A Comparison Between Turret and Spread Moored F(P)SOs for Deepwater Field Developments

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Deep Offshore Technology 2001

ABSTRACT

With the planned development of a large number of deepwater fields offshore Brazil and West Africa, F(P)SO owners and operators need to evaluate turret versus spread mooring in terms of CAPEX, OPEX and system availability during service life. These two mooring systems are each unique resulting in large differences in general arrangements, operational characteristics and life of field costs. The selection of a tailored mooring system for an F(P)SO depends on a variety of factors including environmental conditions, field layout, production rates, storage capacity and offloading method and frequency.

This paper presents information and results that allow a structured evaluation of turret versus spread moored F(P)SOs from a technical, commercial and operational viewpoint. The objective of the paper is to guide the decision-making process towards the selection of the appropriate F(P)SO based on comparative mooring and fluid-transfer issues, CAPEX, OPEX and life of field costs.

This paper compares turret and spread moored F(P)SO systems by:

1. defining typical design parameters for the two systems;
2. evaluating the mooring and fluid-transfer systems;
3. contrasting the engineering, procurement, construction and field installation costs (CAPEX); and
4. assessing operational considerations such as system availability, product offloading and OPEX for life of field.

Examples are used to illustrate the selection process between the two systems for generic deepwater fields in West Africa and Brazil. The examples present results from the global analysis to allow comparison of the mooring and riser performance, and the availability of the production and offloading systems. Cost estimates of the two systems are presented showing the breakdown between various components and comparisons between the two based on CAPEX, OPEX and system availability. The CAPEX, OPEX and lost production costs are evaluated as a total cost by computing the Present Value at the first oil milestone. The paper provides a mechanism to help owners and operators evaluate F(P)SO options with alternative mooring systems.

INTRODUCTION

As more deepwater fields are being discovered and preparation is under way for their exploitation, Floating (Production) Storage and Offloading systems (F(P)SOs) provide a mature technology for the production, storage and export of hydrocarbon products in remote or deepwater regions. F(P)SOs have been installed in a variety of configurations over the past thirty years. In general, the two characteristic systems for large production throughputs are either spread moored or turret moored to the seabed.

A spread moored F(P)SO involves a storage vessel, typically a converted tanker or new-build hull, moored by anchor legs from the bow and stern of the vessel in a four-group arrangement similar to that used for a semisubmersible. The risers that bring the product to and from the vessel are hung off receptacles off the side of the vessel. This type of mooring system maintains a fixed orientation of the F(P)SO in global coordinates. Though this mooring arrangement is typical for semisubmersibles, the F(P)SO is more sensitive to the global environmental direction due to its large aspect ratio (L/B ratio between 5 and 6) than the typically symmetric semisubmersible. Another difference is that F(P)SOs are designed to offload to shuttle tankers and the offloading performance is very affected by the relative F(P)SO-environment direction.

A turret moored F(P)SO is designed as a Single Point Mooring (SPM) that allows the F(P)SO to weathervane about the mooring system, in response to the environment. This weathervaning ability allows the vessel to adapt its orientation with respect to the prevailing environmental direction to reduce the relative vessel-environment angles and the resulting load on the mooring. This also allows for a more optimum offloading orientation than that with a spread moored system. The riser systems are also supported within the turret structure and products are transferred to the vessel via a manifold and swivel system.

The two methods of mooring an F(P)SO lead to very different performance characteristics that can have an impact on the life of field costs. This paper compares the two F(P)SO systems in terms of performance (system loads, motions and offloading efficiency) and in terms of costs (CAPEX, OPEX and a present value estimate). This paper emphasizes the financial analysis and comparisons of the differences in technical performance between the two systems. This is accomplished by providing a description of the unique characteristics of the two mooring systems and by identifying the various sub-systems to provide an accurate CAPEX estimate. For example, the turret mooring system contains installation and fluid-transfer equipment that is also present on the spread moored vessel but typically is not considered a “mooring” cost.

The F(P)SO motions and offloading performance are also discussed as a function of the environment and evaluated to provide an estimate of the relative OPEX costs. A present value for each system is estimated using the calculated CAPEX and OPEX costs to provide a “benchmark” for the relative total cost differential between the two systems.

The comparison between these two systems is demonstrated by two case studies in this paper for deepwater fields offshore West Africa and Brazil. Both spread and turret moored systems are considered and a common design basis has been developed for a meaningful comparison. The case studies evaluate the systems in detail by developing a technical basis to accurately estimate CAPEX, OPEX and Present Value (PV) cost estimates. The results are presented in the form of tables and figures that allow easy comparison between the various sub-systems and systems.

COMPARISON BETWEEN TURRET AND SPREAD MOORED SYSTEMS

This section of the paper provides a more detailed description of the two F(P)SO systems and identifies the unique characteristics between the two.

Turret Moored Systems

In the early 1960s, a new type of mooring system was developed for drillships. A rotating turret was inserted into the hull of The Offshore Company's "Discoverer I" and mooring lines were extended out from the bottom of the turret and anchored to the seabed in a circular pattern. This SPM system allowed the drillship to continuously weathervane into the predominant seas without interrupting on-board drilling activities. At the same time SPM fluid-transfer systems (CALM buoy systems) were also being developed to allow easy offloading of liquids in shallow water offshore. The production "turret mooring system" evolved from these two concepts and was adapted to F(P)SO units that had to remain on location to provide a reliable means for storage and offloading for years without incurring significant downtime regardless of environmental conditions. Today, two types of turret systems are commonly used for F(P)SOs – the internal turret system where the turret is mounted within the F(P)SO hull, and an external turret system where the turret is mounted on an extended structure cantilevered off the vessel bow.

An F(P)SO turret system is a compact multi-functional structure that includes many stand-alone sub-systems found on other moored floating systems. The turret integrates the F(P)SO mooring system, the installation equipment for the anchor legs and the risers, the fluid-transfer system including riser support, manifold, pig launching and receiving, metering, chemical injection, and subsea control systems into one compact, self-contained module.

Figure 1 provides an illustration of the internal turret mooring system developed for the Barracuda early production system (P-34) in the Campos basin, offshore Brazil. This turret system was designed for 34 risers in water depth of 835 meters and installed in a converted 50,000 DWT tanker. The figure provides a good illustration of the various sub-systems and their typical arrangement within the internal turret mooring system.

The mooring sub-system of the internal turret includes the anchor legs, the turret shaft and the bearing system. The turret provides the load-transfer mechanism between the mooring and the vessel and also provides the mechanism for the weathervaning capability of the turret mooring system. The fluid-transfer sub-system includes the support for the risers, the manifold, the injection, and the swivel stack systems that allow transfer of the fluids from the earth-fixed turret and risers to the weathervaning ship-fixed production system. In addition, the turret typically includes the installation sub-system comprised of winches and sheaves, and possibly miscellaneous subsea-control systems.

The bearing and swivel stack systems provide the weathervaning capability for the turret mooring system. The location of the turret determines whether the system can weathervane passively (requires location near the bow of the vessel), or by the use of a thruster assist system. This weathervaning feature reduces the F(P)SO mooring loads and hull motions by maintaining a heading aligned with the incident environment. The 360-degree weathervaning feature of a turret moored F(P)SO significantly reduces the impact of greenwater on the vessel deck and production equipment and wave-frequency vessel motions, affecting both crew comfort and production plant uptime. As the F(P)SO maintains a heading into the predominant environment, greenwater is generally limited to the area forward of the turret and away from process and other key main deck systems. Also, vessel motions, particularly rolling motions, are typically reduced thus allowing more operating uptime during inclement weather conditions. This weathervaning ability is very important for the offloading operation as the headings of the F(P)SO and the export tanker are both into the predominant sea or winds, thus creating safer approaches and alignments during offloading operations. As the risers are contained within the turret structure, offloading operations are simplified as the F(P)SO hull is uncluttered with risers or exposed mooring lines.

