Espirito Santo: Design and Operational Experience of the Use of Steel Risers on a Turret-Moored FPSO

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Summary

The floating production, storage, and offloading (FPSO) facility *Espirito Santo*, located offshore Brazil in the Parque das Conchas (BC-10) field, is the world's first turret-moored FPSO facility to use steel risers for fluid transfer. The FPSO facility is moored in a water depth of 1780 m, and the internal turret incorporates a total of 21 riser and umbilical slots. The steel risers, which are in a lazy-wave configuration, were pulled into the turret through inclined I-tubes. Clamps at the top of the I-tubes retain the risers, thus transferring axial loads from the risers to the turret. A clamp casting welded at the bottom of the I-tubes houses a stopper arrangement designed to transfer shear forces and moments from the risers to the turret.

The FPSO facility began oil production in July 2009, and now has more than 5 years of operational experience. During this period, inspection of the riser system and the associated flex joint has confirmed the integrity of the design, giving further confidence in the use of steel risers in turret-moored systems.

This paper summarizes the basis for selecting steel risers for the development, how the risers and umbilicals interface with the turret, and the impact of the riser choice on the turret design. The in-service inspection of the riser system is described, and the results are reported.

Introduction

The Parque de Conchas (BC-10) field is located offshore Brazil in the northern Campos basin, approximately 120 km southeast of the city of Vitória **(Fig. 1).** The project is a joint venture, with operator Shell holding a 50% interest and partners ONGC and Qatar Petroleum International holding 27% and 23%, respectively.

The development of BC-10 is based around a centrally located floating production, storage, and offloading (FPSO) facility; subsea wells producing through manifolds; subsea pressure-boosting systems; and a network of flowlines and risers. The development plan comprises three phases, of which the first two are complete.

Phase 1 involved the development of three fields tied back to the FPSO facility by means of subsea wells and manifolds. These fields were the Ostra, Abalone, and Argonauta-BW, and their development involved nine production wells and one gas-injection well. These fields came on stream in July 2009, with a peak production of 94,000 BOE/D. The field layout is shown in **Fig. 2.**

Phase 2 of the project, the tie-in of the Argonauta-ON field, came on stream in October 2013, with an expected peak production of 35,000 BOE/D.

The joint-venture partners have also agreed to a third phase, which will include the installation of subsea infrastructure at the Massa and Argonauta O-South fields. Once on stream, Phase 3 is expected to have a peak production of 28,000 BOE/D.

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The centrally located FPSO facility is the *Espirito Santo*. The BC-10 joint venture charters the FPSO facility from SBM Offshore jointly with MISC under a long-term lease and operating contract.

A unique feature of the BC-10 development is the use of steel lazy-wave risers (SLWRs) in conjunction with an internal turret-mooring system. This is the first use of SLWRs in the industry, and the first time a steel-riser system of any configuration has been used with an internal turret-mooring system. After more than 5 years of operational experience, the integrity of the turret and riser system has been demonstrated in field conditions. The intent of this paper is to describe the impact of the use of SLWRs on the turret-mooring system, and to report the in-service inspections carried out to verify the ongoing integrity of the riser system.

General Description of the *Espirito Santo*

The floating production, storage, and offloading (FPSO) facility is based on a single-hull steam tanker built in 1975. The hull was converted to a floating storage and offloading vessel in 1992 before then being converted into the FPSO *Espirito Santo* in 2008–09. The conversion to an FPSO facility included the addition of sponsons along the length of the cargo block to provide a double side to the vessel.

The *Espirito Santo* topside is designed to produce 100,000 BOPD, with gravities ranging from 16 to 42 °API. The unit is also designed to treat up to 45 MMscf/D of gas for reinjection into the reservoir or for export, and it has a water-injection capacity of 75,000 B/D.

The FPSO facility incorporates an internal turret-mooring system integrated into the forward central-cargo oil tank. Three sets of three mooring lines are connected to the turret, maintaining the FPSO facility on station and limiting the excursions of the FPSO facility relative to the subsea systems. A multibogie bearing system between the turret and the hull allows the vessel to weathervane around the geostationary mooring system to take up the heading of least resistance to the prevailing weather. The turret also incorporates a swivel stack to provide the means of transferring the well fluids and services between the geostationary turret and the rotating FPSO facility. The *Espirito Santo* is shown in **Fig. 3.**

The internal turret includes a total of 21 risers and umbilical slots. Seven risers and three umbilicals were installed as part of the Phase 1 field development, and a further three risers and three umbilicals were installed for Phase 2. No additional risers will be required for Phase 3, leaving five slots still available.

The swivel stack comprises eight toroidal fluid swivels, one double-drum high-pressure/low-pressure multipath utility swivel, two high-voltage electric swivels, and one power/control/optical swivel. The turret-mooring system is described in more detail in later sections of this paper and elsewhere in the literature (Martineau et al. 2009).

