ANNEXES

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ANNEX A

Look-up Tables for UK FPSO and FSU Installations

Key
UK FPSOs and FSUs listed in alphabetical order

- N/K: Not Known
- N/A: Not Applicable
- Blank: Not Known

See Annex E for more detail on individual UK and North Sea FPSOs and FSUs
See Annex F for more detail World-wide FPSOs including other North Sea
<table>
<thead>
<tr>
<th>Name</th>
<th>Ailsa Craig</th>
<th>Alba</th>
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<td>PGS Offshore Tech./ Hyundai Mipo</td>
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<td>Bluewater Engineering BV</td>
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<td><strong>Vinga</strong></td>
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ANNEX B

Detailed information on individual turret designs
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Annex B Information on Individual Turret designs

The types and key elements in FPSO turret systems have been summarised in Section 5 of the main report. A distinction was made between the *turret* which provides the mooring and weathervaning of the vessel; the *fluid transfer system (FTS)* which transfers the process fluids and other signals from the turret to the vessel; the *turret transfer system (TTS)* or turntable manifolding linking the turret and FTS; and *interfacing systems* such as the swivel access structure and other ancillary equipment. This section provides detailed information on individual turret designs and description is confined to the *turret* only. Information is given on the designs themselves, key elements, operational and safety factors and maintenance and inspection practice. Detailed information on swivels and other fluid transfer systems is given in Annex C.

Seven main types of FPSO/FSU turret system were identified in Section 5. These are as follows:

- Internal Passive Turret (IPT)
- Internal Active Turret (IAT)
- Submerged Turret Production (STP)
- Submerged Turret Loading (STL)
- Internal Turret Disconnectable (ITD)
- External Cantilevered Turret (ECT)
- External Turret Disconnectable (ETD)

These individual turret types are now considered in turn.
1 INTERNAL PASSIVE TURRET (IPT)

This is the standard configuration for turrets in the UK North Sea sector. The turret is normally mounted near the bow end of the vessel. The turret is single-point-moored to the seabed and axial and radial bearings allow free and unrestricted weathervaning of the vessel 360° around the turret. The weathervaning is described as 'passive' as the vessel is free to rotate and no active drive is required. This turret type is sometimes described as an internal permanent turret. In this report, turrets with an active drive but otherwise similar to the IPT turret are also described as IPT. The term internal active turret (IAT) is used specifically to refer to the 'Tentech' design of turret which has quite different design features (See Section B2). Accommodation is ideally near the bow, but in earlier designs may be downwind of the turret.

The key element is the top turret bearing; which takes the load of the turret, transfers loads between the turret and vessel structure and allows the turret to rotate or weathervane. This is usually a roller or axial bogey bearing dependent on the turret manufacturer and operator preferences. A lower radial bearing helps centralise the turret and keep it in alignment. Fluid transfer to the process system is normally undertaken using a multiple swivel assembly mounted on top of the turret at deck level (See Annex C). In the conventional 'passive' system, the flexible risers and umbilicals are pulled up individually through the turret and connected above the top of the shaft to the turret transfer system.

The turret diameter is typically 5-10m but can vary from 4-20m, depending on the number of wells involved. Moorings are typically evenly spaced in bundles, for example at 120° intervals (3x3), to facilitate access for the risers and umbilicals. Disconnection of permanent turret systems is slow and not straightforward.

1.1 Principles

A cylindrical turret casing and the turret shaft is dropped into a cavity in the vessel's hull. The turret casing contains prealigned axial and radial bearings which hold the turret in place and allow the vessel to weathervane freely 360° around the turret to adjust to climactic conditions. The turret provides passive single-point mooring to the seabed. Very little additional hull reinforcement is required for maximum speed and economy.

The 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 give higher friction. The bearing type and location depends on turret design.

The turret itself is a relatively simple technology constructed from welded steel components. A large forging is welded on the top of the turret to provide support for the bearing raceways and housings. A separate forging is welded on the vessel turret cavity. The turret contains a guide tube, through which individual flexible risers pass to be connected to the turntable located above the turret.

Dependent on the manufacturer and design, access may be possible to the cavity between the turret and the vessel and to the inside of the turret; this is not always so. The preferred practice is to have the turret well ventilated and accessible at all times and not to use inert gas, except in emergencies such as hydrocarbon release.
Figure 1
Pictures of turret shafts prior to installation in the FPSO; Top - SOFEC, Bottom - Bluewater design for Petrobras FPSO
Courtesy Bluewater, SOFEC
Figure 2
The external support structure for turret bearing welded to top of the turret cavity. Avoids the need for complex machining operations. Lufeng internal turret FPSO. Courtesy SOFEC

Figure 3
Bearing ring for main turret bearing internal passive turret(IPT). Courtesy SBM
1.2 Systems and components

The main components found in a typical FPSO internal passive turret (IPT) are as follows:

- Turntable to turret transfer system TTS
- Flexible risers
- Flexible riser connections
- Umbilicals
- Upper bearing assembly
- Upper bearing support vessel deck
- Turret shaft
- Channels for flexible risers
- Channels for mooring chains (some designs)
- Lower bearing assembly
- 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)
- Bending stiffeners

These can be seen in the cross section of an SBM turret shown in Figure 5.
1.3 **Key elements**

The key elements are the bearings, the vessel turret support structure, the flexible risers and connections, the bending stiffeners on the risers, the turntable which provides the interfacing to the swivel or fluid transfer system and the mooring spider and connections

1.3.1 **Turret Bearings**

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 raceway diameters for turrets are huge, from 4m up to 20m in diameter, and require precision forgings. The bearing rings are usually manufactured from a low carbon steel such as case-hardened EN30A.
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 are normally configured to take radial loads.

The second, or lower, bearing assembly is usually a radial bearing using either wheels or segmented pads that centralizes 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. The mated surface is provided by an Inconel weld overlay located on the turret cavity. The lower bearing is usually protected by seals and is self lubricating, and is designed to operate satisfactorily in seawater. There will usually be a separate manual grease supply to the bearing. Note that in this report the term 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 simply accessible for maintenance. If a problem does occur it can be slow and costly to put it 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. Therefore it is crucial 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.

1.3.2 Bearing Configuration
The configuration and types of main bearing have been described in detail in Section 4 of the main report.

1.3.3 Bend-stiffeners
The bend-stiffeners, attached to the risers at the point of entry to the turret, take the large bending moments and protect the flexible risers from abrasion damage. These are usually made from elastomers with metal connections.

1.3.4 Turret cavity or moonpool
Refers to the vessel structure within the turret cavity and the access space between the turret and cavity. This structure is prone to ovality on dynamic loading and can be subject to fatigue cracking particular in conversions where the turret alignment and vessel structure surrounding the turret is less likely to be adequate. The accessibility will depend on the turret design.

1.3.5 Flexible risers
Production fluids are carried through the turret on flexible risers, which pass through riser tubes within the turret and are tied off onto the turret transfer system. Elastomeric bend-stiffeners on the risers take the bending loads on the riser where it passes into the turret.

The flexible risers, bend-stiffeners and connections are important safety-critical-elements in all FPSO turret designs.
1.3.6 Mooring Spider/ Mooring Buoy
In some IPT turrets, a large forging known as the mooring spider is connected by welding or bolting onto the lower end of the turret shaft. This facilitates access of the risers into the turret. The mooring lines are pulled in and stoppered off in the mooring spider.

1.3.7 Mooring lines
These are commonly chain, wire or polymer rope and then chain leading to piled anchors. The flexible risers are an integral part of the mooring system and allowed for in design calculations.

1.4 What can go wrong
The turret itself is perhaps the simplest part of the turret system and the prime concerns are with the turret bearings and the 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 (Annex C) which has high pressure dynamic seals. Relevant damage mechanisms are as follows:

- Progressive degradation of the bearings
- Loss of mooring connections or lines in adverse sea conditions
- Cracking of the adjacent vessel support structure and turret cavity - very common especially in conversions. Very difficult to put right as it is indicative of inadequate stiffness in the structure or excessive loading on bearings
- Excessive friction on turret
- Sudden movements and 'fishtailing'
- Crane and winch failure
- Loss of bearing alignment
- Loosening of failure of securing bolts on bearing housing, cranes and mooring spider attachments
- Leakage of flexible risers (unusual) and connections in the turret and at the point of connection to the turntable manifolding
- 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

For the bearings and 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 cage in roller or axial bogey bearings - harder to turn the bearing - may jam or less freely weathervane - amplified loads
• Loss of weathervaning capability - may get sudden uncontrolled movement of vessel or turret

1.5 Maintenance and inspection practices
Typical maintenance for an internal passive turret (IPT) is as follows:

• Maintenance of flexible risers and connections as manufacturers specification
• Diver inspection of mooring lines
• Functional and torque check on turret rotation and weathervaning
• Monitoring of turret bearing condition
• Examination of bend-stiffeners in-situ with diver or ROV or after retrieval onshore - in-situ ultrasonic inspection now possible.
• Visual and NDT examination, ultrasonic and MPI, of vessel structure for fatigue cracking or loss of wall thickness
• Check torque on all bolting on bearing housings, cranes and attachments - remove and inspect on 5 yearly basis.
• Check integrity of all connections to turntable manifolding
• Check condition of elastomeric seals around bearings for contamination or degradation

Specific maintenance practice for bearings has been summarised in Section 6 of the main report
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. The turret represents a significant evolution on conventional turret design and has a number of unique features designed to facilitate turret operation and maintenance.

Principal features include:

- Sliding ring bearing system with axial and horizontal bearing pads (Except Petrojarl 1 Roller Bearing)
- Bearing pads are accessible topside for visual inspection or individual replacement
- Flexible risers tie off vertically above deck level and are inspectable
- Can be used with drag chain or swivel as fluid transfer system (FTS)
- Active drive mechanism for turret rotation
- Thrusters to allow controlled positioning of vessel in variable weather conditions
- Accommodation upwind of turret protected by firewall
- 1st generation 20m diameter - 2nd Generation 13.5m. Can accommodate up to 24 12” risers
- Firewalls separate process system, turret and accommodation
- Swivel and turret manifolding are elevated to facilitate inspection of safety critical elements
- With drag-chain as FTS can continue operation in adverse weather conditions. Swivel connection hoses have to be disconnected in storms
- New Build vessel design with stabilizers to minimise roll and greenwater damage
• Anchor chains pass up through turret over fairleads and can be drawn up for inspection on deck (conventional turrets require diver inspection)

Information on design, safety critical areas and current maintenance practice was obtained from site visits with Maritime Tentech the designers and Statoil who operate two FPSOs with IAT turrets.

The background to the design was in the mid 1980's when concern was expressed about the ability of swivel technology to handle larger numbers of flow paths and higher pressures. This lead to the development in 1986 of the TUMOPS turret system in Norway by Maritime Tentech, designed to utilise a 'drag chain' system in place of the swivel.

The large turret diameter needed to accommodate the drag chain system, the number of risers and the rotational limits dictated that the turret be positioned midships, or near the vessels third point. Issues of turret location have been discussed earlier (Section 3.2). The 1st generation turret was installed in Petrojarl, Gryphon A, Captain, Rasmussen, Norne and Asgard A FPSOs, with a turret diameter of 20m and accessing up to 24 wells. A slimline second-generation turret has been used in Banff and in Kristian (concept stage) with turret diameter of 13.5m.

The Tentech turret is an evolution of the TUMOPS design. Of the seven turrets of this type operational in the North Sea sector, four have drag chains and three multipath swivels for fluid transfer. The turret can be designed to take most proprietary transfer systems. The Conoco Banff FPSO used a Brown Brothers swivel, others SBM or Framo swivels. The swivel proposed for Kristian has three production swivels, one electrical, one fibre optic and heating to eliminate hydrate formation. A new turret drum transfer system (TDTS) design for FTS is at the concept stage.

2.1 Principles
The turret is located centrally in the vessel, with the accommodation upwind and process plant downwind of the turret. Firewalls separate and isolate the accommodation, turret and process plant. The central location gives lower dynamic loads and reduced susceptibility to greenwater damage than if located at the front of the vessel. This location is considered by the designers as a much safer solution than that found in older FPSOs in the North Sea, which had no intermediate firewalls and accommodation downwind of the turret.

Turret rotation is thruster-assisted to improve control and optimize orientation. This reduces the variability and rolling that can occur in passive freely weathervaning turrets. It also reduces ‘fishtailing’ or small fluctuations in vessel location, which can be a hazard on offloading.

Most FPSOs of this type are newbuild and the shape of the vessel is important. The design is optimized to give lower motions and less greenwater including damping plates. The vessel shape has been optimized, backed up by extensive model tests.

The turret size is dictated by the enclosures. These normally comprise 24 risers, 12 anchor lines and 12 winches.

2.2 Systems and components
The major components for an IAT turret are shown in cross section in Figure 6 and Figure 7 with swivel and drag-chain transfer systems respectively.
Figure 6
Cross section through 'Tentech' internal active turret (IAT), showing major components. In this case a multipath swivel is used as the fluid management system with associated intermediate manifolding.

Diagram courtesy Maritime Tentech AS
Cutout model showing ‘Tentech’ internal active turret (IAT) with drag-chain fluid transfer system. Note, turntable manifolding is jacked up above deck by vertical bearings Courtesy Maritime Tentech
2.3 **Key elements**

2.3.1 **Flexible risers**

The flexible risers hang off the top deck through channels taking vertical loads with horizontal bending at the bottom. The connections are accessible above deck at the bottom of the turntable manifolding. This manifolding and swivel are jacked up above deck level to facilitate access.

![Schematic showing location of vertical and horizontal bearing pads and flexible riser (FR) tie-offs in IAT turret.](image)

**Figure 8**

Schematic showing location of vertical and horizontal bearing pads and flexible riser (FR) tie-offs in IAT turret.

2.3.2 **Turret bearings**

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 provided by Ulstein. The vertical bearings have 67 separate bearing pads, which are sprung loaded with separate hydraulic cylinders.

In contrast to conventional turret bearing systems, the main bearings are above deck level and all accessible. Individual pads can be examined and replaced by releasing the hydraulics (there is 50mm play when unloaded). Note, in conventional turrets the swivel may only be 2-3” above the deck and the bearings are not easily accessible.
The pads can be replaced. Both pads and steel bearing surface can be inspected visually at deck level. This is advantageous over conventional bearing systems such as SKF radial/axial sliding ring bearings, similar to those used in cranes, and conventional roller bearings which are very difficult to access. The bottom turret bearing uses alignment pads and is not a significantly load bearing.
2.3.3 Moonpool / Turret cavity
There is a 80cm gap to facilitate access. This is not usually found to be a problem area. The Norsk FPSO with a passive weathervaning FTS system has a 75cm gap.

2.3.4 Turning System
A turning system is required to ensure controlled rotation of the turret at 5° intervals. Gliding ring bearings have higher friction than conventional roller bearings. Without this, the turret would not move until 20° out of alignment and then move suddenly.

The turning system comprises a turning cylinder, a *gripper* to hold in place, and a jack. This feature is common on all Tentech turrets including Gryphon A and Captain. Second generation turrets such as Banff use a hydraulic pushing cylinder.

It is very rare that a drag chain system would be rotated the full 270°. Swivel systems have full 360° rotation.

2.3.5 Centralised winch
A centralized winch and sheave arrangement is used to pull in the mooring lines and risers. 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.

2.4 Operational and Safety Concerns
The primary concern is sudden rotation of the turret if orientation is more than 20° away from optimum. Turret rotation is usually controlled by the grippers. There have been isolated incidences of slippage.

2.5 What can go wrong
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 to the turntable
- 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 bend-stiffeners on the risers. Bending of the risers is more critical in shallow waters. The moonpool is a fatigue sensitive and critical area which is accessible for inspection, there is 80cm clearance for access in IAT turrets. There have been two occasions of *Greenwater damage* on these vessels but not affecting the turret.

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 above
There is not always feedback from the operators as the designs are licenced and operators may only contact the designers for difficult issues where they need help. A very open cooperation was noted between Tentech and Statoil with a joint paper given at the ONS conference in 2001\(^1\).

2.6 Maintenance and Inspection Practice

The IAT 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

Table B1

Summary of FPSOs turret systems by Tentech with Internal Active Turret (IAT) design

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<th>Particulars</th>
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<th>Tentech 859 S “Norse”</th>
<th>Tentech 769 T “Capitan”</th>
<th>Tentech 485 “Petrojarl”</th>
<th>Tentech 980 S Anglo FPSO</th>
<th>Tentech 788 R Ramnes</th>
<th>Ramboll Bufl FPSO</th>
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<td>Multi path swivel</td>
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<td>49 mill. scf/d</td>
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\(^1\) Operating experience of Tentech turrets, Statoil, Maritime Tentech, Offshore Northern Seas Conference, June 2001, Stavanger.
Figure 11
Tentech IAT turrets. Left- 1\textsuperscript{st} generation Statoil Norne. Right - 2\textsuperscript{nd} generation slimline turret Banff. Both have multipath swivel stacks as transfer system. Courtesy Maritime Tentech AS
Figure 12
Top illustration - Asgard A FPSO shown under construction. Bottom illustration - Swivel and Turret Transfer system for Tentech 900 Turret in Statoil Asgard A FPSO - SBM swivel.
Figure 13
Cross section through 1st generation Tentech IAT turret with swivel.
Statoil Norne.
Figure 14
Cross section through 1st generation Tentech IAT turret with Drag Chain Transfer. Texaco Captain FPSO.
3 SUBMERGED TURRET PRODUCTION (STP) AND SUBMERGED TURRET LOADING (STL)

The basis of the STL 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 and thus connecting the mooring system - see Figure 15. 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 swivel via the loading manifold to the piping system of the vessel. When disconnected, the buoy will float in an equilibrium position ready for new connection.