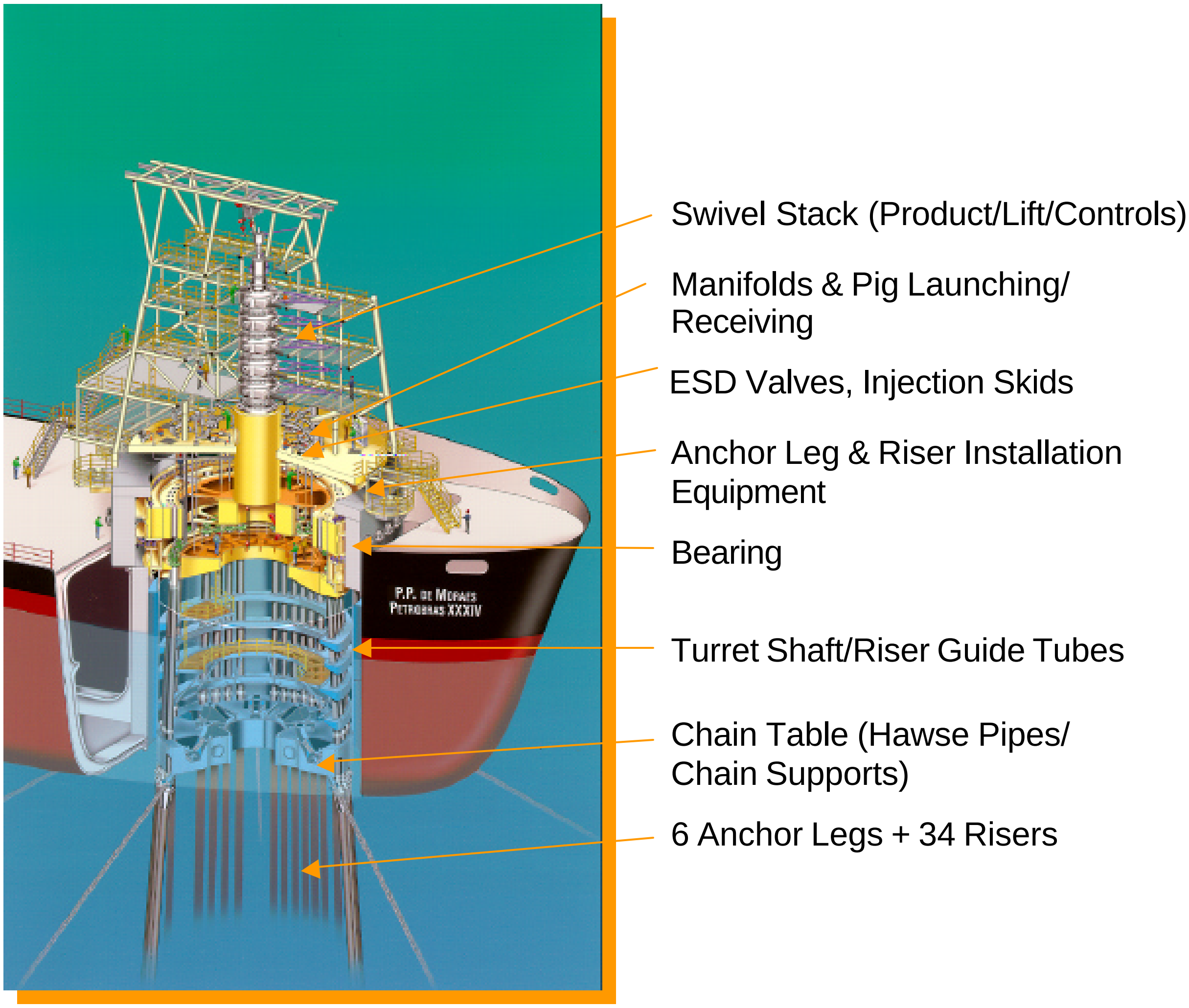

Figure 1: The P-34 Internal Turret Mooring System.

For a turret system, anchor legs may be arranged symmetrically or grouped in multiple sets of three or more legs such that openings between sets allow for varied and more direct riser approaches to their connections on the base of the turret. This "direct approach" may allow for more economical seabed flowline arrangements by eliminating loop routings around anchor leg arrays. In addition, turret mooring systems typically have fewer anchor legs of smaller component size than a mooring system for an equivalent spread moored F(P)SO.

Until recently, internal turrets were assumed to be limited to 60 or so risers before the cost and turret congestion became unmanageable. Now, new and cost-effective turret designs can accommodate up to 100 or more risers in water depths ranging up to 2000 meters or more.

Various designs for lower-cost external turret systems permit up to 20 or more risers for deepwater activities.

Spread Mooring Systems

Spread mooring or Multi-Point Mooring (MPM) systems have long been the traditional means of mooring all kinds of ships and barges in open and protected waters. For this type of mooring, multiple anchor lines extend from the bow and stern of the hull and anchor the unit to the seafloor in a fixed or slightly variable heading. Spread mooring systems can be designed for shallow or deepwater stationkeeping, in mild to moderate environments. The performance of the spread moored system is dependent on the prevailing weather and it is considered suitable for regions with a fairly restricted range of weather direction. They are not so effective, however, in harsh or multi-directional environments where changing wind, waves and currents may impose severe loads on the anchoring system and create excessive motions on the unit. It is also important to consider the feasibility of offloading as a function of the day-to-day environment taking into account the approach and offloading operations with the export tanker.

Figure 2 provides an illustration of a typical, large-field, spread moored F(P)SO system. The figure also indicates the various sub-systems identified within the turret mooring system and their typical location on the spread moored F(P)SO. Note how the various sub-systems are distributed about the deck of the F(P)SO. Also note the increasing complexity of the on-deck arrangement of the various F(P)SO systems that require additional interfaces between the various providers of design and equipment. All of these sub-systems must be accounted for in the CAPEX of a spread moored system when compared to that for a turret mooring system.

For deepwater spread moored F(P)SO units, the number of anchor legs required may range between 12 and 20 lines, compared to 6 to 12 anchor legs for a turret moored system. This creates considerable congestion on the forward and aft deck for fairleads and installation equipment. The anchor legs typically fan out in a 45-90 degree pattern on each side of the unit's bow and stern centerline as they extend towards the seabed. Frequently, submerged fairleads are attached to the F(P)SO hull so anchor legs depart the hull below the water line to minimize the risk of collision with service vessels, offloading hoses, and offloading tankers. A spread moored F(P)SO must be designed to withstand beam seas and the resulting greenwater and vessel roll. For many areas of the world, this may necessitate the addition of bilge keels, splash barriers, and raising the processing equipment skids.

Riser attachments for spread moored F(P)SO units are commonly located on "porches" installed along the length of the F(P)SO hull. The ability of a spread moored F(P)SO to accommodate a large number of risers (100 or more) provides the operator with additional flexibility with regards for installation, expansion and a more direct connection to individual wells by minimizing subsea manifolding. A steel "cage" to reduce accidental impact from support vessels or other equipment/vessels protects the risers coming up the side of the vessel.

For many large spread moored F(P)SOs, the mooring system installation requires separate winches for the forward and aft anchor legs with a system of sheaves to allow access to each fairlead. This adds to the congestion on the deck and becomes a major interface requirement for the topsides arrangement for the ship and production systems of the vessel. The riser system typically requires its own winch and sheave arrangement.

Anchor leg and riser arrangements for the spread moored F(P)SO often impact both the subsea arrangement of the flowlines and the selection of the offloading system. In order to limit the possibility of an anchor leg breaking and falling onto a subsea flowline, the flowlines are generally routed around the seabed anchor arrays so the risers approach the F(P)SO perpendicular to the riser porches. Side-by-side and tandem offloading creates a high degree of exposure to collision as the F(P)SO remains fixed in position as the export tanker maneuvers or floats about it, even with tug assistance. For safer operations, dual offloading systems on the vessel bow and stern to accommodate export tankers during changing environmental directions may be used, or even satellite export systems may be installed that move the offloading activities away from the F(P)SO system. Specialized dynamically positioned export tankers also may be also used for offloading from a spread moored F(P)SO.

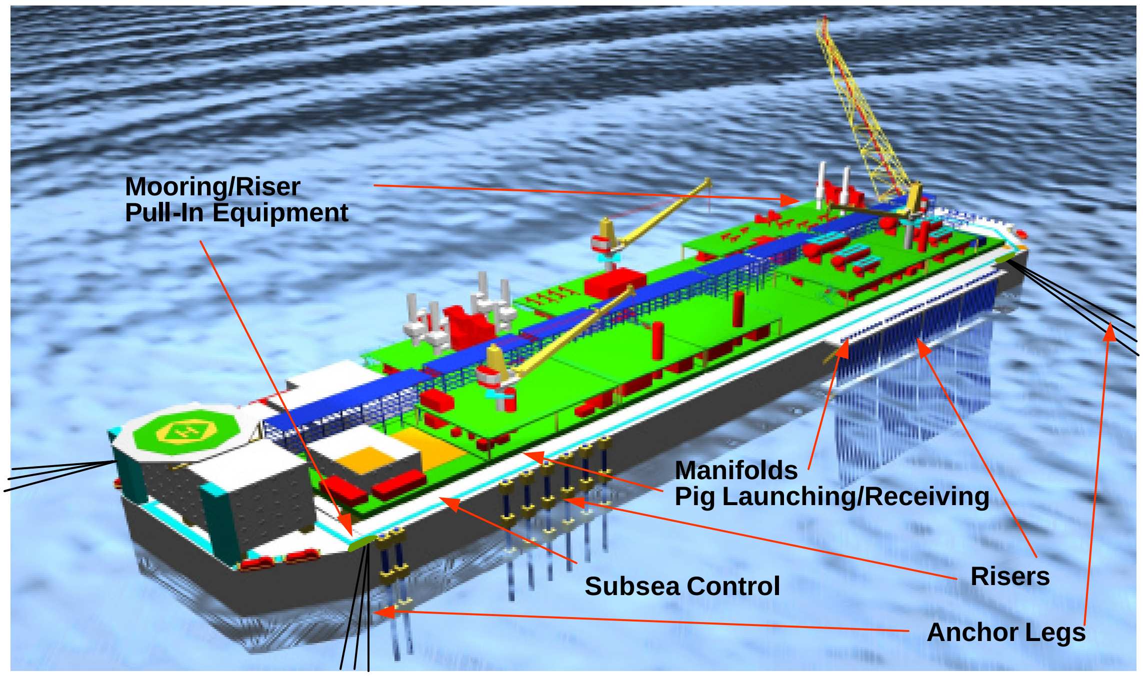

Figure 2: Typical Large-Field New-build F(P)SO System.