Mooring-System Selection

Turret-moored floating production, storage, and offloading (FPSO) vessels and spread-moored FPSO vessels are both operating offshore Brazil, but the spread-moored systems rely on shuttle tankers with dynamic positioning (DP) to ensure sufficient availability of

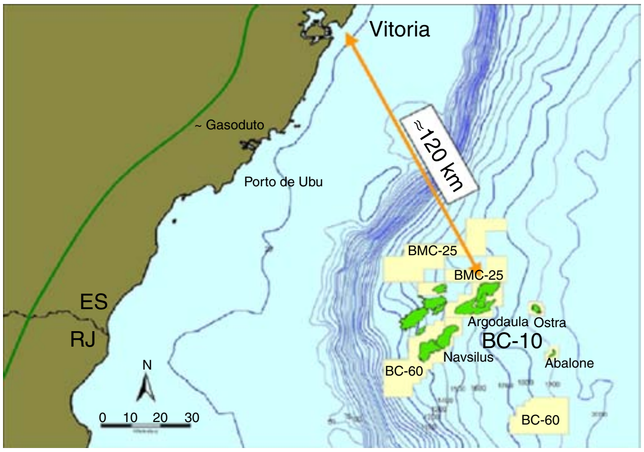

Fig. 1—BC-10 field location.

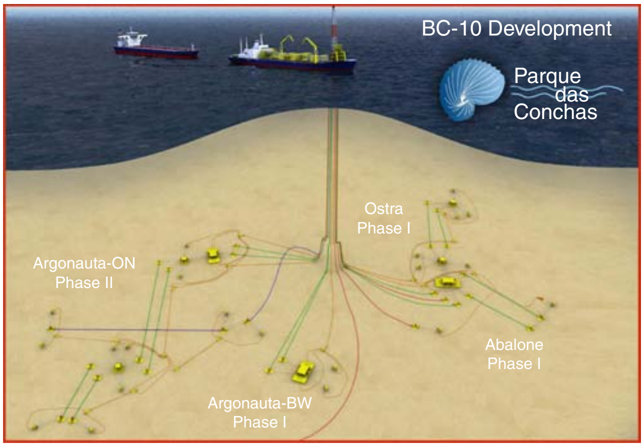

Fig. 2—Field layout.

cargo-offloading operations. The use of DP is necessary to allow shuttle tankers to stay aligned with the spread-moored FPSO vessel and minimize the risk of collision as a result of changes in weather direction.

The FPSO facility *Espirito Santo* is not serviced by a dedicated fleet of DP shuttle tankers; instead, it uses tankers of opportunity for cargo offloads. To ensure these tankers can offload safely and to minimize delays to offloads because of environmental conditions, a weathervaning top-mounted internal turret (TMIT) was selected as the appropriate mooring system.

SBM Offshore has supplied a large number of turret moorings for FPSO facilities in Brazil, the most recent of them being all TMITs based on a multibogie bearing system (MBBS). A typical TMIT configuration is shown in **Fig. 4.** The MBBS allows the FPSO facility to weathervane around the geostationary mooring system to take up the heading of least resistance to the prevailing weather. The ability to weathervane minimizes the load on the vessel's hull girder

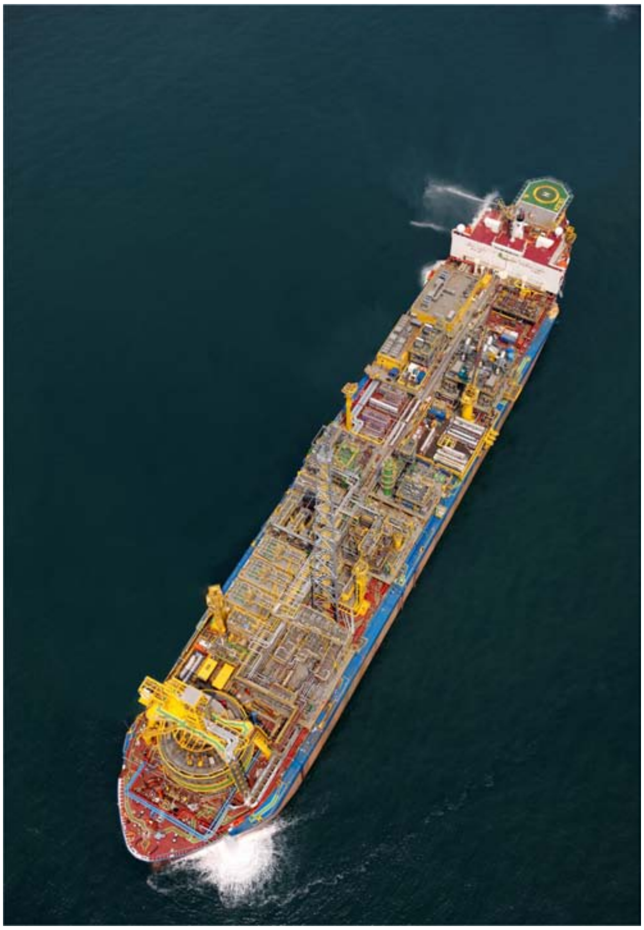

Fig. 3—FPSO facility *Espirito Santo*.