The Submerged Turret Production (STP) system 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 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 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 new connection.

Figure 15
Submerged Turret Production (STP) disconnectable turret-buoy, Lufeng Field. The conical buoy can be disconnected and float submerged 30-50m below the surface. The compact swivel sits above the turret inside the turret cavity, known in this case as the STP room. 
Courtesy APL
Figure 16
STL buoy after 5 years service and unused spare. at APL test facility in Arendal near Kristiansand Norway Courtesy APL

Figure 17
Picture of Submerged Turret production (STP) Turret buoy Courtesy APL
3.1 Principles

The turret-buoy is drawn up into the vessel using the winch on board. The buoy is locked in place with hydraulically operated locking pins. A conical guide tube on the vessel below the STP room guides the STL/STP buoy and keeps it in position (Figure 21). The compact swivel is moved across on a guide rail and connected to the top of the turret buoy. The flexible-risers are pulled up and connected in position. A static-seal arrangement protects the interface. The compact swivel is located in the STP room and sits above the turret-buoy. Flexible pipes connect the FTS and take production fluids to the process plant on the vessel. The STP room is freely ventilated except during connection and disconnection, when inert gas is used and the STP room is flooded with seawater.

Both sides of the bearing are in the turret-buoy and the rotation is fully within the turret-buoy system. A simple sliding bearing system is used with graphite and water lubrication. The risers are temporarily connected at the top of the turret-buoy. When the turret buoy connection has been made, the risers are lifted up to connect to the swivel. An ESD valve-block is attached to the top of the turret-buoy providing additional protection: this can be stowed away and stored once the turret-buoy is connected. During disconnection the turret-buoy is usually dropped with the ESD valve block on top. Inflatable rubber fenders separate the guide tube and turret buoy. This dynamic bearing seal inflates and expands to take the motion and keep the turret-buoy in position. The STP room is kept drained in normal operation.

Disconnection takes only a few minutes and can be performed in any weather condition. The buoy drops clear eliminating any danger of collision when the ship sails away. The main element of disconnection is shutdown of the process plant and swivel.

The standard interface on an STL buoy, e.g. Fulmar, is 780mm diameter with a diameter of 2.7m at the bottom of the cone. The interface is a precision item and supplied by APL. The conical guide tube is produced to shipyard tolerances and welded into a conical cut-out in the vessel, supported by three transverse bulkheads. APL supply the turret-buoy and interfaces.

Lifting the mooring buoy up generates the required tension in the catenary mooring lines. There are typically 6 mooring lines on an STL turret system. There is a 130 tonnes traction winch on the vessel. The additional **flotation tank** on the STP turret-buoy gives added buoyancy and ensures the correct turning moment.

3.2 Systems and Components

The main components in an STL turret system include the following:

- **STL Room**
- **Conical guide tube**
- **Trolley rail for compact swivel**
- **ESD valve block with interfaces**
- **Locking connector**
- **Turret-buoy**
  - Disconnection interface
  - Sliding main axial and radial bearing
  - Body of Turret Buoy
  - Buoyancy modules
  - Central core
  - Flexible riser connections
  - Mooring attachments with locking pins
  - Rubber fender
• Flexible risers
• Mooring chains and lines

An STP system is similar, but larger than an STL turret-buoy, 2.7m maximum diameter for Pierce, 5m proposed for STP5000 design for the White Rose field in Canada (Figure 23). The STP buoy shares the same conical guide tube, interface size and conical profile as the STL system. In addition to the above the STP buoy has the following components:

• Flotation tank (below turret buoy)
• Bend-stiffeners on risers

![Figure 18](image)

**Figure 18**
Left - Central core - the ‘turret’ - of the STL turret buoy showing chain table for mooring attachments. Right - STL turret buoy recovered after 5 years service
Figure 19
Top photo - Mooring attachments on spare STL buoy showing locking pins. Bottom photo - mooring attachments at bottom of STL central core (or 'turret') after 5-years service.
3.3 **Key elements**

Safety-critical elements are the main axial and radial sliding bearing, the connection interface, the flexible riser connections and the bend-stiffeners on STP systems.

The main bearing is a patented pocketed sliding bearing which is self-lubricating and can operate in seawater (Figure 20).

![Spare sliding bearing for submerged turret loading (STL) turret-buoy on wooden pallet at APL facility](image)

3.4 **Operational and Safety concerns**

The most critical operational issue is connection and disconnection of the turret buoy. To mitigate against the risk of hydrocarbon leakage, the STL room is flooded with seawater and an inert gas blanket is used during these processes. The STL room is freely ventilated during normal operation. The tension on the mooring lines is not monitored during operation. Any difficulties would be indicated by a change in vessel position.

3.5 **What can go wrong**

The main hazards identified in the Safety Cases for STL and STP buoys are:

- Anchor failure
- Turret seizure
- Hydrocarbon leakage

The finite-element analysis in design concentrated on fatigue aspects at high stress areas such as the mooring connections. APL base their design on calculations which are considered conservative. The riser calculations are done by the flexible riser suppliers. The Fulmar STL buoy was designed for 10 years life, 5 years in two different locations. A spare buoy was held onshore (Figure 16).
Existing STL and STP systems have operated reliably with little incident or damage. Issues that have arisen include:

- Damage to the inflatable rubber fender due to more severe than anticipated sea conditions.
- Some water leakage into the STP compartment
- Water leakage through the top bearing seals
- Failure of a locking pin on a mooring connection
- Minor impact damage to external panels (Figure 16)
- Problems in initial installation of turret-buoy
- Large friction on swivel ring

The main concerns are:

- Leakage into STL/ STP turret-buoy compartments
- Hydrocarbon leakage from flexible riser connections, top and bottom. These are connected up and hydrotested
- Dimensional control- tolerances correct for buoy to fit vessel
- Interface to swivel - pre-fabricated, tight dimensional control - dummy test before installation
- Fatigue of swivel support - 50- 80 ton - all forces below support taken up
- Flange on flexible riser connection to bottom of STP turret-buoy - made up by diver

Figure 21
Schematic of Submerged Turret Production (STP) system connected to compact swivel in STP room. Courtesy APL
Figure 22
Cross-section through STL Turret buoy showing internal structure, buoyancy modules, central core and bearing and mooring arrangements

Courtesy APL
Figure 23
Cross-section through STP-5000 concept turret-buoy showing internal structure, buoyancy modules, central core, bottom flotation-tank and bearing and mooring arrangements Courtesy APL
3.6 Maintenance and inspection practices

The first inspection and maintenance (I&M) is done early in the project to tie the customer into the philosophy. The strategy is based on a HAZOP assessment backed up by reliability centered maintenance (RCM) and a failure modes effects and criticality analysis (FMECA). An overall design review is done at the start of each new project to identify anything new or requiring special consideration.

An inspection manual is supplied to the customer and forms the basis for inspections. Standard forms are supplied by APL to the customer to record maintenance actions. These are copied back to APL so that information arising can be passed onto other STL/STP installations. Sacrificial anodes and protective coatings protect the turret-buoy from corrosion. The STL and STP buoys can be disconnected and retrieved on board the vessel to facilitate inspection. Areas that cannot be inspected are compensated for with higher safety factors in design. There are no individual components that have been identified as Safety-Critical.

A number of types of inspection or maintenance are carried out, for example:

- **GVI** General visual inspection
- **CVI** Close visual inspection
- **CPM** Cathodic protection measurement
- **IBCM** Instrument based
- **OCM** Oxygen content measurement
- **REP** Replacement
- **BSI** Boroscope
- **EVI** Event-based inspection

Video surveillance and leak detection is in place in the STP room. A remotely operated vehicle (ROV) is used to verify the condition of umbilicals, risers and moorings. There is access from the STP compartment for visual inspection of the top of the buoyancy cone and turret shaft, including the bearing. First measurement of clearance on the bearings is made when installed and this is used as a reference. There is a 10 step specific procedure to check for wear on the bearings. The swivel torque is measured to rotate the vessel. The first time the turret buoy is generally difficult to rotate. The function of the bearing is also measured onshore prior to installation, including the force required to turn.

Additional maintenance checks include the following:

- Wear of bearing (6 monthly) - quick measurement at 24 points
- Rotation test on turret bearing (6 Monthly)
- CVI of specific components in STP compartment
- Gas vent system
- Condition of pedestal and hang of connections to swivel
- GVI at 2 year intervals
- Condition of anodes
- Condition of connections and locking pin devices
- Check condition of flanges to ESD valves
- Check general condition of surface protection
- Leakage into buoyancy units controlled
- Continuous monitoring of torque on swivel support arm
- Measure friction required to turn buoy - confirm within allowable levels - typically 400kNm 950kNm allowable

A copy of all inspection reports is returned to APL. This has proved very useful and provides an alert on operational problems.
4 INTERNAL TURRET DISCONNECTABLE (ITD)

Disconnectable internal turret systems have been developed by SBM and SOFEC. In most aspects of turret operation these are similar to the permanent systems. The moorings and risers are connected to a separate mooring buoy, which can be swiftly disconnected from the main turret and drops to about 40m below the sea surface. This feature 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 3 hours. Disconnectable systems potentially offer safer operation and reduced pollution risk in offshore areas subject to seasonal adverse weather conditions.

4.1 Principles

Turret operation is in most aspects identical to a conventional internal passive turret (IPT). The main difference is that the mooring spider can be disconnected to give a separate mooring buoy, allowing the FPSO vessel to sail away.

The mooring buoy is retrieved and pulled near the turret by a winch and chain jack system, aligned and pulled into position. The risers are then pulled through the turret shaft and attached for operation. Connection is made with a tensioned collett connector at the disconnection interface (Figure 24). The mooring buoy is locked in place and held in place by a tensioner (Figure 25) which prevents bending moments affecting the integrity of the seal. The risers are individually pulled up using the winch on board and connected in a standard manner to the tie-off connections, normally located at the turntable. In some recent designs the riser connection is made directly at the disconnection interface with static seals. It is usual to use inert gas during both connection and disconnection in case of hydrocarbon leakage.

Disconnection is by a reverse of the above procedure and is preceded by shutting down production and isolating the swivel stack. There are usually special procedures in place that allow faster disconnection in emergencies or adverse conditions. The ability to disconnect the FPSO from the moorings is considered a safety benefit and features strongly in Safety Cases.

4.2 Systems and Components

The systems and components are the same as for a conventional internal passive turret (IPT) with the following additions:

- separate mooring buoy
- locking device
- connection/ disconnection interface
- tensioner
- buoyancy aids to optimise the flotation of the buoy and catenary moorings

4.3 Key elements

The key elements are the same as for a conventional internal passive turret (IPT) with the following additions.

4.3.1 Mooring buoy

The mooring buoy (Figure 26) provides the single-point-mooring for the FPSO vessel, provides the interface with the turret, and is the point of connection for the mooring lines. The flexible risers from the wells pass into the mooring buoy and are held in position at the interface ready to
be pulled up into the vessel. Alternatively the risers may be tied off directly to connections within the mooring buoy. There will be bend-stiffeners on the risers where they enter the mooring buoy to take the bending loading.

4.3.2 Connection/disconnection interface
This is a collet type connector with static seals. Separate mating interfaces on the mooring buoy and turret enable the two to be connected. The specific interface method used is proprietary to the turret supplier.

4.3.3 Locking device
Once connected the turret and mooring buoy are held together by a mechanical or hydraulic locking device. This enables the mooring buoy to be released in the event of an emergency.

4.3.4 Tensioner
A tensioner holds the mooring buoy in position under tension and prevents bending moments affecting the integrity of the interface (Figure 25).

4.3.5 Buoyancy aids
The mooring buoy is designed to float under neutral buoyancy connected to the catenary moorings. This is assisted by buoyancy aids on the catenary moorings.

4.4 Operation and safety concerns
Operation and safety concerns are the same as for a conventional internal passive turret (IPT) with the major difference that the turret is able to connect and disconnect from the moorings. The connection and disconnection processes are the times of highest risk of hydrocarbon leakage and appropriate procedures need to be in place.

4.5 What can go wrong
Operation and safety concerns are the same as for a conventional internal passive turret (IPT) with the additional issues associated with the connection and disconnection process. These include:
- hydrocarbon release during connection or disconnection
- failure to properly connect or disconnect
- loss of integrity during operation of the interface between the turret and mooring buoy
- failure of the locking mechanism
- failure of the tensioning device

The ability to disconnect is seen as a positive safety feature and to outweigh these possible disadvantages. Disconnectable internal turrets are a relatively new development, although there is a longer history of operation for disconnectable external systems.

4.6 Maintenance and inspection practices
Maintenance and inspection practices are the same as for a conventional internal passive turret (IPT) with additional checks associated with the connection and disconnection process. These include
- check functionality of connection and disconnection process
- visual and functional checks on mating surfaces and all aspects of the connection system
- monitoring for hydrocarbon leakage from the interface
The mooring buoy could in principle be recovered topside for inspection and maintenance, although diver or ROV inspection is more common.
Figure 24
Cross section through disconnectable internal turret showing the separate mooring buoy being winched towards the turret. Courtesy SOFEC
Figure 25
Connector tensioner for disconnectable internal turret showing the separate mooring buoy being winched towards the turret. Courtesy SOFEC

Figure 26
Disconnectable mooring buoy, internal disconnectable turret (IDT) Courtesy SOFEC
5 EXTERNAL CANTILEVERED TURRET (ECT)

This turret type consists of a swivel or multipath swivel assembly mounted on a cantilevered support structure attached to the bow of the vessel. Mooring connections to the turret provide single point mooring to the seabed and allow the vessel to rotate freely around the turret adjusting to climatic conditions. The riser or risers from the well are connected to intermediate manifolding below the swivel.

Figure 27
FPSO Vessel with external cantilevered turret (ECT) design. Courtesy SOFEC
The turret design does not differ in principle to the internal turret but is generally smaller and handles fewer flow paths. The main difference is that the turret is located at the end of a cantilevered support structure and not in a cavity in the vessel itself. The pros and cons of the turret location have been identified in Section 3 of the main report. The location necessarily gives a restriction on turret size. There are currently no FPSO’s of this type in UK waters, as the cantilevered external design is not suited to the adverse weather and current conditions pertaining in the North Sea. Greenwater damage would be of prime concern.

Potential failure modes and maintenance is the same as for internal passive turrets (Section 1), except that the cantilever structure should be considered in place of the vessel structure. 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.
The principal features include:

- external cantilevered turret elevated above water level at the bow of the vessel
- multipath swivel for FTS
- Conventional turret bearing and support
- multiple wells
- articulation via universal joint to accommodate riser movement.
- mooring by conventional anchor chain and wire catenary mooring
- isolation valves on each riser.

Information on this turret type was obtained from literature, company brochures and examination of risk assessments on two FPSOs of this type in Far East waters.

5.1 Principles

The external turret is cantilevered from the bow of the vessel in a similar manner to a conventional external turret. The system will usually use a single or multipath swivel as a fluid transfer and have a simple turret bearing system. The design of the turret and swivel itself in the ECT turret does not differ appreciably to internal turret designs but is simpler and will generally handle fewer wells.

5.2 Systems and components

The principle components in an ECT turret might typically comprise:

- cantilever support
- conventional multipath swivel
- turntable and manifolding
- bearing support and turret bearing
- risers
- chain table
- winch for connection
- mooring chains

A more detailed cross section can be seen in Figure 28.

5.3 Key components

Key components are the swivel, the turret bearings, the universal joint and the mooring connections. External turrets can handle production from several wells.

5.3.1 Swivel

Fluid transfer for this turret type is normally by a multipath swivel assembly. The precise design will depend on the number of wells and the field configuration. See Annex C.

5.3.2 Mooring

This might typically comprise eight anchor legs supported from the chain table.
5.4 **Operational and safety concerns**

The process plant and accommodation on the vessel is downwind of the turret and is a safety consideration. Consequences of hydrocarbon leakage could escalate if not controlled and appropriate evacuation procedures put in place. The turret is exposed at the bow of the vessel and susceptible to Greenwater or wave damage and corrosion from seawater.

5.5 **What can go wrong**

The main areas of concern for the external cantilevered turret (ECT) turret system are as follows:

- corrosion of the manifolding pipework
- corrosion and erosion of inaccessible pipework in the cantilever structure.
- damage to flexible risers and failure of flexible riser connections
- progressive damage to mooring chains and connections - failure in adverse storm conditions
- integrity of cantilever support structure
- functioning of ESD valves on individual risers

Damage mechanisms for the fluid transfer system are the same as for other multipath swivels and considered separately in Annex C.

