

# FPSO MOORING & OFFLOADING SYSTEM ALTERNATIVES FOR DEEPWATER WEST AFRICA

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## ABSTRACT

With the planned development of a large number of deepwater fields in West Africa, FPSO owners and operators need a way to evaluate turret versus spread mooring systems to determine the most reliable means of offloading processed crude oil to tankers of opportunity. The selection of a mooring and offloading system for an FPSO 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 for a structured evaluation of an example deepwater field for West Africa for the following three cases:

- **Case 1:** a turret moored FPSO
- **Case 2:** a spread moored FPSO with a large displacement catenary anchor leg mooring (CALM) terminal to support the offloading flowlines and to provide a single point mooring for the tankers of opportunity and;
- **Case 3:** a spread moored FPSO, a modification of Case 2, using a method that dramatically reduces the fatigue damage to the rigid flowlines and still provides a conventional offloading interface for the tankers of opportunity.

## **INTRODUCTION**

Recently the offshore market has started developing deepwater fields in West Africa. This has quickly become the most active area in world market for deepwater offshore field development.

This paper evaluates three cases of FPSO mooring systems: an internal turret FPSO and two spread moored FPSOs with remote Offloading systems using parameters for a deepwater field likely to be developed.

The following are example criteria of an average West Africa oilfield:

- The water is over 1,000 meters deep
- The Floating Production Storage and Offloading (FPSO) vessel has approximately 2.2 million barrels of cargo storage
- The offloading tanker of opportunity is between 150,000 and 320,000 dwt
- The field life is between 25 to 30 years
- The oil production rate is 200,000 barrels/day
- The offloading rate is 50,000 barrels/hour for a parcel size of 1 to 2 million barrels

Today, there are at least a dozen deepwater prospects in West Africa with similar criteria that are presently under active consideration.

This paper will attempt to guide an FPSO owner and operator through the process that is involved in selecting the right combination of a mooring system with an oil offloading system suitable for his application. This is done by comparing the three Cases using a set number of design parameters and deciding the most viable solution based on the analytical results.

### **Available FPSO Mooring Options**

#### ***Spread Mooring***

A spread moored FPSO 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. 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 FPSO in global coordinates. The FPSOs are designed to offload to tankers of opportunity and the offloading performance is affected by the relative FPSO environment direction.



### ***Turret (Internal and External)***

A turret moored FPSO is designed as a Single Point Mooring (SPM) that allows the FPSO 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 compared to a spread-moored system. The riser system is also supported within the turret structure and products are transferred to the vessel via a manifold and swivel system.



Please note that external turrets are not recommended for this example of the average West Africa deepwater field because current external turret designs are limited to approximately a capacity to twenty (20) risers. This limitation is necessary or otherwise the loads on an extension on the bow or stern to attach the external turret become too large to be economically and technically viable.



## Available FPSO Oil Offloading Options

### *Tandem Offloading*

In many areas of the world including West Africa, tandem offloading is the primary method of offloading turret-moored (weathervaning - Case 1) and spread-moored (non-weathervaning – Case 2 and 3) FPSOs. However, the close proximity between the offloading tanker of opportunity and the FPSO during offloading for Case 2 and Case 3 is a safety concern that has caused tandem offloading recently to be a secondary means of offloading from spread moored FPSOs.



### ***Remote CALM***

The remote CALM terminal enables the tanker of opportunity to achieve rapid connection and disconnection and to weathervane while connected. Normally the tanker of opportunity is able to connect to the CALM terminal in sea states that approximate to a significant wave height of 2.5 meters and to remain connected in seas up to 4.5 meters.



Due to the tanker of opportunity weathervaning about the remote CALM terminal, it needs to be located in an area where the tanker of opportunity is free to move through a 360-degree arc without any risk of collision with the FPSO or any other field traffic. The present standard clearance in the West African region for the terminal is one nautical mile (approximately 1,850 meters).

### ***Side-by-Side Offloading***

The tanker of opportunity is moored abreast of the FPSO and hoses or Chicksan loading arms are connected between both vessels to transfer the product. For spread moored FPSOs, this offloading method can be complicated as the tanker of opportunity 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 development because of the inherent risks.