Offloading
An important difference between a turret moored and spread moored F(P)SO system is the reliability and ease of use of the offloading operation. The choice of F(P)SO mooring systems can impact the reliability and equipment used for offloading liquid product from the unit. The offloading technique may be one or more of the following methods and is a function of whether the export tanker is a vessel of opportunity or from a dedicated tanker fleet.

Tandem Offloading: The export tanker approaches forward or aft of the F(P)SO, depending on sea and environmental conditions. It is then "tethered" by a hawser line downstream from the F(P)SO unit. Floating hoses from the F(P)SO are connected to the export tanker's manifold, and the product is transferred between the two units. Typically one to two assist tugs are used to keep tension on the hawser to maintain the tanker relative alignment with the F(P)SO and to prevent the tanker migration towards the F(P)SO during benign or changing sea conditions. This is the most common and preferred offloading arrangement for all F(P)SOs. It is a well-established offloading method in use at marine terminals and F(P)SOs for several decades and utilizes standard OCIMF equipment. In some regions of the world, dynamically positioned shuttle tankers are used that do not require assist tugs to maintain position during offloading. However, they are typically dedicated to a region or group of fields, and this "dedicated" feature reduces the favorable economics associated with the use of "tankers of opportunity" for offloading F(P)SO units. The overall field CAPEX and OPEX also increases substantially because of the investment, operating and maintenance costs associated with the dedicated tanker fleet.

Satellite Offloading: A deepwater CALM buoy or other terminal structure is positioned some distance away from the F(P)SO unit (approximately one nautical mile). Flowlines are connected between the two facilities to allow the transfer of product to the export tanker moored to the terminal. While this distances the offloading operations from the F(P)SO, and provides excellent uptime over the life of the field, it also adds significant cost to the overall project for the installed buoy and flowlines, and the additional power and pumping requirements on board the F(P)SO.

Side-by-Side Offloading: The export tanker is moored abreast of the F(P)SO and hoses or Chiksan loading arms are connected between both vessels to transfer the product. For spread moored F(P)SO units, this offloading method can be complicated as the export tanker must carefully navigate between the bow and stern anchor patterns to avoid collision with the hull or legs or risers (if nearby). This method of offloading is not very common for deepwater field developments because of the inherent risks.

For spread moored F(P)SO systems, side-by-side and tandem offloading creates a high degree of exposure to collision as the F(P)SO remains fixed in position as the export tanker maneuvers about it. For a turret moor F(P)SO system, side-by-side and tandem operations are simplified as the unit's beams are uncluttered with risers or exposed mooring lines, however, the offloading system of choice is the tandem offloading for both tankers of opportunity or DP shuttle tankers. Also, the headings of the F(P)SO and the export tanker are both into the predominant sea or winds, thus creating safer approaches. For safer operations, expensive satellite export systems may be rationalized for spread moored F(P)SO units yet remain a debatable option for turret moored F(P)SO offloading.

Pros and Cons of the Two Mooring Systems

The description of the two mooring systems has highlighted many of the differences between a turret moored and spread moored system in terms of design and performance. Table 1 provides a comparative summary between the two systems that illustrates the differences discussed above.

As discussed earlier, turret moored systems orient themselves to the prevailing environment direction that allows its use in harsh, multi-directional environments with minimized loads and vessel motions. A not so obvious advantage of a weathervaning turret mooring system is that as it adjusts itself to the prevailing environment it is not as sensitive to poor design environmental criteria which is common in areas where new development takes place. A spread moored system is moored in a fixed orientation and thus is more sensitive to global environment intensity and direction. The turret system provides a compact load and fluid-transfer system with a minimum number of anchor legs required. The weathervaning ability helps provide more constant offloading conditions for export tankers, helicopter operations, and discharges from flares. However, the passive weathervaning ability of the turret mooring system requires the location of the turret at the vessel bow that is the location of the maximum vessel motions and thus requires a riser system that is robust enough to withstand the motions at the turret. A turret mooring system is not readily adapted to the addition/modification of riser systems (needs to be designed in to the system), and its design and fabrication requires specialized engineering and manufacturing techniques and knowledge.

Table 1: Comparative Summary of Turret Moored and Spread Moored F(P)SO Systems.

	Turret-Moored	Spread-Moored
Vessel Orientation	360 degree weathervaning	Fixed orientation, can impact flare
Environment	Mild to extreme, directional to spread	Mild to moderate, uni- to fairly directional
Field Layout	Fairly adaptable, partial to distributed flowline arrangements	Prefers flowline arrangement to approach beam-on
Riser Number & Arrangement	Requires commitment, moderate expansion capability	Can be designed for flexibility, additional tie-ins
Riser Systems	Location of turret (bow) requires robust riser design	Adapts to various riser systems, combinations of various types
Stationkeeping Performance	Number of anchor legs, offsets minimized	Larger number of anchor legs, offsets variable
Vessel Motions	Weathervaning capability reduces motions	Dependent on relative vessel/ environment directionality
Vessel Arrangement	Turret provides "compact" load and fluid transfer system	Components spread on deck, requires extensive interfaces
Offloading Performance	FPSO typically aligned with mean environment	Dependent on vessel/ environment orientation

The spread moored system is typically installed with its bow towards the prevailing environment. This makes the vessel susceptible to waves incident at large relative wave angles, increasing the probability for substantial vessel motions, especially roll. The spread moored system typically has a larger number of legs with increased component size than an equivalent turret moored F(P)SO. This results in typically four groups of anchor legs, and coupled with the installation equipment and requirements leading to extensive interfaces between mooring, vessel and topsides engineers. The spread moored F(P)SO is easily expandable as it is more flexible to riser addition during the life of the field, but prefers a riser arrangement that has the flowlines approaching beam-on to the vessel.

An important aspect to consider with spread moored vessels is the offloading performance of the system over the life of the field. As the vessel orientation is fixed, a tandem moored export tanker has a limited range of relative heading with respect to the F(P)SO when tandem offloading from the vessel, especially in inclement weather, not directly aligned with the F(P)SO orientation. In order to maintain the shuttle within this allowable zone additional tug assistance may be required as compared to a similar turret moored system, or a second offloading station may be required at the other end of the F(P)SO to improve the offloading uptime. The environment mis-alignment with the F(P)SO orientation can also lead to difficulties in approaching and leaving the F(P)SO before and after the offloading of product.

In extreme cases where the use of a spread moored system and multi-directional environmental conditions does not provide the desired uptime for tandem offloading, a satellite offloading station may be installed approximately one nautical mile from the F(P)SO. In deepwater, flowlines are suspended between the F(P)SO and the remote offloading station (typically a large CALM buoy). This alternative provides a very high uptime due to its single point mooring ability (similar to a turret moored system) but results in much higher CAPEX costs and the risk associated with the reliability of the flowlines.

F(P)SO units have grown in number, size and sophistication, and the type of mooring system selected for each unit is a key design consideration. Technically, a spread mooring system is a single F(P)SO sub-system whereas a turret system is an integrated grouping of several F(P)SO sub-systems. A comparative cost evaluation between the two systems should normalize the inherent differences between a turret and spread mooring system, and also consider how each selection impacts the overall cost of the F(P)SO, the field layout design, and the development and operations cost and activities. The case studies below provide two examples of such a comparison.

CASE STUDIES: F(P)SO SYSTEMS FOR WEST AFRICA AND BRAZIL

The differences in design and performance between turret moored and spread moored F(P)SO systems have been described in detail in the previous sections. This section of the paper utilizes two case studies to illustrate the differences between utilizing a spread moored F(P)SO versus a turret moored F(P)SO both in terms of design and performance, and also in terms of CAPEX, OPEX and lost production. The two case studies are based on hypothetical fields in West Africa and Brazil. Environmental data typical for the two regions have been used to evaluate the system performance described in the case studies.

To provide a consistent basis for comparison a detailed global analysis was performed to design and evaluate the mooring performance of the turret moored and spread moored alternatives. Then a detailed financial analysis is performed utilizing the results obtained from the global analysis and design of the two mooring systems to provide a direct comparison.

CAPEX and OPEX estimates are made consistently for both systems based on common sub-systems and relative operational expenses. As a final comparison a Present Value (PV) estimate is made for both systems, allowing for a direct comparison of total cost of each system at the first oil milestone. The following sections provide a description of the global system analysis and financial analysis performed, and then a detailed description and evaluation of the two case studies.

Global Analysis and Mooring System Performance

Each F(P)SO mooring system was analyzed and designed with sufficient detail to provide a +/- 15% accurate cost estimate. Care was taken to ensure consistent analysis, design methodology, and design margins between the spread and turret moored F(P)SOs for each case study. The global analysis and design was performed with state-of-the-art industry analysis tools and design methodology. This allowed a consistent development of the mooring system design for both systems including the definition of all anchor leg components, anchors, fairleads and required vessel-based installation equipment. In addition system loads (turret loads) and responses were computed for both systems, thus allowing an evaluation of the vessel motions, and associated production system relative downtime analysis. The offloading system design and performance as a function of mooring system and environment was also obtained from a detailed numerical analysis of the offloading operation with export tankers of opportunity (with tug assistance).