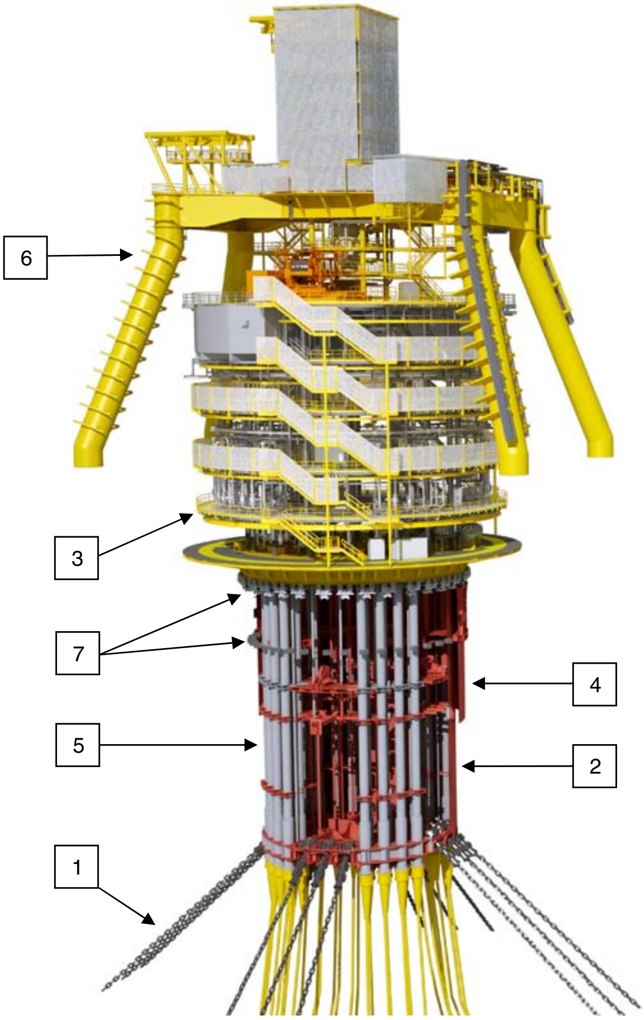

Fig. 4—Typical TMIT based on an MBBS.

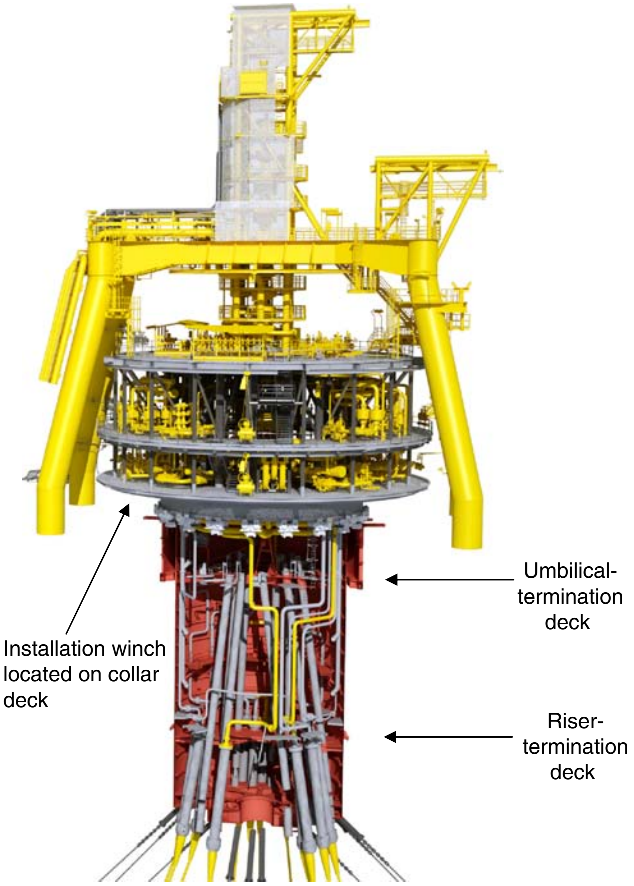

Fig. 5—BC-10 TMIT.

and on the mooring system, and allows the shuttle tanker to offload safely in tandem in a large range of environmental conditions.

The first application of an MBBS was for the turret-mooring system of the *Schiehallion* FPSO vessel in 1996. The system was developed to withstand the high mooring loads generated by the harsh environmental conditions of the Atlantic Margin, west of Shetland (Fromage et al. 2013). After more than 15 years of successful operational experience, the MBBS has proved to be a reliable weathervaning system for large-diameter turrets and for turrets subject to high environmental loading. The use of an MBBS avoids the restrictions on turret diameter that occur with traditional roller-bearing arrangements, allowing the use of the 15.5 m diameter turret cylinder needed to accommodate the riser arrangement for BC-10.