5.6 **Maintenance and inspection practice**

Typical maintenance and inspection practices for an external cantilevered turret may comprise:

- external visual examination of the turret for corrosion damage
- functionality check on turret bearing and including torque checks
- grease monitoring of turret bearings
- examination of the swivel and dynamic seal performance
- replacement of static seals
- examination of flexible risers as recommended by the manufacturer - particularly connections
- leak monitoring of the riser connections, the interfaces, the manifolding and the swivel
- diver examination, or recovery and examination, of the mooring chains and connections
- visual inspection of pipework in cantilever structure for corrosion damage
6 EXTERNAL TURRET DISCONNECTABLE

This type of turret is similar to the external cantilevered turret (ECT) but has a tensioned riser connector that enables the riser and moorings to be quickly disconnected. This enables the vessel to sail away from the station in adverse storm conditions. Examples of this turret type include the riser turret moored (RTM) system produced by SBM. There are no examples of FPSOs with this turret type in UK waters. This design is common World-wide include the Cossack Pioneer FPSO in the Wanaea field in Australia. The main manufacturers of this turret type are SBM and SOFEC.

The principal features are the same as for the external cantilevered turret (ECT) with the following additions:

- disconnectable in adverse weather conditions
- riser and mooring chain table can be disconnected and float as a mooring-buoy below the sea surface. The buoy is pulled back up by the winch on the vessel to reconnect.

Information on this turret type was obtained from literature sources, company brochures and examination of risk assessments on two FPSOs of this type in Far East waters.

6.1 Principles

The principal of operation are the same as for the external cantilevered turret (ECT) with the additional feature that the turret system can be disconnected from the FPSO in severe storms/cyclones, or for scheduled dry-dockings. This allows the vessel to sail away under its
own power. Disconnection of the turret system can be carried out from the FPSO bridge or locally at the bow. Reconnection is performed without the need for external assistance.

Such a turret design may be used on a sites subject to seasonal cyclones. While connected the turret may be able to endure a sea state equal to a 10-year non-cyclonic storm (for example, significant wave height 4.5m, current 1 m/sec). While disconnected, the mooring buoy is able to withstand a 100-year cyclonic condition with one damaged chain (for example, significant wave height 10m, current 2.5 m sec).

### 6.2 Systems and components

The principal systems and components are the same as for the external cantilevered turret (ECT) with the following additions:

- connection/disconnection interface
- tensioner
- locking mechanism
- universal joint to control riser orientation
- riser column
- winch for reconnection

### 6.3 Key elements

Key elements are the same as for a conventional external cantilevered turret (ECT). The additional concerns are the components associated with connection and disconnection of the mooring buoy. These include the tensioner, disconnection interface, universal joint and the mooring buoy itself.

### 6.3.1 Connection/disconnection interface

The disconnection interface between the riser column and FPSO is a structural connector usually based on a hydraulic collet type connector typically 50-60” diameter. The articulations of the riser column are accommodated by a universal joint mounted on the rigid arm turntable structure at the bow of the FPSO. The mooring loads are transmitted from the structural connector to the main bearing via the universal joint to the bearing support structure.

### 6.3.2 Universal joint

This controls the orientation of the risers relative to the turret. It is an important load-bearing component and any damage would affect the weathervaning of the FPSO.

### 6.3.3 Riser column:

The riser column supports the chain table and the anchor legs once disconnected from the FPSO. Flexible or conventional risers may be used.

### 6.3.4 Typical configuration

A typical configuration may be as follows. A gear ring located on the rigid arm turntable controls the orientation of the main connector and the fluid transfer connectors. Risers between the seabed PLEMs and the riser RTM are flexible hoses in a steep wave configuration. Risers are routed through J-tubes or to hard-pipe connections at two levels on the riser column. The disconnection interface is at the top of the riser column at the main structural connector level. All flow-lines are routed through flow line connectors with integral isolation ball-valves through jumper hoses around the universal joint. Typical riser configuration for an RTM internal disconnectable turret may include the following: Oil production - 2 x 10" risers, 3 x 8" risers, 3 x 6" risers; gas export - 1 x 8" riser; gas lift 1 x 4" riser; umbilicals 4 hydraulic and 4 power/signal.
6.3.5 Connection
The riser column is reconnected by means of a linear winch. The reconnection wire rope is
winched through the connector, universal joint and swivel stack over the top pulley mount onto
the support structure above the rigid arm. Once the connector flanges are face-to-face, the
turntable structure is rotated to align the flowline connectors and the structural connector is
locked. Each flowline connector can then be connected individually.

6.3.6 Mooring
This might typically comprise eight anchor legs supported from the chain table of the riser; for
example: 8 x 550m x 4.25” chain legs, connecting chain table with anchor boxes; 8 x 4000 mt
iron ore filled gravity box anchors.

6.4 Operational and safety concerns
The operational and safety concerns are the same as for the external cantilevered turret (ECT)
with additional issues associated with connection and disconnection. The ability to connect and
disconnect is a key part of Safety Cases. There is the potential for hydrocarbon release during
connection and disconnection. The production and the swivel would be shutdown and isolated
before disconnection. Disconnection is a safety measure in the event of hydrocarbon leakage in
the turret or manifolding systems.

6.5 What can go wrong
The principal damage mechanisms are the same as for the external cantilevered turret (ECT)
with the following additions:

- loss of integrity of connection and disconnection systems and interfaces
- failure of static seals on the disconnection interface
- wear, increased friction or seizure of universal joint

6.6 Maintenance and inspection practices
Maintenance and inspection practices are the same as for the external cantilevered turret (ECT)
with the following additions associated with the disconnection interface and universal joint:

- check functionality of connection/disconnection interface
- check functionality of turret bearing and universal joint including torque checks
- check integrity of all riser connections and interfaces
- diver examination or recovery and examination of mooring chains and connections
- check function and maintain winch for connection/disconnection
ANNEX C

Detailed information on Individual Fluid Transfer Systems (FTS) and Swivel Systems
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1 INTRODUCTION

A fluid transfer system (FTS) is needed as a rotating connector in order to enable the transfer of the hydrocarbons, utilities and all turret system functions from the geo-stationary turret system to the process plant on the weathervaning FPSO. The alternative is spread mooring, which is not feasible in the adverse weather conditions pertaining in the North Sea.

The main FTS types were identified in Section 5, these are as follows:

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

The principle behind a toroidal swivel is illustrated in Figure 1. The evolution in swivel design leading to multipath swivel stacks is shown in Figure 2. The different FTS types are each discussed in turn in the following sections.

Figure 1
Sectional diagrams of internals of multipath toroidal swivel assembly showing internal piping and toroidal flow paths, left and bearing and seal arrangements, right
Diagram courtesy Brown Brothers & Co Limited
There are five main manufacturers 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 their toroidal swivel designs. Drag-chain systems are manufactured by Metool Ltd. to a design developed by Maritime Tentech AS in Norway. As part of the present study site visits were made to Brown Brothers, Framo and Maritime Tentech. Bluewater, Sofec and SBM design and supply turrets as well as the fluid management system.

Figure 2
Evolution of swivel design between 1986 and 2000 from simple axial swivel to 3-path toroidal swivel (1993) to multipath swivel stacks

Courtesy Brown Brothers & Co Limited
Conventional *in-line or axial swivels* are widely used in external turret FPSOs, offloading systems for FSO and FPSOs, and mooring buoys. The axial swivel is two-piece, with a straight through arrangement, and can only handle a single flow path (Figure 3). In FPSOs with internal turrets, axial swivels have been almost completely superceded by *toroidal* and *multipath* swivels. Axial swivels are commonly used in offloading lines to hang flexibles and are still preferred by some operators to toroidal swivels for gas export, production and lift. Axial swivels are often seen at the top of multipath swivel stacks for gas use.

This FTS type was used in the first FPSO in the UK North Sea, the Golar Nor Petrojarl 1 operating since 1986. The swivel was produced by Brown Brothers to a John Hastie design with an operating pressure of 345 bar. This swivel was subsequently replaced by a toroidal swivel. Current in-line or axial swivels incorporate the same principles and philosophy as that used on Petrojarl 1. In-line swivels are available incorporating gas and liquid products for pressures up to 5000psi. Suppliers are investigating the feasibility of such swivels to operate at higher pressures. There are no production swivels of this type remaining on the turrets of FPSOs in UK waters, except as part of a multipath swivel assembly.

The principle features are as follows:

- Single flow path axially through swivel
- Ball roller bearings with dynamic seals
- Bolted connections
- No internal pipework
- Usually plain carbon steel not Ni-plated

This design has evolved from other offshore applications requiring a rotating connector, such as offload systems and mooring buoys.
2.1 Principles

The swivel is produced in two pieces (Figure 4), the outer piece is fixed - the inner piece is rotating. A simple ball roller-bearing system allows free relative rotation of the two halves of the swivel. An elastomeric dynamic seal prevents loss of production fluids to the atmosphere. There is no internal pipework as there is only a short distance between the flanges. Production fluids can be accommodated from several wells by manifolding before entry into the swivel. For example some external turret FPSOs may have three or more wells feeding into a single axial swivel. The main virtue is it's simplicity and the many years of experience in mooring buoys.

A barrier fluid is used as with other swivels to maintain seal integrity, to provide cooling and to lubricate the bearings. The seal design is simple with no auto-recovery system for the barrier fluid. The design may include stepped primary and secondary seals. Leakage from the seals is monitored.

Some recent designs, for example that by Brown Brothers, incorporate a replaceable seal. The spare seal is stored underneath in the housing. Replacement simply involves lifting up the bearing with no need to disassemble.

Figure 3
Simple axial or in-line swivel
Courtesy Advanced Production and Loading AS (APL)
2.2 Systems and components
An axial swivel has the following main components:
- Outer casing
- Inner casing
- Ball roller bearing and raceways
- Energised dynamic seal (elastomeric)

2.3 Key components
The key components are the bearings, seals and connections.

2.4 Operational and safety concerns
The main operational concerns are leakage from the seals or connections and the rotation mechanism. Any difficulty in rotation, for example due to bearing wear, would increase loading on the connections and the connecting pipework.

2.5 What can go wrong
The key technology is the seal and bearing technology, which is well established.

The Petrojarl 1 axial swivel operated successfully from 1986 until 1993 when it was replaced. On inspection, some rusting was found to have occurred, but there was no pitting or crevice corrosion. The swivel was dressed-out for re-use but not electro-less nickel plated. There is no internal pipework.
Potential failure mechanisms are:
- Hydrocarbon or gas leakage from the seals - issues as for other dynamic seals
- Loss of connection
- Wear to bearings or raceway increasing the torque required to operate the swivel
- Cracking at stress concentrators in bearing housing

2.6 Maintenance and inspection practice
Inspection and maintenance is straightforward and will include:
- Checking of torque on bolts
- Torque and function check on swivel rotation - high torque may be indicative of bearing problem
- Monitoring for hydrocarbon leaks
- Visual examination

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.

In-situ spares would give around 15 years operation and give added time to intervene. There is the possibility of disassembling during planned maintenance. Typically the seals would be replaced after 5 years, as is normal for an axial swivel.
3 SIMPLE TOROIDAL SWIVEL (STS)

This designation is used here for single toroidal swivels or simple multipath production swivels, to distinguish these from the complex multipath swivels used in recent FPSO installations discussed later in Section C3 which handle a diversity of functions.

In a toroidal swivel an outlet ring or rings rotate on bearings around a central core, giving the rotation necessary for fluid transfer. Fluid flowing up through the core flows round a doughnut shaped or toroidal cavity between the outlet ring and the core (Figure 1). Dynamic seals prevent loss of production fluid to the atmosphere. Flexible or hard piping connects the outlet rings to the process plant on the vessel, normally with flanged connections or specialised connectors for flexible pipe. By stacking toroidal rings around a central core it is possible to produce swivels with multiple flow paths, something that is not possible with the simple axial swivel.

The need for toroidal swivel stacks, to transmit liquids and gases from geo-stationary flexible risers to the weathervaning vessel in FPSOs, was first identified in the early 1980’s. This initiated a lot of development work on seal testing and materials selection. For example, Brown Brothers commenced design of toroidal swivels in 1985 utilising John Hastie in-line swivel technology with OSO and DTI funding. This produced a successful combination swivel. The toroidal swivel has been developed over several years. Having developed the engineering configuration, the main area of expertise has been in the development of the seal technology. Other suppliers have had a parallel development.

The first installation in the UK North Sea was a 5” replacement swivel, 340 bar design pressure, retrofitted on Petrojarl 1 FPSO, Blenheim field, in 1993. This swivel is shown in Figure 5 and has 3 fluid paths: an 8” toroidal ring, a 6” toroidal ring and a 4” toroidal ring. The operating pressure is 50 bar, with a typical production of 40,000 Barrels per day. There is no leakage recovery system. Hand valves are opened to check for any leakage on the seal. If a problem occurs, then normal practice would be to take the swivel off and refurbish. The Petrojarl 1 FPSO has had 15 years of operation. The roller bearing is axial, with an elastomeric bush to stabilise. The two bottom outlet-rings share the same bearing.

This proven concept can be customised for liquids and gases: to meet the particular swivel requirements for a number of varying sized product lines, flow rates and pressures, to be pumped or extracted simultaneously from a floating production vessel.

The main systems and components can be seen in Figure 1. For detailed information on components, failure mechanisms and maintenance practice see under multipath swivels in Section 3.
Figure 5
Top – In-line toroidal swivel stack for Petrojarl 1 FPSO. This was the replacement for the original axial shown bottom. Courtesy Brown Brothers
A multipath swivel stack has become the standard configuration for FPSO swivels in the UK North Sea and Norwegian sectors since their introduction in the early 1990’s. Examples include the Foinavon, McCullough and Schiehallion FPSOs. The Petrojarl Foinavon, operated on a long term contract for BP, has an 8m high stack which weighs 100 tonnes - typical in size of many internal turret configurations.

Multipath swivels are produced by stacking toroidal swivels around a central core. Other swivel types such as electrical or utilities are placed higher up the stack. The exact configuration will depend on the specific installation requirements, the number of wells being serviced, and the other functions required. The swivel can simultaneously handle production, reservoir management and export functions. Because of the variety of functions there is often quite complex manifolding between the turret and the swivel stack, referred to as the turntable manifolding or turret transfer system (TTS). It will typically take 10 months to a year from design to delivery of a swivel stack. Most are bespoke systems for a specific installation. There is a trend towards modularisation of components. The swivel stack will be designed for the lifetime of the field, which was 20 years plus for the Foinavon FPSO.

A recent development has been the Compact Swivel by Framo in Norway with a solid internal core and duplex steel forgings which is lighter and more compact. This swivel type has many unique features and is discussed separately in Section 4. It is fair to say that other multipath swivels have also become more compact as the technology has advanced.

Multipath swivels are similarly used in both internal and external turrets, the latter are generally smaller because of the smaller number of wells being serviced. Information on this type of swivel stack was assisted by visits to Brown Brothers in Edinburgh and Framo AS in Norway.

The principal features are:

- Stacking of multiple toroidal swivels and other utilities on a central core to give a swivel stack
- Ability to simultaneously handle a variety of production, export, utilities and reservoir management functions
- Connection via flexible hoses or hard piping via flanged connections
- Internal pipework within the central core to carry the fluids to the outlet rings on the toroidal swivels
- Fluid flows in a toroidal annulus between the outlet rings and the central core
- Rotation of the outlet rings obtained using 3-roller bearings
- Energised double dynamic seals prevent hydrocarbon leakage from individual swivel units
- Other swivel types at top of swivel stack to handle electrical and utilities functions an gas export
Figure 6
Examples of multiple path swivel stacks. Left to Right - Bluewater stack for Petrobras 34 FPSO, Brown Brothers Swivel BPS Foinavon field, SOFEC swivel Terranova FPSO, Framo Compact Swivel - Pierce field
4.1 Principles

The principles of operation are as described above and illustrated below in Figure 7. The key components are the dynamic seals, the outlet rings and the bearings, which allow passive rotation. On passive turrets the swivel stack itself may also have an active drive mechanism to ensure the optimum positioning of the turret and avoid undue stresses on connections. Torque arms maintain the positioning of the swivel stack in response to relative motions of the vessel and turret and the torque and angular rotation on these is actively monitored.

Figure 7
Schematic through multipath swivel showing toroidal annulus for fluid flow, dynamic seals and bearing Courtesy Brown Brothers

4.2 Systems and components

The main components associated with a typical multipath swivel fluid transfer system are as follows:

- Swivel access structure
- Swivel stack
- Central core and tensioners
- Torque support arms
- Gas swivel
- Electrical swivels
- Utilities swivels (gas, water injection, hydrate prevention etc.)
- Control and Fibre optics swivels
- High Pressure HP production swivels
- Medium Pressure MP production swivels
- Low pressure LP production swivels
- Connections to transfer system
4.3 Key elements

4.3.1 Swivel configuration
The configuration of the swivel will depend on the field requirements. The largest units are generally installed at the base of the swivel. There is a trend towards modularisation for conventional swivels. Compact swivels (Section 4) are already modularised. Conventional swivels are usually produced in carbon steel.

For example, the FTS system for the Foinavon FPSO, the first high pressure multipath toroidal swivel installed in the UK sector (1993), has 6 main parts to the swivel stack: production swivels, water injection, air utilities, electrical slip rings, gas lift and injection 7” internal diameter operating at 260 bar.