Financial Analysis Basis and Methodology

The financial analysis performed in this paper provides a means of making an "apples-to-apples" comparison between the two F(P)SO mooring systems and is considered to be accurate within +/- 15%. As the turret mooring system contains various sub-systems and has certain performance characteristics it is important to identify similar sub-systems required for the spread moored system, and ensure that the system has the desired motion and offloading performance.

First, based on the design basis for each example, the various sub-systems and components were identified using the table in Appendix A as a guide to determine the appropriate CAPEX of the common sub-systems between the two mooring types, including engineering, management, and fabrication/assembly costs. For the purpose of this paper the CAPEX costs were accumulated for the following sub-systems based on present costs with typical profit and overhead rates. The table in Appendix A provides a more detailed breakdown.

- **Mooring Group:** This includes all systems of the mooring to vessel load-transfer system including anchor leg components, fairleads and chainstoppers, the turret structure, mooring installation equipment, etc.
- **Fluid-Transfer Group:** This includes all equipment required for fluid-transfer from the risers to the topsides production stream. This includes the riser porches, manifolding, pig launching and receiving, swivel stack, riser specific installation equipment, etc.
- **Hull Systems Group:** This group includes mooring system specific modifications for the hull, e.g., the turret moonpool, underwater fairlead supports, bending shoes, bilge keels, etc.
- **Topsides Systems Group:** This includes equipment specific to topside system cost due to mooring system selection, e.g. metering, chemical injection skids, electrical and hydraulic systems that may be located in a turret system, modifications to topsides to accommodate the selection of either system, etc.
- **Offloading System Group:** This includes the specific offloading system components required for each mooring system type. This includes offloading system related equipment on board the vessel and remote offloading systems and associated flowlines if required.
- **Installation Group:** This includes all installation costs to installing and hook-up the FPSO to its moorings and remote offloading system if required.
- **Services and Administration Group:** This includes all engineering, management, procurement and mark-up costs associated with the spread moored or turret moored specific items described above.

The operational costs (OPEX) of the two systems are also estimated within +/- 15% accuracy again focusing only on the costs that are specific to mooring system selection. They also assume an inflation rate of 3% per year. The OPEX estimates are based on:

- **Demurrage:** Tanker demurrage time and charges.
- **Maintenance and Inspection:** This includes all maintenance and inspection requirements for the mooring system specific components including the requirements for a remote offloading system if utilized.
- **Offloading Tugs and Pilots:** This includes the costs for offloading assistance from support vessels, and pilots required for navigation around the FPSO. The offloading costs

are developed to provide a relative offloading OPEX cost as this has been used to ensure comparable offloading performance from both F(P)SOs.

- **Offloading Hoses and Hawsers:** Replacement costs associated with replacing hoses and hawsers with each system, based on standard industry practice.

Production loss due to excessive vessel motions is computed as a relative cost difference between the spread moored and turret moored systems rather than the actual values for each system obtained from the analysis. This minimizes the high sensitivity of the overall cost estimate to production loss, compared to the CAPEX and OPEX costs associated with the two systems.

The Present Value (PV) of the two systems serves as a method of comparing the total cost of the mooring systems on the same time reference, accounting for inflation and the present value of future expenses. The PV for each case study is based on a 10.5% discount rate computed from the first oil milestone.

Case 1: 80,000 BOPD Field, Deepwater West Africa

Case 1 represents a generic deepwater field offshore West Africa with a water depth of 1,400 meters. The environmental conditions assumed for the site are typical of West Africa; a fairly mild environment with long swells from the south and uncorrelated wind and current events. The region is also subject to wind squalls with velocities up to 30 m/s.

The oil production is assumed to be 80,000 barrels per day over a 15-year service life. The field layout assumes two drill centers and the system is designed for expansion to a third. Gas production is 150 MMsfd with the production pressure at the vessel of 85 to 200 bars. The F(P)SO vessel is assumed to be a converted 180,200 DWT tanker with 1,250,000 barrels of storage. The maximum offloading parcel is assumed to be 960,000 barrels within 24 hours.

For this example we have compared two typical F(P)SO systems being considered for West Africa: (1) a spread moored vessel with a remote offloading buoy, and (2) an external turret moored F(P)SO with conventional tandem offloading.

The spread moored system is designed as 4x3 (four groups of 3 anchor legs) mooring system with the bow of the vessel oriented to the South. The F(P)SO orientation is aligned with the predominant swell direction to minimize motions and forces due to the swell; however, the orientation is not optimized for local waves, wind and currents that are uncorrelated and have very diverse directions. Due to these environmental conditions the availability of tandem offloading from the stern of the spread moored vessel is estimated to be 75 – 80%. This is due the difficulty in maintaining the export tanker within the strictly defined offloading zone at the stern and the difficulty of approaching the F(P)SO due to misaligned environmental conditions with the F(P)SO orientation.

To improve the availability for offloading, and to provide safer approach conditions, deepwater spread mooring F(P)SOs in West Africa typically use a remote offloading buoy with a six leg taut polyester mooring that improves the offloading availability to approximately 99%. Buoyed mid-water flowlines link the buoy (typically located one nautical mile away) to the FPSO so the export tanker can weathervane about the buoy during the offloading operation. This option also requires export pumps on the spread moored F(P)SO to provide the required flowrate at the buoy.

The turret mooring system is designed as a large external turret (see Figure 3) with a capacity for 18 risers and umbilicals, allowing for future expansion to the third drill center. The mooring system designed for the external turret F(P)SO is a 6x1 arrangement (six equally spaced anchor legs). The turret mooring system requires fewer anchor legs with smaller components than the spread moored option. This is due to its ability to weathervane and thus minimizes the loading of the mooring system. The mooring systems for both cases are designed as semi-taut chain and wire mooring systems and have been designed to achieve similar maximum offsets and factor of safety on the mooring system components.

The turret system favors tandem offloading as the relative orientation of the F(P)SO continuously orients itself to the environment, thus making the export tanker approach and offloading alignment more consistent. Offloading in tandem from the turret moored F(P)SO results in availability rates ranging between 90 - 95%, sufficient for the production rate (and low frequency of offloading) required for this field.

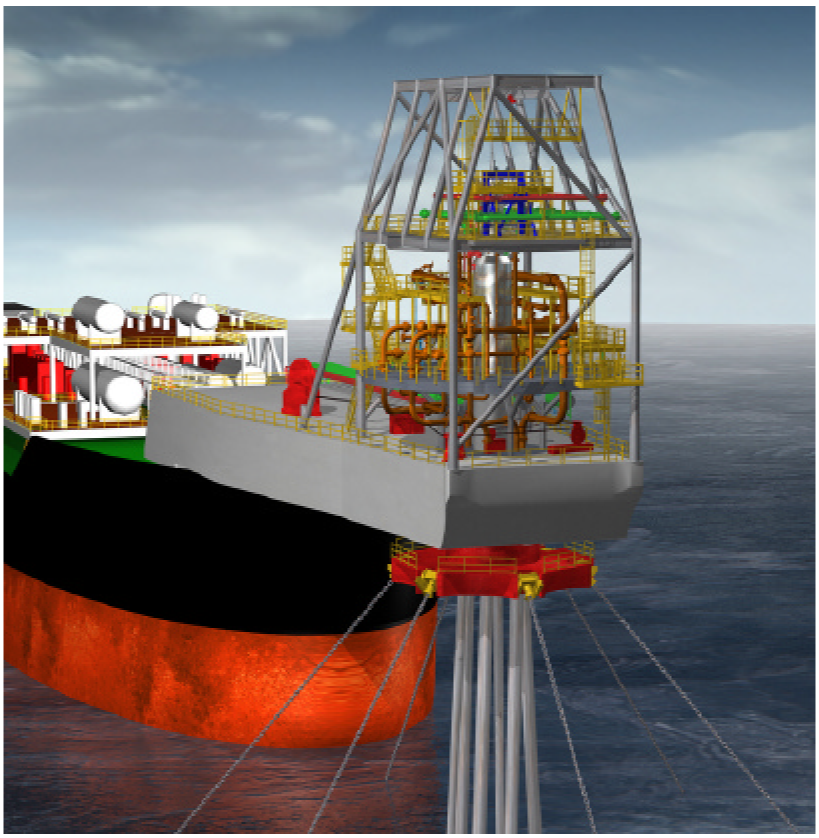

Figure 3: Illustration of a large capacity external turret system for West Africa.

Both the turret moored and spread moored F(P)SOs require one 35 MT tug to assist in offloading and in keeping tension in the offloading hawser. Due to the mild environment offshore West Africa, wave-frequency motions of both F(P)SOs are small enough to provide a weather related production availability around 99%. This indicates that relative lost production due to weather for each system is zero.

Figures 4 and 5 provide a comparison of the CAPEX to first oil for the two FPSO systems. Figure 4 provides a comparison of the CAPEX costs for each system as a function of percentage contribution of the various groups considered in the estimate. Figure 5 presents the normalized CAPEX costs for each system that provide a comparison in US$ between the two systems. The figures show that the remote offloading system for the spread moored F(P)SO has a large impact on the total CAPEX due to the cost of the offloading buoy and the associated flowlines. Installation costs are also seen to be greater for the spread moored F(P)SO due to the installation the additional anchor legs, and the remote offloading system. This results in a much higher total CAPEX for the spread moored system than the equivalent turret moored F(P)SO.