Specifically for West Africa, side-by-side offloading is not an acceptable method due to 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 that can develop very quickly, which is a high risk for this method during the offloading operation. There is also a high risk of collision during offloading due to the close proximity of the FPSO and tanker of opportunity.

## DESIGN CRITERIA

- **Environment:** 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
- **Field Characteristics:** The existing structures, number of wells, soil conditions, and etc.
- **Production Criteria:** Production rate, which is required to be higher compared to other deepwater area scenarios in the world
- **Field Life:** Extensive continuous field life which is normally required to be over a twenty-five to thirty year period for a deepwater West Africa field
- **Flexibility –Operability-Risk:** These factors must be analyzed in accordance with the field parameters of the field being evaluated

## DESIGN BASIS

The Design Basis for this paper to evaluate the aforementioned three cases is summarized below. The following parameters represent the normal range for a deepwater field to be developed in West Africa:

Water Depth:	1,400 meters
Service Life:	30 years
Vessel:	320,000 DWT
Storage;	2,200,000 Barrels
Maximum Offloading Parcel:	2,000,000 Barrels
Oil Production:	200,000 Barrels Oil/Day
Gas Production:	270 MMsfd
Pressure at FPSO:	85 to 200 Bars
Offloading Rate:	50,000 Barrels/hr

### Risers

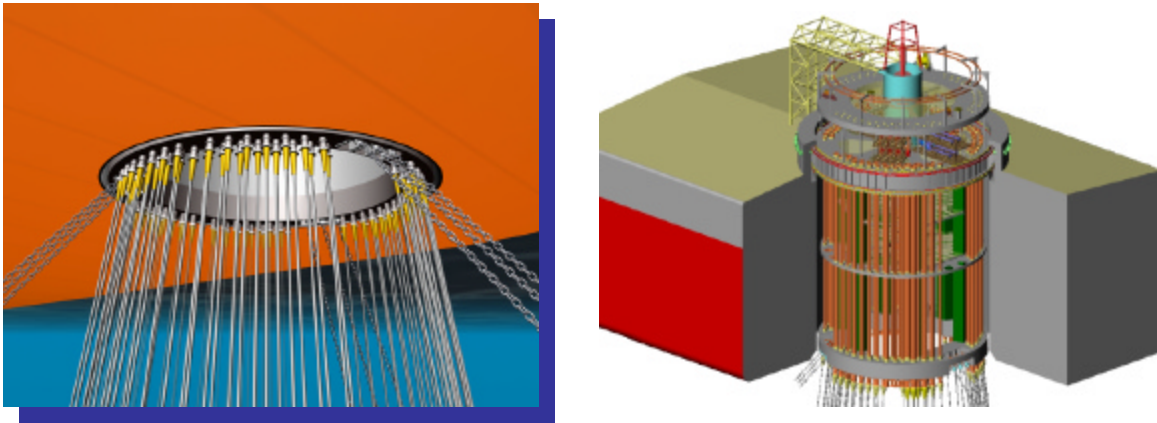
6" Production:	22 lines
4" Gas Lift	22 lines
Umbilicals:	28 lines
Future:	8 lines
Total Risers:	80 + 8 Spares

## CASE STUDY OVERVIEW

The three cases of mooring and offloading an FPSO can lead to substantially different performance characteristics that can have an impact on the life of field costs. This paper compares the three cases in terms of performance, offloading efficiency, safety, operational efficiency, technical feasibility, CAPEX, OPEX and a present value estimate. The present value for each case is estimated using the calculated CAPEX and OPEX costs to provide a "benchmark" for the relative total cost differential between the cases.

