chain system on top of turret for fluid transfer
Figure 11
Top, double hull construction Terra Nova FPSO
Figure 12
Turret cavity on deck with turret inserted – Terra Nova FPSO
4 TURRET SYSTEM COMPONENTS AND TYPES

All FPSOs currently operating in the North Sea have internal turrets. An external turret would not be suitable for the adverse wave and weather conditions; though could be possible in sheltered inland waters such as Liverpool Bay where a wishbone structure is already present. With these delineations, the turret can be seen to have two discrete functions:

- To provide single point mooring (SPM) via catenary mooring to the seabed.
- To allow weathervaning or rotation of the FPSO vessel in response to weather and sea conditions

The key factors in turret design are the riser loads, the bearing loads, the turret loads and the movements or weathervaning. The diameter of the turret is dictated by the need to accommodate the risers and umbilicals coming from the subsea wells. This may typically vary from 5 to 20m. In an active turret there is a drive mechanism usually assisted by thrusters to give controlled rotation of the turret. An active drive is necessary because of the gliding pad bearing used, which has higher friction, and to give control on weathervaning, which is important for partial weathervaning systems and which is advantageous for unloading.

![Cross-section through the Terranova FPSO Internal Disconnectable Turret (IDT) showing the major systems. Courtesy SOFEC](image_url)
4.1 MAJOR COMPONENTS AND BOUNDARIES
The major components and interfaces in a turret system have been described earlier in Section 2.3. The turret system comprises four main parts:

- **Turret (T)** provides the mooring and weathervaning of the vessel
- **Fluid transfer system (FTS)** transfers the process fluids and other signals from the turret to the vessel - normally a multiple swivel assembly
- **Turret transfer system (TTS)** or turntable which links the turret and the FTS
- **Interfacing systems (IS)** including, swivel access structure, mooring lines and flexibles below the turret and other ancillary equipment.

Each of these four parts of the turret system is now considered separately.

4.2 COMMON COMPONENTS IN TURRET (T)

The term *turret* is used here only to refer to the cylindrical part of the turret system that allows weathervaning of the vessel and provides single point mooring to the sea bed. This is the majority of the turret system, and comprises all the parts except for the fluid transfer system (FTS), the turret transfer system (TTS) and interfacing systems (IS) which are considered separately below. Flexible risers, bend-stiffeners, umbilicals and mooring lines where they lie within the turret section are considered to be part of the turret.

The common components found in a typical FPSO turret can be seen in Figure 14 and are as follows:

- Turret drive assembly - gripper or hydraulic
- Turntable to turret transfer system (TTS)
- Flexible riser connections
- Umbilicals
- Bolting
- Upper or main bearing assembly
- Upper bearing support vessel deck
- Turret shaft
- Channels for flexible risers
- Flexible risers (within the turret)
- Channels for mooring chains (some designs)
- Lower bearing assembly
- Turret casing
- Moonpool or turret cavity
- Access to moonpool
- Mooring chains
- Fairleads (some designs)
- Winches one per well (some designs)
- Chain stoppers and tensioners
- Mooring spider or buoy (disconnectable systems)
- Riser buoy connector assembly tensioner (disconnectable systems)
- Bend-stiffeners

These components have the following functions:
4.2.1 Turret drive assembly - gripper or hydraulic
Most turrets are passive and freely weathervane. An active drive is used primarily in the Tentech design of turret which has hydraulically-assisted pad bearings for the main bearing. The increased friction for this bearing type requires an active drive.

4.2.2 Turntable to turret transfer system (TTS)
There will usually be a turntable representing the interface between the turret and the manifolding in the TTS.

4.2.3 Flexible riser connections.
This is a key and safety critical part of the turret because of the risk of hydrocarbon leakage. The connection usually takes place above the turret to the manifolding or TTS system. For disconnectable turrets the risers from the seabed will be connected near the interface of the mooring buoy. In this case there will be additional connections within the turret shaft.

4.2.4 Umbilicals
Various umbilicals will pass through the turret system; for example electrical supplies, signals or for chemical, water or gas injection.

4.2.5 Bolting
As with other large slew-ring bearings, bolts are an important component to hold the parts of the bearing assembly together. Bolting and loading pins will also feature elsewhere in the turret for example in mooring connections.

4.2.6 Upper or main bearing assembly
The main bearing assembly is usually located at the top of the turret and allows the vessel to weathervane about the turret. This is the main region for load transfer between the turret and the vessel. The standard configuration is a three-roller bearing, with axial bogey bearing systems sometimes preferred for larger diameter turrets (~20m). Tentech IAT designs of turret use hydraulically-assisted vertical and horizontal pad bearings. Alignment and proper maintenance of the main bearings is essential. Some smaller diameter SBM internal turrets have the main bearing at the bottom (Figure 15) which differs to the usual convention.

4.2.7 Upper bearing support vessel deck
A large forging is usually welded to the vessel deck to support the loads on the vessel side of the turret bearing. This is an important area because of the high loading it will incur.

4.2.8 Turret shaft
Contains the riser tubes for risers and umbilicals that are pulled in and hung off the top of the turret shaft. Axial and radial bearings allow the turret to rotate within the turret casing and transfer loads to the vessel structure. The turret may freely rotate with segmented roller or bogey bearings or may be assisted where large guided ring bearings are used, which have higher friction levels. The bearing type and location depends on turret design. The turret shaft is protected from corrosion by the use of sacrificial anodes.
Figure 14
Cross Section of an FPSO turret system showing the main components. The *turret* here refers to the main cylindrical part of the turret system providing the weathervaning and single-point-mooring and excludes the FTS and TTS also shown.
Figure 15
Cross-section through two SBM FPSO turrets. Top- large diameter turret with axial bogey as main bearing. Bottom – with three-roller main bearing, in this case located at bottom of turret.

4.2.9 Channels for flexible risers
The flexible risers will usually pass through channels in the turret shaft. In some designs they are accessible within the turret.

4.2.10 Flexible risers (within the turret)
Production fluids are carried through the turret on flexible risers, which are tied off onto the turret transfer system or to the mooring buoy interface in disconnectable systems. The flexible risers, bend-stiffeners and connections are important safety critical elements in all FPSO turret designs.
4.2.11 Channels for mooring chains (some designs)
Typical mooring attachment is via pad-eye connections to the bottom of the turret, mooring spider or mooring buoy. These connections can usually only be accessed via diver or remotely operated vehicle (ROV). In some turret designs such as the Tentech Internal Active Turret (IAT) the mooring chains pass up through the turret over fairleads and winches. This allows mooring tension to be controlled and for the chains to be drawn up on deck for inspection of the first 25m.

4.2.12 Lower bearing assembly
This provides the load bearing interface between the turret and the turret casing in the lower part of the turret in the moonpool. The loading is much less than for the main bearing and this bearing mainly provides alignment. Lower bearings are usually bronze pad bearings. Although designed to operate in seawater, the bearings are protected by a seal.

4.2.13 Turret casing
In a conventional internal turret, this includes pre-aligned upper and lower bearings and drops quickly into the vessel's hull as a single unit. Very little additional hull reinforcement is required for maximum speed and economy.

4.2.14 Moonpool or turret cavity
Refers to the vessel structure adjacent to the turret and the access space here between the turret and vessel. This area is known as the moonpool because it is partially filled by seawater. The surrounding vessel structure is prone to ovality on dynamic loading and can be subject to fatigue cracking. Accessibility will depend on turret design; approximately 0.8m clearance for a Tentech internal active turret (IAT) design. In STP and STL systems this area is known as the STP room or STL room, respectively, and contains the compact swivel.
4.2.15 Access to moonpool
Access to the turret cavity or moonpool will depend on design and in some cases will be inaccessible because of the main bearings. For Tentech turrets access is facilitated by the simple design of the turret pad bearings and there is about 0.7m of clearance.

4.2.16 Mooring lines
These are commonly chain, wire and then chain leading to piled anchors. Polymer rope is used in some deeper water applications. The flexible risers are an integral part of the mooring system and allowed for in design calculations. The mooring chains are usually connected by pad-eye connections to the bottom of the turret, mooring spider as applicable; or mooring buoy for disconnectable turret systems such as the STP and STL systems in the North Sea. In the Tentech IAT Turret the chains pass up through the turret over fairleads and winches and can be controlled or pulled topside for inspection. Examples of mooring lines and connections are shown in Figure 17, Figure 18 and Figure 19.

4.2.17 Fairleads (some designs)
In some designs the chains are pulled up over fairleads as described above. See Annex B under IAT turret.

4.2.18 Winches one per well (some designs)
In some designs the chains are pulled up on winches located within the turret as described above. See Annex B under IAT turret.

4.2.19 Chain stoppers and tensioners
Mooring connections are usually by pad-eye connections and may include chain stoppers and tensioners. The mooring chains may pass through chain guides or over fairleads.

4.2.20 Turret shaft/mooring spider interface
In some turret designs, for example Bluewater turrets, a separate welded steel section known as a *mooring spider* is connected to the bottom of the turret shaft either by a bolted, or more typically, welded connection.

4.2.21 Mooring spider (some turret designs)
This is a separate section bolted or welded to the bottom of the turret. Mooring lines are pulled in and stoppered off here to pad-eye connections on the *mooring spider*. Different suppliers have their own proprietary mooring configurations designed to facilitate access to the turret for the flexible risers. For example, Bluewater use a 120° three bundle configuration. Many designs of turret do not have a separate mooring spider and mooring connections are simply made to the bottom of the turret or pulled through under tension - as in the Tentech IAT design.

4.2.22 Mooring buoy (some turret designs)
In disconnectable systems the mooring spider is a separate section which disconnects to form a separate *mooring buoy*. When disconnected this rests subsea at a depth typically of 35-50m. The mooring buoy is held in place by a tensioner. The interface with the turret is a safety critical region because of the presence of flexible riser connections and seals.

4.2.23 Tension connector (disconnectable systems)
This is found in disconnectable systems and holds the mooring buoy in position to maintain the integrity of the interface and seals and to reduce bending moments.

4.2.24 Bend-stiffeners
Where the risers come into the bottom of the turret, high bending moments can be encountered. This is countered by use of bend stiffeners around the riser to accommodate and spread out the
bending moments. These are usually a compound metal/elastomeric component and are conical or double conical in shape.

Figure 17
Mooring connections, Submerged Turret Loading (STL) turret-buoy.

Courtesy APL
Figure 18
Typical mooring wire for catenary mooring of Submerged Turret Loading (STL) turret-buoy. Courtesy APL.

Figure 19
Typical anchor chain for mooring, Submerged Turret Loading STL turret buoy. Courtesy APL.
4.3 TURRET BEARINGS

The turret itself is a relatively simple technology constructed from welded steel components. A large forging is welded on the top of the turret, and another large forging welded on the vessel turret cavity to provide support for the bearing raceways and housings.

The turret bearing technology has evolved from other marine applications such as mooring buoys and the large slew-ring bearings found in cranes. This technology is well established, but not without operational difficulties. The bearing raceways for turrets are huge, from 4m up to 20m in diameter, and require precision forgings usually made by specialist manufacturers from a low-carbon steel such as EN30A with the raceways being case-hardened.

Most turrets have two main bearings. The top bearing is the key load-bearing component and in most turret designs is a roller or axial bogey. An axial bogey is a combination of small aspect rollers or wheels on an axle within a metal grid or containment. The top bearing takes all the axial loads and the weight of the turret. Such bearings may also be configured to take radial loads.

The second or bottom bearing is usually a radial bearing, using either wheels or segmented pads that centralises and maintains the alignment of the bearing. This is situated lower in the turret cavity and often at keel level. This serves more for alignment and is not usually heavily loaded. Note that in this report the terms axial and radial refer to the direction of the load taken by the bearing. An alternative definition in terms of the axis of the turret or wheel is sometimes used in Safety Cases.

Such bearings are generally slow moving and damage is slow and progressive. Because of the sealing requirements, such bearings are not readily accessible for maintenance. If a problem does occur with the turret bearings, it can be slow and costly to put right. The large cylindrical forgings or slew-rings that provide the bearing surface for the raceway are produced by only a few specialist suppliers and are custom built. Ulstein, SKF/RKS, Roth Erd and AmClyde are the main suppliers of turret bearings for FPSOs. A consequence of this is that replacements may take many months to procure. Therefore, it is crucial that bearing condition and functionality is regularly monitored.

It is not possible to divorce the bearing performance of large turret bearings from that of the seal and the structural support. Alignment is also crucial. It is important for the inspector to ascertain that the factor of safety allowed for in bearing design is realistic in terms of the level of loading as the bearing will amplify loads according to the cube rule (see below). This will have a major impact on fatigue loading on the vessel structure and frictional load on the bearings.

4.3.1 Main Bearing Configuration

The actual bearing configuration will depend on the turret manufacturer. It is usually true that the same configuration will be used by a given manufacturer. There are exceptions where the operator may have a design preference, for example in Petrojarl a freely weathervaning axial bogey was preferred by the operator to the standard pad bearings used in all other Tentech turrets. Bluewater turrets have a top axial roller bearing with a segmented radial pad bearing at keel level that is functional in seawater, but which is protected by an elastomeric seal. SOFEC and SBM turrets invariably use an axial bogey for the top bearing for larger diameter turrets, but roller bearings for smaller diameter turrets. For example, a bogey system was used on BP’s Schielhallion FPSO in the North Sea. The axial bogey system which is most commonly used is
a system developed by AmClyde (Figure 20). This is more accessible for maintenance than a roller bearing.

*Tentech* turrets, described in this report as internal active turrets (IAT) have a proprietary gliding turret design with 200 axial and radial pad bearings supporting the turret. This is accessible above deck level and simple to inspect and maintain. Individual pads can be replaced and minimal lubrication is required. Because of the greater friction associated with pad bearings an active drive is required. The submerged turret loading (STL) and production (STP) turrets have a detachable conical buoy in place of a conventional turret. This has an integral sliding bearing which takes the axial and radial loads and can operate reliably in seawater.

![Figure 20](image_url)

**Figure 20**

*AmClyde axial bogey system for the main turret bearing of FPSOs.*

*Courtesy AmClyde*

**Roller or wheel bearings**

Roller or wheel bearings are not stiff and rely on the stiffness of the supporting structure to give rigidity. Therefore, it is crucial that the stiffness of the supporting structure is taken into account. Such bearings are grease lubricated, freely rotate with very low friction, and are suited for turrets which need to move passively or freely weathervane. A consequence of the rolling contact is that damage and load transfer is amplified according to the cube rule:

$$\text{Damage, Load } \propto \sigma^3$$
Where $\sigma$ is the stress. Small changes in stress will have a major impact on loading. The consequence of this is that any lack of stiffness in the supporting vessel structure will be amplified thus increasing the loading on the turret bearings and increased wear. For example, doubling the stress on the vessel structure will give 8x the load on the bearing. Conversely any misalignment or increased frictional loading on the bearing will lead to amplified stresses in the vessel structure. This is particularly a problem in tanker conversions though design errors can also occur in new build. Cracking of the supporting vessel structure is not uncommon.

It is important, therefore, for the inspector to ascertain that the factor of safety allowed for in design is realistic in terms of the level of loading. This will have a major impact on fatigue loading. Checking of bearing alignment is crucial, as any misalignment will generate large bending moments which will be amplified by load transfer through the bearing in a similar manner.

The bearing integrity will also depend on the quality of the sealing. Sealing is required to keep out the environment - protecting from sea, saltwater or dirt - and for retaining the lubrication. The seal may also assist in controlling bearing alignment and position and in limiting deflections of the bearings. Sealing is usually done with an elastomeric dynamic seal. In practice the seal is usually a compound structure of elastomeric, polymer and metal components. Seals are vulnerable to vibrational damage and also to contamination. Explosive decompression of the seals is not an issue for the turrets, but is an issue for dynamic seals on the swivels.

### 4.3.2 Gliding or pad bearings

The alternative to roller or wheel bearings is gliding or pad bearings. The pads are usually made of lubricated manganese bronze which, as with wheel and roller bearings, glides along a solid ring or raceway. Such bearings are often segmented. There are two technologies: pocketed bronzes in which bronze is inserted into drilled holes to reduce the friction coefficient, or oil/grease lubricated bearings. Other liquid lubricants may be used as well. Lubrication is more important in sub-sea bearings as these can be subject to saltwater attack.

An example of a sliding bearing that passively rotates is the main bearing for the STP turret-buoy, as shown in Figure 21. The STP turret buoy has an integral sliding pocketed bearing within the buoy that allows the vessel to rotate without requiring an active drive. This is lubricated by seawater and rotates freely not requiring any active drive.

![Figure 21](image)

**Figure 21**

Sliding pocketed main bearing, STP turret buoy. Spare bearing on wooden racks at APL Arendal, Norway. Courtesy APL.
The pad bearing for the main bearing of the Tentech internal active turret is shown in Figure 22. Approximately 200 of these are used on each turret, vertically and horizontally, and they are easily inspected and replaced. Sliding pad bearings have a significantly higher friction coefficient than roller or wheel bearings. However, they are much simpler to deploy, inspect and maintain. Over lubrication can, however, lead to corrosion pitting.