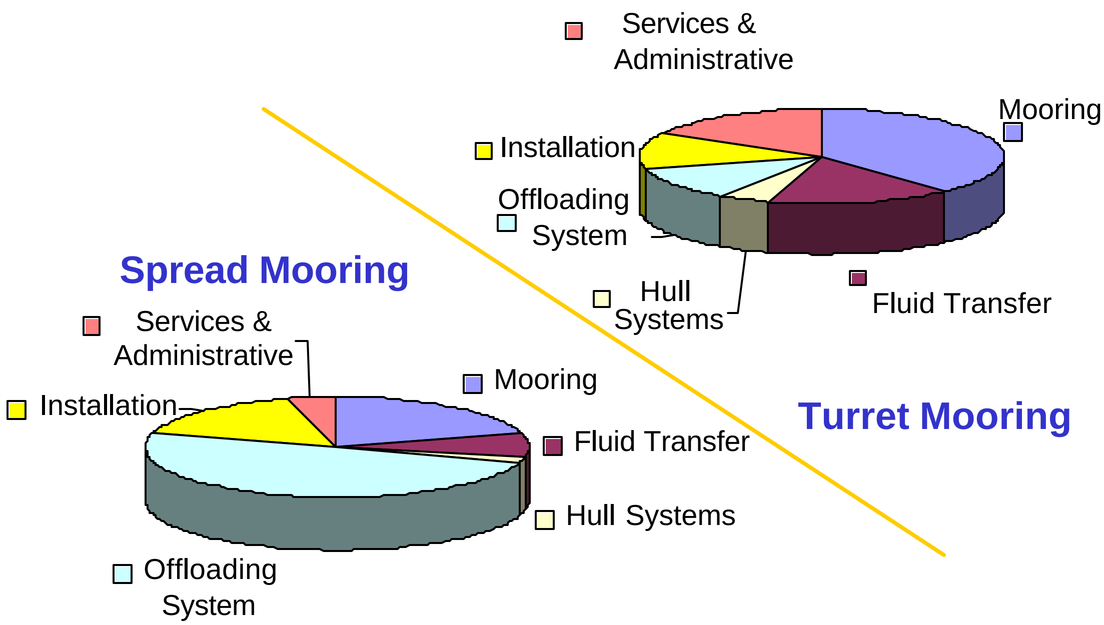

Figure 4: CAPEX (%) for spread and turret moored F(P)SO systems for West Africa.

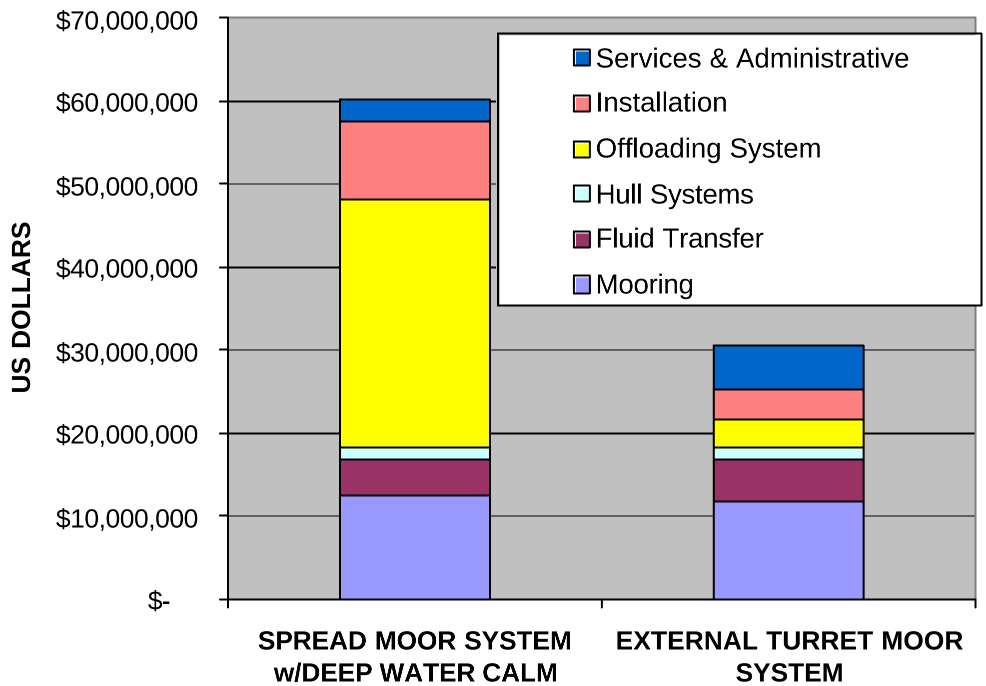

Figure 5: CAPEX (normalized US$) for spread and turret moored F(P)SO systems for West Africa.

Figure 6 compares the normalized OPEX per year for both systems in US$. The figure shows that the costs for both systems are similar except for the additional inspection and maintenance required for the remote offloading system. As both systems require a 35 MT tug to assist during offloading the OPEX costs for offloading are the similar. As described earlier the relative lost production due to weather related production facility downtime is zero and thus does not impact the cost comparison.

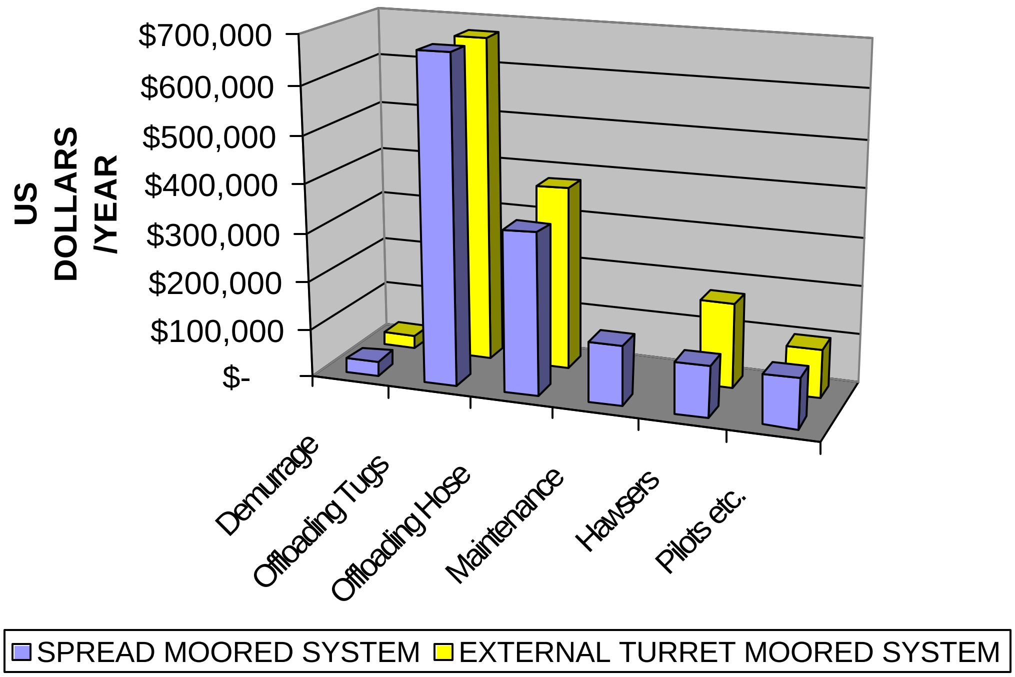

Figure 6: OPEX per year (normalized US$) for spread and turret moored F(P)SO systems for West Africa.

To provide a comparison of the total cost of the two systems for West Africa, the PV of both systems at first oil has been computed in normalized US$ and presented in Figure 7. The PV at first oil has been based on a 10.5% discount rate per year over the 15-year life of the field. The figure shows that the total cost of the spread moored F(P)SO is 50% greater than that of the turret moored FPSO. As shown from Figures 4 and 5 this is due to the CAPEX of the remote offloading system that does not provide an OPEX advantage over the turret moored system. This case study shows that the turret moored system is more cost-effective over the spread moored system for a moderate production, deepwater F(P)SO system in West Africa.