North Sea Producer has a completely passive Bluewater turret with a Brown Brothers swivel stack. This has 6 fluid paths for production, water injection and oil export, a hydraulic drive system, a 16” double outlet swivel at 50 bar, a 10” oil export swivel at 110 bar; a 12” water injection swivel at 260 bar; a 4” gas lift swivel, subsea communications, electricity, power ; utilities; a 10” production test swivel and a 6” gas export swivel operating at 224 bar.

The swivel stack for the Banff FPSO, supplied by Brown Brothers to Maritime Tentech, has 6 fluid paths, 90 power and signal paths giving a huge amount of redundancy, an axial gas swivel, an electrical swivel, a hydraulics swivel, 2 water injection swivels, an interface block, a 10” Production swivel, and 12” Oil export.

4.3.2 Central core and outlet rings
Fluids flow through the swivel stack through internal pipework. Utilities and smaller swivels higher in the stack usually have a machined forging as the internal core. For the production swivels, the central core and pipework is welded together from carbon steel tubulars. The outlet rings in a conventional swivel are bolted together from several components. Some recent designs, such as the straight-through arrangement on the Conoco Banff FPSO, have a solid machined central core. A solid core is a key feature of compact swivels (Section 4). Flow is around the annulus between the outlet ring and the central core of the swivel.

4.3.3 Torque bracket/ tensioner
To maintain the dynamic seal it is necessary to limit axial movement of the outlet rings. This tensioning is done either by using torque brackets or tension rings screwed around the central core, dependent on supplier and location in the swivel stack. This controls movement, and helps orientate the outlet flanges. Most seal alignment is done through the bearing.

4.3.4 Materials
Swivels are usually manufactured in carbon steel with a corrosion-erosion allowance, and are designed for 20 year plus operation or field life. The usual coating is ~ 1 Micron electro-less Ni plating, earlier designs used two coat epoxy. Compact swivels (Section 4) use duplex stainless steel for all components, which is more expensive, but does not require coating.
Figure 8
Schematic of multipath swivel showing internal structure and different swivel elements. Drawing courtesy Brown Brothers & Co Ltd
Figure 9
Details of swivel stack in North Sea Producer FPSO, Conoco MacCullough field:
Top Left - Production swivels, Top- right - utilities and test swivels; Bottom -
gaslift, electrical and power signals. Swivel stack also shown
Courtesy Brown Brothers
4.3.5 Bearings
Rotation of the outlet rings on the swivel is achieved using internal bearings. The standard configuration is a three-roller slew-ring bearing as illustrated in Figure 11. Bearings may be shared by more than one outlet ring. The size of swivel bearings is necessarily large because of the location not the load. The highest loads are seen in an axial swivel.
4.3.6 Seals

All suppliers of toroidal swivels use a double dynamic seal arrangement on the swivel rings. For example, this may comprise a stepped seal arrangement with primary and secondary energised dynamic seals (Figure 12). This is the key swivel technology and the design details and features are proprietary to the supplier. A barrier fluid is used to provide sealing, lubricate the bearings and to prevent contamination. There is cross drilling between the inner and outer seals. All are explosion proof and built for Zone 1 operation.

Any leakage from the dynamic seals is monitored. If leakage gets above design levels, then the seal would be changed out. Brown Brothers swivels include automatic leakage recovery to a tank. In other designs leakage is contained internally and can be checked using access ports. Design measures may reduce the possibility of leakage: for example, pressure differentials between the seals, or the primary seal is 'fail-safe' and automatically shuts down if flowline pressure drives fluid towards the recovery pump. Some clients have expressed a wish for third seal if low temperature is a factor in operation.

Seals are typically produced in three parts: a PTFE shell working part, an elastomer energiser and an industrial plastic anti-extrusion ring. Pressure changes can cause problems in some dynamic seals. Seals are extensively tested against explosive decompression and sudden pressure changes. The sealing surface is provided by weld overlays on the core: Inconel is now favoured as it is easier to apply; previously Stellite was used, but this can be difficult to overlay in a way that avoids cracking.

Preventing contamination of dynamic seals is crucial. Seals may be fitted with a silt-barrier system to prevent any difficulties with sand or particles getting into the seals. For example, the barrier fluid may be over-pressurised by 3 bar and the grease would backflush any particles back into the flowline. Such systems may be automated or by semi-automated once-per-shift injection. The flowline is pressurized. No external pressure is generally applied to energise the seals.

![Figure 11](image)

*Figure 11*  
Typical roller bearing arrangement in toroidal swivel. Three-roller slewing bearing. The bearing may be shared by one or more outlet rings. Also visible in swivel cross sections (Figure 1, Figure 7)
Figure 12
Top - schematic diagram of toroidal swivel ring; Bottom - detail of stepped seal arrangement between the outlet ring and central core
4.3.7 Drive system
On passive turret systems an active drive is commonly used on the swivel to ensure optimum orientation. Hydraulic arms drive the outer body to the correct position and restrict lateral movement of the swivel stack.

4.3.8 Connections to the swivel
Connections to the swivel may be by hard pipe or flexible piping. Flexible pipework is more common for outlet pipes from the swivel to the process plant.

4.3.9 Recovery system
Barrier fluid leaking through the seals is monitored and in some designs recovered to a tank by a recovery system. The client keeps graphical plots of the leakage. Normally it would be expected that only a few cc’s of fluid would leak. If leakage rates go above acceptable levels this would automatically cause system shutdown (for example, 1 litre/hour OK, above 2.5 litre/hour shutdown). Acceptable leakage levels to the recovery tank will depend on the design; HSE inspectors should ascertain the leakage history and the levels pertaining in a particular installation. The recovery tank is vented to flare and atmosphere. There is no inert gas blanket. An auto-recovery system is normal in Brown Brothers swivels but not was not used in Petrojarl 1 as this was an earlier design and there was no expectation of sand problems. An auto recovery system is 'nice to have', but not essential, as there is a lot of redundancy.

4.3.10 Heating of Swivel
Heating of the swivel stack has been considered for low temperature operation. Repurcussions of heating would be on the electrical slip ring and there may be a need to inert. Heating was, for example, initially considered for the Foinavon FPSO, but was not used as no problems occurred with icing.

4.4 Operational and safety concerns
Adverse 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 advisable as it could affect seal integrity and is prevented by hydraulic torque arms, a key component.

4.5 What can go wrong?

The main concern is failure of the dynamic seals leading to hydrocarbon release which could escalate. This risk is minimised by use of a double seal barrier, design features such as pressure differentials and accurate monitoring and intervention procedures should either seal fail or leakage rates are above accepted 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 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 and it is necessary to ensure they are not exposed to UV. Temperature may cause degradation of the seals, deterioration is slow.

Multipath swivels have not been in service that long and the condition of internal pipes is not known. Experience with axial swivels suggest 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. Greenwater damage is a concern for swivels, particularly when mounted towards the bow of the vessel.

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 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 to have flexible risers to the walkway
- There was oscillation and a problem with twisting of flexible hoses between the turret and the swivel - the solution was to put an active drive on the swivel - this allowed 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
- The flexible piping on the swivel outlets was believed to be turning the swivel - the torque from the flexibles was fighting the hydraulic drive system - this is an issue for both passive and actively driven swivels, most swivels are passive - outlet rings should be kept at zero rotation relative to the vessel
- Overpressurised the swivels and blew the static seal - swivels had been tested to 390 Bar, pressure exceeded 400 bar
- Leakage from flange, the client bought the wrong spare
- Excessive motion of the FPSO giving higher stresses on the turret drive mechanism - no problems were observed with the swivel which had flexible connectors
- Incidents of intermittent failure of dynamic seals due to slug formation etc. - only 1” of hydrocarbon fluid seen in the recovery tank and there was no external leakage
- We received anecdotal information on one North Sea FPSO in which most of the dynamic seals in the swivel stack failed during the year 2000 resulting in hydrocarbon leakage, but no explosion

4.6 Maintenance and inspection practices

Little feedback is often received by suppliers and it is assumed operators follow the maintenance manual procedures. Dialogue is encouraged. Most multipath swivels are designed for a 20 plus year field life and are very conservative on design. The suppliers aim is for a 'fit-and-forget' philosophy. Typical maintenance is as follows:

Routine
- Check torque on the bolts and ensure none are slack
- Don’t open seals, may cause damage or contaminate.
- Monitor amount of liquid in the leakage recovery tank
- Check for corrosion
- Check bearing functioning and lubrication OK - doesn’t need much checkover.
- Monitor torque on the swivel units, check OK - has in fact dropped in use in some cases
- Continuous monitoring of torque and the angular position of the torque arms
- Continuous monitoring of the leakage rates for dynamic seals and the fluid level in the recovery tanks where fitted
- Leak detection systems sited adjacent to the swivel

After 5 years
- Test the capscrews
- Pull studs, inspect and replace, with new studs if necessary
- Check there are no sub-surface 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 a water injection swivel and replacement of a leaking gas swivel after 2 years.

It is not normal to replace studs and nuts though these will be checked for torque and condition on a regular basis.

Stripdown and replacement of seals depends on the weather etc. Typically 7-10 days minimum is required in good weather. Stripdown utilises the crane on the turret transfer system. In-situ seals take 1-2 days to replace in the field or 24 hours in the workshop.
5 COMPACT SWIVEL (FRAMO)

This compact design of swivel was designed in parallel with the development by APL of Submerged Turret Production (STP) and Submerged Turret Loading (STL) disconnectable turret systems by Framo AS in Norway, the sole supplier. Financial support came from Statoil and the Norwegian government. Initial swivel development was based on the insert technology from subsea pumps and flow meters.

A compact design was needed to sit within the turret cavity and interface with the STL, STP turret-buoys. In this 'in-line' configuration the compact swivel simply connects and sits on top of the ESD valve block on the turret buoy (Figure 13). This type of swivel is increasingly used as a topside swivel with conventional turrets, for example a SOFEC turret in the Terranova FPSO and the external turret in the Petronas Carigali FPSO in the MASA field. The compact swivel allows much simpler manifolding to the turret than a conventional swivel system. More recently subsea swivels have been designed with retrievable swivel cartridges for use with the SAL and SAP subsea turrets. The swivels are manufactured near Bergen by a sister company of Framo, Frank Mohn Engineering.

The major feature is a solid internal core, containing channels, in place of the more complex internal pipework found in conventional swivels. Solid forged swivel rings rotate about the center core on bearings, with double barrier dynamic seals. The rings are kept in location by tension rings screwed on to the center core, which avoids the need for the complex bolting and tension plates found in standard swivels. Indeed the only bolting needed is for the connections. All components are manufactured in duplex stainless steel.

The first swivel of this type was installed in the Lufeng FPSO in June 1997. There are currently three examples of this swivel type in UK waters, the Pierce FPSO which has an STP Turret System, and the New Baffin and Viga FPSO’s which have STL turret systems. Other FPSOs with compact swivels include STP disconnectable systems for the Wenchang and Bayer Undon, East Timor FPSOs and topside swivels for Terranova, Buffalo and MASA. Compact swivels were due for installation on the Kerr McGee Leadon FPSO and Golar Nor Petrojarl 1 FPSO Glitne Field in June 2001.

The insert-type rotating connector development programme in Framo Engineering AS was initiated in the summer of 1993 and was funded by Statoil. The construction, manufacturing and testing/verification of a full-scale specification unit were successfully carried out in 1994. This rapid development was possible since technological key elements and reference engineering experience had been gained from the successful installation of subsea booster pumps, securing an important basis for the development. The original development programme was run in two phases where critical elements were tested and verified prior to building and testing the complete connector system and increasing the pressure rating, especially for gas injection service. Information on this swivel design was obtained from a review of Safety Cases and risk assessments, and site visits to Framo and APL in Norway.

The principal features are as follows:

- A fluid swivel-unit functioning as a rotating connector - in order to enable the transfer of the hydrocarbons and utility fluids from the geostationary riser system to the weathervaning FPSO's piping
- Solid internal core with internal channels for transmission of process fluids and utilities. Solid forged swivel rings in a toroidal arrangement - tensioning by tension rings screwed onto the central core - manufactured in duplex stainless steel, the internal core usually using powder metallurgy with hot isostatic pressing
- All swivels or sections in the swivel stack have a double barrier fluid energized seal arrangement, - the seals are pressurised by a barrier oil system at a slightly higher pressure than the maximum shut-
in pressure - an overpressure provides 100% redundancy of the seals towards process - there are four (4) dynamic seals between process and atmosphere

- A continuous remote condition monitoring system verifies system availability and ensures that produced hydrocarbons are not released
- If a leakage should occur, the barrier system can precisely identify which seal element is leaking and automatically isolate the failed swivel segment
- The complete electrical system is designed for Zone 1 operation
- All interfaces are simple piping and structural framework, thus suitable with any turret system available

5.1 Principles of operation

When the swivel stack has been installed, assembled, and all piping is connected, the swivel is in operation. The production fluids enter from rigid piping into the lower section of the swivel central body. Each product is transferred through individual bores, with radial outlets at individual levels or segments (swivels) into a toroidal channel within the swivel rings.

The swivel rings can rotate freely on roller and pad bearings and a double energised dynamic seal prevents loss of production fluid to atmosphere. The outlet or swivel rings are connected with hard piping or flexibles to the topside process piping on the FPSO. Compactness in design is a key feature.

Tension arms support and prevent undue loading on the swivel stack. The supply of barrier seal oil for the swivel stack is by a dedicated HPU package with a control panel feedback to the central control room.

5.2 Systems and components

The key components in a compact swivel stack are the centre body, toroidal forging ring elements, bearings and the dynamic sealing system. The centre body is a field specific item; designed according to field specific requirements like number and sizes of main flow paths, and the utility functional requirements. The body is usually produced by a powder metallurgy route, using hot isostatic pressing (HIP). The core in the Wenchang FPSO is a straight through design and was forged.

The swivel stack has different segments; for example production fluids, hydraulic, utility, power and gas and water injection, at pressures up to 520bar. Overall throughput capacity is very much dependant on the number of utilities, how many different functions will be passed or transferred through the swivel and the required operating pressures.

A torque-arm transfers loads from the swivel to the vessel structure and limits any lateral movement in the swivel stack, for example, due to roll of the vessel. The swivel outlets are maintained at 0° to the vessel length axis.

A main objective in the development of the compact swivel was to provide a standardised swivel system to be utilised for different applications and functional requirements. A modularised approach is used. By utilising the three standardised swivel stack sizes, a number of features and capabilities may be incorporated. Typical large swivel stacks utilise the “small size” as high-pressure gas & water injection swivel at the top, the “medium size” as export utility functions and the “large size” as the production swivels at the bottom. Normally, it is sufficient with a combination of the “medium size” and “small size”. The standard sizes with current design pressure limits, and typical flowpath capacities through the centre body, for an in-line swivel for an STL system are shown in Figure 16.
5.3 **Key elements**

A modularised approach is used with three main sizes of forged outlet rings being 393, 529 and 777mm respectively in diameter. Duplex stainless steel is used throughout. The larger the ring the lower the pressure: 393mm - 500bar, 527mm - 500 bar, 77mm - 345 or 210 bar. Features include:

- One or multiple rings
- One or multiple outlets
- Double dynamic sealing with barrier oil
- High, medium and low pressure
- The swivel core will differ in diameter along the core - all components are produced to a very high manufacturing tolerance and gap compensation - there are flange connections to the process pipework

5.3.1 **Torque arms**

Flexible torque arms connect the vessel to the swivel stack allowing ± 50mm movement. The torque and angular movements are monitored continuously and an alarm goes off should any malfunction occur. The outlet rings must be kept fixed relative to the vessel with zero rotation.

5.3.2 **Dynamic seals**

The core technology in the compact swivel is the dynamic seals, which have a double energised seal arrangement with primary and secondary seals. A barrier seal fluid (Lipseal) is used which has three functions:

- to seal and protect the seals
- for cooling
- to lubricate the bearings.

The primary seal is underpressurised 10-15 bar (115bar compared to 130bar for the secondary seal) so, in the event of any seal failure oil flows and seals against the environment. Leakage goes back into the process fluid and not to atmosphere. Principal elements of the seal system have been identified above. There is an alarm if the primary seal is lost and shutdown of the stack and isolation of the valves takes place if the swivel loses integrity of the secondary seal. The seal is described as 'fail-safe' or 100% redundant to process.

A lot of investment has been made in the seal technology; which has arisen from an extensive development programme at different cycling frequencies between 0-5000rpm, and in multiphase test loops. Experience is that it is the instrumentation rather than the seals themselves on compact swivels that can fail.

The barrier oil condition, temperature, pressure and consumption is monitored with sensors with automatic feedback. There is a standard control panel (Figure 23) that monitors the oil pressure to the seals and the function of the hydraulic power unit (HPU).

5.3.3 **Premixing**

All production fluids are premixed before being pumped into the swivel. This ensures homogeneous smooth flow and prevents slug flow within the swivel.

5.3.4 **Upper swivel**

There is a lot of structure in the upper swivel (Figure 13, Figure 19) including hydraulics, electrical, fibre optics and chemical injection. The power swivel will usually use a ring and brushes. These systems may come from a number of manufacturers.
5.3.5 **Flexible risers and hard piping**

High pressure specification flexible risers are used, typically 400bar for swivels for STP turret systems such as Pierce: it would not be normal to get conventional piping to these tolerances. For the *Wenchang* FPSO pressure was 40 bar and hard piping connections were used.