Figure 22
Bearing Pad used for main axial and radial bearings in Tentech internal active turret (IAT). Courtesy Maritime Tentech AS
4.4 TURRET TYPES

Details of the turret design will vary with the manufacturer. It is possible to classify these into five main types of internal turret and three main types of external FPSO or FSU turret, as summarised in Table 2. There is not a fundamental difference between internal and external turrets, though the latter are generally simpler and smaller and service fewer wells. Both external and internal turrets may be disconnectable, though this is more usual for external cantilevered turret designs.

Of the five main types of internal turret designs, only the first four are currently found in the UK sector of the North Sea. It is a slight misnomer to talk about ‘generic’ turret types since the design of a turret will depend on the field requirements, how many wells are serviced and what other functions are required. Yet the turret types noted above are sufficiently different to have unique features and is a suitable way to classify the turrets.

The STP and STL turrets represent radical departures from conventional turret design. Here the whole complexity of the turret is replaced by a simple disconnectable *turret buoy* used with a compact swivel. The Tentech (IAT) turret is an active turret centrally located and has a unique pad bearing design. The ITD disconnectable turret is in many ways similar to the conventional internal turret, but the bottom half of the turret may disconnect from the vessel as a mooring buoy.

An alternative way to delineate turret types would be in terms of the turret manufacturers themselves, since each has a specific solution to key elements of the turret including the turret bearing and the mooring configuration. In each case there has been a gradual evolution in design, yet there are features that are characteristic of each turret supplier.

Main turret suppliers worldwide are: Advanced Production and Loading AS (APL), Bluewater Engineering BV, Maritime Tentech AS, SBM and SOFEC. Other turret suppliers World-wide for specific FPSOs have included Astano, El Ferrol, Golar-Nor Offshore, IMODCO, Nortrans Offshore Limited. Main suppliers of *swivel* systems are Bluewater BV, Brown Brothers Limited (now part of Rolls Royce Marine), Framo A.S , SBM and SOFEC. Main supplier of *drag-chain* systems are the cable management company METOOL with the design owned by Maritime Tentech AS

Mooring buoys and loading systems either separate to the vessel or integral but not including turrets such as CALM, SALM, SALS and CALRAM are not included in this study. These are, however, included in the Glossary in Annex G.
<table>
<thead>
<tr>
<th>Location</th>
<th>Turret System</th>
<th>Permanent/Disconnectable</th>
<th>Main Suppliers</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Internal</strong></td>
<td>Internal Passive Turret (IPT)</td>
<td>Permanent</td>
<td>Bluewater, SBM, SOFEC</td>
</tr>
<tr>
<td></td>
<td>Internal Active Turret (IAT)</td>
<td>Permanent</td>
<td>Maritime Tentech AS</td>
</tr>
<tr>
<td></td>
<td>Internal Disconnectable Turret (ITD)</td>
<td>Disconnectable</td>
<td>SOFEC, SBM</td>
</tr>
<tr>
<td></td>
<td>Submerged Turret Production (STP)</td>
<td>Disconnectable</td>
<td>Advanced Production and Loading (APL)</td>
</tr>
<tr>
<td></td>
<td>Submerged Turret Loading (STL)</td>
<td>Disconnectable</td>
<td>Advanced Production and Loading (APL)</td>
</tr>
<tr>
<td><strong>External</strong></td>
<td>External Cantilevered Turret (ECT)</td>
<td>Permanent</td>
<td>SOFEC, SBM</td>
</tr>
<tr>
<td></td>
<td>External Disconnectable Turret (EDT)</td>
<td>Disconnectable</td>
<td>SOFEC, SBM</td>
</tr>
<tr>
<td></td>
<td>External Wishbone (EW)</td>
<td>Swivel-No Turret</td>
<td>Various</td>
</tr>
</tbody>
</table>


4.4.1 Internal Passive Turret (IPT)

In harsh environmental conditions more effective single point mooring of an FPSO vessel can be achieved by use of an internal turret mooring system. Most North Sea FPSOs are of this type. A cylindrical turret casing and turret shaft is dropped into a cavity in the vessel’s hull. The turret casing contains prealigned axial and radial bearings that hold the turret in place and allow the vessel to weathervane freely 360\(^\circ\) around the turret to adjust to climatic conditions. The turret provides passive single-point mooring to the seabed. Fluid transfer to the process system is usually undertaken using a multiple swivel assembly mounted on top of the turret at deck level. In the conventional 'permanent' system the flexible risers and umbilicals are pulled up individually through the swivel and connected above the top of the shaft to the swivel assembly. The turret diameter is typically 5-10m but can vary from 4-20m depending on the number of wells involved. Moorings are usually evenly spaced in bundles, say at 120\(^\circ\) intervals (3x3), to facilitate access for the risers and umbilicals. Disconnection of permanent turret systems is slow and not straightforward.
Figure 23
BP Schiehallion FPSO with SBM Internal Passive Turret (IPT). Courtesy SBM

Figure 24
Petrobras 35 FPSO Marlim Field with IMODCO Internal Passive Turret (IPT).
Courtesy Petrobras
Figure 25
SOFEC Internal Passive Turret (IPT) in Petrobras 31 FPSO.
Courtesy Petrobras
4.4.2 Internal Active Turret (IAT) – ‘Tentech’ Design

This design is used in the Captain and Gryphon FPSOs in the UK sector and in seven FPSO turrets in the North Sea including Norne. Within the industry it is more commonly referred to as a Tentech turret. In this report the term Internal Active Turret (IAT) is used. This turret represents a significant evolution from conventional turret designs and has a number of unique features designed to facilitate turret operation and maintenance. This includes a gliding pad bearing system above deck that is very accessible allowing individual pads to be replaced. The higher friction for this compared to normal passive roller or wheel bearings requires an active drive, this also gives control over turret rotation, which is particularly useful in offloading.

The turret can uniquely accommodate both 'drag-chains' or swivels for fluid transfer. Of the seven IATs currently used in the North Sea, four use a ‘drag-chain’ as the fluid transfer system (FTS). The turret itself allows full unrestricted 360° weathervaning, but is restricted to 270° if a 'drag-chain' is used. The turret diameter is dictated by the number of risers it needs to accommodate and is not inherently larger than conventional turret types.

The large turret diameter needed to accommodate the 20 or so risers commonly used and the rotational limits when used with a 'drag-chain' transfer system dictate that the turret be positioned midships or near the vessel’s third-point. There are pros and cons to this, see Section 3.2. This is in fact a preferred design option and has safety benefits with firewalls between the turret and the process plant and allowing accommodation to be placed securely upwind away from the turret. Location here allows a large number of risers to be accommodated.

![Texaco Captain FPSO with 'Tentech' Internal Active Turret (IAT) and drag-chain for fluid transfer system (FTS). Courtesy Maritime Tentech AS](image)
Figure 27
Statoil Norne FSPO with Internal Active Turret (IAT), in this case fitted with a multipath swivel for fluid transfer. Courtesy Statoil
4.4.3 Submerged Turret Loading (STL)

The basis of the STL system is a conical *turret-buoy* moored to the seabed. The buoy is pulled into and secured in a mating cone in the bottom of the vessel and thus connecting the mooring system. Internal in the buoy is the turret with connections to the mooring and riser systems. The outer buoy hull can rotate freely with the vessel around the center of the *turret-buoy* by means of internal turret bearings. Oil is transferred through a *compact swivel* via the loading manifold to the piping system of the vessel. When disconnected, the buoy will float in an equilibrium position ready for a new connection.

![Schematic of Berge Hugin submerged turret production (STP) System, Pierce Field, showing the conical 'turret-buoy' locked in place in the mating cone in the turret cavity. Courtesy APL](image)

Figure 28

*Schematic of Berge Hugin submerged turret production (STP) System, Pierce Field, showing the conical 'turret-buoy' locked in place in the mating cone in the turret cavity. Courtesy APL*
Figure 29
Left: STL turret buoy recovered after 5 years service and, right, unused spare. APL shipyards Arendal near Kristiansand, October 2000.

Figure 30
STP turret buoy Lufeng field with Framo compact swivel stack for FTS system. Courtesy Advanced Production and Loading AS (APL).
4.4.4 Submerged Turret Production (STP)

This is an elegant adaptation of the STL system to allow production as well as loading and is a much more compact design than conventional turrets. The basis of the STP system is a conical buoy moored to the seabed. The buoy is pulled into and secured in a mating cone in the bottom of the vessel, thus connecting the mooring system. Internal in the buoy is the turret with connections to the mooring and riser systems. The outer buoy hull can rotate freely with the vessel around the turret by means of internal turret bearings. Oil is transferred through a compact multiple swivel via the loading manifold to the process system of the vessel. The turret is submerged and has water lubricated bearings. When disconnected, the buoy will float in an equilibrium position ready for a new connection. The STP Turret buoy shares the same standard interface and conical profile as the STL buoy, but is larger in order to accommodate the greater number of risers. In addition there is an additional flotation tank on the bottom of the turret-buoy (Figure 31) and bend-stiffeners on each of the flexible risers.

Figure 31
Submerged Turret Production (STP) disconnectable turret-buoy and Framo compact swivel stack, Pierce Field. The conical buoy can be disconnected and float submerged 30-50m below the surface. The compact swivel sits inside the turret cavity, known in this case as the STP room. Courtesy APL
4.4.5 Internal Turret Disconnectable (ITD)

In recent years, disconnectable versions of conventional internal turret systems have been developed. In most aspects of turret operation these are similar to the permanent systems. The moorings and risers are connected to a separate mooring buoy that can be swiftly disconnected from the main turret and drops to about 40m below the sea surface. This permits the vessel to disconnect and reconnect to the mooring, in the case of severe weather conditions or for maintenance requirements. Time for riser and buoy disconnect is typically one hour and time for reconnect typically 3 hours. The mooring buoy is retrieved and pulled near the turret by a winch and chain jack system, aligned and pulled into position. Connection is made with a collett connector and the risers are then pulled through the turret shaft and attached for operation. Disconnectable systems potentially offer safer operation and reduced pollution risk in offshore areas subject to seasonal adverse weather conditions. An example of this type is the Terranova FPSO. A disconnectable SBM turret of this type is shown in Figure 32. No turrets of this type are currently in UK waters.

Figure 32
Internal Disconnectable Turret (IDT) - Huizhou Field South China Sea.
*Courtesy SBM*
Figure 33
Top - Schematic section through SBM Internal Disconnectable Turret (ITD). Bottom - mooring buoy onshore in disconnected state. The SBM version of this turret type is known as Buoyant Turret Moored (BTM). Courtesy SBM
4.4.6 External Cantilevered Turret (ECT)

The turret consists of a swivel or multiple swivel assembly mounted on a cantilevered support structure attached to the bow of the vessel. Mooring connections to the turret provides single point mooring to the seabed and allows the vessel to rotate freely around the turret adjusting to climatic conditions. The risers from the well are connected to the swivel. FPSO vessels of this type with conventional or multipath swivels can take oil production from several wells. No external turret FPSOs are found in the North Sea as the design is not suited to the adverse weather and wave conditions.

One recent FPSO of this type, the Petronas Carigali FPSO in the MASA Field in Malaysia, included a multipath compact swivel produced by Framo in Norway and is similar to the fluid transfer technology encountered in internal turret systems.
4.4.7 **External Turret Disconnectable (ETD)**

This is similar to the external cantilevered turret but has a tensioned riser connector that enables the riser and moorings to be quickly disconnected and allow the vessel to sail away from the station. Otherwise known as Riser Turret Moored (RTM).

All these turret types are discussed in detail in Annex B including maintenance procedures and what can go wrong.

![Figure 35](Image)

**Figure 35**

FPSO with External Disconnectable Turret (ETD) inset. Otherwise referred to as Riser Turret Moored (RTM). The main photo shows the riser being reconnected to the turret. **Courtesy SBM**
Figure 36
Schematic showing disconnection of an External Disconnectable Turret (EDT). Otherwise referred to as Riser Turret Moored (RTM). Courtesy SBM
4.4.8 External Wishbone (EW)

Early design of external FSO. Connected via a metal wishbone to an axial swivel located on a mooring buoy. No turret as such. Not included further in present study. Example in UK sector is Ailsa Craig FSO.

Figure 37
Liverpool Bay FSO with wishbone attachment to mooring buoy. Inset – examples of wishbone type CALRAM mooring arrangements for FSU vessels
4.5 FLUID TRANSFER SYSTEMS (FTS)

A fluid transfer system (FTS) is needed to accommodate the rotation of the vessel around the turret and allow fluids and utilities (e.g. control signals) transfer. The FTS provides a rotating connector in order to enable the transfer of the hydrocarbons, utilities, and all turret system functions, from the turret to the process pipework on the deck of the FPSO vessel. An FTS is necessary as the turret is geostationary and single point moored to the sea-bed, while the vessel is weathervaning. The alternative is spread-mooring, which is not feasible in the adverse weather and sea conditions pertaining in the North Sea. Full details can be found in Annex C.

Most FPSOs use a multipath swivel stack for fluid transfer. This is otherwise referred to as a multiple swivel assembly. A series of swivel rings, or toroids, rotate on bearings about a central core. The production fluids flow up through pipes in the central core and round a toroidal shaped annulus between the swivel ring and the core, as illustrated in Figure 38. The fluids can exit through outlets in the swivel rings to reach the process plant on the vessel. Multiple dynamic seals prevent escape of hydrocarbon fluids to atmosphere. The central core rotates with the turret. The swivel rings rotate with the vessel as it weathervanes. Torque arms support the swivel stack and limit any sideways movement. The main alternative is the drag-chain system in which the flexible risers are looped in a large cage in a pipe management system, known as the drag-chain. By unwinding this can allow rotation of up to 270° in either direction with no need for dynamic seals.

The swivel is designed to meet the field configuration, the number of wells being serviced and the utilities required. There is a trend towards modularising of swivel components. There is no intrinsic difference between swivels for internal and external turrets, though the latter will generally be simpler and will handle fewer wells. A multipath swivel can handle both import and export functions, for example production, and oil or gas export. Production and gas swivels will have different sealing requirements. The major types of FTS are as follows:

- Simple axial swivel
- Simple toroidal swivel
- Multiple swivel assembly
- Compact Swivel (Framo)
- Drag Chain
- Double Barrel – (Tentech-Conceptual)

4.6 FTS SYSTEM COMPONENTS

The main components associated with a typical multipath swivel stack FTS are as follows:

1. Swivel access structure (Interfacing)
2. Swivel stack
3. Swivel core
4. Torque support arms
5. Tension rings
6. Gas swivel
7. Electrical swivels
8. Utilities swivels (gas, water injection, hydrate prevention etc.)
9. Control and fibre optics swivels
10. High Pressure (HP) Production Swivels
11. Medium Pressure (MP) Production swivels
12. Low pressure (LP) production swivels
13. Connections to turret transfer system (TTS)
14. Swivel outlets
15. Connections and piping to FPSO/Turret Interface
16. Bolting

The majority of these components are visible in Figure 40. More detailed information on individual fluid transfer system designs and components can be found in Annex C.

4.6.1 Swivel access structure
Scaffolding to provide access to different levels of swivel stack for routine inspection and maintenance. In some turret system designs the swivel is surrounded by a firewall. In STL and STP turret designs the swivel sits within the turret cavity or STP room above the turret.

4.6.2 Swivel stack
Name given to the series of swivel rings, internal core and other individual components that comprise the multipath swivel. Tensioning rings separate the individual toroidal swivel rings.

4.6.3 Swivel core
Central internal core of the swivel stack around which the individual swivel rings rotate. Usually contains internal piping to take the production fluids to the appropriate swivel. Compact swivels have a solid core with internal channels, produced by powder metallurgy.

4.6.4 Torque support arms
These support the swivel stack and prevent lateral movement during operation.

Figure 38
Sectional diagram of internals of multiple toroidal swivel assembly showing internal piping and toroidal flow paths, left and bearing and seal arrangements, right. Diagram courtesy Brown Brothers & Co Limited
4.6.5 Tension rings
Springs or intermediate rings provide tension between the individual swivel rings or units on the swivel stack. These prevent vertical movement of the rings which could affect dynamic seal integrity.

4.6.6 Gas swivels
Toroidal swivel rings for transfer of gas produced gas from the turret to the process plant on the vessel turret.

4.6.7 Electrical swivels
Usually slip-rings, these transfer electrical signals to and from the turret.

4.6.8 Utilities swivels (gas, water injection, hydrate prevention etc.)
These transfer utilities operations such as gas or water injection or hydrate prevention through the fluid transfer system to the wells. In early turret system designs, these systems would sit in the turret transfer system (TTS) and rotate with the turret. The utilities swivels allow these systems to be installed on the vessel.

4.6.9 Control and fibre-optics swivels
To transfer control and fibre-optic signals through the fluid transfer system to the turret and production wells.

4.6.10 High Pressure (HP) Production Swivels
To transfer high pressure production fluids from the flexible risers in the turret to the weathervaning vessel. These comprise a toroidal swivel ring with bearings and dynamic seals that rotates with the vessel around the central core of the swivel stack, which is geostationary and fixed to the turntable above the turret.

4.6.11 Medium Pressure (MP) Production swivels
To transfer medium pressure production fluids from the flexible risers in the turret (geo-stationary) to the weathervaning vessel.

4.6.12 Low pressure (LP) production swivels
To transfer low pressure production fluids from the flexible risers in the turret (geo-stationary) to the weathervaning vessel.