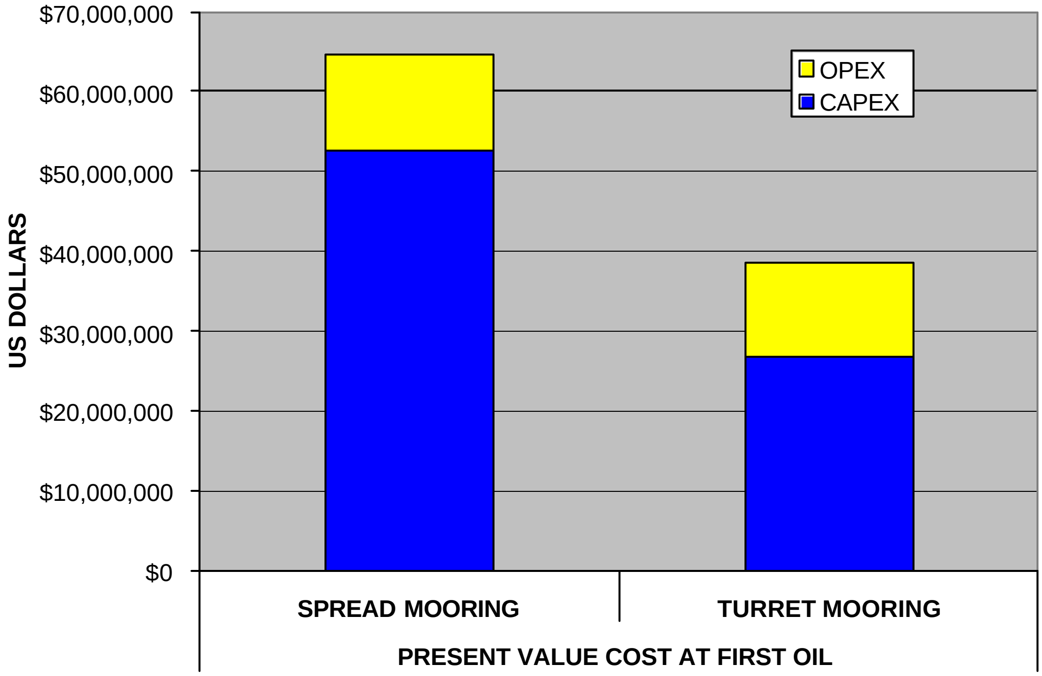

Figure 7: Present Value at first oil (normalized US$) for spread and turret moored F(P)SO systems for West Africa.

Case 2: 150,000 BOPD Field, Deepwater Brazil

Case 2 represents a generic deepwater field offshore Brazil with a water depth of 1,000 meters. The environmental conditions assumed for the site is typical of the Campos Basin with swells from the South West and storms from the North East. Deep, strong currents and wind velocities of approximately 30 m/s also characterize the region.

The oil production is assumed to be 150,000 barrels per day over a 20-year service life. The field layout assumes 80 production and gas lift risers and umbilicals from wells distributed about the field center. Gas production is 270 MMsfd with the production pressure at the vessel of 85 to 200 bars. The F(P)SO is assumed to be a converted 280,000 DWT tanker with 2,000,000 barrels of storage. The maximum offloading parcel is assumed to be 1,540,000 barrels within 24 hours.

For this case, we compare two F(P)SO systems typically considered or in operation for deepwater Brazil: (1) a spread moored F(P)SO with bow and stern tandem offloading, and (2) an internal turret moored F(P)SO with conventional tandem offloading at the stern.

The spread moored system is designed with 4 groups of anchor lines with two groups of five anchor legs, and two groups of four anchor legs. The anchor legs use polyester rope in a taut leg configuration. The F(P)SO is oriented with its bow towards the South West as the predominant 100-year environment is from South West to the East as shown in Figure 8. As the direction of the operational weather conditions are very distributed, the F(P)SO is provided with both bow and stern tandem offloading systems to maximize the vessel uptime for export tanker approach and offloading. It has been estimated that offloading from the stern only would result in unacceptable offloading operability.

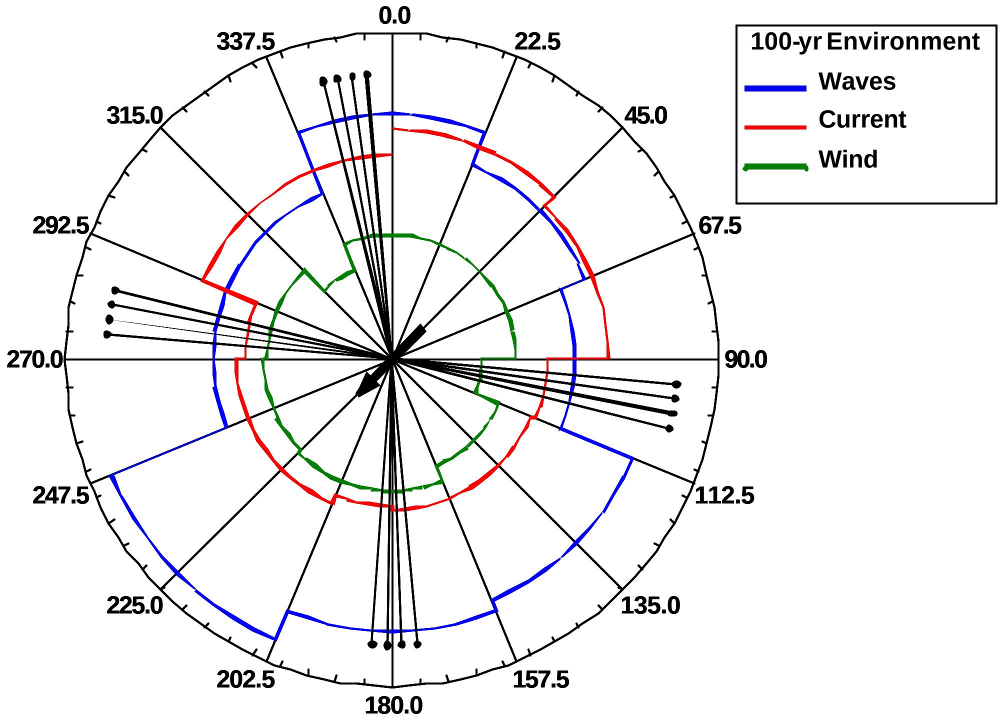

Figure 8: Description of the 100-year design environment offshore Brazil.

The turret moored system is a specially designed large internal turret equipped with 80 risers (the concept has been developed for up to 120 risers). Figure 9 illustrates one such concept developed for offshore Brazil. The mooring system is arranged in three groups of three anchor legs each and is designed as a polyester taut-leg system. Conventional tandem offloading is off the stern of the F(P)SO using a 100 to 150 meter hawser to tether the export tanker to the weathervaning F(P)SO. This method of offloading from turret moored F(P)SOs has been very successful in Brazil over the past five years.

As the environment offshore Brazil is much more severe compared to West Africa, F(P)SO motions are much greater. This can have an impact on the design of equipment on the vessel, crew comfort and safety, and on production uptime. For a spread moored F(P)SO with a fixed heading, an important factor in determining vessel motions is the relative wave to vessel heading. A weathervaning vessel like the turret moored F(P)SO aligns itself with the mean environmental loads and typically the relative wave to vessel heading is minimized. Figure 10 demonstrates the difference in this heading for both F(P)SO systems as it presents the relative wave-vessel attack angle (0 degrees is head-on) as a function of the percentage of occurrence of the wave environment. These curves have been computed for the entire wave, wind and current joint probability distribution for the Campos Basin. The figure illustrates that the spread moored FPSO has a much higher probability of waves incident at attack angles greater than 20 degrees than the turret moored FPSO, thus resulting in much higher vessel motions (roll, pitch and heave). Extra wide bilge keels are recommended for spread moored vessels offshore Brazil to reduce the roll motions.

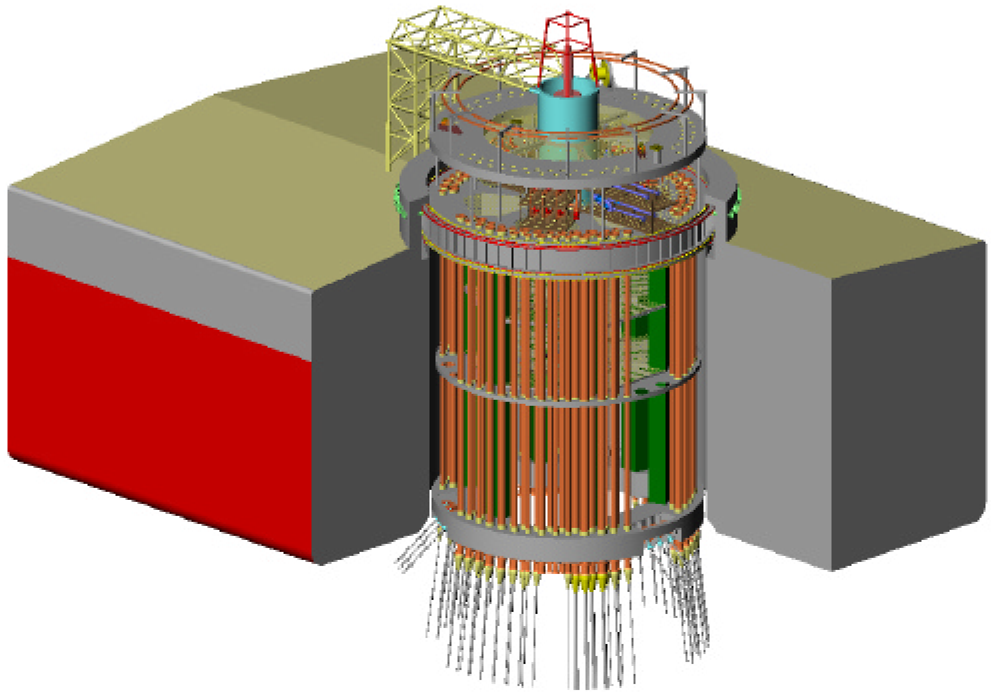

Figure 9: Illustration of a large capacity internal turret for offshore Brazil.