5.3.6 **Pig block**

The pig block in an STP system is mounted between the buoy and the swivel above the STP buoy. There is an intermediate chamber protected by stopper-bus valves, which can rotate to isolate the chamber from the production flow stream. This ensures that production can be maintained when removing the pig.

**Figure 13**

Schematic of Inline compact swivel stack for use with STP system

*Courtesy Framo/ APL*
Figure 15
Compact in-line swivel attached to STL disconnectable turret with intermediate ESD valve block  Courtesy Framo AS
Figure 16
Compact swivel stack for Asgard A FSO showing modularized arrangement with large, medium and small swivels for different process and utilities functions. Courtesy Framo AS
Figure 17
Compact swivel stack for Pierce FPSO, UK sector, showing a combination of two small and 3 medium size swivels, intermediate tensioning rings, outlet flanges on swivel rings and connections for tension arms supporting turret

Courtesy Framo AS
Figure 18
The compact swivel for the external turret MASA FPSO with 5 toroidal swivels.
Petronas Carigali FPSO MASA field
Courtesy Framo AS
Figure 19
Integrated high pressure hydraulics, chemical injection, controls and power connections in compact swivel design
Courtesy Framo AS Norway
Figure 20
Cross section through compact swivel showing outlet rings, cross section through internal core and bearing and dynamic seal arrangement

Courtesy Framo AS
Figure 21
Close up of bearing elements and dynamic seal arrangement for outlet rings on compact swivel. Each outlet ring has axial roller and radial pad bearings with primary and secondary energized dynamic seals. Courtesy Framo AS

Figure 22
Schematic of bearing arrangements in compact swivel
5.4 Operational and safety concerns

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 the swivel stack is functioning correctly.

For topside-mounted compact swivels, the issues are similar to conventional multipath swivels, though intermediate manifolding is simpler.

For in-line swivels connected with STP or STL turret systems, disconnection is straightforward from the turret buoy. The ESD valve block can be quickly disconnected from the turret buoy sealing off the wells. The turret buoy is then submerged under neutral buoyancy with the mooring lines 50m below sea level. Disconnection is thus a useful emergency measure and features heavily 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. 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.

5.5 Critical areas and potential damage mechanisms

Leakage from the dynamic seals is the major safety concern as with conventional swivels. Flexible pipe connections conditions 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 give less susceptibility to longer term degradation mechanisms such as corrosion and erosion. It is also arguable that the dynamic seal system may have less
risk of 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 don’t anticipate problems as the swivel core is large and consider that difficulties would be likely to occur elsewhere first. Similar seals have been used in 5000rpm pumps and other high pressure rotating equipment for more than 20,000 hours in sand producing fields with no difficulty, the swivel is an evolution of the pump design.

5.6 Maintenance and inspection practice

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 malfunction occurs. If there is no consumption of barrier oil then the seals can be assumed to be OK. The torque arm reading is also monitored, any inconsistency may be indicative of a seal or bearing problem. Dismantling and checking could initiate damage and is not advised in normal operation. 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 as a moving component. Usually once a month 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 instrumentation working OK
- Check tensioning and torque on swivel
- Check alignment and gap tolerances
- Check condition of flexible and hard pipe connections
- Check condition of flexible and hard pipe
- Check electrical and utilities connections upper swivel

The modularised approach allows spare parts and service to be delivered to the operator at short notice in the field with short delivery times. There are specialised tool packages and guides, assembly is quick, approximately 1 day to assemble a swivel ring.

The swivel design has been standardised 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 on a very short notice.
5.7 Pre-service testing

The sole supplier of compact swivels, Framo AS, has modern manufacturing, assembly and testing facilities and a test dock in Bergen for system and integration testing prior to shipment. Several test programmes have been carried out on sealing materials in order to verify the capability of the compact swivel system.

Four different test jigs/rigs have been built to date for different applications, sealing diameters and pressures. This has included long term testing and verification of 420 bar dual gas injection swivels, and high capacity production swivels at 220 bar ratings. There is ongoing verification work on 520 bar swivels. High pressure and high capacity testing has been carried out over several years, simulating up to 40 year field life for different sealing diameters and applications to prove the availability and reliability of the system. Ongoing testing is undertaken with potential clients and operators to improve the present swivel design.

Figure 24
Left - testing of multiple swivel assembly in test facility; right - compact swivel under construction.
 Courtesy Framo AS
6 SUBSEA SWIVEL STACKS FOR LOADING/PRODUCTION

Framo have recently extended the use of the swivel technology into subsea operation, with the single anchor loading SAL and single anchor production SAP mooring systems developed by APL. The subsea swivel interfaces as a retrievable unit with the flowline piping on the anchor for the SAL mooring system, produced by APL, and located on the seabed. The SAL system has been accepted by the industry as a cost-effective system with the first operation in 1998. Several swivels have been awarded for loading purposes and the technology is being extended for use in high pressures, multipath stacks and new applications.

The key features of an SAL Swivel are as follows:
- No rotational limitations
- Process activated seals with back-up sealing system.
- In-line swivel, pig-able
- Standardized design
- High external loads
- Typically 14” diameter at 50 bar & 60 C

Framo are currently conducting a full-scale system verification of the swivel technology into high pressure, multipath, subsea swivel stacks for FPSOs - the SAP system. This utilises core components from the compact Framo swivels and the proven SAL system, to produce a cost-effective and innovative alternative to both internal and external turret systems for FPSOs.

The insert type swivel technology is ideal for SAP, enabling retrieval of the critical components to surface with simple tools. The SAP system being verified has a throughput capacity identical to the initial Fenris (Varg) specification, with six (6) swivels including: a 10” production swivel, an 8” water injection swivel, a 6” gas injection swivel, 2”methanol injection swivel, a hydraulics swivel and control signals. The SAP swivel stack is based on a 5000 psi design.

Key features of the SAP swivel stack are as follows
- Subsea multipath swivel stack
- High pressures and temperatures
- Retrievable Insert (RI) cartridge
- Barrier fluid energised seals
- Continuous remote monitoring of seals to verify performance
- No rotational limitations
- Passive system at low torque
- Easy running/retrieval of insert
- Proven procedure from pumps
- Proven sealing from dry swivels
- Potential for extending the rotating turntable for location of subsea equipment – intelligent subsea turret.
Figure 25
Subsea SAP turret swivel system showing retrievable insert cartridge with the critical swivel components  Courtesy Framo AS
7 DRAG-CHAIN

The main alternative to a multipath swivel stack for fluid transfer is the drag-chain system, currently installed in two FPSOs in the UK sector; the Texaco Captain FPSO and Gryphon A. The drag-chain system removes the need for a swivel stack and can accommodate large numbers of flexible risers and umbilicals. The risers run from the seabed, through the turret, and are tied off at the turntable. From here new risers pass in a looped arrangement through a pipe management system known as a drag-chain, where they are tied off at deck level on the vessel to scaffolding known as the ESDV tower. The drag-chain lies within a large cage attached to the top of the turntable. The manifolding is much simpler than with a conventional swivel assembly. Information on this technology was obtained by a visit to Maritime Tentech AS and consultation of Safety Cases and risk assessments.

The principle features are as follows:

- used in combination with a Tentech internal active turret (IAT)
- partial weathervaning of 270° by rotation of a ‘drag-chain’ within a large cylindrical cage attached to the top of the turret
- fluid transfer is by direct connection of flexible risers and umbilicals from the drag-chain system to the process system - at a gantry on the vessel known as the ESDV tower
- risers and umbilicals uncoil as the vessel rotates about the turret
- the flexible risers and umbilicals are coiled within the drag-chain system in an S-arrangement
- the drag-chain takes up the loading as the system rotates and minimises loading on the risers
- no swivel stack is required
- there are simple connections between the turret and the drag-chain system - intermediate manifolding is very simple compared to the turret transfer system (TTS) required for a swivel stack

7.1 Principles

Flexible risers are looped in an S-arrangement in a pipe management system known as a drag-chain. From here the risers are connected to a manifolding system, the ESDV tower, on the vessel deck. The drag-chain is installed in a large cage above deck level that rotates with the turret and provides partial weathervaning - see Figure 26 and Figure 27. Loads are taken by the drag chain. The flexible risers can unwind to rotate the vessel up to 270° from a neutral position, compared with the free (360°) allowed by a conventional swivel. An active-mooring mechanism is needed to rotate the vessel into the weather to accommodate the system's rotational limits. The rotation allowed is adequate in most purposes.

The chief advantage is the absence of a swivel assembly and the number of risers and umbilicals that can be accommodated. Intermediate manifolding, between the turret and FTS, is much simpler than for a swivel design. The disadvantages are the larger size, the space taken up on deck, and the partial weathervaning. The flexible risers, riser connections and the turret rotation system become the most safety critical elements.

The turret diameter needed to accommodate the drag chain system and number of flexible risers is generally larger than conventional internal turrets, though not intrinsically so. The rotational limits dictate that the turret be positioned mid-ships or near the vessel's third-point. Location issues for the turret have been addressed in Annex B and Section 3.2 of the main report.
7.2 **Systems and components**

The drag chain fluid transfer system has the following components:

- turntable - tie-off for flexible risers from the turret
- drag-chain cage mounted on turntable above the turret
- drag-chain to provide the weathervaning and take the loads
- flexible risers and umbilicals, in an S-arrangement through the cage
- connections to the turntable
- active turret drive - gripper or hydraulic (mounted on turret)
- tie-off to the process system at scaffolding on the deck known as the ESDV tower - the FPSO/turret interface
- flexible riser and umbilical connections at turntable and ESDV tower
- very simple simple manifolding compared to swivel system
- Used with Tentech internal active turret (IAT)
- thruster to give active positioning of vessel and aid turret rotation within the constraints of partial weathervaning.

Cross sectional drawings through Tentech turrets with drag chain systems can be found in Annex B. The Gryphon A FPSO has the facility for drilling new wells through the centre of the the turret and drag-chain system.

7.3 **Key elements**

The critical elements are the flexible risers and connections and the drag-chain structure itself. The specification for the flexible risers does not differ appreciably to those used in conventional installations. The risers must accommodate the pressures associated with the production fluids and the variable rotational and dynamic loading as the turret weathervanes.

7.3.1 **Drag Chain**

This is an inter-linked pipe-management structure produced by Metool through which the risers and umbilicals are threaded. This can be seen for the Gryphon A FPSO in Figure 47 of the main report.

7.4 **Operational and safety concerns**

The functioning of the drag chain and the drag-chain cage itself is key to achieving partial weathervaning. Partial weathervaning is adequate in most circumstances. The cage is directly attached to the Tentech turret, and rotation is provided by the active drive on the turret. The stiffness of the flexible risers will increase loading on the turret drive mechanism. The key concern is wear and progressive damage to the flexible risers and connections, with the potential risk of hydrocarbon leakage.

The Tentech Turret has an accessible gliding ring bearing system with bearing pads. Because of the greater friction compared to standard roller bearings, there is a risk of sudden movement if the turret becomes misaligned by more than 20° - frictional loads dictate that the turret will not weathervane at smaller alignments. Such circumstance is unlikely, as the turret has an active drive controlled by a gripper or hydraulic system. There have been isolated incidences of sudden unexpected rotations. As the drag-chain cage is fixed to the turret, both will rotate by the same amount.

7.5 **What can go wrong**

The design introduces considerable simplification in fluid transfer. The disadvantages are the greater bulk and weight. There is no requirement for a multiple swivel, nor any dynamic seals with their attendant risk of hydrocarbon leakage. It seems surprising the system is not more widely specified.
The risks are associated with the partial weathervaning and the large numbers of flexible risers and connections. The progressive uncoiling and rotation of the risers may introduce fatigue damage in internal riser layers.

The most likely location for riser failure is at the connections to the turntable and the ESDV tower. Progressive damage to the riser connections may occur with slippage or corrosion-fatigue of the internal layers. Static loading is greatest at the vertical connections where the turret risers tie-off at the turntable. Static loads are less but rotational loading and fretting highest within the drag chain cage itself. It is fair to say that movement of the drag-chain is slow and unlikely to be dynamic, except if there is uncontrolled slippage of the turret.

The drag-chain may itself suffer progressive fatigue damage, which may affect the integrity of individual links. This can be checked. There is a lot of redundancy in the chain design and loading is not excessive. The risers themselves can also accommodate some of the loading. The consequences of damage to the drag-chain would be a progressive increase in loading on the risers and connections. Excessive loading could arise on risers and connections or turret support structure if the FPSO was forced to weathervane outside the 270° limits: this is unlikely and could be avoided in the short term by using thrusters.

7.6 Maintenance and inspection practice

Maintenance and inspection practices for drag-chain systems are as follows:

- Coflexip now advise the flexible risers are replaced 5-yearly, although the original design was for field life
- visual inspection and NDT of the flexible risers as recommended by the manufacturers, Coflexip
- checking and non-destructive testing of the flexible riser connections to the turret, turntable and the ESDV tower as recommended by the manufacturers, Coflexip
- visual inspection of condition and functionality of the drag-chain pipe management system
- visual inspection of the condition of the drag-chain cage
- functional check on turret rotation mechanism and active positioning systems
Figure 26
Model of a drag-chain system on top of a Tentech IAT Turret.
Courtesy Maritime Tentech AS

Figure 27
Schematic showing partial weathervaning using a Drag-Chain System
A variant on the drag chain system for fluid transfer has been proposed using a central drum called the Tentech drum transfer system (TDTS). This was qualified for the Kristian FSU-Halterbaken Sor (1999) but has not yet been applied in the field.

The concept, illustrated in Figure 28, is similar to the drag-chain except that the risers uncoil around a central turret. There are two variants: a single TDTS and a twin TDTS, which can achieve relative degrees of rotation of $\pm 400^\circ$ and $\pm 260^\circ$ respectively. The twin system can accommodate twice the number of hoses.

Advantages are claimed as:
- flexibility and robustness
- very low sensitivity to the hose dimension
- very low sensitivity to the degree of relative rotation
- very low sensitivity to the number of hoses, due to the possibility of a twin system

Figure 28
Schematic diagram of Tentech Drum Transfer System TDTS (Conceptual)
Courtesy Maritime Tentech AS
Figure 29
Schematic diagram of single and twin Tentech Drum Transfer Systems TDTS (conceptual).
Courtesy Maritime Tentech AS
9 SPECIAL FEATURES OF INDIVIDUAL MANUFACTURERS
SWIVEL DESIGNS

The suppliers of swivel systems have a similar background in dynamic seal and bearing technologies for pumps and flowmeters. This is the crucial technology. The designs have many similarities, but most will have their own proprietary sealing arrangement and may use different methods for tensioning between the outlet rings. The most radical is the compact swivel designs produced by Framo with a solid internal core. The swivel systems from most suppliers have evolved significantly during the 1990s and now adopt a modularised approach. As a result, some swivel stacks now combine individual swivels from different suppliers.

9.1 Bluewater

Similar to generic design. Own proprietary dynamic sealing system. Bluewater supply and operate complete FPSOs including their own turret and swivel systems. This includes both internal and external turret systems. To date, Bluewater have not produced any disconnectable turrets.

9.2 Brown Brothers

Brown Brothers, now part of Rolls Royce Marine, were the original innovators of toroidal swivels and multiple swivel assemblies. Swivel designs are as described in Sections 2 to 4 inclusive. Particular features in Brown Brothers multipath swivels include:

- stepped double seal arrangement
- leakage recovery system
- active drive system for swivel bearings - a supplier reported that this could extend seal life by up to 3 times
- shared bearings between outlet rings
- tension plates for positioning of swivel rings
- dual high-integrity dynamic seals
- silt barrier and leakage recovery
- can handle all well fluids, including gases

9.3 Framo

Framo AS have developed unique designs of compact swivel with solid central cores and energised double barrier seal arrangements. See Section 4 for detailed description.

9.4 SBM

SMB swivels are similar to the generic design described. SBM design their own turrets and swivel systems. The swivel stacks are assembled in the Netherlands.

9.5 SOFEC

SOFEC and Brown Brothers were both owned previously in the same period by Vickers. Hence, SOFEC multipath toroidal swivels have a very similar arrangement to Brown Brothers swivels. There are differences in seal arrangement. Tension rings are used in place of tensioning plates. SOFEC have used Framo compact swivels in a number of recent turret designs. The Terranova FPSO used a combination of Framo and SOFEC swivel components within the swivel stack.
ANNEX D

Summary Look-up tables on failure modes and FMEA analysis

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2 FTS AND INTERFACING SYSTEMS 35

INTRODUCTION

A Failure Modes and Effects Analysis (FMEA) is presented in this section for the four main types of Turret found in FPSOs. For each system or component a summary is given of failure modes, failure mechanisms, consequences and maintenance practice. The most important mechanisms are indicated in bold. More detailed information on safety relevant components, what can go wrong, and maintenance practice for each individual turret system can be found in Annex B. General information on failure modes and inspection for FPSO turret systems can be found in Sections 5 and 6 of the main report.