4.6.13 Connections to turret transfer system (TTS)
Piping connections usually flexible will transfer production fluids to the swivel stack from the intermediate manifolding above the turret. There will also be connections for utilities, other control signals as well as well control systems such as gas-lift or water injection. In some designs the flexible risers from the turret will feed directly into the bottom of the swivel stack without intermediate manifolding.

4.6.14 Swivel outlets
Outlet from the toroidal swivel rings. This usually comprises bolted flanged connections to hard or flexible piping.

4.6.15 Connections and piping to FPSO/Turret Interface
Hard piping or flexible piping from the outlets on the toroidal swivel rings to transfer production fluids from the swivel stack to the process plant on the vessel.
4.6.16 Bolting

There is extensive bolting within the swivel, for example, holding the bearing housing together in the swivel rings. The amount of bolting is much reduced in compact swivel designs.

Figure 39
Schematic of top part of an internal turret system showing the multipath swivel stack, supporting torque arms and the surrounding swivel access structure
Figure 40
Schematic showing the main components in a typical multipath swivel stack FTS.
Courtesy Brown Brothers
Figure 41
Schematic of multipath swivel and, inset, cross-section through toroidal swivel ring showing the annulus for fluid flow and the sealing and bearing arrangements between the outlet rings and central core. Fluid flows up through pipes or machined forgings in the core and into the toroidal annulus. Courtesy Brown Brothers
4.7 TYPES OF FLUID TRANSFER SYSTEM (FTS)

4.7.1 Axial and Toroidal Swivels

There has been considerable evolution in fluid transfer system design since the first FPSO entered UK waters in 1986. Petrojarl 1 had a simple axial swivel provided by Brown Brothers (Figure 42). Development of the toroidal swivel (which rotates around a central core with dynamic seals) allowed development of multiple swivel assemblies with separate paths for high, medium and low pressure production fluids (Figure 35). In the toroidal swivel, fluid flows round a toroidal or ‘doughnut shaped’ annulus between the swivel rings and central core. The way in which this works can be seen in Figure 38 and Figure 41. Rotation in most conventional swivels is via a 3-roller slew-ring bearing with a double dynamic seal arrangement.

Figure 42
Simple in-line axial swivel for Petrojarl 1 FPSO Golar Nor Offshore. Courtesy Brown Brothers
Figure 43
Replacement simple toroidal swivel for Petrojarl 1 FPSO Golar Nor Offshore.

Courtesy Brown Brothers
4.7.2 Multiple Swivel Assembly (Multipath Swivel Stack)

By combination, toroidal swivels provided the technology necessary to develop multiple swivel assemblies to handle the production flow from larger numbers of wells. These are otherwise known as a multipath swivel stack. Swivel technology also evolved to include swivels for utilities and electrical functions and for gas and water injection as well as gas production. In earlier FPSOs some of these systems would need to have been located on the turret turntable itself.

Figure 44
Left - Production and water injection rings on a conventional multipath swivel, North Sea Producer FPSO, Brown Brothers. The torque arm, tensioners, swivel rings and outlets are visible. Right - Bluewater swivel stack for Petrobras 37 FPSO. Courtesy Brown Brothers, Bluewater
Figure 45
SBM multipath swivel for Statoil Norne FPSO.

Courtesy SBM
4.7.3 Compact Swivel

An important development of this technology is the compact swivel developed by Framo Technology in Bergen that is designed for operation with the STP turret (Figure 46). This has a solid core with internal channels produced by powder metallurgy from duplex stainless steel. This replaces the series of internal pipes in the core of conventional swivels and allows a more compact and much lighter design which can fit internally within the turret cavity in the vessel, known in this case as the STP room. This design includes solid forged outlet rings and is detailed in Annex C.

Figure 46
Compact Swivel for Pierce FPSO Submerged Turret Production (STP), solid internal core duplex stainless steel. Courtesy Framo
4.7.4 Drag-Chain System
The main alternative to a swivel system in North Sea applications is the *drag-chain* system developed by Maritime Tentech and seen in the Captain FPSO. In this system the flexible risers from the turret are directly connected to the process plant on the vessel in an S-arrangement. These are accommodated in a large cage (Figure 47) which rotates with the turret. Associated loads are taken by a large pipe handling system within the cage called a *drag-chain*. The drag-chain is bulky, but gives considerable simplification, eliminating the need for a multipath swivel, dynamic seals and a complex turret transfer system. A full description of the construction and operation of *drag-chain* FTS systems can be seen in Annex C.

By uncoiling the risers this allows partial weathervaning of up to 270 degrees in each direction, sufficient for most applications. The partial weathervaning requires that the turret is centrally positioned in the vessel. Active positioning on the vessel is required and the turret needs to have an active drive mechanism. Flexible hoses are an issue for drag chains. Coflexip, the hose manufacturer, now advises change out of the flexible hoses after 5 years having previously suggested that no replacement would be necessary throughout field life. This fluid transfer system is used exclusively with the Tentech internal active turret (IAT). The benefits of multipath swivels versus drag chains are compared in Table 3.

Figure 47
'Drag-Chain' fluid transfer system on Tentech internal active turret (IAT).
*Courtesy Maritime Tentech AS.*
Examples of METOOL pipe management systems similar to those used for the flexible risers in the Drag Chain fluid transfer system.

Table 3
Benefits of a multiple swivel stack versus a Drag-Chain Fluid Transfer System

<table>
<thead>
<tr>
<th>Fluid Transfer Type</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple Toroidal Swivel</td>
<td>Compact - Can accommodate large number of functions</td>
<td>Complex multiple swivel assembly required</td>
</tr>
<tr>
<td></td>
<td>Pipe diameters up to 24&quot; can be used giving high throughput</td>
<td>Dynamic seals on swivels give risk of hydrocarbon leakage</td>
</tr>
<tr>
<td></td>
<td>Established technology</td>
<td>Complex intermediate manifolding to turret. Main source of FPSO incident</td>
</tr>
<tr>
<td></td>
<td>5000psi operating pressure, up to 7500 psi possible</td>
<td>reports to HSE</td>
</tr>
<tr>
<td></td>
<td>Don't need thruster</td>
<td>More complex maintenance required</td>
</tr>
<tr>
<td></td>
<td>Fully weathervaning (usually passive)</td>
<td>May be difficult to maintain at correct orientation, putting stress on</td>
</tr>
<tr>
<td></td>
<td>Usually requires smaller turret diameter</td>
<td>connections</td>
</tr>
<tr>
<td>Drag-chain</td>
<td>Allows direct connection of process plant to turret by flexible hoses.</td>
<td>Drag-chain has limited rotation. Partial weathervaning 270°</td>
</tr>
<tr>
<td></td>
<td>Simple manifolding to turret</td>
<td>Flexible risers and connections need replacing after 5 years</td>
</tr>
<tr>
<td></td>
<td>No swivel or dynamic seals required with associated risk of hydrocarbon</td>
<td>Bulky and larger weight. Large steel structure - the drag-chain cage - on</td>
</tr>
<tr>
<td></td>
<td>leakage</td>
<td>the deck of the vessel</td>
</tr>
<tr>
<td></td>
<td>Partial weathervaning adequate in most circumstances</td>
<td>Turret must be mounted centrally in vessel to allow weathervaning</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Generally requires larger turret</td>
</tr>
</tbody>
</table>
4.7.5 FTS Suppliers

There are five main suppliers of swivel systems:

- Bluewater
- Brown Brothers & Co. Ltd. (Rolls Royce Marine)
- Framo AS
- SOFEC
- SBM

In all cases their involvement stems from a background in the key dynamic seal technology developed in rotating equipment, such as pumps and flowmeters. Both SOFEC and Brown Brothers were formerly owned by Vickers and there is a lot of commonality in the toroidal swivel designs. Drag chain systems are manufactured by Metool Limited, to a design developed by Maritime Tentech AS in Norway. Bluewater, SOFEC and SBM all design turrets in addition to designing the fluid management system. As part of the present study site visits were made to Brown Brothers, Framo and Maritime Tentech.

More detailed information on individual Fluid Transfer System designs and components can be found in Annex C.
4.8 TURRET TRANSFER SYSTEM (TTS)

Known more generally as the turntable manifolding, the turret transfer system (TTS) this provides the interfacing between the Swivel or FTS system and turret with access to intermediate wells at this point. The TTS rotates with the turret and is geostationary with the seabed. The many lines entering the turret are manifolded here so that a smaller number of flow lines can pass through the swivel. This may vary from simple manifolding below the swivel to a complex multilevel manifolding structure in turrets handling larger number of wells. Equipment for well intervention, choke valves, pig receivers, inert gas systems and even slug catchers could, if needed, be installed at this level. Individual communication with each well still remains possible from this level.

In simpler turret designs, the turret transfer system is a simple turntable with manifolding, which the swivel rests on. In recent larger turret designs handling multiple wells the TTS can be a complex multilayered structure containing extensive piping, valves and manifolding and can completely surround the swivel, as seen in Figure 50. In this case the swivel lies centrally within the TTS and pipes pass out to the process plant above the TTS via the scaffold access structure. Most turret systems will also include an integral crane to pull through the flexible risers and tie-in to the transfer system; this is normally attached to either the TTS or the swivel access structure.

Given it’s location below or surrounding the swivel and rotating with the turret, the TTS is a safety-critical area with a high potential for hydrocarbon leakage. Location aside, it does not differ appreciably to other topside piping systems and the possibility of leakage at flanges, corrosion, fatigue cracking and erosion are very similar.

The TTS may contain peripheral items and safety relevant components. The main components found in a turret transfer system associated with a typical multipath swivel are as follows.

Safety relevant components

- wind-wall around turret
- firewall around swivel (some systems)
- piping and manifold systems
- ESDV valves, one per well
- riser connections
- choke valves, one per well
- access to individual wells
- pipe to flare headers (typically 6”)
- Gas and water injection (via swivel)
- Piping to flare header
- torque arms to swivels
- individual well control panels

Peripheral components

- turntable
- intermediate decks and access structure (e.g. control deck, lower manifold deck, middle manifold deck, upper manifold deck)
- stair tower
• access to moonpool
• access hatches, walkways and laydown areas
• pig launchers and traps, one per well
• pedestal crane to pull in risers
• stair tower
• electrical control building
• accumulators
• turret control panels
• hydraulic manifold skid
• well hydrate prevention unit (HPU skid)
• wax depressant injection skid
• inhibitor injection skid
• closed drains vessel

Note: these features will not be present in an STL or STP turret, which has no TTS as such. In STP systems the swivel sits on top of the turret buoy with intermediate ESDV valves. Drag chain systems will also have a much simpler interface structure.
Figure 50
Complex Turret Transfer System (TTS) Bluewater for Petrobras 37 FPSO. The swivel sits centrally within the TTS. Both are attached to and rotate with the turret. Courtesy Petrobras

4.9 INTERFACING SYSTEMS
The main interfacing systems are the swivel access structure linking the swivel to the process plant and the mooring lines. Remote equipment such as the vessel structure or loading computer which may impact on turret operation are also included here. These include the following:

- Swivel Maintenance Structure (Swivel Access Structure)
- Torque arms to swivel stack
- Crane
- Risers below turret level
- Loading computer
- Mid-water arch buoy
- Whole vessel
4.9.1 Swivel access structure / ESDV Tower
This consists of scaffolding allowing access to the swivel assembly. Production flowlines for the swivel or other fluid transfer system will pass through this to the process plant. In drag chain systems this is known as the ESDV Tower. In this case the drag chain and flexible risers rotate in a large cage attached to the top of the turret and the ESDV tower provides the tie-off and connections to the process system.

4.9.2 Mooring Lines
The mooring lines are attached directly to the mooring spider at the base of the turret, or drawn up through the turret over fairleads by dedicated winches. As with most other single point moorings, mooring is catenary with a combination of anchor chains, wire and polymer rope with buoyancy aids to give the appropriate mooring configuration.

The connections of the catenary moorings to the turret are by anchor chain, which may pass within the turret dependent on design. In conventional internal turret designs, such as the SOFEC systems, the mooring lines are only inspectable by diver or ROV. In the Tentech ICT turret the anchor chain can be pulled up 25m by the winches and inspected in-situ on the deck; this requires no intervention and is a specific design feature requested by Norwegian operators. In the STL and STP systems the conical ‘turret buoy’ can be disconnected and pulled up on board to allow maintenance and examination of mooring lines. The risers are an integral part of a single point mooring in FPSOs and are allowed for in design calculations.

4.9.3 Loading Computer
The loading computer computes the loading and unloading pattern to the tanks to best distribute the cargo.

Potential hazards are:
- Human or software error resulting in cargo being placed in wrong tanks
- Measurement equipment causing unknown oil level in the tanks

Either of these hazards may result in the vessel listing and in increased strain being put on the turret bearings.
5 FAILURE MODES, OPERATION AND SAFETY RELEVANT COMPONENTS

As with other offshore systems, FPSO turret systems can be subject to degradation mechanisms in service. Available information on operational experience and failure modes for FPSO turret systems to date is summarised in this section. Most FPSOs in the North Sea have only been in operation for a short time, not yet sufficient to produce consistent service data. There will usually be some teething problems early in life following commissioning as most FPSO turret systems have unique features to their design.

Information is included from literature sources, from incident reports passed to HSE up to the year 2000, anecdotal reports of difficulties in field operation and failure modes identified in discussions with FPSO turret system suppliers. This Section of the report provides guidance on ‘what can go wrong’ and components of the turret that may be of concern in the context of safe operation. This includes items that may be considered safety-critical and others that are safety-relevant.

As FPSO turrets are part of an offshore installation, they are covered by the DCR\textsuperscript{ii} regulations. This places an onus on the operator to demonstrate that safety critical elements are fit-for-purpose (suitable) and remain in good order. Information on inspection and maintenance practices to mitigate against the possibility of failure, or of hydrocarbon leakage, can be found separately in Section 6. Section 7 gives examples of good and poor operation and maintenance practices. In Annexes B and C, detailed information can be found for individual designs of turrets and fluid management systems.

As part of the present study, a failure modes and effects analysis (FMEA) has been undertaken for the main types of turret and FTS designs identified in Section 4. This analysis looks on a system-by-system basis at potential failure modes, causes, consequences and maintenance practice. The detailed summary tables arising from the FMEA for all the main turret system designs are given in Annex D.

Interactions and feedback between operators and turret designers is something that should be encouraged. In many cases information on operational difficulties is not passed back to the designers, where a field solution has been implemented. The review did, however, highlight several good interactions, for example between Maritime Tentech and Statoil, and between APL and operators of STP and STL turret vessels.

5.1 HISTORICAL PERSPECTIVE

There have been over 15 years of operation of FPSOs in the North Sea without major incident. FPSOs have been deployed in other areas of the world for much longer, and to date there have been no FPSO total losses\textsuperscript{iii}. The most serious incident recorded to date was an engine room fire that occurred on the converted tanker Lan Shui in 1990. In the North Sea the most serious incidents identified have been: failure of the dynamic seals on the swivel in one FPSO with hydrocarbon release; excessive roll on a new design FPSO with associated component failures; mooring line or connection failures in severe storm conditions; hydrocarbon leakage in the TTS manifolding, cracking of the bend stiffeners on the risers and degradation of flexible riser connections. As far as we are aware, none of these escalated or caused a serious threat to the integrity of the installation.

\textsuperscript{ii} A guide to the installation, verification and miscellaneous aspects of amendments by the offshore Installation and wells (Design and Construction, etc.) Regulations 1996 to the offshore installations (Safety case) regulations 1992, GUIDANCE ON REGULATIONS L83, UK Health and safety Executive HSE
The vessels designed for use in the North Sea are designed for considerably higher environmental loads than others World-wide and often with much higher throughput, not atypically 200,000 plus barrels of oil per day. The ones so far installed, or under construction, are internal turrets, located fore of midships, with high-pressure production and injection streams through the turret. Accommodation is usually in the bow, upwind of the weathervaning vessel.

The development of these vessels has built quite considerably on the standard technology of commercial crude tankers - a class of vessel that has been relatively prone to severe accidents, often caused by operator error.

5.2 KEY ISSUES FOR TURRET SYSTEM

The crucial technologies in FPSO turret systems are the *dynamic seals* in the swivels the *flexible risers* and connections, the *turret bearings* and load bearing components such as the *bend-stiffeners* on the risers.

Many of the reported incidents to HSE between 1995 and 2000 have been associated with the turret transfer system (TTS) in internal turret designs. Issues here are similar to other process pipework and are covered by the Design & Construction Regulations (DCR).

Connections to the swivel or FTS could be of concern if operating parameters, vessel roll, weathervaning etc. go outside design requirements.

Degradation of the turret bearings is likely to be gradual. Methods exist for monitoring bearing condition. Severe bearing wear would give increased load transfer to adjacent vessel structures and, if weathervaning is limited, could increase loading on swivel connections and other components. Adequate maintenance and cleanliness of the bearings is essential.

5.3 RISK ASSESSMENT

A risk assessment of FPSOs has been undertaken in a Norwegian joint industry programme executed by the Norwegian University of Science and Technology (NTNU) whose first phase was completed and reported in 1997iii iv. This concerned the operational risks and safety of FPSOs and a comparison was made with fixed offshore installations.