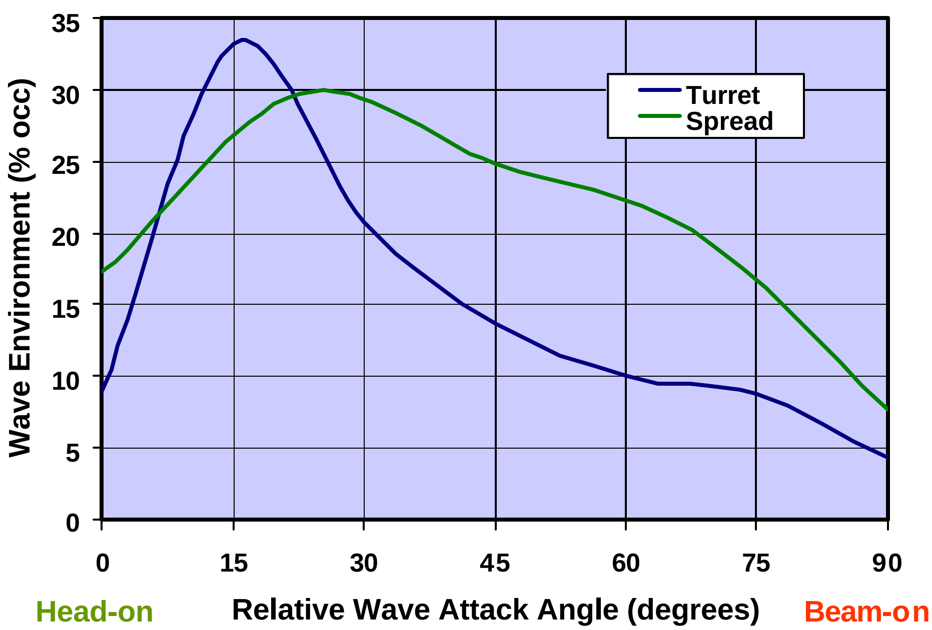

Figure 10: Probability of relative wave-vessel attack angle.

The analysis performed with this environment database indicated that the spread moored FPSO would have an estimated production downtime of 2.3 days/year greater than the turret moored vessel. The large relative wave attack angles for the spread moored F(P)SO also impacts the offloading performance of the F(P)SO as it makes maintaining the export tanker within the "defined offloading zones" at bow and stern more difficult, requiring additional tug assistance at times. The offloading analysis performed for both systems shows that for the spread moored system to provide a similar offloading operability percentage as the turret moored system with one 50 MT tug for assistance, an additional 50 MT tug is required for assistance at least 50% of the time.

The financial analysis performed for this case study follows that used for the West Africa. Figures 11 and 12 present the CAPEX to first oil for both the spread moored and turret moored F(P)SOs with Figure 11 providing the relative contribution of the various groupings to the CAPEX and Figure 12 providing a direct CAPEX comparison in normalized US$. The figure shows that the spread moored vessel has a lower CAPEX than the turret moored FPSO (approximately 10%). The main difference is the additional costs for engineering and managing the design and fabrication of the sophisticated turret mooring system compared to the mooring engineering and fabrication costs for the spread moored F(P)SO. The increased engineering and fabrication requirements for a turret moored system typically does not impact the schedule for the F(P)SO as the turret engineering and fabrication runs parallel to that of the vessel and topsides.

One important item not included in this analysis is the cost of extra subsea flowline lengths to accommodate the required riser approach to the spread-moored or turret moored F(P)SO. As mentioned in an earlier section, a turret mooring system can provide a more economical solution for field layout with distributed subsea wells, while a spread moored system may be more suited to a field layout with a large number of risers approaching from one or two directions. As it is very dependent on specific field characteristics this item has not been evaluated in this case study.

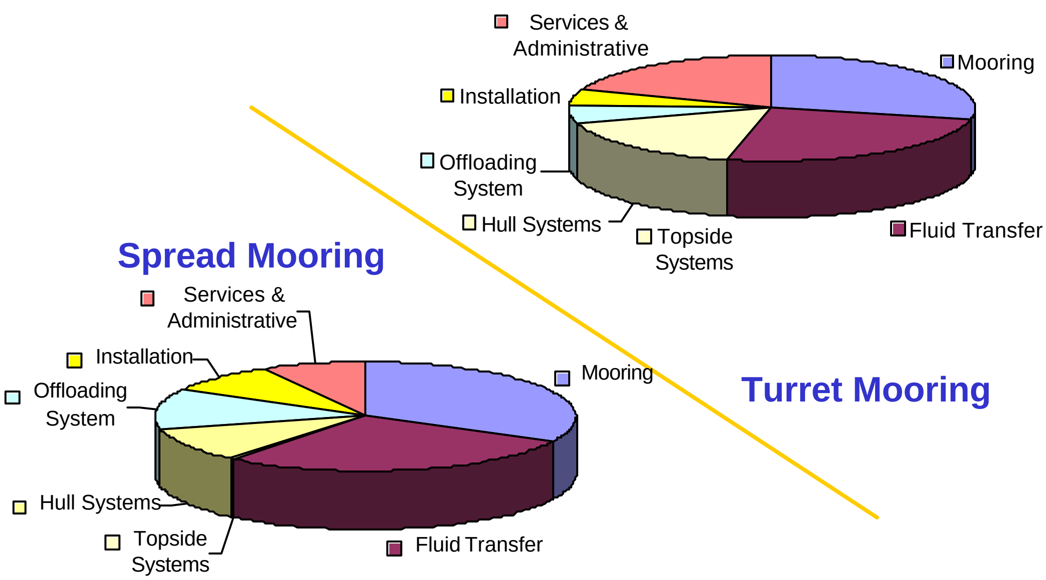

Figure 11: CAPEX (%) for spread and turret moored F(P)SO systems for Brazil.

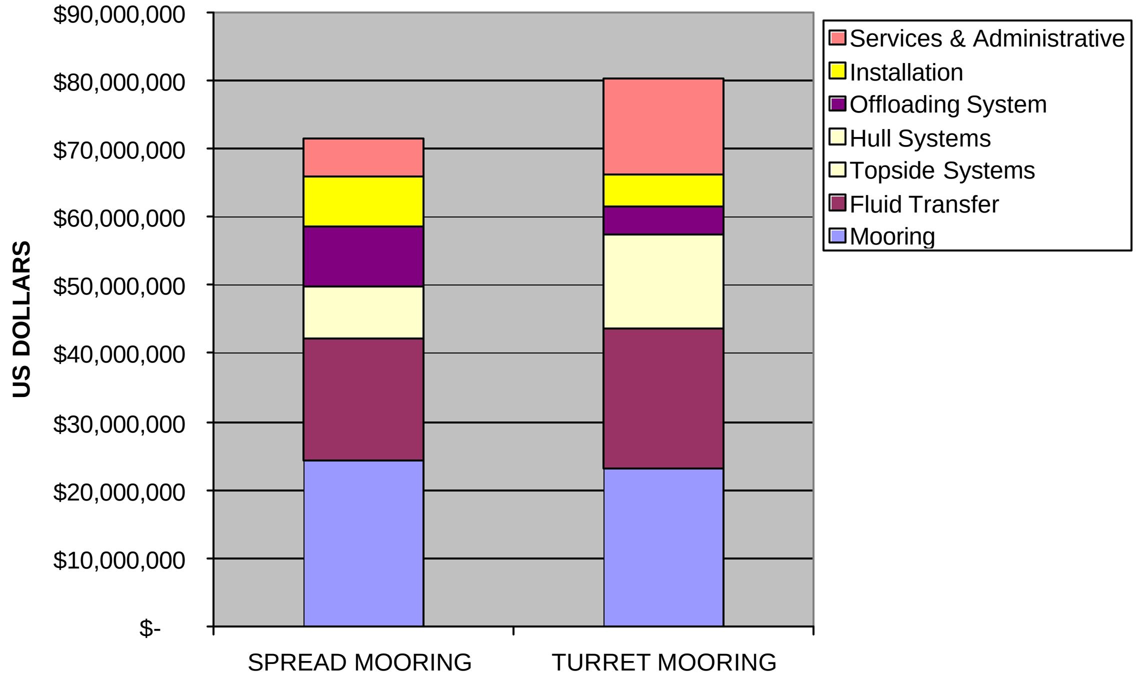

Figure 12: CAPEX (normalized US$) for spread and turret moored F(P)SO systems for Brazil.

Figure 13 presents a description of the OPEX per year for each of the F(P)SO mooring systems. The figure illustrates that the OPEX of the spread moored FPSO is greater than that of the turret moored FPSO primarily due to the increased tug assistance requirement for the spread moored system and additional maintenance and expenses of maintaining two offloading stations.