The Choice of Steel Risers

During the front-end engineering-design (FEED) phase of the BC-10 project, a number of riser systems were considered, including steel catenary risers, flexible risers, and hybrid risers. However, analysis identified that steel catenary risers were not a feasible solution because of the high fatigue damage that would be incurred at the touchdown point, and consequently, it was decided to investigate steel lazy-wave risers (SLWRs) as an alternative. In parallel, Shell performed a detailed FEED study to verify that flexible risers were feasible given the BC-10 riser diameters and water depths.

Having established the technical feasibility of SLWRs and flexible risers, quotations were obtained for both solutions as input to a study of their relative economics. The use of hybrid risers was ruled out at this point on the basis of cost.

The SLWRs and flexible risers were then evaluated on the basis of payload, cost, and schedule. The payload of the SLWR system was found to be approximately 50% of the flexible-riser system, while the costs of the two systems were comparable. However, the main driver in the selection of SLWRs was their shorter delivery time compared with the flexible-riser system. At the time of award, the high demand for flexible risers resulted in a delivery schedule that was incompatible with the overall BC-10 project schedule, resulting in the SLWRs being selected as the solution.

The selection of the SLWR system resulted in two industry firsts:

- The first use of SLWRs
- The first turret-mooring system to support steel risers of any configuration

It should be noted that the use of an internal turret rather than an external bow-mounted turret facilitated the use of SLWRs. The pitch motions imposed on risers in an internal turret are less than those for risers supported by an external turret, resulting in reduced fatigue damage.

Key Features of a Typical Top-Mounted Internal Turret (TMIT) Supporting Flexible Risers

As a basis for discussing the impact of steel lazy-wave risers (SLWRs) on the turret design, this section of the paper briefly describes a typical TMIT supporting flexible risers.

A typical TMIT can be considered to comprise seven key subsystems, as identified in Fig. 4:

1. Mooring lines, including anchor points.
2. Turret cylinder (i.e., the load-transfer path from anchor lines to vessel).
3. Manifold structure: The installation winch is located on a trolley on the top manifold deck, allowing a straight pull through the I-tubes for riser installation.
4. Vessel structure, supporting the weathervaning system.
5. Fluid-transfer system consisting of risers, manifold, swivels, and vessel piping. The risers are vertical from the chaintable at the bottom of the turret cylinder to their support points on the collar deck at the top of the cylinder.
6. Gantry structure, which is supported on the vessel deck.
7. Weathervaning system (i.e., the multibogie bearing system).

The mooring lines, turret cylinder, manifold structure, and the majority of the fluid-transfer system form the geostationary element of the TMIT. The vessel structure, gantry structure, and the portion of the fluid-transfer system located on the gantry form the rotating element of the TMIT. The weathervaning system and swivel stack are the interface between the geostationary elements and the rotating elements. The weathervaning system allows the floating production, storage, and offloading facility to rotate around the turret, and transmits the turret loads to the vessel; the swivel stack transfers well fluids and services between the geostationary and rotating parts.

More-detailed descriptions of typical TMIT systems can be found in George et al. (2008), Naciri et al. (2010), and Fromage et al. (2013).

Modifications to the Typical Top-Mounted Internal Turret (TMIT) To Accommodate Steel Lazy-Wave Risers (SLWRs)

The design principles and overall configuration of a TMIT are similar whether flexible risers or SLWRs are used, but the use of SLWRs for BC-10 did result in some modifications to the typical turret layout:

1. Termination of the risers and umbilicals in the turret cylinder rather than at the collar deck; this was to avoid interference between the inclined I-tubes.
2. The location of the pull-in winch on the collar deck rather than the upper manifold deck; this was to facilitate a straight pull-in of the SLWRs, which also required a movable platform to be developed to situate the winch in line with each of the I-tubes.
3. The development of an interface mechanism to connect the SLWRs to the I-tubes.

An overview of the resulting turret design is shown in **Fig. 5,** and the differences from a typical TMIT design are discussed in