The main hazards associated with an FPSO were shown to be process accidents and collision accidents. Fires and explosions in the cargo tanks were not considered to be major contributors to risk, but are important aspects for crude oil carriers and were also considered relevant for FPSOs. A specific feature in FPSOs is the close proximity of the process plant on deck immediately above the storage tanks. Offloading was not considered a high risk activity.

The safety critical elements were considered for an FPSO to be the engine room, process plant and the turret.

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iv Risk Assessment of FPSOs, Jan Erik Vinnem, Faulty of marine Technology, Trondheim University, preventor AS Risk Management Norway.
Potential hazards were categorized in terms of marine and hull related accidents (M), hydraulic system accidents (H) and auxiliary systems accidents (A). Typical hazards and operational errors that may initiate such risk are summarised below in Table 4.

Table 4
Summary of hazards and operational factors considered in Risk Assessment of FPSOs in 1997 NTNU study

<table>
<thead>
<tr>
<th>No</th>
<th>Hazard</th>
<th>Typical Human Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Hull failure due to extreme wave load</td>
<td>• Failure to react to increasing sea state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>M2</td>
<td>Hull failure or marine accident due to ballast failure or failure during loading/off-loading operations</td>
<td>• Failure during ballasting and/or loading/off-loading operations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error to respond timely to warnings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>M3</td>
<td>Leak from cargo tank caused by fatigue</td>
<td>• Error during preparations for intervention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error during inspection or repair</td>
</tr>
<tr>
<td>M4</td>
<td>Accident during tank intervention</td>
<td>• Error during preparations for intervention</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error during inspection or repair</td>
</tr>
<tr>
<td>M5</td>
<td>Passing vessel collision with FPSO or shuttle tanker</td>
<td>• Operational failure on passing vessel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error in response by tanker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>M6</td>
<td>Strong collision by supply vessel with FPSO or shuttle tanker</td>
<td>• Operational error on supply vessel</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to react timely in case of warning</td>
</tr>
<tr>
<td>M7</td>
<td>Other vessels or floating structures operating on the field colliding with FPSO or shuttle tanker</td>
<td>• Operational error on installation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to react timely in case of warning</td>
</tr>
<tr>
<td>M8</td>
<td>Collision during offloading</td>
<td>• Operational error on shuttle tanker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error in response by tanker</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>M9</td>
<td>Rapid change of wind direction</td>
<td>• Error to respond timely by operating turret or thrusters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>M10</td>
<td>Multiple anchor failure</td>
<td>• Error to respond timely by operating turret or thrusters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>H1</td>
<td>Leak that may lead to fire or explosion in process plant</td>
<td>• Errors during operation or maintenance of equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error during response to accident development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>H2</td>
<td>Leak from turret systems that may cause fire or explosion in turret</td>
<td>• Errors during operation or maintenance of equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error during response to accident development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>H3</td>
<td>Leak or rupture of riser</td>
<td>• Errors during operation or maintenance of equipment</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Error during response to accident development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>H4</td>
<td>Impacting loads due to</td>
<td>• Failure to take necessary precautions</td>
</tr>
<tr>
<td>Category</td>
<td>Event Description</td>
<td>Contributing Factors</td>
</tr>
<tr>
<td>----------</td>
<td>-------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>H5</td>
<td>Dropped object from retrieval of cargo pumps.</td>
<td>• Failure to avoid contact with equipment</td>
</tr>
<tr>
<td>H6</td>
<td>Severe rolling during critical operations, such as crane operations</td>
<td>• Failure to carry out work tasks safely due to extensive movements • Failure to control possible threats due to extensive movements</td>
</tr>
<tr>
<td>H7</td>
<td>“Topside” fire threatening cargo tank</td>
<td>• Error during response to accident development • Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>H8</td>
<td>Emergency flaring with approaching shuttle tanker during off-loading</td>
<td>• Failure to warn vessel in time • Failure to react to warnings</td>
</tr>
<tr>
<td>H9</td>
<td>Unintended release of riser</td>
<td>• Error in responding to alarms</td>
</tr>
<tr>
<td>H10</td>
<td>Work in open air spaces during winter conditions</td>
<td>• Errors during operation or maintenance of equipment</td>
</tr>
<tr>
<td>A1</td>
<td>Failure of cargo tank explosion prevention function</td>
<td>• Failure to respond adequately to threat • Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>A2</td>
<td>Fire or explosion in pump room</td>
<td>• Errors during maintenance • Error during response to accident development • Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>A3</td>
<td>Spill from off-loading system.</td>
<td>• Operational error during making connection or disconnection</td>
</tr>
<tr>
<td>A4</td>
<td>Engine room fire or explosion</td>
<td>• Errors during maintenance • Error during response to accident development • Failure to initiate evacuation in time</td>
</tr>
<tr>
<td>A5</td>
<td>Helicopter crash</td>
<td>• Pilot error during approach • Pilot failing to react to special wind conditions</td>
</tr>
</tbody>
</table>

*Marine and hull related accidents, structural impacts (“M” category)*

*Hydrocarbon systems accidents (“H” category)*

*Auxiliary systems accidents (“A” category)*
5.4 OPERATIONAL ISSUES

Operational control is much more essential for safe operation of an FPSO compared to a fixed platform. The key issues are:

- Structural intactness
- Station keeping
- Transfer of crude oil from the FPSO to shuttle tanker

Experience from anchor lines from Semi-submersibles indicates that failures of anchor lines are not uncommon even in recent yearsiv. Such failures are commonly single line failures, but even multiple line failures are not uncommon. It should be noted that Petrojarl 1 has experienced at least two multiple line failures during the ten years of operation.

In the event of severe storm conditions the swivel system would typically be disconnected and production shut down. Disconnectable systems may be disconnected during the period of the storm. The disconnectable STP system can keep producing in adverse weather conditions.

Standard practice is for turret systems to be freely ventilated and accessible without requiring inverting. Inert gas systems are available for emergencies, but it is generally considered that inverting would increase the risk if used during normal operation. For STL and STP turrets, inert gas is used in the STP room, also flooded with seawater, during connection and disconnection to reduce the risk of explosion in the event of any hydrocarbon leakage. All turret system equipment is designed for Zone 1 operation.

Other operational factors include:

- Transfer of well fluid from wells to process pipework through turret with extensive movements in three dimensions. More complex than for fixed installations, therefore it is probable that the risk is higher
- Closeness of the storage of crude oil in tanks below the process area
- Difference in culture ship owners and oil and gas installations
- Differences in the training requirements for emergency incidents
- Operational control is required to protect the storage tanks from the hazards posed by the adjacent process plant, as well as ensure tank operations - including offloading - are carried out in a safe manner
- The hull of an FPSO, particularly in single-skin vessels, may be susceptible to puncture on external impact or collision.

5.5 FACTORS CONSIDERED IN SAFETY CASES

In most FPSO Safety Cases the areas identified to be at potentially highest risk are the engine room, process plant and the turret.

For the turret and process areas the Safety Case is generally based on the likelihood and consequences of a process facilities explosion. It is assumed that a release of gas or process fluids in the process areas would, if ignited, lead to a jet fire. Other explosion scenarios are also considered.

The frequency of a release of gas within the turret enclosure is typically estimated (for an internal turret) as approximately $2 \times 10^{-2}$/year with a risk of turret explosion of approximately $2 \times 10^{-4}$/year.
The consequences of a turret explosion could typically be:

- Structural damage or plastic deformation of the turret. Missile generation is not considered credible. No potential for escalation to the gas injection manifold
- Fatality to all individuals involved in the initial blast
- Serious injury confined to turret and immediate surrounding area. High number of serious casualties
- Local escape and evacuation routes potentially destroyed or damaged
- Process area inventories potentially vulnerable to escalation but not envisaged

As the swivel is usually mounted on top of the turret turntable, some deformation and damage could be envisaged affecting the dynamic seals. The ESDV valves are located on each riser and would be shut down in the event of an incident.

For disconnectable turret designs the connection and disconnection is an important part of the turret safety case. This is because the ability to disconnect is a key feature of such designs: both a virtue and a potential area of risk. Measures are made to minimize the risk of hydrocarbon leakage during connection processes. The ability to quickly disconnect in the event of an incident or adverse weather conditions is a positive feature used in Safety Case discussions.

For an STL turret-buoy the main hazards identified during safety case discussions were anchor failure, turret seizure and hydrocarbon leakage.

5.6 SAFETY-CRITICAL ELEMENTS

Safety-critical is defined in the context of the definitions given in the DCR regulations.

"Safety-critical means such parts of an installation and such of it's plant (including computer programmes, or any part thereof -

(a) The failure of which could cause or contribute substantially to; or
(b) a purpose of which is to prevent, or limit the effect of,

a major accident."

The turret system is considered in most Safety Cases to be a safety-critical element. Components that would generally be considered as safety-critical include the swivel stack, dynamic seals in the swivels, the main flexible risers connections, the main turret bearings and the mooring lines and connections. The first three have the most safety-critical implications because of the risk of hydrocarbon leakage, which with escalation could lead to explosion.

These issues are well recognised by FPSO designers and operators and there are safety measures in place to mitigate against failure of such components. For example, the dynamic seals on the swivel contain both primary and secondary seals, have 'fail-safe' elements to the design, leakage is recovered, and barrier pressures are accurately monitored.

Many other turret system components which, although not safety-critical in accordance with DCR, could be considered as safety-relevant. This includes all components associated with hydrocarbon transfer and load bearing components (such as the bending stiffeners on the risers). There are global issues such as collision or process incidents and vessel build quality that may impact on the turret.
Connections to the swivel or FTS are of particular concern if operating allowances, vessel roll, weathervaning etc. go outside design requirements. Degradation of the turret bearings is likely to be gradual and is of economic significance to the operator. Methods exist for monitoring bearing condition. Severe bearing wear or bearing seizure would have safety implications because of the increased load transfer to adjacent vessel structures and, if weathervaning is limited, increased loading on the swivel connections and other components could occur. Adequate maintenance and cleanliness of the bearings is therefore essential.

Key elements and principal design features for individual turret and fluid transfer designs are discussed in Annexes C and D.

5.7 PUBLISHED INFORMATION

Despite frequent dedicated conferences, there is little published information on operational failures or unusual occurrences within FPSOs and less so on turrets. This may be reflective of their general reliability, though difficulties are certainly encountered as can be seen from HSE incident reports. It is more common to report issues and challenges during the development and field installation of a new technology. Operators and suppliers are relatively open at discussing their experiences. For example, operational experiences from the Statoil Asgard and Norne FSPO which use a Maritime Tentech turret were discussed at the ISOPE 2000 conference in June 2001 in a joint paper. Operational failures prior to 1997 have been reviewed by Vinnem. The following incidences were noted:

- The converted tanker Lan Shui experienced an engine room fire on 21/1/90. The fire is described in Lloyd's List as lasting for 29 hours with extensive damage sustained to the engine room, but no damage to the process areas and no pollution.
- Petrojarl 1 UK Sector experienced multiple anchor line failure in 50-55 knots NW wind after being hit by a 20-25m high wave on 30 January 1994 about 60 miles North East of Lerwick. The multiple line failure (4 of 8) was gradual and occurred over a period of about 8 hours, initially losing two lines due to the big wave. After that incident, production was shutdown, and the vessel kept on station by the remaining lines and main propulsion. She was never off station and reconnection of the anchor lines started the same day. Personnel were never taken off and the vessel had the possibility of quick disconnection.
- Another event of multiple line failure (7 out of 8 anchor lines) is reported to have occurred on Petrojarl 1 caused by a wave of height 10 m.
- Station keeping error on Petrojarl 1 where the shuttle tanker offloading experienced a station keeping error.
- Cracking in forward wing-tank in the Fulmar FSU on 31 March 1986.

5.8 INCIDENT REPORTS

Table 5 summarises incidents reported to HSE on FPSOs between 1995 and 1999. It is not clear if this is the total incidents reported or selective. The majority of the reported leakages are associated with production piping or flanges within the turret transfer system. A significant number of leaks relate to flexible hose failure. One incident was associated with back-flow of hydrocarbon to the swivel from the swivel seal recuperation tank. One incident of a gas leak occurred in an STP turret system during intervention for gas injection.

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vi Terranova, Floaters enter a new territory: Offshore Engineer, August 2000 pp16-26
### Table 5

**Summary of incidents reported to HSE on FPSOs 1995 to 1999**

<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>108298</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>GRYPHON A</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>19-Oct-95</td>
</tr>
<tr>
<td>Severity</td>
<td>Significant</td>
</tr>
<tr>
<td>Location</td>
<td>TURRET TRANSFER SYSTEM 10&quot; COFLEXIP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>MANIFOLD, OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>PIPING, FLEXIBLE, 3&quot;&lt;D&lt;=11&quot;</td>
</tr>
</tbody>
</table>

**Incident Description**

During normal operations the gas detection detectors in the produced water package area picked up gas and went into alarm. Production personnel in the area investigated the scene and found an oil spillage which had come from a burst section on the 10" production hose in the turret transfer system. The plant was manually shutdown closing all ESDV’s and down hole safety valves. The plant was depressurised and all blowdown valves opened. All personnel were mustered due to the GPA being set off and personnel held at muster point until plant made safe and isolations in place. Wind speed -30 knots, wave height - 4.0m, air temp - 12 °C direction - 220 °, light - darkness, sea temp - 4°C
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>113045</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>UISGE GORM</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>20-Mar-98</td>
</tr>
<tr>
<td>Severity</td>
<td>Significant</td>
</tr>
<tr>
<td>Location</td>
<td>Turret Transfer System Production well P4 Choke</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>FLOWLINES, OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>FLANGES, 3&quot;&lt;D&lt;=11&quot;</td>
</tr>
</tbody>
</table>

**Incident Description**

Normal production operations were in progress. Vessel motion was slight with +/- 1 degree roll and +/- 1 m heave. During routine plant patrol, a production tech in the turret area noted a leak of water/oil/gas from the upstream flange of production well P4 choke. He immediately contacted the control room and the lead production tech and production superintendent visited the site. The well was closed in on the wing valve and topside ESD valve. The line was then depressurised.
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>113703</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>UISGE GORM</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>05-Jun-98</td>
</tr>
<tr>
<td>Severity</td>
<td>Significant</td>
</tr>
<tr>
<td>Location</td>
<td>TURRET TRANSFER SYSTEM Downstream flange, Production well P3 Choke</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>FLOWLINES, OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>FLANGES, 3&quot;&lt;D&lt;=11&quot;</td>
</tr>
</tbody>
</table>

Incident Description
Normal production operations were in progress. Minimal vessel motion. Whilst checking a scaffold in the turret area the marine superintendent noticed a leak of oil/water/gas from the downstream flange of production Well p3 choke. He immediately informed the CCR who sent the lead production tech to investigate. On arrival the lead production technician closed in on the well wing valve and the topside ESD valve (manually). The line was then depressurised there was no GPA.
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>113944</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>CURLEW</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>20-Sep-98</td>
</tr>
<tr>
<td>Severity</td>
<td>Minor</td>
</tr>
<tr>
<td>Location</td>
<td>SWIVEL STACK LP crude oil. Backflow from recuperation tank</td>
</tr>
<tr>
<td>System</td>
<td>FLOWLINES, OIL</td>
</tr>
<tr>
<td>Equipment</td>
<td>FLANGES, 3&quot;&lt;D&lt;=11&quot; Turret Drain Tank</td>
</tr>
</tbody>
</table>

**Incident Description**

A leak of hydrocarbon fluid was observed coming from the top of the lowest crude oil swivel stack. Investigation showed this to be a mixture of methanol and crude oil. Leak was caused by turret drain tank over the recuperation tank, which in turn, back flowed into the topside of the swivel secondary seal.
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>113982</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>SCHIEHALLION</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>02-Oct-98</td>
</tr>
<tr>
<td>Severity</td>
<td>Significant</td>
</tr>
<tr>
<td>Location</td>
<td>TURRET TRANSFER SYSTEM Block Valve, riser sample valve</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>MANIFOLD, OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>VALVE, MANUAL, BLOCK, 3”&lt;D&lt;=11”</td>
</tr>
</tbody>
</table>

**Incident Description**

During the leak test of the Loyal riser assembly to 265 bar. The internal seal failed on block valve HV 161861 at 75 bar allowing 125 litres of crude oil and glycol water mix [70% - 30%] to escape to deck via riser sample valve 161(3rd level turret). No fluids were lost to sea. Weather: wind 13 knots, 186 degrees, dry, good visibility, wave height 3m significant.
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>115308</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>BERGE HUGIN</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>26-Apr-99</td>
</tr>
<tr>
<td>Severity</td>
<td>Minor</td>
</tr>
<tr>
<td>Location</td>
<td>STP room Gas Leak during gas injection.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>FLOWLINES, GAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>FLANGES, 3&quot;&lt;D&lt;=11&quot;</td>
</tr>
</tbody>
</table>