Note that these FMEA tables do not cover the swivel or fluid transfer system (FTS) in detail, or the turntable manifolding or turret transfer system (TTS). Leakage of the swivel seals, and failure of connections to the swivel or FTS, are important potential failure mechanisms for all FPSOs. A detailed description of potential failure modes and maintenance practices for individual FTS and swivel systems is given in Annex C. Sections 5 and 6 of the main report summarise historical information on past service failures for FPSO turret systems, including failure modes and inspection practices for the FTS and TTS systems.
1 FPSO TURRETS

FPSO Internal Turret Types and Major Systems

- **IPS**
  - Internal Passive Turret
  - Turntable to TTS
  - Turret Shaft
  - Upper Bearing Assembly
  - Lower Bearing Assembly
  - Turret Casing/Moonpool
  - Ship Turret Structure
  - Mooring Spider
  - Risers and Umbilicals
  - Bend-stiffeners
  - Mooring Lines

- **IAT**
  - Internal Active Turret
  - Turntable to TTS
  - Turret Shaft
  - Upper Bearing Assembly (above deck)
  - Lower Bearing Assembly
  - Turret Casing/Moonpool
  - Ship Turret Structure
  - Winches and fairleads
  - Mooring connections
  - Risers and Umbilicals
  - Bend-stiffeners
  - Mooring Lines

- **STP**
  - Submerged Turret Production
  - STP Room/STL Room
  - Conical Guide Tube
  - Trolley Rail for Compact Swivel
  - ESDV Valve Block with Interfaces
  - Locking Connector
  - ESDV Valve Block
  - STP Turret Buoy/STL Turret Buoy
    - Disconnection Interface
    - Sliding Main and Axial bearing
    - Body of Turret buoy
    - Buoyancy Modules
    - Central Core ('Turret')
    - Flexible Riser Connections
    - Mooring Attachments with Locking Pins
    - Rubber Fender (Inflatable)
  - Mooring Buoy Tensioner
  - Disconnection interface
  - Mooring Buoy Disconnectable
  - Risers and Umbilicals
  - Bend-stiffeners
  - Mooring Lines

- **IDT**
  - Internal Turret Disconnectable
  - Turntable to TTS
  - Turret Shaft
  - Upper Bearing Assembly
  - Lower Bearing Assembly
  - Turret Casing/Moonpool
  - Ship Turret Structure
  - Mooring Buoy Disconnectable
  - Mooring Buoy Tensioner
  - Disconnection interface
  - Risers and Umbilicals
  - Bend-stiffeners
  - Mooring Lines

Mooring Attachments with Locking Pins
Flexible Risers
Mooring Chains and Lines
Flotation Tank (STP only)
Bend-stiffeners on Risers (STP only)
1.1 Internal Passive Turret (IPT)

FPSO Internal Turret Type Major Systems

- Turntable to TTS
- Turret Shaft
- Upper bearing assembly
- Lower bearing assembly
- Turret Casing
- Ship Turret Structure
- Mooring Spider
- Risers and Umbilicals
- Bend-stiffeners
- Mooring Lines
## INTERNAL PASSIVE TURRET (IPT)

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Potential Failure Modes</th>
<th>Potential Causes</th>
<th>Consequences</th>
<th>Maintenance Practice</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turntable to turret transfer system (TTS)</td>
<td>Flexible riser connections</td>
<td>Loss of containment</td>
<td>Slippage of internal layers, degradation, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, X-ray tomography</td>
</tr>
</tbody>
</table>

|   |   |   | Hard piping, manifolding | Loss of containment | Corrosion, erosion, fatigue, overload | Leakage, hydrocarbon release | Visual inspection, NDT | Flange or welded connections most susceptible area |
|   |   |   | Interface | Interface cracking | Corrosion, fatigue | Increased stress on interface | Visual inspection | Unlikely |
|   |   |   | Turntable | Deformation, buckling | Overload, mechanical strength degradation | non-uniform loading | Visual inspection | Unlikely |

| 2  | Turret shaft | Turret shaft structure | Shaft deformation | Buckling, ovality, weld cracking, corrosion | High stresses due to the weather, load transfer from bearings, inadequate design, corrosion, degradation | Unusual stresses on equipment within turret | Visual inspection of inside and outside, protective coating, cathodic protection | Not found to be a problem |

|   |   | Upper bearing support - turret shaft | Cracking of interface welds, deformation | Corrosion, fatigue, excessive load transfer from bearings | Loss of integrity, overloading of ship structure | Visual inspection, strain gauging | Overdesigned deformation unlikely |

| 3  | Upper or main bearing assembly | Upper bearing support vessel deck | Cracking of interface welds, deformation | Corrosion, fatigue, excessive load transfer from bearings | Loss of integrity, overloading of ship structure | Visual inspection, strain gauging | Overdesigned deformation unlikely |
| Radial bearing | **Increase in friction**  
| Jamming or seizure  
| Loss of load bearing capability  
| Misalignment  
| Wear of raceways | **Bearing surface wear or degradation**  
| Loss of lubricant  
| Seal failure  
| Bearing buckling or out of alignment | **Loss of turret rotation**  
| Safety-critical | **Grease monitoring**  
| Torque monitoring  
| Examining the debris generated in the grease | **Access for inspection**  
| Usually difficult  
| Difficult to correct  
| Need to ensure loading on bearing within design limits |
| Axial bearings | **Increase in friction**  
| Loss of load bearing capability  
| Misalignment | **Bearing surface wear or degradation**  
| Loss of lubricant  
| Seal failure  
| Bearing buckling or out of alignment | **Loss of turret rotation** |
| **Grease monitoring**  
| Torque monitoring  
| Examining the debris generated in the grease | **Access for inspection**  
| Usually difficult  
| Difficult to correct  
| Need to ensure loading on bearing within design limits |
| Bearing housing | Loss of integrity  
| Overloading  
| Cracking at shoulders | **Bearing failure**  
| Loss of turret rotation | **External NDT for crack detection**  
| Check bolt tensioning | **Internal visual or NDT**  
| If accessible. Issues as large crane bearings |
| Bolting | Loss of tension  
| Bolt failure | **Stress relaxation**  
| Cracking | **Damage to bearing**  
| **Check bolt tensioning**  
| Removal, NDT and replacement | **Special washers can monitor bolt tension**  
| In-situ NDT possible |
| 4 Lower bearing assembly |  |
| Lower bearing pads | Increased friction | Wear, corrosion | Increased load on ship structure and turret casing  
| Affect main bearing alignment | **Designed for no inspection**  
| Visual or diver inspection possible from moonpool | **Not aware of being a problem**  
| Bearings designed to operate in seawater |
| Elastomeric seals | Seal failure | Wear, material problem | Contamination  
<p>| Increased wear on bearing pads | <strong>Visual inspection from moonpool, Diver inspection</strong> | <strong>Bearings designed to operate in seawater</strong> |</p>
<table>
<thead>
<tr>
<th>Impact</th>
<th>Failure Mode</th>
<th>Cause</th>
<th>Inspection</th>
<th>Repair Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inconel weld overlays</td>
<td>Increase in friction</td>
<td>Wear, corrosion</td>
<td>Increased friction</td>
<td>Visual inspection from moonpool, Diver inspection</td>
</tr>
<tr>
<td><strong>6 Turret Casing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turret casing</td>
<td>Insufficient rigidity</td>
<td>Larger than expected force e.g. weather</td>
<td>Increased loading and wear on bearing, bearing failure</td>
<td>Visual inspection from moonpool, Structural integrity survey</td>
</tr>
<tr>
<td>Moonpool or turret cavity</td>
<td>Ovality, deformation, corrosion or cracking - leading to structural failure</td>
<td>Non-uniform loading Larger than anticipated loading</td>
<td>Uneven loading on turret, bearings and adjacent ship structure</td>
<td>Accessible via stairwell, Visual or diver inspection dependent on sea level, Structural integrity survey</td>
</tr>
<tr>
<td><strong>7 Ship Turret Structure</strong></td>
<td></td>
<td>Misalignment or overloading of bearings Poor design</td>
<td>Increased wear and loading on bearings Risk of structural failure if not corrected</td>
<td>Visual and NDT inspection from vessel</td>
</tr>
<tr>
<td><strong>8 Risers and Umbilicals</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flexible riser connections</td>
<td>Loss of containment</td>
<td>Slippage of internal layers, degradation, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, X-ray tomography</td>
</tr>
<tr>
<td>Channels for flexible risers</td>
<td>Deformation, degradation</td>
<td>Corrosion, abrasion from contact with risers</td>
<td>Increased wear of flexible risers</td>
<td>Visual inspection</td>
</tr>
<tr>
<td>Flexible risers (within turret)</td>
<td>Loss of containment</td>
<td>Corrosion-fatigue (internal layers) Degradation of thermoplastic Over-pressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
</tr>
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</tr>
<tr>
<td>Re-injection risers</td>
<td>Loss of containment</td>
<td>Corrosion (internal and external) Overpressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
</tr>
<tr>
<td>Umbilicals - electrical</td>
<td>Loss of power</td>
<td>Wear, degradation corrosion</td>
<td>Loss of power</td>
<td>Function check, visual or diver /ROV inspection</td>
</tr>
<tr>
<td>Umbilicals - communication</td>
<td>Joint failure</td>
<td>vibration</td>
<td>Loss of communications</td>
<td>Function check, visual or diver /ROV inspection</td>
</tr>
<tr>
<td>9 Mooring Spider</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chain stoppers</td>
<td>Failure of mooring connection</td>
<td>Mooring line connection point failure Overloading Mooring line failure</td>
<td>Extreme or non-uniform loading on other moorings</td>
<td>Annual visual inspection by diver or ROV Chains inspected 5-yearly</td>
</tr>
<tr>
<td>Chain guides (some designs)</td>
<td>Increased friction</td>
<td>Wear, corrosion, impact damage</td>
<td>Increase wear and loading on mooring lines Jamming of anchor chains</td>
<td>Visual inspection by diver or ROV</td>
</tr>
<tr>
<td>Chain tensioners</td>
<td>Loss of tension</td>
<td>Slippage Mechanical or systems failure</td>
<td>Increase or non-uniform load on other mooring chains</td>
<td>Monitoring of tension on lines or vessel position</td>
</tr>
<tr>
<td>Mooring spider body</td>
<td>Deformation, cracking or corrosion</td>
<td>Corrosion Impact damage Wear</td>
<td>Not significant Non-uniform loading on turret shaft</td>
<td>Protective coating, Cathodic protection Annual visual inspection by diver or ROV</td>
</tr>
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<td>---------------------</td>
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<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Fairleads (some designs)</td>
<td>Fair leads failures</td>
<td>Corrosion, wear Mechanical damage Extreme loading</td>
<td>Extreme or non-uniform loading on other mooring chains and uneven loading on turret</td>
<td></td>
</tr>
<tr>
<td>Winches one per well (some designs)</td>
<td>Loss of function or slippage</td>
<td>Mechanical or systems failure</td>
<td>Extreme loading on other mooring chains and uneven loading on turret</td>
<td>Issues as other offshore winches</td>
</tr>
<tr>
<td>Emergency release link</td>
<td>Failure to release Releasing prematurely</td>
<td>Jams, mechanical failure</td>
<td>Failure to disconnect in emergency Loss of mooring</td>
<td></td>
</tr>
<tr>
<td>10 Bend-stiffeners</td>
<td>Cracking leading to Structural failure Loss of bend stiffener from riser</td>
<td>Decohesion of metal/elastomer interface Cracking of elastomer component</td>
<td>Increased loading on flexible risers leading to premature failure. Risk of hydrocarbon leakage if not corrected</td>
<td>Cracking of bend-stiffeners common and found in several North Sea FPSOs Key issue Ultrasonic inspection methods and procedures recently developed.</td>
</tr>
</tbody>
</table>

Annual visual inspection by diver/ROV. Recovered and inspected every 5 years
<table>
<thead>
<tr>
<th></th>
<th><strong>Mooring Lines</strong></th>
<th>Integrity failure</th>
<th>Corrosion High stresses Corrosion fatigue</th>
<th>Annual visual inspection by diver/ROV Each chain recovered and NDT inspected typically every 5 years</th>
<th>Issues as for other mooring chain applications and floating installations</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td></td>
<td>Stretching</td>
<td></td>
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</tr>
</tbody>
</table>
1.2 Internal Active Turret (IAT) - 'Tentech'

- Turntable to TTS
- Turret Shaft
- Upper Bearing Assembly (above deck)
- Lower Bearing Assembly
- Turret Casing/ Moonpool
- Ship Turret Structure
- Winches and fairleads
- Mooring connections
- Risers and Umbilicals
- Bend-stiffeners
- Mooring Lines
<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Potential Failure Modes</th>
<th>Potential Causes</th>
<th>Consequences</th>
<th>Maintenance Practice</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turntable to turret transfer system (TTS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Key issue</td>
</tr>
<tr>
<td></td>
<td>Flexible riser connections</td>
<td>Loss of containment</td>
<td>Slippage of internal layers, degradation, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, X-ray tomography</td>
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</tr>
<tr>
<td></td>
<td>Hard piping, manifolding</td>
<td>Loss of containment</td>
<td>corrosion, erosion, fatigue, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, NDT</td>
<td>Flange or welded connections most susceptible area</td>
</tr>
<tr>
<td></td>
<td>Interface</td>
<td>Interface cracking</td>
<td>Corrosion, fatigue</td>
<td>Increased stress on interface</td>
<td>Visual inspection</td>
<td>Unlikely</td>
</tr>
<tr>
<td></td>
<td>Turntable</td>
<td>Deformation, buckling</td>
<td>Overload, mechanical strength degradation</td>
<td>non-uniform loading</td>
<td>Visual inspection</td>
<td>Unlikely</td>
</tr>
<tr>
<td>2</td>
<td>Turret shaft</td>
<td></td>
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<tr>
<td></td>
<td>Turret shaft structure</td>
<td>Shaft deformation</td>
<td>High stresses due to the weather</td>
<td>Unusual stresses on equipment within turret</td>
<td>Visual inspection of inside and outside, Protective coating, Cathodic protection</td>
<td>Not found to be a problem</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Buckling</td>
<td>Load transfer from bearings</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Ovality</td>
<td>Mechanical strength degradation</td>
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<tr>
<td></td>
<td></td>
<td>Weld cracking</td>
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<tr>
<td></td>
<td></td>
<td>Corrosion</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Upper bearing support - turret shaft</td>
<td>Cracking of interface</td>
<td>Corrosion, fatigue</td>
<td>Loss of integrity</td>
<td>Visual inspection</td>
<td>Overdesigned deformation unlikely</td>
</tr>
<tr>
<td></td>
<td></td>
<td>welds</td>
<td></td>
<td>Overloading of ship structure</td>
<td>Strain gauging</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Deformation</td>
<td></td>
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<tr>
<td>3</td>
<td>Upper or main bearing assembly (above deck)</td>
<td></td>
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</tr>
<tr>
<td>Upper bearing support vessel deck</td>
<td>Cracking of interface welds Deformation</td>
<td>Corrosion, fatigue Excessive load transfer from bearings</td>
<td>Loss of integrity Overloading of ship structure</td>
<td>Visual inspection Strain gauging</td>
<td>Overdesigned deformation unlikely</td>
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</tr>
<tr>
<td>Radial bearing pads</td>
<td>Increase in friction Jamming or seizure Loss of load bearing capability Misalignment Wear of guided ring</td>
<td>Bearing surface wear or degradation Loss or contamination of lubricant</td>
<td>Loss of turret rotation Safety-critical</td>
<td>Grease monitoring Torque monitoring Examining the debris generated in the grease Visual or NDT examination of raceways (where accessible)</td>
<td>1.5m above deck, Access for inspection straightforward Pads can be individually replaced Need to ensure loading on bearing within design limits</td>
<td></td>
</tr>
<tr>
<td>Axial bearing pads</td>
<td>Increase in friction Loss of load bearing capability Misalignment</td>
<td>Bearing surface wear or degradation Loss or contamination of lubricant</td>
<td>Loss of turret rotation</td>
<td>Grease monitoring Torque monitoring Examining the debris generated in the grease.</td>
<td>1.5m above deck, Access for inspection straightforward Pads can be individually inspected Need to ensure loading on bearing within design limits</td>
<td></td>
</tr>
<tr>
<td>Hydraulic cylinders</td>
<td>Failure to operate</td>
<td>Hydraulic failure</td>
<td>Can't remove pad easily for inspection</td>
<td>Functional check</td>
<td>Cylinder for each bearing pad</td>
<td></td>
</tr>
<tr>
<td>Guided ring</td>
<td>Wear</td>
<td>Overloading Cracking at shoulders</td>
<td>Bearing failure Loss of turret rotation</td>
<td>Visual or NDT inspection. Readily accessible</td>
<td>1.5m above deck and easily accessible for visual inspection</td>
<td></td>
</tr>
<tr>
<td>Bolting</td>
<td>Loss of tension Bolt failure</td>
<td>Stress relaxation Cracking</td>
<td>Damage to bearing</td>
<td>Check bolt tensioning Removal, NDT and replacement</td>
<td>Special washers can monitor bolt tension In-situ NDT possible</td>
<td></td>
</tr>
<tr>
<td>4 Lower bearing assembly</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Component</td>
<td>Issue</td>
<td>Effect</td>
<td>Inspection Method</td>
<td>Notes</td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
</tbody>
</table>
| Lower bearing pads               | Increased friction   | Wear, corrosion                              | Visual inspection from moonpool, Diver inspection       | Not aware of being a problem
<p>|                                  |                      |                                             |                                                        | Bearings designed to operate in seawater |
| Elastomeric seals                | Seal failure         | Wear, material problem                      | Visual inspection from moonpool, Diver inspection       | Bearings designed to operate in seawater |
| Inconel weld overlays           | Increase in friction | Wear, corrosion                              | Visual inspection from moonpool, Diver inspection       | Bearings designed to operate in seawater |
| <strong>6 Turret Casing</strong>             |                      |                                             |                                                        |                                            |
| Turret casing                    | Insufficient rigidity | Larger than expected force e.g. weather     | Visual inspection from moonpool, Structural integrity survey | ovality and cracking of adjacent ship structure common |
|                                  | Structural failure   | Inadequate design                            |                                                        |                                            |
| Moonpool or turret cavity        | Ovality, deformation, corrosion or cracking - leading to structural failure | Non-uniform loading Larger than anticipated loading | Visual inspection Structural integrity survey | Ovality and cracking of adjacent ship structure common |
| <strong>7 Ship Turret Structure</strong>      | Ovality, deformation, corrosion or cracking - leading to structural failure | Misalignment or overloading of bearings Poor design | Increased wear and loading on bearings Risk of structural failure if not corrected | Much less likely than conventional IPT turrets because of rigidity of sliding bearing design |
| <strong>8 Risers and Umbilicals</strong>      | Flexible riser connections | Loss of containment | Leakage, hydrocarbon release | Visual inspection, X-ray tomography | Key issue. Connections often not easily accessible for inspection |</p>
<table>
<thead>
<tr>
<th>Channels for flexible risers</th>
<th>Deformation, degradation</th>
<th>Corrosion, abrasion from contact with risers</th>
<th>Increased wear of flexible risers</th>
<th>Visual inspection</th>
<th>Not encountered as an issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible risers (within turret)</td>
<td>Loss of containment</td>
<td>Corrosion-fatigue (internal layers) Degradation of thermoplastic Over-pressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
<td>As other flexible riser applications. Flexible riser connections are main issue Designed for 20+ year field life</td>
</tr>
<tr>
<td>Re-injection risers</td>
<td>Loss of containment</td>
<td>Corrosion (internal and external) Overpressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
<td>Connections the key issue. Issues as other flexible risers.</td>
</tr>
<tr>
<td>Umbilicals - electrical</td>
<td>Loss of power</td>
<td>Wear, degradation corrosion</td>
<td>Loss of power</td>
<td>Function check, visual or diver /ROV inspection</td>
<td>Connections main issue</td>
</tr>
<tr>
<td>Umbilicals - communication</td>
<td>Joint failure</td>
<td>vibration</td>
<td>Loss of communications</td>
<td>Function check, visual or diver /ROV inspection</td>
<td>Connections main issue</td>
</tr>
</tbody>
</table>