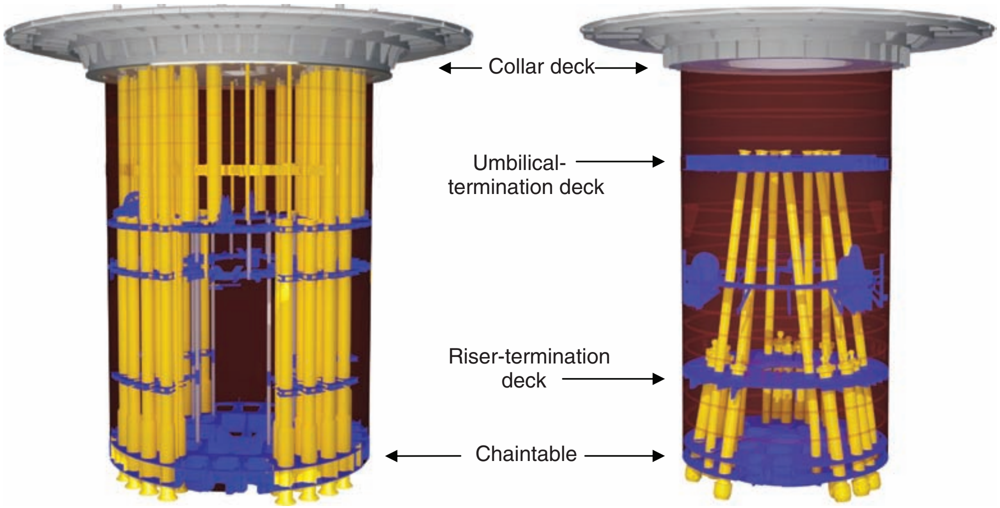

Fig. 6—Comparison of lower turret I-tube arrangements.

more detail in the following sections of the paper. More details of the overall turret design can be found in Martineau et al. (2009).

Riser-Termination Level

In top-mounted internal turrets (TMITs) incorporating flexible risers, the risers run through vertical I-tubes, and are supported at the collar deck of the turret. For BC-10, the field layout resulted in the steel lazy-wave risers (SLWRs) and umbilicals entering the turret at an angle, requiring them to be terminated in the lower turret cylinder, as explained in the following.

The SLWRs and umbilicals entered the turret at angles ranging from 4 to 10° to the vertical, and in a nonradial arrangement with respect to the turret cylinder. Extending the I-tubes to the collar deck would have resulted in clashes between them. To avoid these clashes, the SLWRs and umbilicals were terminated at a lower level than the collar deck, and piping was then routed from the riser head to the collar deck along a path that avoided clashes, as shown in Fig. 5. To accommodate this, a new lower turret configuration was developed with three deck levels in the lower turret cylinder. The lowest deck was the riser deck, located just above the floating production, storage, and offloading (FPSO) facility's minimum draft of 6.8 m. The riser I-tubes were terminated at the riser deck, allowing the risers to be hung off with split collars in a dry-installation environment. The umbilical I-tubes were terminated on the umbilical deck, still within the lower turret, but located 25 m above the FPSO facility's keel. This elevation is above the FPSO facility's maximum draft, allowing the umbilical terminations to be located in a dry-operating environment. Between the riser and umbilical decks is the installation deck, which provides access to the chain sheaves required for the mooring-line pull-in. **Fig. 6** shows a comparison of the lower turret arrangement of a typical TMIT with flexible risers and the lower turret arrangement of BC-10.

In addition to implementing the arrangement described in the preceding, it was also necessary to include a bend of between 1 and 5° in the umbilical I-tubes to modify their inclination to avoid clashes between pull-in paths. The bend is at chaintable level, as shown in **Fig. 7,** and has a radius of 12 m. While this arrangement was not optimal, it was driven by the constraints of the overall field layout.

The inclination of the SLWRs and umbilicals resulted in their pull-in paths intersecting with the collar deck in the central zone of the deck. To facilitate a straight pull-in path for the risers, the pull-in winch was located on a moveable platform within this zone, as shown in **Fig. 8.** This differs from a typical TMIT, in which a traveling pull-in winch is located close to the perimeter of the upper deck to allow a straight pull-in of vertical flexible risers. The winch arrangement is described in more detail in a later section of this paper.

Steel Lazy-Wave Riser (SLWR)/Turret Interface

The design of the interface mechanism to secure the riser in the I-tubes drew on Shell's experience with the use of steel risers on

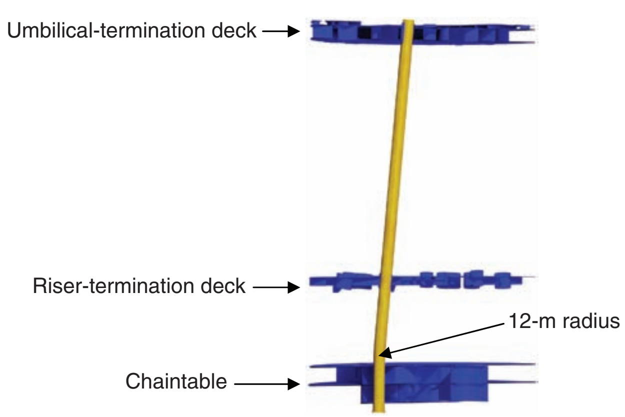

Fig. 7—BC-10 umbilical I-tubes.