**Incident Description**

Normal production with gas injection in progress several gas detectors went into the alarm condition at the same time (07:54). Levels of 15% of LFL were measured on average. As soon as all personnel were accounted for a manual blowdown of the gas GPA was sounded and the process train shutdown. Injection riser was initiated and the nitrogen purge to STP room increased to maximum to dilute and purge the hydrocarbon content of the contained atmosphere. A further investigation to find the source of leaks using inert gas was organised.
<table>
<thead>
<tr>
<th>Incident Number/ID</th>
<th>432</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installation Name</td>
<td>GRYPHON A</td>
</tr>
<tr>
<td>Date of Incident</td>
<td>04-Dec-99</td>
</tr>
<tr>
<td>Severity</td>
<td>Significant</td>
</tr>
<tr>
<td>Location</td>
<td>TURRET TRANSFER SYSTEM 10&quot; production coflexip</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System</th>
<th>MANIFOLD, OIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipment</td>
<td>PIPING, FLEXIBLE, 3&quot;&lt;D&lt;11&quot;</td>
</tr>
</tbody>
</table>

| Incident Description | Release of oil from a 10" production coflexip to the vessel main deck, (spill contained on deck). Wind 350deg, 15k sea state 1.5m, swell 2.5m conditions dry. At the time of the release production to the 1st stage separator was shut down and the separator was being isolated for maintenance. Pressure in the production manifold and coflexip increased from normal operating pressure of 12 barg to 23.5 barg (max. design operating pressure 154 barg) when failure of the coflexip occurred. Witness statement indicates an initial pressure release and a cascade of oil when the outer casing failed followed by non pressured residual flow of oil from the split outer casing of the coflexip. The production manifold pressure remained at 23.5 barg post failure indicating minor leakage into the coflexip outer casing rather than a catastrophic failure. The production manifold blowdown valve was operated from the CCR to depressure the system. (turret transfer system between manifold and pipe tower) Further investigation required. |
5.9 RECENT FAILURE AND OPERATIONAL EXPERIENCE

Anecdotal information on recent damage or failures in FPSO turret systems has come from a number of sources. This information is reproduced generically here, as it is relevant in identifying future problem areas that have not been brought up in incident reports:

a) Failure of swivel seals
It is understood that all the seals failed on the swivel stack of one North Sea FPSO in 2000. This produced hydrocarbon leakage but with no escalation. Production was shut down and the swivel seals were replaced.

b) Turret – cracking of elastomeric riser bend-stiffeners
There have been recent reports of several North Sea FPSO installations experiencing cracking of the elastomeric/metal bend stiffeners at the point of access of the flexible risers into the turret. These stiffeners are designed to take up the high bending and tensile loads acting on the risers at this point. Cracking could lead to loss of the stiffener and high loading on the flexible risers themselves with the possibility of premature failure.

c) Flexible riser connections – slippage of internal layers
Flexible riser connections are the area with the highest potential for failure of the flexible risers. Damage to the risers has been observed in drag chain systems under the rotational loading experienced and replacement at 5 yearly intervals is now specified. Slippage of internal layers at the main turret connections has been reported in some Norwegian FPSOs. Limited access can make inspection difficult without having dismantled the riser connections.

d) Vessel structure – cracking around turret cavity and moonpool
A number of FPSO installations have been reported as experiencing fatigue cracking of the vessel structure in the vicinity of the turret cavity or moonpool. This is an area of high stress due to load transfer from the turret bearings and ovality due to wave and environment dynamic loading. The method and quality of construction here is very dependent on the shipbuilder and the individual vessel dynamic loading. These problems may be indicative of poor design, construction faults or wear of the main turret bearings. High frictional forces in the turret bearing will be amplified by load transfer.

e) Greenwater damage
One North Sea operator reported that the swivel and adjacent support structure had been damaged by greenwater in an FPSO with a forward mounted turret. A second operator reported damage by Greenwater to the bow of the FPSO vessel and modules in the process plant. The fore of the vessel was raised by 5m and barriers had been installed at the deck sides in key areas to limit damage.

f) Gas swivels - leakage
In early swivel designs some leakage was experienced form gas swivels; more common in gas toroidal swivels than axial swivels. Technology has advanced and robust gas swivels are available.

g) Drag Chain Systems -flexible riser leakage
Leakage from flexible risers in the drag-chain system is reported as having occurred on one FPSO. Flexible risers were also reported to have suffered erosion.
h) **Flexible risers**
Several operators had experienced progressive damage to flexible riser connections. One reported rupture of an end fitting region and also of a bell mouth connection.

i) **Sudden rotation of turret**
One operator had encountered sudden movement of an IAT active turret by 27° during blackout conditions. Future occurrence was prevented by introduction of an operating restriction not allowing the vessel angle to go more than 7 ° out of alignment.

j) **STL turret-buoy**
Existing STL turret-buoys are reported to have performed well over 5 years of operation with few difficulties. There was one case of failure of a locking pin on a mooring line. Some damage was encountered to the rubber inflatable fender on the bottom of one mooring buoy. Some water ingress occurred through the top seals. Wear of the axial bearings was reported as negligible in 5 years of operation.

k) **Effects of excessive roll North Sea FPSO**
Extensive damage to equipment including cranes. No specific damage, however, reported on the turret or swivel system.

l) **Vessel Structure**
Microbial corrosion was reported underneath oil sediments on the bottom of the FPSO storage tanks. The operator concerned noted that no structural failures had been reported in the last 3 years.

m) **Cracking of pipe supports**
One operator had encountered cracking of pipe supports on the vessel deck.

n) **Production Pipework - Corrosion and weld root erosion**
Significant degradation of production and process pipework has been observed on inspection of a number of FPSO installations. Since FPSO design is based on ships, more shipyards are able to compete for business since the structure is conventional. Much equipment meets the required marine standards, but there is a tendency for this to be extended to pipework and process equipment where offshore standards are more appropriate. This does not, however, appear to be the case in most UK or newbuild FPSOs. Marine standards allow for lower wall thickness of pipe than would be allowable in conventional offshore installations and this is often combined with poor weld quality, including lack of penetration. This can give increased risk of corrosion and erosion damage and highlights a need for good corrosion management. Such difficulties are associated with process pipework distant from the turret and we are not aware of this being an issue in the turret system.

5.10 **FAILURE MODES FOR TURRET**
The turret itself is perhaps the simplest part of the turret system and the prime concerns are with the turret bearings and ability to weathervane. Hydrocarbon release is possible from the flexible risers or connections. It is fair to say that this risk is much less than for the turntable manifolding or the fluid transfer system (FTS) which has high pressure dynamic seals. Relevant damage mechanisms are as follows:

- progressive degradation of the main turret bearing which takes all the load
• cracking of the adjacent vessel support structure and turret cavity. Very common particularly in conversions. Very difficult to put right as it is indicative of inadequate stiffness in the structure or excessive loading on bearings.

• degradation of the flexible riser hang-off connections

• loss of mooring connection or line in adverse sea conditions.

• excessive friction on the turret

• sudden movements and ‘fishtailing’

• crane and winch failure

• loss of bearing alignment

• loosening or failure of securing bolts on the bearing housings, cranes and mooring spider attachments

• Leakage of flexible risers and connections (unusual)

• Cracking of the elastomeric bend-stiffeners observed in a number of North Sea installations. This reduces their load bearing capacity and eventually they may detach or break off. The consequence is increased loading on the flexible risers and a risk of failure and hydrocarbon release

• Greenwater damage - more likely to affect fluid transfer system on deck

The potential issues and failure modes for specific turret components are as follows:

5.10.1 Flexible risers and connections

Flexible risers are a crucial technology for FPSO turret systems. The issues are not substantially different to other applications. Integrity of connections, failure of the PVDF thermoplastic barrier layers and corrosion fatigue of the reinforcements being the main damage mechanisms of concern. The location of flexible risers within the turret can make access for inspection difficult. Connections to the turntable manifolding are usually accessible and of a high quality.

Flexible piping is also used for connections from swivel to the process plant. Flexible riser issues in FPSO installations have recently been considered in a separate HSE project and a review of failure modes and inspection methods has also been conducted by the HOIS joint industry project. There are a number of major Norwegian joint industry projects currently being carried out on flexible risers. Inspection and maintenance requirements are specified by the manufacturer such as Coflexip or Bluewater.

5.10.2 Umbilicals

These may be subject to time-dependent degradation and are not safety critical. Function of electrical and control signals needs to be assured.

5.10.3 Bolting

Bolting, such as that associated with the upper bearing assembly and mooring connections, can be subject to a number of damage mechanisms. These include load relaxation, corrosion, crevice corrosion, cracking - usually associated with the thread roots - and fatigue.

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5.10.4 Main Turret bearings

The main turret bearings are a key load-bearing and structural component. Roller or wheel bearings are not stiff and rely on the stiffness of the supporting structure to give rigidity. Therefore it is crucial that the stiffness of the supporting structure is taken into account. Such bearings are grease lubricated and freely rotating with very low friction and are suited for turrets which need to move passively or freely weathervane.

A consequence of the rolling contact is that damage and load transfer is amplified according to the cube rule: $(\text{Damage}, \text{Load} \sigma^3)$. Small changes in stress will have a major impact on loading. The consequence of this is that: any lack of stiffness in the supporting vessel structure will be amplified in increased loading on the turret bearings and increased wear. For example, doubling the stress on the vessel structure will give $8x$ the load on the bearing. Conversely any misalignment or increased frictional loading on the bearing will lead to amplified stresses in the vessel structure. This is particularly a problem in tanker conversions though design errors can also occur in new build. Cracking of the supporting vessel structure is not uncommon. Therefore, it is important for the inspector to ascertain that the factor of safety allowed for in design is realistic in terms of the level of loading. This will have a major impact on fatigue loading.

For the Main turret bearing and adjacent vessel support structure the following are the issues:

- Ovality or lack of stiffness in vessel support structure, giving substantially increased load on bearings
- Wear to bearing components or raceways requiring intervention and costly refurbishment
- Reduced functionality. Higher torques needed to rotate. Reduced ability to weathervane. Increased loading on connections, flexibles and fluid transfer system
- Loosening of securing bolts leading to increased loading and if undetected failure
- Degradation or damage to seals. Loss of, or reduced, lubrication. Consequence is more rapid degradation of bearings
- Cracking of raceways and bearing housings due to work hardening, eventually leading to catastrophic failure
- Damage to the cage in roller or axial bogey bearings. Harder to rotate, bearing may seize or less freely weathervane - amplified loads
- Loss of weathervaning capability - may get sudden uncontrolled movement of vessel or turret

5.10.5 Upper bearing support vessel deck

This is welded to the vessel and subject to high load transfer from the main turret bearing. The bearing support is normally over-designed and there is no history of problems in this area. Cracking of the ship support structure is more likely. Some consideration of the integrity of the attachment welds would be advisable if bearing loads exceed design, or cracking has been observed in the ship support structure.

5.10.6 Turret shaft

There is no history of problems associated with the turret shaft, which is a welded structural steel component. Corrosion is likely to be minimal due to the cathodic protection and protective coatings.
5.10.7 Lower bearing assembly
The lower bearings are normally manganese bronze bearing pads sealed but designed to operate in seawater. Damage or wear of these bearings may affect turret alignment and make it more difficult for the turret to rotate. Adjacent parts of the vessel structure may see higher loading than the some other parts of the turret casing. These are secondary effects and it is the main (upper) turret bearing that takes the majority of the loading and needs most consideration. We are not aware of problems associate with the lower bearing assembly.

5.10.8 Moonpool and turret cavity
Dynamic loading by waves and the environment can cause non-uniform loading and ovality of the moonpool or turret cavity. The practical consequences of this is fatigue cracking in these regions and of the surrounding vessel structure - not uncommon in FPSOs. The severity of this will depend on loading conditions and the quality of the design and vessel construction. These areas are not always easily accessible.

5.10.9 Mooring lines
Anchor chains and mooring lines can be subject to a range of degradation mechanisms including abrasion, cracking and corrosion. Polymer ropes, used in deepwater FPSO's can suffer water ingress and progressive environmental degradation. Bottom chains are designed for 20 years continuous use without inspection. Top chains can degrade particularly the links connected to the chain stopper and sections of chain passing over fairleads and winches.

5.10.10 Fairleads (some designs)
There have been several instances of fairlead failures in offshore installations and the possibility of damage due to abrasion or fatigue should be allowed for.

5.10.11 Winches one per well (some designs)
Integrity issues are as for other winches in offshore installations and described later under interface systems. The consequence of winch failure would be to affect mooring loading and redistribution of loads to other mooring lines.

5.10.12 Chain stoppers and tensioners
There have been several incidences of failure of mooring connections due to overloading or corrosion or cracking of components such as bolts and loading pins.

5.10.13 Turret shaft/mooring spider interface
There is no history of problems in this interface area which is either a bolted or welded structural connection. Failure is unlikely but is safety-relevant, since failure of this internal interface would remove the single-point-mooring to the FPSO and result in increased loading on the flexible risers and umbilicals passing through the turret.

5.10.14 Mooring spider
Failure of the mooring connections is the most likely damage scenario. Corrosion is unlikely to be significant due to the cathodic protection applied to the turret and protective paint coatings.

5.10.15 Mooring buoy (some turret designs)
Damage mechanisms are as for the mooring spider in conventional turrets, with the additional issue of the disconnection interface. Degradation or damage to the static seals could lead to hydrocarbon release. The interface itself could be damaged by corrosion or impact. The functionality and integrity of the locking mechanism to the turret needs to be ensured.
5.10.16 Tension connector (disconnectable systems)
It is important that this functions correctly as effective disconnection is an important feature of the Safety Case for disconnectable turrets.

5.10.17 Bend-stiffeners
Cracking of the bend-stiffeners on the risers is common. There are two main mechanisms: decohesion of the metal elastomer-interface and cracking of the elastomer component under service loading. Either mechanism could result in the stiffener falling off the riser giving increased loading on the riser with the risk of premature failure.

5.11 FAILURE MODES FOR FLUID TRANSFER SYSTEMS (FTS)

5.11.1 Swivel and multipath swivel systems
Severe sea conditions could cause swaying of the swivel stack, for example heave >10m at the helideck is not uncommon in the North Sea or West of Shetland. Such lateral movement is not desirable as it could affect seal integrity - it is prevented by hydraulic torque arms.

The main concern is failure of the dynamic seals and release of hydrocarbons which could escalate. This risk is minimized by use of a double seal barrier, design features such as: pressure differentials; leakage recovery systems; and accurate monitoring and intervention procedures should either seal fail, or leakage rates are above acceptable levels. The seal technologies in place are the result of extensive research and testing and perform reliably in most circumstances. Incidents of hydrocarbon leakage have occurred in certain installations and have been reported to HSE. Leakage is more likely in gas swivels and air utilities.

Seals come from specialised suppliers and have a limited shelf life. It is necessary to ensure they are properly stored and not exposed to UV light. Temperature may cause degradation. Deterioration is slow.

Multipath swivels have not been in service that long and the condition of internal pipes is not well known. Experience with axial swivels suggests that corrosion and erosion should not be severe. Condition can be visually inspected through access ports. There is a lot of redundancy in design. Corrosion or erosion of swivel internals and cracking of welds is a potential concern in longer term service but not an issue to date. Greenwater damage is a concern for swivels, particularly when mounted towards the bow of the vessel.

There is extensive bolting on swivel stacks, particularly associated with the bearing housings on the swivel rings and flanged connections. It needs to be assured that the integrity of such bolting is properly managed as failure could initiate hydrocarbon leakage form the seals. Cracking of bearing housings at stress concentrators due to bearing wear is common in 3-roller bearings and should be considered as a potential damage mechanism for the swivel outlet rings.

Sour gas is not an issue in most current FPSO fields. Suppliers can design for this and would use duplex stainless steel in place of carbon steel if high H₂S levels were anticipated.

Incidents reported by swivel manufacturers include:

- Failure of the drag link on the link arm, which takes the torque on the swivel. A ball-joint broke on a drag-link which had not been properly lubricated, seized up and fatigued. The solution is now to have flexible risers to the walkway.
- Oscillation and problem with twisting of flexible hoses between turret and swivel. The solution was to put an active drive on the swivel. This allows the swivel to rotate by 5°
before the drive cuts in, to give controlled movement. 90% of the time the vessel is stationary and the swivel is not moving.

- Flexible pipes believed to be turning swivel. Torque from flexible piping fighting hydraulic drive system. An issue for both passive and actively driven swivels, most swivels are passive. Outlet rings should be at zero rotation relative to vessel.
- Over-pressurised swivels and blew static seal. Tested to 390 Bar, pressure exceeded 400 bar.
- Leakage from flange - client bought wrong spare.
- Excessive motion of FPSO giving higher stresses on the turret drive mechanism. No problems observed with the swivel which had flexible connectors.
- Incidents of intermittent failure of dynamic seals due to slug formation etc. Only 1” in recovery tank.

### 5.11.2 Compact Swivel

The major concern is the integrity of the dynamic seals, flexible risers and connections. The swivel is passively rotating. Monitoring of barrier oil pressure and torque and rotation on the torque arms is essential to ensure correct functioning. For topside mounted compact swivels, the issues are similar to conventional multi-path swivels, though intermediate manifolding is simpler.

For inline swivels connected with STP or STL turret systems disconnection is straightforward from the turret-buoy. Disconnection is usually at the interface with the ESD valve block is which remains attached to the turret-buoy, sealing off the wells. The turret buoy is then submerged under neutral buoyancy with the mooring lines to 50m below sea level. Disconnection is thus a useful emergency measure and features prominently in Safety Cases. Conversely, connection and disconnection is an important consideration from a safety standpoint and at this time there is an increased risk of hydrocarbon leakage. The swivel is mounted inside the turret cavity known as the STP room (Section 7). Inert gas systems are available which can be used during connection, disconnection or in the event of hydrocarbon leakage. HSE incident reports show one case of such use of inert gas following a gas leak during gas injection on an STL system swivel.