**9 Mooring Spider**

<table>
<thead>
<tr>
<th>Chain stoppers</th>
<th>Failure of mooring connection</th>
<th>Mooring line connection point failure Overloading Mooring line failure</th>
<th>Extreme or non-uniform loading on other moorings</th>
<th>Annual visual inspection by diver or ROV Chains inspected 5-yearly</th>
<th>Key issue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain guides (some designs)</td>
<td>Increased friction</td>
<td>Wear, corrosion, impact damage</td>
<td>Increased wear and loading on mooring lines Jamming of anchor chains</td>
<td>Visual inspection by diver or ROV</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Loss of tension</td>
<td>Slippage Mechanical or systems failure</td>
<td>Increased or non-uniform load on other mooring chains</td>
<td>Monitoring of tension on lines or vessel position</td>
<td></td>
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<tr>
<td><strong>Chain tensioners</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mooring spider body</td>
<td>Deformation, cracking or corrosion</td>
<td>Corrosion Impact damage Wear</td>
<td>Not significant Non-uniform loading on turret shaft</td>
<td>Protective coating, Cathodic protection Annual visual inspection by diver or ROV</td>
<td></td>
</tr>
<tr>
<td>Fairleads (some designs)</td>
<td>Fair leads failures</td>
<td>Corrosion, wear Mechanical damage Extreme loading</td>
<td>Extreme or non-uniform loading on other mooring chains and uneven loading on turret</td>
<td>Visual or NDT inspection Function check</td>
<td></td>
</tr>
<tr>
<td>Winches one per well (some designs)</td>
<td>Loss of function or slippage</td>
<td>Mechanical or systems failure</td>
<td>Extreme loading on other mooring chains and uneven loading on turret</td>
<td>Visual inspection Function check Issues as other offshore winches</td>
<td></td>
</tr>
<tr>
<td>Emergency release link</td>
<td>Failure to release Releases prematurely</td>
<td>Jams, mechanical failure</td>
<td>Failure to disconnect in emergency Loss of mooring</td>
<td>Annual visual inspection by diver/ROV Recovered and inspected every 5 years</td>
<td></td>
</tr>
</tbody>
</table>
| 10 | **Bend-stiffeners** | Cracking leading to Structural failure  
Loss of bend stiffener from riser | Decohesion of metal/elastomer interface  
Cracking of elastomer component | Increased loading on flexible risers leading to premature failure.  
Risk of hydrocarbon leakage if not corrected | Annual visual inspection by diver/ROV  
Dismantle, lay-down risers and recover bend-stiffener onshore for inspection  
Ultrasonic (UT) inspection on barge now possible | Cracking of bend-stiffeners common and found in several North Sea FPSOs  
Key issue  
Ultrasonic inspection methods and procedures recently developed. |
| 11 | **Mooring Lines** | Integrity failure  
Stretching | Corrosion  
Overloading  
Corrosion fatigue | Increased loading on other mooring lines, flexible risers and umbilicals | Annual visual inspection by diver/ROV  
Each chain recovered and NDT inspected typically every 5 years | Issues as for other mooring chain applications and floating installations |
1.3 Submerged Turret Production (STP) and Submerged Turret Loading (STL)

- STP Room/STL Room
- Conical Guide Tube
- Trolley Rail for Compact Swivel
- ESDV Valve Block with Interfaces
- Locking Connector
- ESDV Valve Block
- STP Turret Buoy/STL Turret Buoy
  - Disconnection Interface
  - Sliding Main and Axial bearing
  - Body of Turret buoy
  - Buoyancy Modules
  - Central Core ('Turret')
  - Flexible Riser Connections
  - Mooring Attachments with Locking Pins
    - Rubber Fender (Inflatable)
- Flexible Risers
- Mooring Chains and Lines
- Flotation Tank (STP only)
- Bend-stiffeners on Risers (STP only)
### SUBMERGED TURRET PRODUCTION (STP)

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Potential Failure Modes</th>
<th>Potential Causes</th>
<th>Consequences</th>
<th>Maintenance Practice</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>STP Room/STL Room</td>
<td>Cracking or structural damage</td>
<td>Excessive loading Time-dependent degradation</td>
<td>Structural failure</td>
<td>Structural integrity survey Visual inspection</td>
<td>Not observed. Low likelihood Accessible</td>
</tr>
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</tr>
<tr>
<td></td>
<td>Water leakage into STP compartment</td>
<td>Leakage in seals</td>
<td>Corrosion, degradation of systems in STP room</td>
<td>Visual and video examination of STP room Pump out and</td>
<td>Flooded with seawater during connection, disconnection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accidental release of inert gas</td>
<td>System or seal failure</td>
<td>Hazard to any personnel in STP room</td>
<td>Controlled and monitored Function check</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fatigue of swivel support</td>
<td>Loading above design loading</td>
<td>Leakage</td>
<td>NDT inspection</td>
<td></td>
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<tr>
<td>2</td>
<td>Conical guide tube</td>
<td>Problems in initial installation of turret-buoy</td>
<td>Poor dimensional tolerances in manufacture</td>
<td>Inability to connect turret-buoy</td>
<td>Dimensional check Functional check Trial connection and disconnection</td>
<td>Tested onshore before installation on FPSO</td>
</tr>
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</tr>
<tr>
<td></td>
<td>Structural failure</td>
<td>Corrosion or cracking due to high stresses</td>
<td>Seawater ingress to STP room Possible impact on vessel integrity</td>
<td>ROV examination when disconnected</td>
<td></td>
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<tr>
<td>3</td>
<td>Trolley rail for compact swivel</td>
<td>Failure to operate</td>
<td>Poor maintenance</td>
<td>Can’t get swivel to location</td>
<td>Lubrication Function check</td>
<td>Not likely to be a problem</td>
</tr>
<tr>
<td></td>
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</tr>
<tr>
<td>4</td>
<td>ESD valve block with interfaces</td>
<td>Fail to close</td>
<td>Loss of power</td>
<td>Regular partial close Regular full closure Leakage</td>
<td>Functional check ESDV valve block removed when swivel connected</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>ESD Valves</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

D23
<table>
<thead>
<tr>
<th>4.2</th>
<th><strong>Flowbend with pig outlet and isolation valve</strong></th>
<th><strong>Blockage</strong></th>
<th><strong>Pig stuck</strong></th>
<th><strong>Unable to resume production</strong></th>
<th><strong>Regular functional check on valves</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td><strong>Locking connector</strong></td>
<td>Locking mechanisms releases</td>
<td>Hydraulic or systems failure</td>
<td>Unexpected release of turret buoy</td>
<td>Function check Monitoring Visual inspection</td>
</tr>
<tr>
<td></td>
<td><strong>Failure to lock</strong></td>
<td>Failure to disconnect</td>
<td>Mechanical or hydraulic failure</td>
<td>Problem in connection Possible leakage</td>
<td>Function check Monitoring Visual inspection</td>
</tr>
<tr>
<td>6</td>
<td><strong>STP Turret-buoy</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>6.1</td>
<td><strong>Disconnection interface</strong></td>
<td>Improper connection</td>
<td>Functional failure</td>
<td>Need to disconnect and reconnect</td>
<td>Continuous monitoring in all connection and disconnection processes.</td>
</tr>
<tr>
<td></td>
<td>Failure to connect</td>
<td>Functional failure</td>
<td>Possibility of leakage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Improper connection Failure to connect</td>
<td>Functional failure</td>
<td>Possibility of leakage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Failure of static seals</td>
<td>Degradation Wear</td>
<td>Possibility of leakage</td>
<td>Monitoring Close visual inspection</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td><strong>Sliding main axial and radial bearing</strong></td>
<td><strong>Increase in friction</strong></td>
<td>Bearing surface wear or degradation</td>
<td>Reduced ability to weathervane Increased loading on interface with vessel</td>
<td>Regular inspection Torque measurement Measure clearances and valve condition</td>
</tr>
<tr>
<td></td>
<td><strong>Jamming or seizure</strong></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td><strong>Bearings designed to operate in seawater</strong></td>
<td></td>
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</tr>
<tr>
<td>6.3</td>
<td><strong>Body of Turret Buoy</strong></td>
<td>Fatigue at areas of stress concentration Impact damage</td>
<td>Fatigue, Corrosion Mechanical damage</td>
<td>Worse fit in guide tube Structural failure Loss of mooring connection</td>
<td>NDT inspection of high stress areas Visual or ROV inspection of buoy</td>
</tr>
<tr>
<td>6.4</td>
<td>Buoyancy modules</td>
<td><strong>Seawater ingress</strong></td>
<td>Seal failure, failure of pumps</td>
<td>Reduced buoyancy</td>
<td>Increased load on</td>
</tr>
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</tr>
<tr>
<td>6.5</td>
<td>Central core</td>
<td>Corrosion</td>
<td>Corrosion</td>
<td>Minimal effect</td>
<td></td>
</tr>
<tr>
<td>6.6</td>
<td>Flexible riser connections</td>
<td><strong>Loss of integrity</strong></td>
<td>Slippage of internal layers Corrosion-fatigue Flange failure</td>
<td>Fluid release Multiple failure could lead to mixing of flow paths.</td>
<td>Visual inspection by diver and ROV</td>
</tr>
<tr>
<td>6.7</td>
<td>Mooring attachments with locking pins</td>
<td><strong>Connection or locking pin failure</strong></td>
<td>Corrosion Cracking mechanisms</td>
<td>Loss of mooring connection</td>
<td></td>
</tr>
<tr>
<td>6.8</td>
<td>Rubber fender</td>
<td><strong>Damage to fender</strong></td>
<td>Adverse sea conditions Impact damage and wear</td>
<td>Free play of turret buoy Increased load on turret-buoy/vessel interface</td>
<td>Visual inspection by Diver and ROV</td>
</tr>
<tr>
<td>7</td>
<td>Flexible risers</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.1</td>
<td>Risers and umbilicals within turret-buoy</td>
<td>Loss of integrity Loss of function</td>
<td>Corrosion Mechanical damage Fluid release Multiple failure could lead to mixing of flow paths.</td>
<td>Not inspectable without recovering buoy on vessel</td>
<td>Main concern is connections see 6.6 above</td>
</tr>
<tr>
<td>7.2</td>
<td>Flexible Risers below turret-buoy</td>
<td>Loss of integrity</td>
<td>Corrosion fatigue Riser failure Leakage Riser failure</td>
<td>Visual inspection by diver or ROV NDT systems under development</td>
<td>As flexible risers in other floating installations</td>
</tr>
<tr>
<td>7.2</td>
<td>Umbilicals</td>
<td>Loss of integrity Fatigue, wear, environmental attack</td>
<td></td>
<td>Monitoring and visual inspection pulse if fibre optic</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Mooring chains and lines</strong></td>
<td>Mooring chain or anchor failure</td>
<td>Corrosion, cracking, environmental attack</td>
<td>Loss of station Increased loading on flexible risers and other moorings</td>
<td>Visual inspection by diver, ROV. NDT inspection if recovered on vessel</td>
</tr>
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<tr>
<td>9</td>
<td><strong>Flotation tank (STP only - below turret buoy)</strong></td>
<td>Leakage of seawater Seal failure, failure of pumps</td>
<td>Increased load on turret buoy, interface and swivel support</td>
<td>Monitoring</td>
<td>Used in STP system to control buoyancy on connection and disconnection</td>
</tr>
<tr>
<td>10</td>
<td><strong>Bend-stiffeners on risers (STP-only)</strong></td>
<td>Cracking leading to Structural failure Loss of bend stiffener from riser Decohesion of metal/elastomer interface Cracking of elastomer component</td>
<td>Increased loading on flexible risers leading to premature failure Risk of hydrocarbon leakage if not corrected</td>
<td>Annual visual inspection by diver/ROV Dismantle, lay-down risers and recover bend-stiffener onshore for inspection Ultrasonic (UT) inspection on barge now possible</td>
<td>Cracking of bend-stiffeners found in several North Sea FPSOs with conventional turrets No problem to date in STL or STP Ultrasonic inspection methods and procedures recently developed</td>
</tr>
</tbody>
</table>
1.4 Internal Disconnectable Turret (IDT)

IDT
Internal Disconnectable Turret

- Turntable to TTS
- Turret Shaft
- Upper Bearing Assembly
- Lower Bearing Assembly
- Turret Casing/ Moonpool
- Ship Turret Structure
- Mooring Buoy Tensioner
- Disconnection interface
- Mooring Buoy Disconnectable
- Risers and Umbilicals
- Bend-stiffeners
- Mooring Lines
### Internal Disconnectable Turret (IDT)