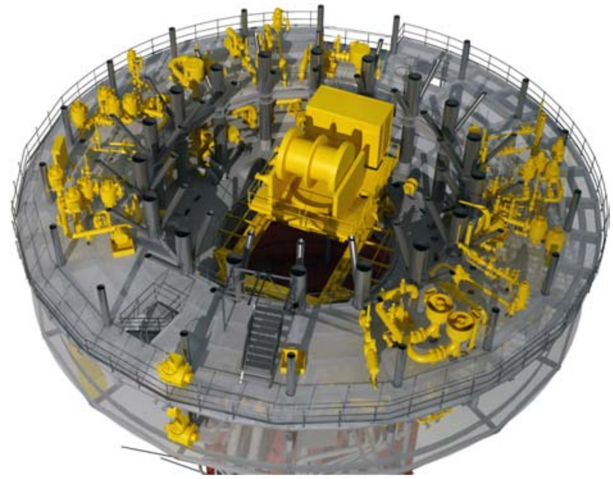

Fig. 8—Installation winch position in the center of the collar deck.

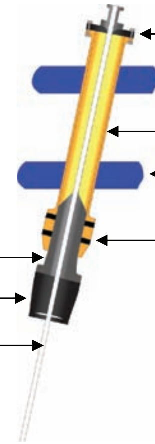

Fig. 9—SLWR/turret interface.

Fig. 10—SLWR/turret interface: riser-clamp casting.

other types of facilities. The I-tubes terminate in a support flange at the upper end, and a clamp casting at the lower end. The riser is terminated by a flex joint connected to a journal forging. The flex joint allows for angular rotations of the riser up to ±20°. The journal forging is attached to the top of the flex joint and interfaces with the I-tube clamp casting. Within the clamp casting, there are eight locking plugs to centralize the riser. The locking plugs are actuated by means of divers and torque tools. The clamp casting transmits the bending moments (and a portion of the riser tension) to the chaintable. At the top of the journal forging, the upper attachment assembly is fitted with a hang-off collar to transmit the riser tensions to the guide tube. **Fig. 9** shows the complete assembly, and the photo in **Fig. 10** shows the clamp casting (in yellow) at the bottom of the turret (in red) during assembly.

It should be noted that the interface for the umbilicals is not affected by the use of SLWRs. The interface consists of an industry-standard bend-stiffener latching mechanism (BSLM) supplied by the umbilical manufacturer, split-flange hang-off collars, and the umbilical bullnose containing the terminations for the contained tubing, low-voltage cables, high-voltage cables, and fiber optics. The BSLM consists of a locking mechanism that is bolted to the end of the umbilical I-tube beneath the turret chaintable. This captures the bend-stiffener stab and secures the stab with four diver-operated locking screws. The BSLM transfers the bending moments to the chaintable, while the vertical tension is supported by the split collar on top of the I-tube.

Steel-Lazy-Wave-Riser and Umbilical Pull-In Equipment

The riser and umbilical pull-in were achieved by use of a rotary drum installation winch located on the turret collar deck. This winch and the hydraulic elements of the movable winch platform supporting it were all powered from a common hydraulic-power unit (HPU) mounted on the winch platform.

The Installation Rotary Drum Winch. The installation winch arrangement comprises the following components:

- A rotating foundation platform incorporating a sliding platform, which in turn supports a secondary rotation winch platform. The split-drum installation winch, designed for an 18:1 minimum bending ratio (drum-diameter/wire-rope diameter), is mounted on the winch platform.
- A transmission system, including three variable-displacement axial piston-type hydraulic motors plus associated reduction gearboxes.
- A brake system to allow the winch to hold load beyond the winch stall load, and a manual emergency brake release system.
- A local control system to control the main winch and platforms.

The main winch motors are designed to provide an adjustable-speed facility from zero to the maximum obtainable speed (2 m/min at 335 t and 10 m/min at zero load), with the drum capable of controlled pay out under maximum load and of inching. The minimum stall load is 370 t, and the minimum brake-holding capacity is 445 t (at the top layer).

The split drum incorporates one wire for riser handling and one for anchor-chain handling. The riser wire rope is 102 mm in diameter and 320 m long, with a minimum breaking load of 950 t, while for chain handling, the rope is 96 mm in diameter and 320 m long, with a minimum breaking load 790 t.

The angle from vertical for riser/umbilical pull-in depends on the I-tube inclination, which varies from 4 to 10° for different risers and umbilicals.

Winch-Platform System. The winch-platform system is based on a rectangular foundation platform that can rotate on a 10-m-diameter circular track. Four bogie wheels support the platform to facilitate the rotation, which is achieved by use of two utility winches mounted on the turret collar deck. Each bogie wheel incorporates a hydraulic retention jack, which is pressurized to bring the bogie wheel in contact with the rail. When the winch assembly is in its required pulling position, the hydraulic jacks are depressurized to park the platform, and two locking pins then provide a positive location for the platform during winching operations.