Leakage from the dynamic seals is the major safety concern as with conventional swivels. Flexible piping and connections can degrade and need to be properly checked and maintained.

The compact design, use of duplex stainless steel and use of a solid core and forged outlet rings gives considerable simplification and may be anticipated to be less susceptible to longer term degradation mechanisms such as corrosion and erosion. It is also arguable that the dynamic seal system may be less prone to leakage than for conventional swivels due to the double barrier design and seal pressure differential. However, conventional multipath swivels also generally have primary and secondary seals.

Leakage in a utilities swivel was observed in an early compact swivel design, sourced in from another supplier. The pipes were not flushed and dirt got into the seal area. There is no barrier seal fluid in this case. The supplier now designs their own utility swivels.

Compact swivels are not currently used in any sand producing fields. Suppliers do not anticipate problems. The swivel core is large it is considered difficulties would be likely to occur elsewhere first. Similar seals have been used in 5000rpm pumps and other high pressure rotating equipment for 20,000h+ hours in sand producing fields with no difficulties experienced, the swivel is an evolution of the pump design.
5.11.3 Drag-chain fluid transfer systems

The absence of any dynamic seals is a considerable advantage from an integrity standpoint. Drag-chains do include large lengths of flexible pipework. Abrasion of the flexible piping can occur as the turret weathervanes. Progressive degradation of flexible riser connections may occur. The most critical connections are the vertical hang-off connections to the turntable: these have a high integrity design.

It needs to be ensured that the turret does not seek to weathervane beyond allowed levels (+/- 270°) as this would put excessive loading on the drag chain system and riser connections. There is the possibility of corrosion or fatigue damage to the drag-chain itself which should be checked for in routine maintenance.

5.11.4 Greenwater Damage

Major Norwegian JIPs and HSE programmes have addressed the issue of Greenwater damage on FPSOs. This is a particular issue for turrets installed at the front of the vessel. Within the turret area, Greenwater can cause damage to the swivel stack and the turret transfer system. Barriers are normally placed around the swivel to limit damage by Greenwater. Damage by Greenwater is also common elsewhere on the FPSO including process plant and barriers are usually installed at the deck sides in key areas to limit damage.

5.12 TURRET TRANSFER SYSTEM (TTS)

There has been an increasing complexity in turret design to handle increasing number of wells. This has lead to larger turrets and to the growth in the size of the manifolding or turret transfer system (TTS) for transfer of production fluids between the swivel and turret. Many of the reported incidents to HSE between 1995 and 2000 have been associated with the TTS.

The issues here are very similar to other process pipework and covered by written schemes of examination and verification schemes drawn up in response to DCR. For this reason the failure modes and maintenance practices for such systems are not covered in detail here as, other than their location, they do not differ appreciably to other process pipework and systems. The main concerns are corrosion, loss of wall thickness, weld root erosion, fatigue and leakage of flanged connections. Pipework, manifolding and other systems within the turret transfer system or turntable are not always easily accessible.

5.13 INTERFACING SYSTEMS (IS)

5.13.1 Cranes and winches

Cranes and winches in FPSO turrets are similar to those used within other offshore systems. The primary concerns are wear or failure of the slew-ring bearings and failure of the supporting bolts. There are two specific issues in FPSO turrets. First, the location of the crane on top of the turret could cause knock-on damage to the swivel and TTS if failure occurred. Second, is excessive roll close to or above design conditions. This can cause high dynamic loading and could affect the integrity of support bolts and bearings. There has been at least one incident in recent times the North Sea involving the failure of cranes on an FPSO due to excessive roll.

ix Offshore Research Focus, No. 122 July 1988, ISSN 0309 -4189 Greenseas damage on FPSOs and FSOs
Condition monitoring and maintenance issues for offshore crane slew-ring bearing assemblies have been reviewed by Lloyd's Register of Shipping\(^x\). Attention is drawn to more general HSE advice on safety issues and maintenance of offshore cranes, for example the recently published pedestal crane lifetime extension criteria (D3765)\(^xi\) and HSE's Offshore Technology report OTO 96 041 on Offshore Lifting and Handling Appliances\(^xii\). The key issues are

- Failure of retaining bolts
- Adequate lubrication and maintenance of bearings
- Internal corner cracking on bearing housings
- Integrity of all welds
- Integrity of chain and chain connections
- Fatigue cracking at all stress concentrators

### 5.14 FAILURE MODES AND ISSUES FOR SPECIFIC TURRET TYPES

#### 5.14.1 Internal active turret (IAT)

The primary concern is sudden rotation of the turret if orientation is more than 20° away from optimum. Turret rotation is usually controlled by grippers or hydraulic drive. There have been isolated incidences of slippage. Operational experience has indicated the following as the most safety critical areas:

- The upper bearings which take all the loads
- The flexible riser hang-off connections
- The mooring line connections

Corrosion pitting has been observed on bearing pads. This was associated with excessive lubrication which removed the graphite. The solution was to remove the lubrication. No problems have been encountered with the flexible riser hang off connections. These utilise a detailed and expensive connector. No problems have been reported in IAT turrets with the bending stiffeners on the risers. Bending of the risers is more critical in shallow waters.

Potential issues identified in design include the following:

- Relative movement of swivel and gantry due to motion of vessel.
- Damage to flexible outlets from swivel to gantry due to the above

The moonpool is a fatigue-sensitive and critical area. There is an 80cm clearance in IAT turrets which make this area accessible for inspection. There have been occasions of Greenwater damage on vessels with IAT turrets, but this did not affect the turret system, which is less vulnerable than conventional turrets because of its central location.

There is not always feedback from the operators as the designs are proprietary and operators may only contact the suppliers/designers when problems arise that do not have a simple

\(^x\) Stuart R: Condition monitoring of offshore crane slewing bearing assemblies, Trans ImarE, Vol 105, Part 5, pp 211-232

\(^xi\) Report on Beyond Lifetime Criteria for Offshore Cranes- Pedestal Crane Lifetime Extension Criteria (HSE No. D3765), BAE Systems, Y3765/YD1464/GW)1351 Issue A, 6 September 2000

\(^xii\) Offshore Technology Report OTO 96 041 Offshore Lifting and Handling Appliances - Recommendations on Design, Construction and Operation, HSE, September 1996
solution. A very open cooperation was noted between Tentech and Statoil with a joint paper given at the ONS conference in 2001\textsuperscript{xiii}.

5.14.2 External Turrets
The potential failure modes are as for internal permanent turrets, with the exception that the cantilever structure should be considered in place of the vessel structure. The pipework and turret is exposed so corrosion of manifold pipework and inaccessible pipework in the cantilever area is of specific concern.

Bearings will usually be of a roller design. There are no FPSOs with external turrets in the North Sea. The closest is the Liverpool Bay FPSO which has a wishbone structure.

5.14.3 External Disconnectable Turret
The main areas of concern for the turret system are as follows:

- Corrosion of manifolding pipework
- Corrosion and erosion of inaccessible pipework in cantilever structure.
- Damage and progressive wear of turret bearing and universal joint
- Damage to flexible risers and failure of flexible riser connections
- Progressive damage to mooring chains and failure in adverse storm conditions
- Connection and disconnection systems and interfaces.
- Static seals on disconnection interface
- Integrity of cantilever support structure
- Functioning of ESD valves on individual risers
- Functioning of universal joint. Excessive friction would increase loading on risers.

5.15 FAILURE MODES AND EFFECTS ANALYSIS FMEA
A Failure Modes and Effects analysis (FMEA) was made for the generic turret and fluid transfer system designs. This looked at the potential failure modes, consequences and maintenance practices for each design and each safety relevant component.

This information is summarized in a series of Look-up tables in Appendix D. Most relevant damage mechanisms are generally shown highest on the list. However, it is important to consider all possible eventualities. The main issues for key parts of the turret system are summarised below:

5.15.1 Swivel and Fluid Transfer Systems
- Dynamic Seals
- Bolt integrity and tension
- Corners on swivel ring (fatigue locations)
- Bearings
- Functionality
- Swivel internals
- Flexible riser attachments
- Connections to swivel. Condition of flexibles and hard piping
- Degradation of flexibles, drag chain systems

\textsuperscript{xiii} Operating experience of Tentech turrets, Statoil, Maritime Tentech, Offshore Northern Seas Conference, June 2001, Stavanger.
• Excessive motion
• External damage

5.15.2 Turret Systems
• Adequacy of bearing design loadings
• Bearing condition
• Condition of raceways
• Support structure often cracked
• Ovality of moonpool due to vessel flexing
• Cracking of bend stiffeners
• Integrity of flexible risers and connections
• Mooring condition and inspection

5.15.3 Turret Transfer System
• Can be very complex, particularly multiple wells
• Accessible but may access may be restricted
• Simpler in drag chain systems
• Similar consequences to process plant
• Higher risk because of location and confinement
• Most common area of hydrocarbon leakage

5.15.4 Process plant
• Issues as conventional process plant
• May be marine not offshore specification
• Location and fire protection important
• Access may be limited

5.15.5 FPSO vessel and marine structures
• Mooring integrity
• Corrosion of hull and vessel tanks - loss of wall thickness (LOWT)
• Microbial corrosion under sediment in tanks
• Cracking of turret support structure
• Impact damage
• Greenwater damage
• Incentives to maintain on station
• Integrity of process plant
6 SUMMARY OF INSPECTION AND MAINTENANCE

FPSO turret systems are specialised items. For this reason, it is standard practice for FPSO operators to follow the manufacturer's guidance in maintaining components in the turret and FTS systems. The required maintenance will usually have been specified by the turret or swivel supplier in their maintenance handbook. This advice is normally based on an FMEA analysis carried out at the design stage, tempered by operating experience. In many cases the operator may have a maintenance contract with the supplier, which ensures that the maintenance practices take account of recent service experience and specialised knowledge of the design. Many operators, however, choose to undertake their own maintenance on the turret and FTS systems: this usually will be part of a broader package for the entire FPSO. Inspection and maintenance may be sub-contracted out to a third party, often on a risk/reward basis.

The turret system for FPSOs includes dynamic seals and moving components. Dismantling of such components is not usually advisable unless a level of damage has been identified that precludes other options. Dismantling could affect the integrity of the seals. The strategy here would be to monitor barrier oil pressure and leakage recovery, and intervene if these indicated an emerging problem with the seals.

It would be expected that the written scheme of examination for the FPSO turret would include components noted in the previous section (Section 5), especially those components that have a history of degradation or failure, and particularly where this could lead to hydrocarbon leakage. It is increasingly common for operators to determine the inspection schedule on a Risk Based Inspection (RBI) basis.

The usual maintenance practices for the main turret and swivel components are summarised below and later in Table 5. More specific information for individual turret and fluid transfer system designs can be found in Annex C and D.

6.1 INSPECTION AND MAINTENANCE FOR TURRET

Typical maintenance for an internal turret is as follows:

- maintenance of flexible risers and connections as manufacturer's specification
- diver inspection of mooring lines, bend stiffeners and connections except for Tentech IAT turrets where chain can be drawn in and inspected on deck
- functional and torque check on turret rotation and weathervaning
- monitoring of turret bearing condition including function check, grease monitoring, visual inspection of raceways where accessible. Magnetic particle or dye-penetrant inspection of raceways
- examination of bend-stiffeners in-situ with diver or ROV or after retrieval onshore - in-situ ultrasonic inspection is now possible
- visual examination and NDT (e.g. ultrasonics or MPI) of adjacent vessel structure to identify signs of fatigue cracking or loss of wall thickness
- check torque on all bolting on bearing housings, cranes and attachments. Remove, inspect and replace bolts on a 5 yearly basis
- check integrity of all connections to the turntable manifolding
- check condition of elastomeric seals around bearings for contamination or degradation

Specific maintenance practices for the turret interfaces, and individual turret components, are discussed below.
6.2 INSPECTION AND MAINTENANCE OF FTS SYSTEM

6.2.1 Multipath Swivels

Suppliers often receive little feedback and it is assumed operators follow the maintenance recommendations. Most multipath swivels are designed for a 20+ year field life and are very conservative in design. Suppliers apply a fit and forget philosophy. Typical maintenance is as follows:

Routine
- check torque on bolts ensuring that none are slack.
- don’t open seals, may damage or contaminate.
- check amount of liquid in leakage recovery tank
- check for signs of corrosion
- check functioning and lubrication of the bearings
- monitor torque on swivel units
- continuous monitoring of torque and angular position on torque arms.
- continuous monitoring of leakage rates for dynamic seals and fluid level in recovery tanks (where fitted).
- install leak detection systems adjacent to the swivel

After 5 years
- test the capscrews on the swivel rings
- pull studs and replace with new studs if necessary
- inspect to ensure no subsurface cracks e.g. on bearing housings.

Normal policy, as with other dynamic seal systems, is not to intervene unless leakage or hydrocarbon monitors indicate a problem. In such circumstances production would be stopped and the swivel dismantled and changed out in the field location. Examples include changing of seals on water injection and replacement of a leaking gas swivel after 2 years. Inspection invariably is non-intrusive from the outside of the swivel stack, although endoscope examination may be used to examine inside the swivel rings or core. The studs and nuts will be checked for torque and condition on a routine basis: it is not normally necessary to replace them with new studs.

The times taken for strip-down and replacement of seals depends on the weather etc. Typical 7-10 days minimum is required in good weather. Strip-down would utilise the crane on turret transfer system. In-situ seals typically take 1-2 days to changeover in the field or 24 hours in the workshop.

6.2.2 Compact Swivels

Framo try to have a service agreement with the operator and their own people on board the FPSO to ensure that maintenance is done correctly. There is good feedback from operators.

No maintenance is undertaken for the bearings and seals. Standard practice is to monitor the barrier oil and intervene as described above and not inspect or change out unless any malfunction. No consumption of barrier oil is indicative of the seals being in good order. The torque arm reading is also monitored - any inconsistency may be indicative of a seal or bearing problem. Dismantling and checking could initiate damage. The operating conditions for swivel seals are more benign than in fast rotating equipment such as pumps. Hydrocarbon monitoring would also be in place.
Standard maintenance would include:

- visual check for leaks in hydraulics and other systems
- check bolt pretensions on a regular basis - usually monthly or every 3 months
- continuous monitoring of barrier oil system for pressure losses, temperature and condition
- continuous monitoring or torque and angular rotation on torque arm
- no maintenance undertaken of bearings or seals - could damage
- check functionality of the instrumentation
- check tensioning and torque on swivel
- check alignment and gap tolerances
- check condition of flexible and hard pipe connections
- check electrical and utilities connections in the upper swivel

The modularised approach allows spare parts and service to be delivered to the operator at short notice in the field. There are specialised tools and guides available and assembly is quick - approximately 1 day is required to assemble a swivel ring.

The swivel design has been standardised, based on a few centre body dimensions. This ensures that the operator will only have to keep a limited number of critical spare parts available offshore for the specific system, and that the suppliers’ service company has a pool of material for ring elements, seals and bearings which could be supplied offshore at short notice.

6.2.3 Drag-chain systems

Drag chain FTS systems are bulky, but intrinsically simpler than multipath swivels to maintain due to the absence of dynamic seals and the simpler manifolding. The main issues are the condition of the flexible risers connections, abrasion of the flexible piping and the condition and functionality of the drag chain cable-management system itself. Typical maintenance for a drag chain FTS may include:

- inspection of flexible risers as manufacturers specification, particularly for abrasion damage.
- replacement of flexible piping at 5 yearly intervals
- visual inspection and leak checking of flexible riser connections to turntable and to ESDV tower.
- visual inspection of condition of drag chain and cage for corrosion and wear
- functionality check on weathervaning of system including torque required to rotate turret
- lubrication and visual inspection of drag chain and replacement of links where necessary
- functionality check on umbilicals and check for abrasion or wear

6.3 TURRET TRANSFER SYSTEM (TTS)

Maintenance practices could include visual inspection and walkround, hydrocarbon monitors and leak detection, wall thickness measurements, corrosion monitoring and ultrasonic inspection for fatigue cracking and weld cracking. The condition of flanged joints would be visually assessed and bolt tension checked. Valves, alarms and monitoring systems would be tested for functionality.
6.4  INSPECTION OF TURRET INTERFACES

6.4.1  FPS/ Vessel interface
Continuous monitoring of torque and angular position on torque arms. Monitor and ensure lateral movement on swivel stack is not excessive. Undertake regular visual inspection and maintenance of all flexible and hard pipe connections to the swivel stack, particularly flexible pipe connections. Ensure monitoring in place for hydrocarbon leakage. Carry out routine condition assessment of all piping for corrosion or other damage mechanisms.

6.4.2  Main Turret Bearing
Manufacturer's recommendations are generally strictly followed. Checking of bearing alignment is crucial as any misalignment will generate large bending moments, which will be amplified by load transfer through the bearing in a similar manner.