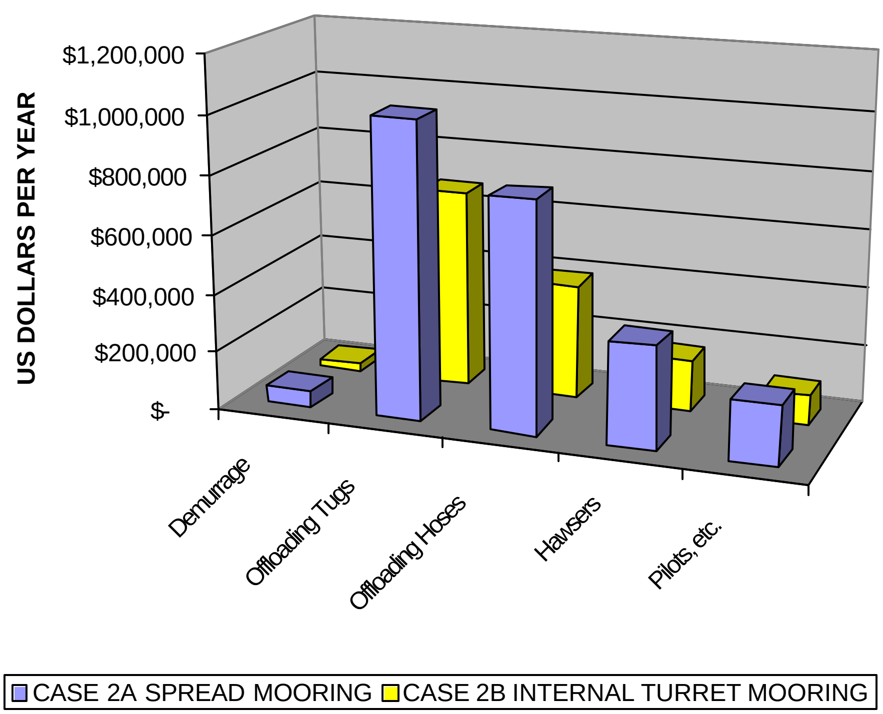

Figure 13: OPEX per year (normalized US$) for spread and turret moored F(P)SO systems for West Africa.

For this example the spread moor vessel motion performance results in a higher production downtime relative to the turret moored vessel. While the analysis performed showed this relative difference to be 2.3 days per year; a conservative estimate of only one day per year of lost production is assigned to the "costs" of the spread moor F(P)SO.

Figure 14 presents a total cost comparison between the turret moor and spread moor F(P)SOs for Brazil discussed in this example. The total cost is presented as the PV at the first oil milestone based on a 10.5% discount rate, 3% inflation per year, and the price of oil in the $20 - $26 per barrel range for the life of the field. A typical field 20-year production profile is assumed for both F(P)SOs.

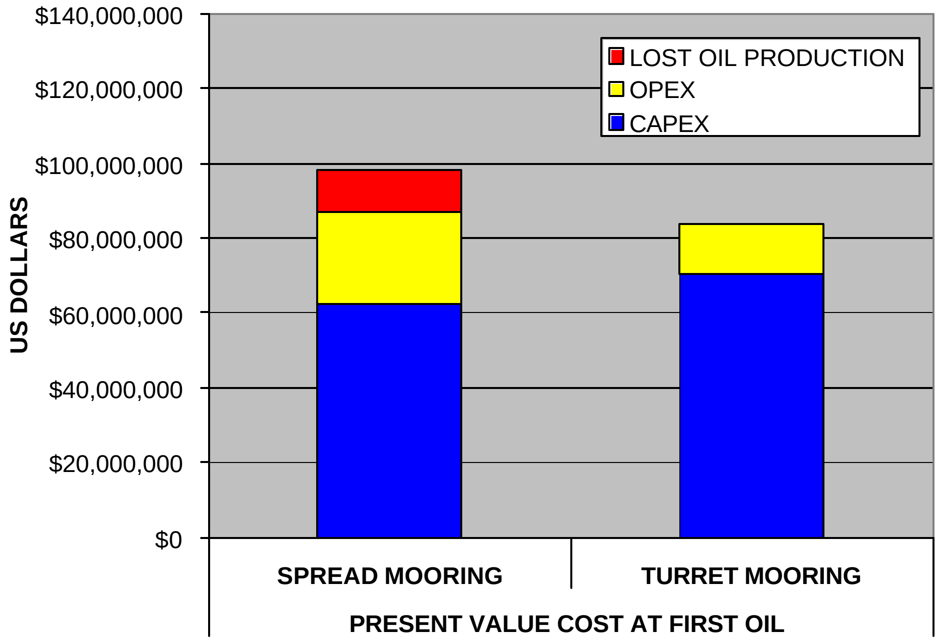

Figure 14: Present Value at first oil (normalized US$) for spread and turret moored F(P)SO systems for Brazil.

The figure illustrates that when the total cost of the two systems are compared the turret moored F(P)SO has a lower cost than the spread moored system. The combined CAPEX and OPEX show the turret mooring system total costs to be less than that of the spread moored FPSO. When the lost production of the spread moored system is factored in the total cost of the spread moored system increases appreciably. This example shows the importance of factoring in the cost impact of system performance over the life of the field in addition to evaluating the CAPEX of the two systems.

CONCLUSIONS

The paper provides a detailed overview of spread moored and turret moored F(P)SOs and highlights the advantages and disadvantages of each system. The paper further illustrates the differences in design, performance and cost by using two case studies of production systems in deepwater; one for West Africa and the other in Brazil. The two case studies help demonstrate that the true total cost of the F(P)SO system must account for CAPEX, OPEX, and system performance over the life of the field when making a cost and performance comparison of the two F(P)SO systems.

When comparing the CAPEX costs of a turret mooring system to a spread moored equivalent, it is important to include the various sub-systems inherently present in a turret mooring when determining the CAPEX of the spread moored system. For example, in addition to the mooring system and load-transfer components of a turret, the turret also contains fluid-transfer and control system components like the riser manifolding, pig launching and receiving, chemical injection skids and subsea control systems. In addition, all mooring and riser installation equipment is usually included within the turret. All of this equipment is also required on the spread moored system; however, it is rarely included in a comparison to turret mooring system costs.

In addition to CAPEX costs, it is important to recognize that turret mooring and spread mooring systems have very difference performance characteristics, both in terms of vessel motions (and thus topsides equipment performance) and offloading. As a turret moored system is a single point mooring system it aligns itself to the environment and provides a means of offloading from the stern of the vessel using equipment and methods well developed over the years of SPM offloading from marine terminals and turret moored F(P)SOs. Though tandem offloading is also common to spread moored vessels, the fixed orientation of the F(P)SO and the changing environmental conditions makes approach and the offloading operation more difficult. Offloading from a spread moored F(P)SO with moderate to large production rates typically requires an upgrade from the conventional offloading system, possibly requiring two offloading stations (bow and stern), additional tug assistance during the offloading operation, and possibly a remote offloading system with high CAPEX costs, to provide a performance comparable to a turret moored system in most environments.

The two case studies in this paper provide a means of evaluating the differences in system costs and performance and address the issues summarized above. The cost of the two systems is described by comparing the CAPEX, OPEX, lost production due to weather related production downtime, and a total cost of each system is provided by determining an estimate of the present value at the first oil milestone. Though these two case studies are only two hypothetical examples out of many, they clearly demonstrate the differences between the two systems in terms of cost and performance and help dispel the notion that turret mooring systems are always “more expensive” than a spread moored alternative.

APPENDIX A
F(P)SO Mooring Selection Worksheet
Project______________Location_____________ Date_______
Water Depth_________No. of Risers_________DWT______

DESCRIPTION	SPREAD MOORING	TURRET MOORING
Mooring Group		
Turret Quote (*may* include specific items with *)	N/A	
Anchors/Piles		*
Chain/Wire/Polyester/Etc. Leg Assemblies		*
Winches/Fairleads/Chain Stoppers/Etc.		*
Fluid Transfer Group		
Subsea Flowlines/Risers/Bend Restrictors etc.		
Riser Porches/Piping/Guide Tubes		*
Riser Pull-in/Pull-out Equipment		*
Surface Manifold System		*
Pigging System		*
Swivel System	N/A	*
Metering System		*
ESD Control/Valve System		*
Electrical and Instrumentation		*
Topside Systems Group		
Chemical Injection		*
Water Injection		
Oil Separation		
Gas Compression/Injection		
Water Treatment		
Heating & Cooling		
Methanol Treatment		
Nitrogen & Hydraulic Systems		
Flare Tower/Knockout Drum		
Fiscal Metering		
Power Generation		
Electrical and Instrumentation		
Hull Systems Group		
Hull Procurement (New or Used) & Coatings		
Hull Conversion/Modification Costs		
Turret Moonpool or Turret Support Structure	N/A	*
Bilge Keels		
Tanks/Piping/Manifolds		
Cranes & Lifts		
Hull Fittings & Equipment		
Fire Detection/Suppression		

Navaids & Lifesaving		
Deckhouse & Hotel Equipment		
Machinery, Electrical, Instrumentation Systems		
Utilities		
Offloading Systems Group		
Hose Systems		
Reel/Tray Systems		
Hawser Systems		
Winches & Lifts		
Export Buoy System and Connecting Flowline		
Export Pumps		
Service & Administrative Group		
Project Engineering & Management (In-House)		
Engineering Inspection & Testing Services		*
Installation Group		
FPSO Mooring System Installation (off-vessel)		
FPSO Hook-up Installation		
Export System Installation Services		
HSEQ		*
Freight Insurance & Etc.		*
Other Outside Services		
Internal Overheads and Fees		
CAPEX Estimate per Above		
OPEX Estimate over Life of Field		
Production Downtime Factor (weather related)		