Within the foundation platform, a second rectangular platform supported on low-friction pads can skid on rails to bring the winch above the I-tube before being locked in position. This rectangular platform supports the winch platform, which can rotate to align the direction of the winch wire with the axes of the I-tubes. Sized to accommodate the rotary drum winch, winch HPU, a control panel, and the two secondary rotation hydraulic motors, the platform is spigot mounted and supported on a circular toothed rack. The central spigot of the platform incorporates a retaining plate to prevent uplift of the platform.

The winch system was used successfully to install seven risers and three umbilicals for Phase 1 of the field development, and a further three risers and three umbilicals for Phase 2. The motions of the winch platform are shown in **Fig. 11.**

Inspection Regime for Steel Lazy-Wave Risers (SLWRs) and Flex Joint

The SLWRs and flex joints are inspected according to the regime presented in **Table 1.** Above-water inspection of riser-associated components is conducted annually as part of the geneal turret-inspection program. The program includes visual inspection of the

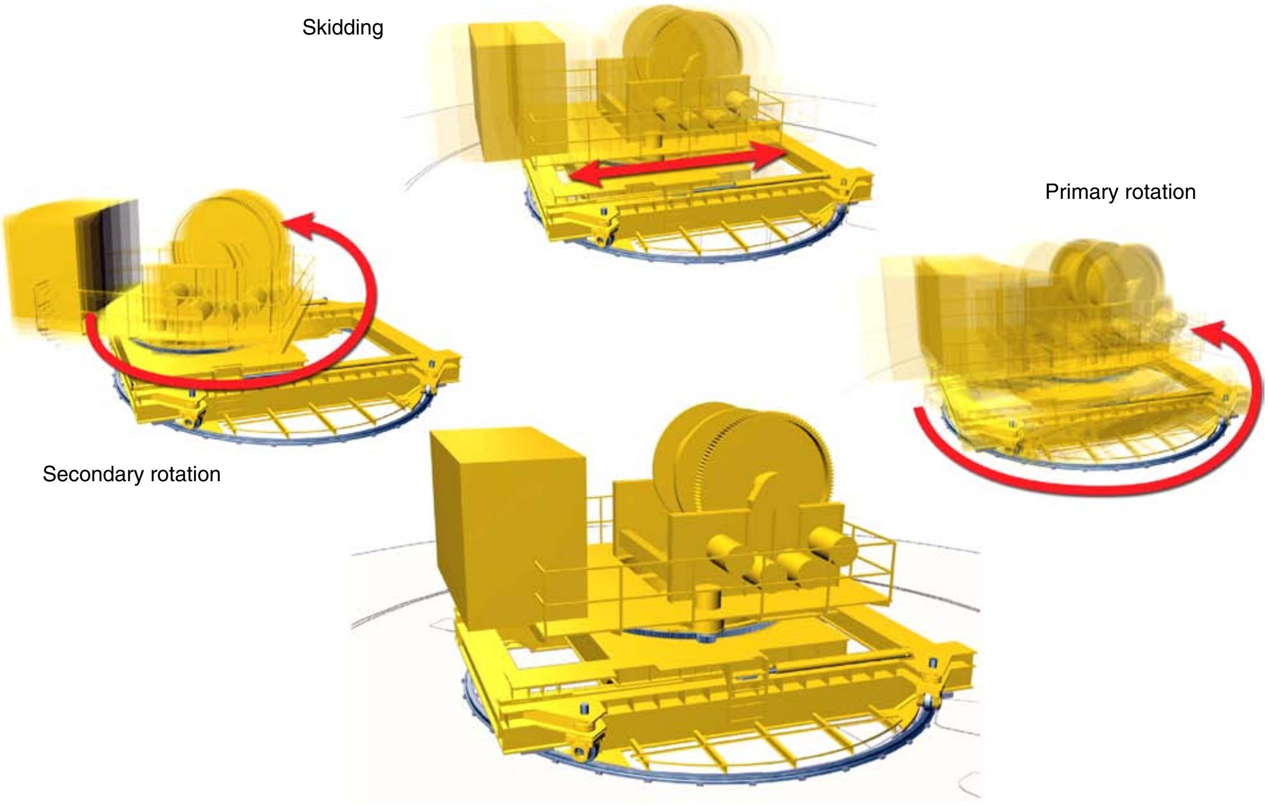

Fig. 11—Installation winch motions.

Description of Activity	Initial Interval	Maximum Interval
Above-water elements	Yearly	2 Yearly
Below-water elements, including flex joints	2 Yearly	2 Yearly

Table 1—Inspection regime for SLWRs and flex joints.

the riser hang-off flange and the hard piping running from the riser termination to the turret collar deck. Hard piping from the riser termination to the collar deck is not required for top-mounted internal turrets (TMITs) incorporating flexible risers, but the inspection of this additional element does not pose any particular problem.