The bearing integrity will also depend on the quality of the sealing. Sealing is required to keep out the environment, protecting from sea, saltwater or dirt and for lubrication. The seal may also assist in controlling bearing alignment and position and limiting deflections of the bearings. Sealing is usually done with an elastomeric dynamic seal. In practice this is usually a compound structure of elastomeric, polymeric and metal components. Seals are vulnerable to vibrational damage and to contamination. Explosive decompression is not an issue for the turrets, but is for dynamic seals on swivels which are usually based on 3-roller slew-ring bearings.

Sliding pad bearings have a significant higher friction coefficient than roller or wheel bearings. However they are much simpler to deploy, inspect and maintain.

Damage to large bearings is slow and progressive and could easily go unnoticed until it is difficult to intervene. It is important to be aware of gradual degradation. It is difficult to put right on station. Bearing life is notoriously difficult to predict even by specialist bearing experts such as at the National Centre of Tribology (NCT).

Such bearings are generally slow moving and damage is slow and progressive. Because of the sealing requirements, such bearings are not simply accessible for maintenance and if a problem does occur can be slow and costly to put right. The large cylindrical forgings or slew-rings that provide the bearing surface for the raceway are produced by only a few specialist suppliers and are custom built. Ulstein and SKF being the main suppliers for FPSOs. A consequence of this is that replacements may take many months to procure. It is crucial, therefore, that bearing condition and function is regularly monitored.

It is not possible to divorce the bearing performance of large turret bearings from that of the seal and the structural support. Alignment is also crucial. **It is important for the inspector to ascertain that the factor of safety allowed for in bearing design is realistic in terms of the level of loading** as the bearing will amplify loads according to the cube rule (see below). This will have a major impact on fatigue loading on the vessel structure and frictional load on the bearings.

Key issues are:

- the stiffness of the supporting structure
- the sealing arrangement and lubrication
- the tension in he bolts that secure the bearing housing

Hence it is essential that a proper procedure and some monitoring system is in place.
This could for example comprise the following:

- Estimate load parameters
- Estimate load transfer to bearing and vessel structure. How much deflection is allowed before it affects the integrity of the bearing structure
- Acceptance of design load parameters
- Check operating requirements
  - support structure
  - alignment limits
  - sealing (what sealing used, lubricant or lip type seal fluid)
  - monitoring system

Oil is better as a lubricant, but is poor as a seal. If the loading or location is altered then the procedure above should be repeated to ensure parameters are within design limits. It is important that maintenance is done properly and not just prescriptively. For example, injecting new grease into the bearing and not replacing old greases which may have hardened.

Monitoring could typically comprise:

- monitoring of grease (presence of metallic particles, water and other contaminants) - It is difficult to get a representative sample
- monitoring of tension in bolts
- rocking tests to check for free play and alignment. This is difficult to obtain for turret bearings
- functional check, measure torque required to rotate
- visual inspection of accessible parts and raceways - including pads on gliding bearings or wheels and raceways on three roller bearings or axial bogeys
- crack detection in areas susceptible to work hardening, such as at areas of stress concentrations on raceways and bearing housings
- dye-penetrant or magnetic particle inspection (MPI) of raceways for signs of cracking or surface degradation

This will usually be specified by the bearing supplier who may also advise on acceptable loading, alignment and deflection limits.

### 6.4.3 Lower Turret Bearing and turret cavity

The lower bearings typically comprise 10-20 bronze bearing blocks in a bearing housing ring integrated in the tanker keel. These mate with an Inconel bearing surface overlaid on the turret. These bearings are designed to be maintenance free, with inbuilt pockets for PTFE/graphite wax lubrication and a manual greasing system that runs from the turret deckhouse at turntable level. Although conservatively designed to operate without sealing or additional lubrication in a seawater environment, the lower bearings are usually protected in a grease environment by a double 'O'-ring energised seal. The allowance made for wear in the bearings and seal is typically two to three times that anticipated over a 20 year lifetime.

The wear on the bearing pads and the tensioning on the seals is checked by an annual inspection. Access for inspection of the lower bearings is usually from the turret cavity or alternatively by diver or ROV.

This is an area of load transfer and the adjacent vessel structure should be checked for cracking from within the vessel. Any difficulties with the bearings would be indicated by difficulties in weathervaning.
6.4.4 **Mooring buoy connections**
The mooring lines are visually inspected by diver and ROV except in 'Tentech' IAT turrets where these can be drawn up on deck and inspected. The link on the chain stopper would be replaced typically every two years.

The condition of the flexible risers where they enter the turret section would also be inspected visually and by ROV. Improved inspection methods for flexible risers are under development.

6.4.5 **Bend-stiffeners**
The bend-stiffeners on the risers are susceptible to cracking by two mechanisms identified earlier in Section 5. Normal maintenance practice is visual inspection by diver or ROV on an annual basis. If damage is suspected or typically on a 5 yearly basis the relevant risers would be disconnected and laid down to the seabed. The bend stiffeners would be taken onshore for more detailed inspection.

Ultrasonic methods and inspection procedures for bend-stiffeners have recently been developed and qualified by AEA Technology for the cracking mechanisms identified earlier. In this case the riser with stiffener attached is disconnected, laid down onto a barge or vessel and inspected then replaced. This method is fast and removes the need for laying down the risers or retrieval of the bend-stiffeners onshore. It is understood these procedures have been applied so far to two FPSO's in the North Sea.

6.4.6 **Turret shaft/ mooring buoy interface**
These are more typically welded than a bolted connection. Visual examination by divers is carried out on the interface between the turret shaft and mooring spider. NDT inspection of the welds may also be conducted using eddy current array methods such as Lizard or ACFM. The turret structure is cathodically protected by galvanic anodes.

6.5 **INSPECTION PRACTICES FOR SPECIFIC TURRET COMPONENTS**

6.5.1 **Moonpool / Turret cavity**
This is not usually found to be a problem area. Accessibility will depend on the turret design and supplier, and may be restricted. For example in the Norne FPSO access for inspection is provided by an 80cm gap. The Norsk FPSO, which has a passive weathervaning 'Tentech' turret, has a 75mm gap.

6.5.2 **Mooring Lines**
A typical inspection scenario for the mooring lines on an FPSO approved by the Classification Societies involved may comprise the following:

- in a 5 year period one mooring line per unit is taken out of operation for inspection.
- bottom chains – designed for 20 years of continuous use without inspection requirements; in a 5 year period one section of the bottom chains would be inspected at the same time as inspecting the selected mooring line
- polyester lines – samples are assembled on the mooring and removed intermittently for assessment - the 1st sample is removed in the first year in use, the others in a 2,5 year period - visual examination by ROV while removing samples.
- top chains – in a 2 year period the link connected on chain stopper is changed - in a 5 year period one whole section is inspected.
- depending on inspection results, periodicity can be changed
6.5.3 **Risers**

In a 2.5 year period underwater visual examination performed by certified divers on the splash zone with an annual inspection performed by remotely operated vehicle (ROV) on the catenaries.

Inspection and maintenance practice for other turret components can be found in Table 6.

### 6.6 INSPECTION PRACTICES FOR SPECIFIC TURRET TYPES

#### 6.6.1 Internal Active Turret (IAT)

The ICT turret is designed for accessibility and maintenance. Inspection practice for safety critical areas is as follows:

- whole fairleads can be changed in-situ from supply boats.
- bearing pads can be released and individually inspected.
- the bearing surfaces and rings are accessible topside for visual inspection
• flexible riser connections are accessible topside for inspection - no difficulties have so far been encountered.
• the most loaded region of the moorings the 25m of chain passing over the fairlead can be pulled up for inspection. This contrasts with conventional turrets, e.g. SOFEC, which require divers for anchor chain inspection.
• tension on the mooring lines is monitored.

Moorings are combined chain and wireline. Mooring chains run through fairleads with chain stoppers. There are jack winches on each mooring line. The main loading point is at the top of the turret.

Main Turret Bearing 'Tentech' (IAT) Turret

The top bearings are a critical element in the design. The turret contains an innovative, patented, upper sliding ring bearing with graphited pads to take axial and radial loads. The pads are produced by DEVA Werke using a patented material. The large diameter sliding ring is produced by Ulstein. The vertical bearings have 67 separate bearing pads, which are spring-loaded, with separate hydraulic cylinders to facilitate release for examination (50mm play when unloaded).

In contrast to conventional turret bearing systems, the bearings of IAT turrets are above deck level and fully accessible. Individual pads can be examined and replaced by releasing the hydraulics. Note that in conventional turrets the swivel may only be 2-3” above the deck and, therefore, the bearings are not readily accessible.

The pads can be replaced. Both pads and steel bearing surface can be inspected visually at deck level. This has advantages over conventional bearing systems - such as SKF radial/axial sliding ring bearings similar to those used in cranes, which have high friction, or conventional three-roller bearings - which can be very difficult to access.

The bottom turret bearing in the 'Tentech' design of IAT turret uses alignment pads similar to other turret systems and is not significantly load bearing. This is accessible for visual inspection and wear measurement from the vessel deck via the turret cavity.

6.6.2 STP and STL Turrets

STL and STP turret-buoys can be disconnected and retrieved and inspected on deck. See Annex C for a detailed description of inspection and maintenance practices relevant to STL and STP turrets.

6.6.3 Internal Disconnectable Turret (ITD)

There are some additional issues compared to inspection of a conventional internal turret in particular the integrity of the disconnection interface to the mooring buoy:
• disconnection interface. Functional check
• functional check and monitoring or tensioner devices
• visual inspection and monitoring of locking devices
• monitoring of condition and for hydrocarbon leakage on the static seals at the disconnection interface
6.6.4 External Turret
This is similar to that for conventional internal turret systems. The turrets are much smaller and easier to access and maintain. The turret and swivel stack is more exposed to seawater being on a cantilever structure on the bow of the vessel. Corrosion and greenwater damage are likely to be more severe than for internal turrets experiencing similar sea conditions. Hard piping passing from the turret and FTS through the cantilever structure is not simply accessible for inspection, but should be inspected for internal corrosion where feasible. Typical maintenance might include:

- External visual examination of turret for corrosion damage
- Functionality check on disconnection/reconnection interface
- Functionality check on turret bearing and universal joint including torque checks.
- Examination of swivel and dynamic seal performance (See Section 8)
- Replacement of static seals
- Examination of flexibles as recommended by manufacturer particularly connections
- Leak monitoring of riser connections, interfaces, manifolding and swivel
- Diver examination or recovery and examination of mooring chains and connections
- Maintenance and functionality check on winch for connection/disconnection

6.6.5 External Disconnectable Turret
This is as for conventional external turret systems. There will be additional maintenance associated with the disconnection interface and universal joint:

- Functionality check on disconnection/reconnection interface
- Diver examination or recovery and examination of mooring chains and connections
- Maintenance and functionality check on winch for connection/disconnection

6.7 GENERAL INSPECTION ISSUES FOR FPSO

6.7.1 Vessel structure
Inspection of the FPSO vessel structure might typically comprise:

- In a 2,5 year period, in compliance with Classification Societies requirements, underwater inspection of the hull, consisting of visual examination, ultrasonic thickness gauging, electro-chemical potential measurement and video recording, performed by certified divers.
- In a 5 year period, visual examination of all crude and ballast tanks in compliance of Classification Societies requirements.
- For double-hull vessels tank bottom condition can be checked from accessible points between the shell using wall thickness gauges or other NDT methods.

6.7.2 Process plant
Inspection and maintenance is as for conventional offshore process plant. This will include corrosion monitoring and routine NDT inspection. There are additional issues in relation to greenwater damage and to condition of structural supports on the vessel deck. Knowledge of areas susceptible to greenwater damage will come from operating experience and inspection be targeted appropriately. The process plant is located above the storage tanks.

6.7.3 Excessive roll
If there is excessive roll or the loading on the turret system goes beyond normal operation or design limits more frequent inspection of critical areas would be advisable. This includes
checking all flexible or hard pipe connections to the FTS system or turret, attached systems such as cranes and winches, the ship structure adjacent to the turret for ovality and cracking, bearing condition and the torques and alignment on swivel rings.

6.8 POTENTIAL INSPECTION DEVELOPMENTS

Turret systems in general perform reliably and integrity can be managed through existing inspection, maintenance and monitoring procedures as specified by the suppliers. There is scope for some developments which could improve safety or reliability or offer economic advantages to operators. These include the following:

- Ultrasonic inspection systems have been developed for crane slew-ring bearings by the FORCE Institute in Germany. These allow the bearing surfaces to be inspected without requiring dismantling. This technology has possible application to FPSO main turret bearings.
- 'Smart' washers are such as BoltSafe™ are now available for monitoring and controlling the tension on bolts and have been used in crane slew-ring bearing housings. These have possible application to bolting in safety critical FPSO components such as the main turret bearing housing or the swivel stack.
- Improvements in FPSO external underwater inspection using special crawlers or ROV equipped with NDT devices (digital cameras, ultrasonic probes, electrochemical measurement cells, eddy current probes, etc).
- Developing of improved preventive and predictive maintenance/inspection practices for turret bearings.
- Developing of remote stress-monitoring practices for turrets.
- Development of sensors for permanently installed monitoring (PIMS) or remote monitoring practices for FPSO turrets and structure and microbial corrosion in oil storage tanks - there is currently some use of strain gauges.
- Improved methods for crack detection in ship support structure around turret - for example detecting voids/cracks under painting.
- Inspection of swivel-seals, swivel rings, etc. - this is very vendor specific and it is probably not possible to make a general project to address this issue.
- Improved inspection of flexible risers and connections - There is a gap for an inspection tool - several ongoing projects, JIPs or users forums have addressed this over a number of years - this is an issue not only for FPSOs - a JIP for eddy current (ET) inspection has been going on for 10 years involving CorrOcean and Robit - Norwegian oil companies are looking into computerised X-ray tomography (CT) as an inspection tool for connections.
- In-situ NDT methods for inspection of bend-stiffeners for cracking - current methods are costly and involve dismantling, lay-down and retrieval - significant recent advance with development of low frequency ultrasonic methods.
- Mooring and chains - ongoing JIP projects involving Norwegian companies.
- Generic guidance document and recommended practice for inspection and maintenance of FPSOs.
- Remote access NDT for inaccessible regions in cantilever external turrets.
- Application of medium and long range ultrasonic methods such as CHIME and guided-wave methods to access inaccessible areas such as slew-rings for inspection.
### Table 6
Summary of usual maintenance practice for main turret and fluid transfer system components

<table>
<thead>
<tr>
<th>Key Areas</th>
<th>Maintenance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SWIVEL</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Seals (HP, MP and LP swivels)</td>
<td>Pressure test, Leak rate, Leak detection. Seal pressures monitored and intervention triggered if difficulty in primary or secondary seal</td>
<td>Leakage is recovered and monitored. Intervene if above design limits.</td>
</tr>
<tr>
<td>Swivel stack</td>
<td>Torque Test on bolting</td>
<td></td>
</tr>
<tr>
<td>Swivel rings</td>
<td>Torque check</td>
<td></td>
</tr>
<tr>
<td>Torque arms</td>
<td>Real-time monitoring of loads, torque and alignment</td>
<td>Crucial to avoid lateral movement of swivel stack</td>
</tr>
<tr>
<td>Bearings</td>
<td>Function check, grease monitoring. NDT of bearing housings</td>
<td></td>
</tr>
<tr>
<td>Gas export swivel</td>
<td>Leak detection, flow rate measurement</td>
<td></td>
</tr>
<tr>
<td>Piping connections</td>
<td>Visual inspection, bolt tensions, hydrocarbon monitoring</td>
<td></td>
</tr>
<tr>
<td>Bolting</td>
<td>Tension checks, UT</td>
<td></td>
</tr>
<tr>
<td>Internal pipework</td>
<td>Not accessible, Dismantling</td>
<td>Conventional swivel</td>
</tr>
<tr>
<td>Torroid surface</td>
<td>Not accessible, endoscope, dismantling or possibly high energy radiography</td>
<td></td>
</tr>
<tr>
<td>Tensioners</td>
<td>Visual, function check, dimensional checking</td>
<td>Disconnectable turrets only</td>
</tr>
<tr>
<td><strong>TURRET</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turret bearings</td>
<td>Function check, grease monitoring, visual inspection of races, magnetic particle or dye-penetrant inspection or UT inspection of bearing surfaces.</td>
<td>dedicated electromagnetic and ultrasonic systems are available specifically for slew-ring inspection</td>
</tr>
<tr>
<td>Turret rotation mechanism</td>
<td>Functionality check</td>
<td>Important to monitor torque required to rotate and avoid sudden unexpected slippage</td>
</tr>
<tr>
<td>Flexible riser connections</td>
<td>Function check, hydrocarbon monitoring</td>
<td>X-ray tomography methods under development</td>
</tr>
<tr>
<td>Flexible riser casing (within Turret)</td>
<td>Usually not inspectable without disconnection</td>
<td>Depends on design</td>
</tr>
<tr>
<td>Bolting</td>
<td>Tension check, dismantling and inspection, ultrasonic (UT) crack detection</td>
<td></td>
</tr>
<tr>
<td>Bend-stiffeners</td>
<td>Visual ROV, Ultrasonic inspection, dismantle - lay down riser- inspect stiffeners onshore</td>
<td>New low frequency ultrasonic methods are available that avoid the need to disconnect and lay down the risers</td>
</tr>
<tr>
<td>Turntable Manifolding</td>
<td>Visual, Leak detection</td>
<td>As inspection and maintenance of conventional process plant</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>------------------------------------------------------------</td>
</tr>
<tr>
<td>Moonpool/Turret support structure</td>
<td>Visual inspection, ultrasonic (UT) wall thickness measurement, Ultrasonic crack detection, TOFD for weld root erosion</td>
<td></td>
</tr>
<tr>
<td>Swivel access structure</td>
<td>Visual checks, bolt tensions, leak detection</td>
<td></td>
</tr>
<tr>
<td>Mooring lines</td>
<td>Tension, visual inspection, MPI. Conventional turrets require diver inspection. IAT turrets can pull mooring lines up through fairlead and inspect top 25m of chain.</td>
<td></td>
</tr>
<tr>
<td>Process pipework</td>
<td>WT measurement, corrosion mapping, Leak monitoring</td>
<td>As DCR. In accordance with operators written scheme of examination.</td>
</tr>
<tr>
<td>Choke Valve Connections</td>
<td>Leak testing, Monitoring, Bolt tensioning</td>
<td></td>
</tr>
<tr>
<td>Pipework connections</td>
<td>Visual inspection, function check, hydrocarbon monitoring</td>
<td></td>
</tr>
<tr>
<td><strong>General</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vessel movement</td>
<td>Roll within design limits</td>
<td></td>
</tr>
</tbody>
</table>
7  EXAMPLES OF GOOD AND POOR PRACTICE

The maintenance afforded to turret and fluid management systems will depend on the design. As these are specialised systems with dynamic seals and moving components, inspection and maintenance will generally follow manufacturers recommended practice. The examples given in this section may provide focus for discussion by HSE inspectors and guidance as to whether inspection and maintenance is being done to an exceptionally good or below average standard.