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Potential Failure Modes</th>
<th>Potential Causes</th>
<th>Consequences</th>
<th>Maintenance Practice</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turntable to turret transfer system (TTS)</td>
<td>Flexible riser connections</td>
<td>Loss of containment</td>
<td>Slippage of internal layers, degradation, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, X-ray tomography</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard piping, manifolding</td>
<td>Loss of containment</td>
<td>corrosion, erosion, fatigue, overload</td>
<td>Leakage, hydrocarbon release</td>
<td>Visual inspection, NDT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interface</td>
<td>Interface cracking</td>
<td>Corrosion, fatigue</td>
<td>Increased stress on interface</td>
<td>Visual inspection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Turntable</td>
<td>Deformation, buckling</td>
<td>Overload, mechanical strength degradation</td>
<td>non-uniform loading</td>
<td>Visual inspection</td>
</tr>
<tr>
<td>2</td>
<td>Turret shaft</td>
<td>Turret shaft structure</td>
<td>Shaft deformation</td>
<td>Buckling, Ovality, Weld cracking, Corrosion</td>
<td>High stresses due to the weather, Load transfer from bearings, Mechanical strength corrosion, degradation</td>
<td>Unusual stresses on equipment within turret</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Upper bearing support - turret shaft</td>
<td>Cracking of interface welds, Deformation</td>
<td>Corrosion, fatigue, Excessive load transfer from bearings</td>
<td>Loss of integrity, Overloading of ship structure</td>
<td>Visual inspection, Strain gauging</td>
</tr>
<tr>
<td>3</td>
<td>Upper or main bearing assembly</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Upper bearing support vessel deck</td>
<td>Cracking of interface welds</td>
<td>Corrosion, fatigue</td>
<td>Loss of integrity</td>
<td>Visual inspection</td>
<td>Overdesigned deformation unlikely</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Deformation</td>
<td>Excessive load transfer from bearings</td>
<td>Overloading of ship structure</td>
<td>Strain gauging</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Radial bearing</strong></td>
<td><strong>Increase in friction</strong></td>
<td><strong>Bearing surface wear or degradation</strong></td>
<td><strong>Grease monitoring</strong></td>
<td><strong>Access for inspection usually difficult.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jamming or seizure</td>
<td>Loss or contamination of lubricant</td>
<td>Torque monitoring</td>
<td><strong>Difficult to correct</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Loss of load bearing capability</td>
<td>Seal failure</td>
<td>Examining the debris generated in the grease</td>
<td><strong>Need to ensure loading on bearing within design limits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Misalignment</td>
<td>Bearing buckling or out of alignment</td>
<td>Visual or NDT examination of raceways (where accessible)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Wear of raceways</td>
<td>Loss of turret rotation</td>
<td><strong>Grease monitoring</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Safety-critical</td>
<td>Torque monitoring</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Axial bearings</strong></td>
<td><strong>Increase in friction</strong></td>
<td><strong>Bearing surface wear or degradation</strong></td>
<td><strong>Grease monitoring</strong></td>
<td><strong>Access for inspection usually difficult.</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Loss of load bearing capability</td>
<td>Loss or contamination of lubricant</td>
<td>Torque monitoring</td>
<td><strong>Difficult to correct</strong></td>
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</tr>
<tr>
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<td>Misalignment</td>
<td>Seal failure</td>
<td>Examining the debris generated in the grease</td>
<td><strong>Need to ensure loading on bearing within design limits</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Bearing buckling or out of alignment</td>
<td>Visual or NDT examination of raceways (where accessible)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Bearing housing</strong></td>
<td>Loss of integrity</td>
<td>Overloading</td>
<td>Bearing failure</td>
<td><strong>Internal visual or NDT if accessible. Issues as large crane bearings</strong></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Cracking at shoulders</td>
<td>Loss of turret rotation</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Bolting</strong></td>
<td>Loss of tension</td>
<td>Stress relaxation</td>
<td>Check bolt tensioning</td>
<td><strong>Special washers can monitor bolt tension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Bolt failure</td>
<td>Cracking</td>
<td>Removal, NDT and replacement</td>
<td><strong>In-situ NDT possible</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Lower bearing assembly</strong></td>
<td><strong>Lower bearing pads</strong></td>
<td>Increased friction</td>
<td>Increased load on ship structure and turret casing</td>
<td><strong>Not aware of being a problem</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wear, corrosion</td>
<td>Affect main bearing alignment</td>
<td><strong>Bearings designed to operate in seawater</strong></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Visual inspection from moonpool, Diver inspection</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### ANNEX D

<table>
<thead>
<tr>
<th><strong>Elastomeric seals</strong></th>
<th><strong>Seal failure</strong></th>
<th><strong>Wear, material problem</strong></th>
<th><strong>Contamination</strong></th>
<th><strong>Visual inspection from moonpool, Diver inspection</strong></th>
<th><strong>Bearings designed to operate in seawater</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased wear on bearing pads</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Inconel weld overlays</strong></td>
<td><strong>Increase in friction</strong></td>
<td><strong>Wear, corrosion</strong></td>
<td>Increased friction</td>
<td><strong>Visual inspection from moonpool, Diver inspection</strong></td>
<td><strong>Bearings designed to operate in seawater</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Increased load on ship structure and turret casing</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 6 **Turret Casing**

<table>
<thead>
<tr>
<th><strong>Turret casing</strong></th>
<th><strong>Insufficient rigidity</strong></th>
<th><strong>Larger than expected force e.g. weather</strong></th>
<th><strong>Inadequate design</strong></th>
<th><strong>Increased loading and wear on bearing, bearing failure</strong></th>
<th><strong>Visual inspection from moonpool, Structural integrity survey</strong></th>
<th><strong>Ovality and cracking of adjacent ship structure common</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Structural failure</strong></td>
<td><strong>Inadequate design</strong></td>
<td><strong>Inadequate manufacture</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Moonpool or turret cavity</strong></td>
<td><strong>Ovality, deformation, corrosion or cracking - leading to structural failure</strong></td>
<td><strong>Non-uniform loading</strong></td>
<td>Larger than anticipated loading</td>
<td><strong>Uneven loading on turret, bearings and adjacent ship structure</strong></td>
<td><strong>Visual inspection Structural integrity survey</strong></td>
<td><strong>Ovality and cracking of adjacent ship structure common</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Larger than anticipated loading</strong></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

#### 7 **Ship Turret Structure**

<table>
<thead>
<tr>
<th><strong>Ovality, deformation, corrosion or cracking - leading to structural failure</strong></th>
<th><strong>Misalignment or overloading of bearings</strong></th>
<th><strong>Poor design</strong></th>
<th><strong>Increased wear and loading on bearings</strong></th>
<th><strong>Risk of structural failure if not corrected</strong></th>
<th><strong>Visual and NDT inspection from vessel</strong></th>
<th><strong>Very common, particularly in conversions</strong></th>
</tr>
</thead>
</table>

#### 8 **Risers and Umbilicals**

<table>
<thead>
<tr>
<th><strong>Flexible riser connections</strong></th>
<th><strong>Loss of containment</strong></th>
<th><strong>Slippage of internal layers, degradation, overload</strong></th>
<th><strong>Leakage, hydrocarbon release</strong></th>
<th><strong>Visual inspection, X-ray tomography</strong></th>
<th><strong>Key issue. Connections often not easily accessible for inspection</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Channels for flexible risers</strong></td>
<td><strong>Deformation, degradation</strong></td>
<td><strong>Corrosion, abrasion from contact with risers</strong></td>
<td><strong>Increased wear of flexible risers</strong></td>
<td><strong>Visual inspection</strong></td>
<td><strong>Not encountered as an issue</strong></td>
</tr>
<tr>
<td>Flexible risers (within turret)</td>
<td>Loss of containment</td>
<td>Corrosion-fatigue (internal layers) Degradation of thermoplastic Over-pressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
<td>As other flexible riser applications. Flexible riser connections are main issue Designed for 20+ year field life</td>
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<tr>
<td>Re-injection risers</td>
<td>Loss of containment</td>
<td>Corrosion (internal and external) Overpressurisation High stresses</td>
<td>Fluid leakage</td>
<td>Visual inspection. NDT methods under development CO2 and H2S levels monitored in inventory</td>
<td>Connections the key issue. Issues as other flexible risers.</td>
</tr>
<tr>
<td>Umbilicals - electrical</td>
<td>Loss of power</td>
<td>Wear, degradation corrosion</td>
<td>Loss of power</td>
<td>Function check, visual or diver /ROV inspection</td>
<td>Connections main issue</td>
</tr>
<tr>
<td>Umbilicals - communication</td>
<td>Joint failure</td>
<td>vibration</td>
<td>Loss of communications</td>
<td>Function check, visual or diver /ROV inspection</td>
<td>Connections main issue</td>
</tr>
<tr>
<td><strong>9 Mooring Spider</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Chain stoppers</td>
<td>Failure of mooring connection</td>
<td>Mooring line connection point failure Overloading Mooring line failure</td>
<td>Extreme or non-uniform loading on other moorings</td>
<td>Annual visual inspection by diver or ROV Chains inspected 5-yearly</td>
<td>Key issue</td>
</tr>
<tr>
<td>Chain guides (some designs)</td>
<td>Increased friction</td>
<td>Wear, corrosion, impact damage</td>
<td>Increased wear and loading on mooring lines Jamming of anchor chains</td>
<td>Visual inspection by diver or ROV</td>
<td></td>
</tr>
<tr>
<td>Chain tensioners</td>
<td>Loss of tension</td>
<td>Slippage Mechanical or systems failure</td>
<td>Increased or non-uniform load on other mooring chains</td>
<td>Monitoring of tension on lines or vessel position</td>
<td></td>
</tr>
<tr>
<td>Mooring spider body</td>
<td>Deformation, cracking or corrosion</td>
<td>Corrosion Impact damage Wear</td>
<td>Not significant Non-uniform loading on turret shaft</td>
<td>Protective coating, Cathodic protection Annual visual inspection by diver or ROV</td>
<td></td>
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<td>-----------------------------------------------</td>
<td>-----------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Fairleads (some designs)</td>
<td>Fair leads failures</td>
<td>Corrosion, wear Mechanical damage Extreme loading</td>
<td>Extreme or non-uniform loading on other mooring chains and uneven loading on turret</td>
<td>Visual or NDT inspection Functionality check</td>
<td></td>
</tr>
<tr>
<td>Winches one per well (some designs)</td>
<td>Loss of function or slippage</td>
<td>Mechanical or systems failure</td>
<td>Extreme loading on other mooring chains and uneven loading on turret</td>
<td>Functionality check Visual and NDT inspection Issues as other offshore winches</td>
<td></td>
</tr>
<tr>
<td>Emergency release link</td>
<td>Failure to release Releases prematurely</td>
<td>Jams, mechanical failure</td>
<td>Failure to disconnect in emergency Loss of mooring</td>
<td>Annual visual inspection by diver/ROV Recovered and inspected every 5 years</td>
<td></td>
</tr>
<tr>
<td>10 <strong>Bend-stiffeners</strong></td>
<td>Cracking leading to Structural failure Loss of bend stiffener from riser</td>
<td>Decohesion of metal/elastomer interface Cracking of elastomer component</td>
<td>Increased loading on flexible risers leading to premature failure Risk of hydrocarbon leakage if not corrected</td>
<td>Annual visual inspection by diver/ROV Dismantle, lay-down risers and recover bend-stiffener onshore for inspection Ultrasonic (UT) inspection on barge now possible Cracking of bend-stiffeners common and found in several North Sea FPSOs Key issue Ultrasonic inspection methods and procedures recently developed.</td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Mooring Lines</td>
<td>Integrity failure</td>
<td>Corrosion</td>
<td>Annual visual inspection by diver/ROV</td>
<td>Issues as for other mooring chain applications and floating installations</td>
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<tr>
<td></td>
<td></td>
<td>Stretching</td>
<td>High stresses</td>
<td>Each chain recovered and NDT inspected typically every 5 years</td>
<td></td>
</tr>
</tbody>
</table>
## 2 FTS AND INTERFACING SYSTEMS

<table>
<thead>
<tr>
<th>ID</th>
<th>Component</th>
<th>Potential Failure Modes</th>
<th>Potential Causes</th>
<th>Consequences</th>
<th>Maintenance Practice</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Swivel Stack and FTS system</td>
<td>Failure of dynamic seals</td>
<td>Material problem</td>
<td>Hydrocarbon leakage with risk of explosion</td>
<td>Monitor for hydrocarbon leakage</td>
<td>Failure of all dynamic seals occurred in one North Sea FPSO in year 2000</td>
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<tr>
<td></td>
<td></td>
<td>Excessive roll</td>
<td></td>
<td></td>
<td>Monitor level in recovery tanks</td>
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<tr>
<td></td>
<td></td>
<td>Loss of tensioning</td>
<td></td>
<td></td>
<td>Monitor bolt tensions and inspect at regular intervals</td>
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<tr>
<td></td>
<td>Excessive leakage from dynamic seals</td>
<td>Wear or damage to seal</td>
<td></td>
<td>Hydrocarbon leakage May escalate with time with potential risk of explosion</td>
<td>Intervention or inspection of seals not advised unless there is a problem Monitor leakage to recovery tanks</td>
<td>Intervention or dismantling of seals may initiate problem</td>
</tr>
<tr>
<td></td>
<td>Failure of flexible or hard pipe connections</td>
<td>Excessive movement of stack</td>
<td></td>
<td>Hydrocarbon leakage May escalate with time with potential risk of explosion</td>
<td>Visual inspection NDT inspection e.g. X-Ray tomography</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Misorientation of swivel rings</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Time-dependant degradation e.g corrosion, fatigue</td>
<td></td>
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<tr>
<td></td>
<td>Excessive torque or</td>
<td>Increased loading on</td>
<td></td>
<td>Stresses and</td>
<td></td>
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<tr>
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<td>--------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>Movement in torque arms.</td>
<td>Misorientation</td>
<td></td>
<td>Swivel stack and connections</td>
<td>Orientation on torque arms continually monitored</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Risk of seal or connection failure</td>
<td></td>
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<tr>
<td>2</td>
<td>Bearing failure</td>
<td>Excessive wear on bearings</td>
<td></td>
<td>Leakage of gas or hydrocarbons</td>
<td>Check bolt tensions</td>
<td>Visual and NDT inspection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cracking of bearing housings</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Relaxation or corrosion/cracking of bolts</td>
<td></td>
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<tr>
<td>3</td>
<td>Large friction of jamming</td>
<td>Wear on bearings</td>
<td></td>
<td>Risk of seal failure</td>
<td>Monitor torque to tune swivel rings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>of swivel rings</td>
<td></td>
<td></td>
<td>Increased loading on connections to swivel stack</td>
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<tr>
<td>4</td>
<td>Swivel mis-orientated</td>
<td>Stiffness of riser connections to process plant</td>
<td></td>
<td>Increased loading on connections</td>
<td>Monitor swivel orientation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>relative to vessel</td>
<td>on vessel, Excessive friction on bearings</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Excessive friction on bearings</td>
<td></td>
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<tr>
<td>5</td>
<td>2 Crane</td>
<td>Bolt failure</td>
<td></td>
<td>Impact damage to swivel and TTS system</td>
<td>Inspection and maintenance practice</td>
<td>Mounted above swivel and TTS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Increased friction on bearings</td>
<td></td>
<td></td>
<td>as other offshore cranes. See Section 5 of main report and existing HSE guidance</td>
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<td>Cracking of bearing housing</td>
<td></td>
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<td></td>
<td></td>
<td>Fatigue, wear, environmental attack, overloading,</td>
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<tr>
<td></td>
<td></td>
<td>poor maintenance practices</td>
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<tr>
<td>3</td>
<td>Risers below turret level</td>
<td>Loss of containment</td>
<td>Corrosion (internal and external)</td>
<td>Subsea release</td>
<td>Internal corrosion inhibitors</td>
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<td></td>
<td></td>
<td></td>
<td>Overpressurisation</td>
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<td>Wall thickness checks</td>
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<td>High stresses</td>
<td></td>
<td>Sacrificial anodes and coatings</td>
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<td>CO2 and H2S levels monitored in inventory</td>
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<tr>
<td>4</td>
<td>Mid-water arch buoy</td>
<td>Loss of buoyancy</td>
<td>Mechanical damage</td>
<td>Stress on risers that could lead to rupture</td>
<td>Visual inspection by diver or ROV</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Corrosion</td>
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<td></td>
<td></td>
<td></td>
<td>Corrosion fatigue</td>
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<tr>
<td>5</td>
<td>Whole ship</td>
<td>Ship motion outside pitch parameters</td>
<td>Extreme weather</td>
<td>High pitch angles of the vessel give high impact loads to ship and equipment and reduces fatigue life</td>
<td>Predict weather conditions and consider turret disconnection.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ship motion outside roll parameters</td>
<td>Extreme weather</td>
<td>High roll and roll angles of the vessel give high impact loads to equipment and reduces fatigue life</td>
<td>Predict weather conditions and consider turret disconnection.</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Ship motion outside yaw parameters</td>
<td>Extreme weather</td>
<td>None - weather vaning</td>
<td></td>
<td>Predict weather conditions and consider turret disconnection.</td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>6</td>
<td>Ship structure</td>
<td>High cycle operating experience</td>
<td>Extreme weather</td>
<td>Life time reduced due to fatigue</td>
<td>Structural integrity survey</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Turret not rigid relative to the structure</td>
<td>Inadequate design</td>
<td>Relative movement between the ship structure. Small movement is accommodated in the flexible fluid transfer connection between the structure and turret. Large movement could result in fracture of fluid transfer and communication link.</td>
<td>Structural integrity survey</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Loss of water tightness due to fracture or corrosion</td>
<td>Corrosion</td>
<td>Water from the moon pool (or equivalent depending on the design) flows through the wall of the turret shaft to adjacent cavities in the ship.</td>
<td>Structural Integrity Survey</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Ship Tanks</td>
<td>Explosion</td>
<td>Explosive mixture of vapours in tanks</td>
<td>Damage to process plant above tanks</td>
<td>Monitor loading carefully Inert gas blanket</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pitting and loss of wall thickness</td>
<td>Microbial induced corrosion (MIC) inside</td>
<td>Potential loss of integrity</td>
<td>External hull thickness survey of hull for</td>
<td></td>
</tr>
<tr>
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<tr>
<td></td>
<td></td>
<td>tank, under sediment</td>
<td>Corrosion</td>
<td></td>
<td>single shell</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Environmental cracking mechanisms</td>
<td></td>
<td>Inspection from between skins for double hull</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Thrusters (Active turrets only)</td>
<td>Loss of motive power</td>
<td>Thruster failure</td>
<td>On a drag chain type design there is the loss of positive weather vaning. Only a problem if the weather rotates the ship greater than 270 degrees.</td>
<td>Disconnect the ship from it's mooring, to prevent damage to the turret transfer system</td>
<td>Booster backup</td>
</tr>
</tbody>
</table>