For below-water visual inspection, any marine growth obstructing either the flex-joint inspection or the vortex-induced-vibration-suppression system functionality is removed. The flex joints are inspected according to the manufacturer's detailed procedure, which includes verifying the absence of any extrusion,

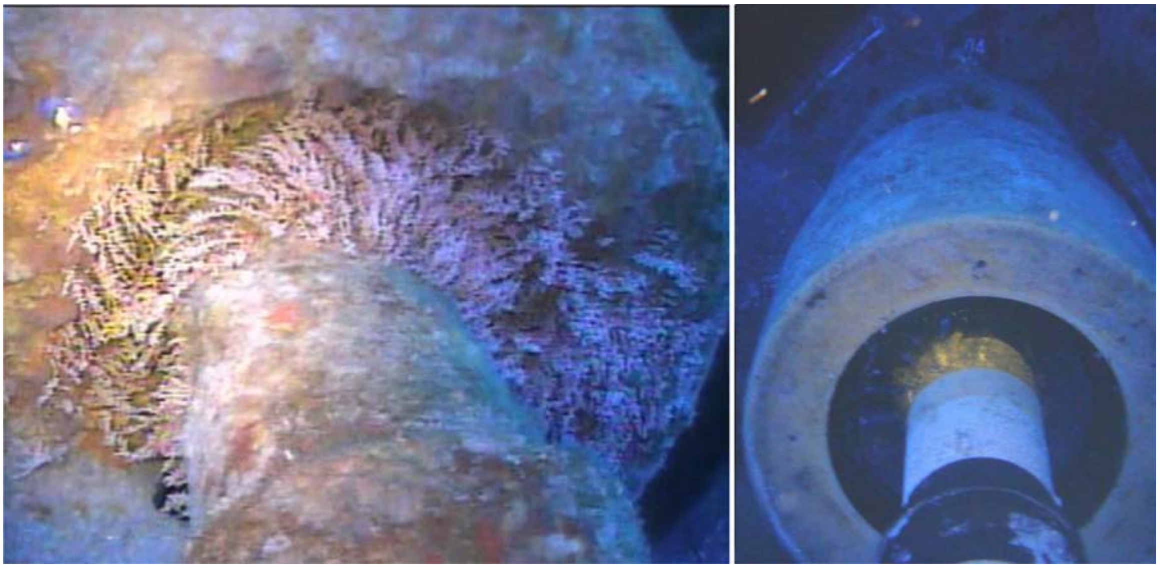

Fig. 12—Flex joint before and after cleaning.

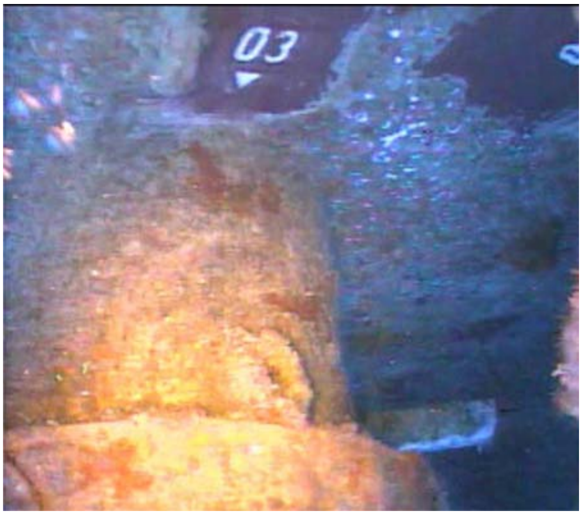

Fig. 13—Flex joint and journal forging.

bulging, cracking, crazing, cuts, or gouges, and verifying that there is no large displacement of any shim (the reinforcement within the elastomeric pad of the flex joints) relative to the shim above and below it.

SLWR- and Flex-Joint-Inspection Results. The flex joints and the top section of the SLWR from 30 m below mean sea level (MSL) up to the flex joint were inspected in 2011 with divers, and again in 2013 with remotely operated vehicles (ROVs). During the inspections, no abnormalities were detected on any of the flex joints or SLWRs. As expected, a considerable amount of marine growth had to be removed to perform the inspection, as shown in **Figs. 12 and 13.**

Inspection of the section of riser from 30 m below MSL downward is conducted every 2 years by use of ROVs. Again, no abnormality or defects have been observed. Similarly, inspection of the above-water sections of the system associated with the risers has shown the components to be in good condition, with no abnormailties or defects observed.

Conclusions

The BC-10 project achieved two industry firsts:

- The first use of steel lazy-wave risers (SLWRs)
- The first turret-mooring system to support steel risers of any configuration

The use of SLWRs did not affect the principles of the typical top-mounted-internal-turret (TMIT) design, but modifications were required to the riser-termination level, the interface mechanism between the risers and turret, and the riser and umbilical pull-in equipment. Design solutions to accommodate these changes were implemented successfully in the BC-10 turret.

The project has demonstrated that the structural interface of stiff steel risers and a turret-mooring system is feasible and compatible with the practical pull-in constraints of a turret. Inspection of the risers has confirmed their continuing integrity, and the turret-and-riser system is now considered field proved.

Acknowledgments

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