7.1  GOOD PRACTICE

- Operating within design conditions
- Appropriate response to conditions outside design conditions (e.g. excessive roll). Inspection strategy modified to reflect this
- Actual loading on main turret bearing known and appropriate changes in maintenance practice made if outside design loading
- Use of specified lubricants
- Key damage mechanisms known and appropriate maintenance strategy in place.
- Areas inaccessible or difficult for inspection identified and appropriate maintenance strategy in place - this may include funding of development programmes to provide a solution
- Swivel maintenance in accordance with supplier's recommendations
- Interaction with swivel and turret suppliers on operational problems
- Subcontracting of swivel maintenance to swivel supplier
- Turret bearing lubrication and maintenance in accordance with manufacturers and design specifications. Good grease monitoring procedures in place
- Dedicated team on board with responsibility for inspection and maintenance and good knowledge of turret and swivel technology.
- Regular inspection of turret support structure and moonpool for ovality and cracking. Integrity management strategy in place for these areas
- Regular inspection of all flexible risers and connections
- Regular inspection of mooring connections and replacement of mooring lines at reasonable intervals
- Appropriate shutdown and disconnection in adverse conditions
- Monitoring of leakage rates from dynamic seals and appropriate action if beyond acceptable limits
- Use of offshore specifications for pipes and welding in turret system and process plant
- Functional check on rotating components
- Function check on drive system for active drive turrets
- Regular inspection of mooring connections
- Condition of turret support structure known and adequate monitoring in place of any cracking.
- Regular check of torque required to operate swivel rings
- Sequential inspection of mooring lines
- Torsion check on all bolting. Sequential replacement at agreed intervals.
- Procedures in place for connection and disconnection of disconnectable turret systems
- Regular visual inspection of components at disconnection interface.
- Frequent monitoring of turret loading and condition. Adjustments in maintenance applied to reflect real loading
- Regular inspection of all bolting and flange connections in turret transfer system and monitoring in place to detect hydrocarbon leakage
- Inspection procedure in place for bend stiffeners on risers
• Appropriate evacuation procedures in place for turret
• Peripheral items, staircases, scaffolding etc. well maintained.
• Locking and drive mechanisms well maintained and functioning for active turrets
• Good accessibility for maintenance.
• Proper lubrication of moving parts on turret and FTS in accordance with manufacturer's specifications
• Adequate storage and protection of replacement seals to limit environmental degradation
• Knowledge of condition of FPSO storage tanks and presence of any corrosion - particularly microbial corrosion

7.2 POOR PRACTICE

• Equipment manufactured to marine standards above deck and in turret systems - relaxation in process equipment standards, for example inadequate pressure relief in tanks
• Inspection of turret and FTS system below that specified by manufacture without due cause
• Poor or infrequent interactions with swivel and turret supplier, particularly when difficulties experienced
• Leakage rates from dynamic seals above recommended limits
• Operating outside original design conditions (unless justified by robust Safety Case)
• Over-frequent intervention on dynamic seals, for example in swivel system
• Spare seals not stored according to supplier's recommendations - risk of environmental degradation or damage
• No dedicated team for swivel and turret maintenance
• Inadequate inspection strategy in place for flexible risers and connections
8 APPLICABLE REGULATIONS

8.1 REGULATIONS

8.1.1 Background Culture

FPSOs operate in a “no-man’s land” between two very different regulatory realms: offshore and maritime. Before the days of mobile platforms, offshore installations were fixed in one location. Thus it was logical that the host nation should bear the full responsibility for regulating the offshore industry in its locality as it saw fit. Thus, in the UK, the Government via the HSE holds responsibility for regulating the offshore industry.

The maritime world is different. Vessels come and go between national waters on a daily basis. They are flagged, owned, managed, crewed and insured in different countries. The maritime industry’s international attributes make a combined multi-national regulatory approach a necessity. The International Maritime Organisation (IMO), based in London, is the body that was created to co-ordinate this function. IMO requires its member states to write their maritime regulations/conventions/protocols (see later section) into their own national law. The UK is a signatory to IMO and the Government delegates the enforcement of the IMO codes to the Marine & Coastguard Agency (MCA).

Both HSE and MCA delegate some of their responsibility to expert third parties, such as Classification Societies. IMO codes formally require vessels to be classed with a Classification Society who will have their own Rules as well as ensuring compliance with the IMO codes.

The UK offshore industry, being much younger than shipping, originally adopted the maritime regulatory model. It relied upon the same Classification Societies to provide the rules. The enquiry following the Piper Alpha incident, however, overturned this and a new approach was developed. The traditional prescriptive approach was replaced by a Safety Case risk-based regulatory approach, in which any independent third party with the requisite credentials can undertake offshore verification. Unlike ships, the Classification Societies’ registers are no longer an obligation for the offshore installations. Old habits die hard, however, and the Classification Societies still have a stranglehold on offshore verification, albeit with the new risk-based culture.

This difference in approach in the UK is now being felt by FPSOs as they can operate as both a vessel and an offshore installation. Should they comply with both sets of regulations? Should they be inspected by HSE, MCA and each of their delegated third parties? This question is still being debated, but a common approach seems to be developing. Classification Societies have developed their rules to cover all types of vessel, including FPSOs. By applying these Rules, the classification societies would argue that a classed FPSO would be in condition to meet the requirements of both shipping and offshore legislation should it need either or both sets of certification. Certification is not, however, applicable to UK offshore installations.

Whilst Rules and Regulations cannot be said to be risk-based:

(a) they can be said to be based upon generic risks identified by hundreds of years of individual experience, and
(b) the Rules do call for formal FMEA for each installation’s critical components and systems.

For this reason, some knowledge of the key ingredients of the Classification Society Rules is important.
8.1.2 Class Rules & Regulations

Each of the different Classification Societies would claim to be novel in its approach and have Rules that differentiate between them. While there will, of course, be differences, the majority of safety critical components can be predefined and thus all the class rules largely cover the same aspects. For this document the requirements of Lloyd’s Register of Shipping & Det Norske Veritas, the two most prominent Classification Societies in the UK offshore industry, have been dissected.

First of all, the interface between the process plant and the mooring system is to be defined for the purposes of classification. Thus an envelope can be drawn around the mooring system.

The following steps are then laid out:

- Structural assessment of the vessel and mooring system components is to follow standard rule scantling assessment with Finite Element Modeling (FEM) being mandatory.

- When evaluating the loads for the structural assessment, the following loading conditions are to be considered:
  - Unit motion induced accelerations
  - Mooring actions
  - Riser actions
  - Turret bearing reactions (calculated based on all the relevant actions on the turret)
  - Moonpool deformations (based on hull bending moments and shear forces)
  - Internal and external pressure actions, covering the intended range of draughts and load conditions including non-symmetric cases as applicable. Filling of void spaces to be accounted for (if relevant)
  - Local actions from equipment and piping system (weight, thermal expansion, mechanical actions)
  - Green seas
  - Wave slamming

- Local analyses are to be performed for structural areas identified, by the FEM, as highly stressed and/or safety critical. The Rules list the following specific items for attention, regardless of the FEM results:
  - Structure in vicinity of riser connection(s)
  - Riser hang-off structure
  - Structure in way of fairleads
  - Hang-off structure for anchor line
  - Local structure transferring bearing reactions
  - Chain lockers
  - Pipe supports (single supports and complex structures)
  - Equipment supports
  - Foundation for transfer system (especially for swivel solutions)
  - Lifting appliances and pad-eyes

- As the turret structure will normally be exposed to high dynamic actions, the choice of fatigue design factor for the turret is to reflect the level of criticality and the access for inspection at the different locations. The design should, however, provide for access to all areas, even if limited.
The following actions shall be considered for the fatigue design of turret structures:
- Dynamic actions (tension and bending moment) from risers
- Varying hydrodynamic pressure due to wave action
- Varying hydrodynamic pressure due to unit accelerations (including added mass effects)
- Reactions in the bearing structure due to other effects
- Inertia actions due to unit accelerations
- Fluctuating reactions in pipe supports due to thermal and pressure induced pipe deflections

In-service-inspection is to be planned. No mandatory period for inspection cycle is spelt out and thus a risk analysis should be used for the basis of the written scheme of inspection.

8.2 INTERNATIONAL MARITIME ORGANISATION (IMO) CODES & CONVENTIONS

Here follows information on international maritime conventions that may apply to FPSOs. It includes a list of the topics covered in the scope of each document. A useful overview of the current status in this area and issues relating to FPSOs from the perspective of a Classification Society, the American Bureau of Shipping (ABS), is given in the proceedings of an Institute of Petroleum Meeting held in February 2001xiv.

8.2.1 Code for the Construction and Equipment of Mobile Offshore Drilling Units (MODU Code)
- Design criteria for structure and arrangement
- Construction methods and standards
- Global maritime distress and safety system (GMDSS)

8.2.2 Convention for the Safety of Life at Sea (SOLAS)
- Stability – intact and damage scenarios
- Structure & its maintenance
- Life saving equipment
- Fire protection, detection and extinction
- Communications
- Navigation equipment

8.2.3 Convention on Load Lines
- Freeboard (distance from loaded waterline to deck)
- Means of access into the vessel
- Protection of openings
- Protection of crew from falling overboard

8.2.4 Convention for the Prevention of Pollution from Ships (MARPOL)
- Allowable substances, rates & zones for discharge of pollutants
- Equipment for mitigating against leakage of pollutants
- Structural requirements for mitigating against leakage of pollutants
- Discharge records (e.g. the “oil record book”)

• pollution by oil
• pollution by noxious liquid substances carried in bulk
• pollution by harmful substances carried in packages, portable tanks, freight containers, or road or rail tank wagons, etc.
• pollution by sewage from ships
• pollution by garbage from ships

8.2.5 Management Code for the Safe Operation of Ships and for Pollution Prevention (ISM Code)
• (Now included as an annex to SOLAS)
• Corporate procedures for management of ships and their crew
• Corporate environmental protection policy
• Communication between ship’s crew and shore based management team
• Responsibilities, authority and communication between all ranks of crew
• Language considerations
• Emergency procedures
• Audit/review

8.3 DESIGN AND CONSTRUCTION (DCR) REGULATIONS
As with other offshore installations in UK waters an FPSO or FSU is covered by the Design and Construction Regulations (DCR). This places the onus on the operator to define Safety Critical Elements (SCEs). A Written Scheme of Examination (WSE) and verification scheme must be put in place. A Failure Modes and Effects Analysis (FMEA) is often used to define the SCEs. Verification must be undertaken by an independent body and there are clear definitions of how this should be put in place.

We understand that HSE inspectors in reviewing the Safety Case would not normally ask to see these documents required under DCR. It is, however, a legal requirement that this documentation is in place. There is an active programme of inspection and verification schemes and the DCR documents are scrutinized closely by HSE.
9 CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

1) FPSO technology has been introduced rapidly in the North Sea Sector with a progressive evolution in turret and FPS systems and designs. Conventional internal turrets have become larger and more complex handling increasing levels of production. Swivels, other fluid transfer systems and associated interfacing systems have evolved to handle the more difficult production conditions associated with HTHP wells and to allow handling of water and gas injection, electrical and utilities functions and gas production through the swivel or FTS. There has been significant development in turret bearing technology, a key area, to make these more accessible for inspection and maintenance, particularly in the Tentech internal central turret designs.

2) The introduction of compact swivels with solid internal cores has simplified swivel designs, reduced the bolting required on swivel components, and is likely to reduce degradation of swivel internals. Dynamic seal technology is not new and is well established in pumps, mooring buoys and other rotating equipment. Most current swivel manufacturers have an established background in these technologies.

3) A modular approach has evolved to swivel production to handle the particular process conditions of individual wells. It is not usual to dismantle swivels to assess dynamic seal condition; indeed this in itself may initiate damage. Most swivels include primary and secondary seals, leakage rates are monitored, and leakage further prevented by seal overpressure. Leaks are still reported to HSE and deficiencies in the seal material are the most likely cause. Such seals have been subject to extensive research covering failure mechanisms such as explosive decompression and it is difficult to identify how seal quality could be improved and any variability eliminated. Degradation of the sealing surfaces and sand production are other potential causes of seal difficulties.

4) The introduction of the disconnectable systems such as the submerged turret production (STP) system, submerged turret loading (STL) systems, and disconnectable versions of existing turrets, has introduced an innovative approach to dealing with more adverse environmental conditions and allowed more economical development of marginal fields. The STL and STP systems are particularly elegant and represent an innovative alternative to conventional turret design. The choice of turret will depend on the operator's preferences and the field conditions. Conventional internal turret designs with swivels for fluid transfer are well established. Alternative designs using drag chain systems, not widely used, introduce considerable simplification eliminating the need for a swivel and complex manifolding. The drawbacks are the partial weathervaning (270°) and the need for active drive systems to eliminate sudden movements arising from the higher friction in the Tentech guided ring bearing system. The latter is, however, much more accessible for inspection and maintenance.

5) Increasing complexity in turret design has lead to the ability to handle increasing numbers of wells. This has lead to larger turrets and growth in size of the turret transfer system for transfer of production fluids between the swivel and turret. Many of the reported incidents to HSE between 1995 and 2000 have been associated with the TTS in internal turret designs. The issues here are very similar to other process pipework and are covered by the Design & Construction Regulations (DCR).
6) The crucial technologies in FPSO turret systems are the *dynamic seals* in the swivels, the *flexible risers* and connections, the *turret bearings* and load bearing components such as the *bending stiffeners* on the risers. The former two have the most safety critical implications because of the risk of hydrocarbon leakage. Connections to the swivel or FTS are another key area and are of particular concern if operating allowances, vessel roll, weathervaning etc. go outside design requirements. Degradation of the turret bearings is likely to be gradual and is of economic significance to the operator. Methods exist for monitoring bearing condition. Severe bearing wear would have safety implications because of the increased load transfer to adjacent vessel structures and, if it limited weathervaning, could increase loading on swivel connections and other components. Adequate maintenance and cleanliness of the bearings is essential.

7) As FPSOs represent both a marine structure and an offshore installation it is important to establish that safety critical items such as process pipework and valves meet offshore specifications. Marine specifications can be less stringent, for example the piping may be specified at reduced wall thickness with poorer weld quality and penetration. This could give increased risk of corrosion and erosion damage. Operators should be aware of the standards used for both marine and offshore structures in their FPSOs and be able to establish that these are adequate to give the required fitness-for-purpose.

8) Much is to be gained from a pooling of experience. Interactions and feedback between operators and turret designers should be encouraged. In many cases information on operational difficulties is not passed back to the designers, where a field solution has been implemented. The review did, however, highlight several good interactions, for example between Maritime Tentech and Statoil, and between APL and operators of STP and STL turret vessels. Joint industry initiatives such as the HOIS2000 programme are valuable in transfer of experience gained elsewhere to the North Sea environment.

9) A common sense approach appears to have evolved to handle the contradictions posed in FPSOs between marine and offshore regulations and interactions of staff within these different disciplines. A single team approach is common amongst North Sea operators.

9.2 RECOMMENDATIONS

1) The present study has included site visits to a number of suppliers of FPSO turrets and swivel systems. It would be extremely valuable to extend the experience base with visits to other major suppliers including SBM and Bluewater. The experience in this study is that such visits are an extremely valuable way of gaining first hand knowledge of maintenance practices and service history. It is strongly recommended that an HSE inspector should be present on such visits because of their unique perspective and the good contacts that this would establish.

2) It is recommended that an electronic ‘Knowledge Base’ version of this report be considered. This could make the information much more accessible throughout HSE and allow key information to be quickly accessed by searches or by drilling down to get more detailed information.
10 ACKNOWLEDGEMENTS

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