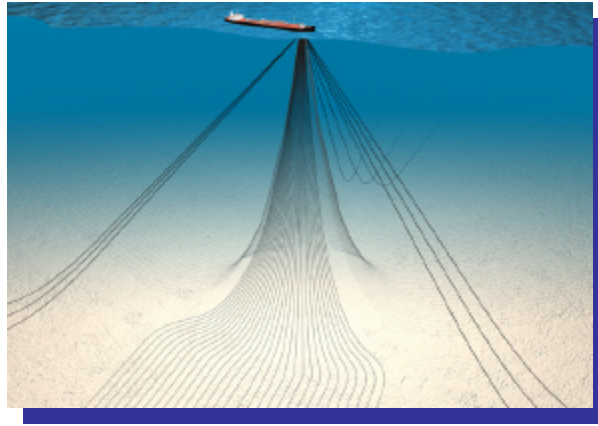
## Case 1 Very Large Turret (VLT) Mooring System with Tandem Offloading

Until recently, internal turrets were assumed to be limited to 60 or so risers before the cost and turret congestion become unmanageable. FMC SOFEC has developed a new and cost-effective turret design, which can accommodate up to 100 risers in water depths ranging up to 2,000 meters. For Case 1, the Very Large Turret (VLT) is designed for this proposed large production field with limited or no sub sea manifolding. The moon pool diameter would be in the range of 25 to 30 meters diameter.



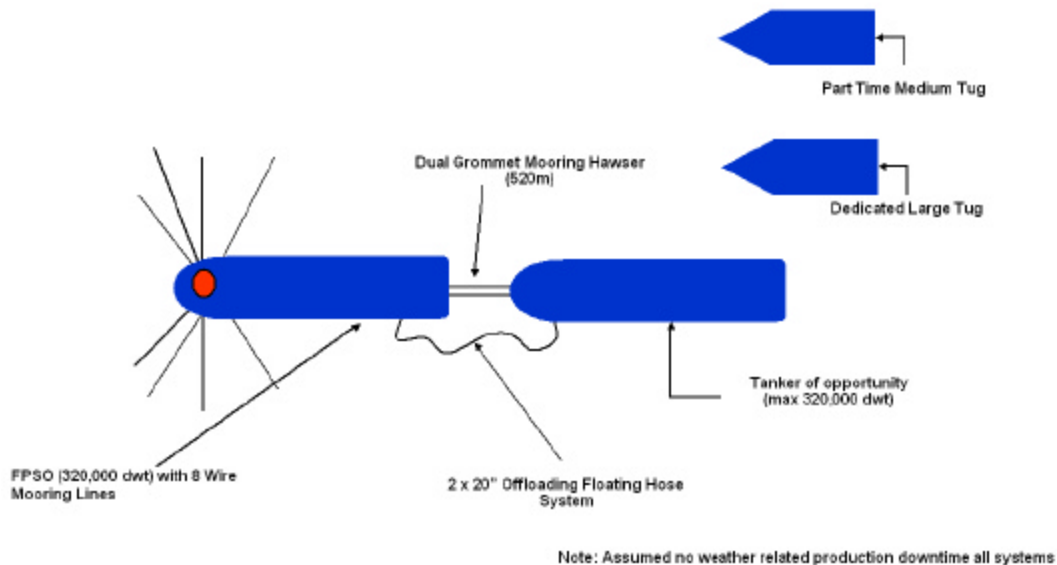
The FPSO turret mooring system would be eight (8) symmetrical lines with the top chain section of 150 meters of 88mm R4 studless, center wire section of 2,200 meters of 88mm SPR2 unsheathed, and the bottom chain section of 150 meters of 88mm R4 studless with a required pretension of 120 metric tons. The estimated capacity of the pull-in winch (es) is approximately 150 metric tons. The suction piles would be designed to a maximum intact load of 300 metric tons and a maximum damaged load of 425 metric tons at a force angle from horizontal of twenty-eight degrees.





The offloading floating hose system would be 2 x 20" lines at approximately 520 meters length from the FPSO to the tanker of opportunity (maximum size of 320,000 dwt). The mooring of the tanker of opportunity will require the assistance of one large size dedicated tug with one part time medium size tug.

### Case 1 – Very Large Turret (VLT) Mooring System with Tandem Offloading



The advantages of the turret system are:

- The weathervaning system allows tandem offloading
- The risers can approach from anywhere in the 360 degrees arc except where the anchor lines are located
- Fewer less heavy anchor lines are required, and
- The FPSO will have good motion characteristics

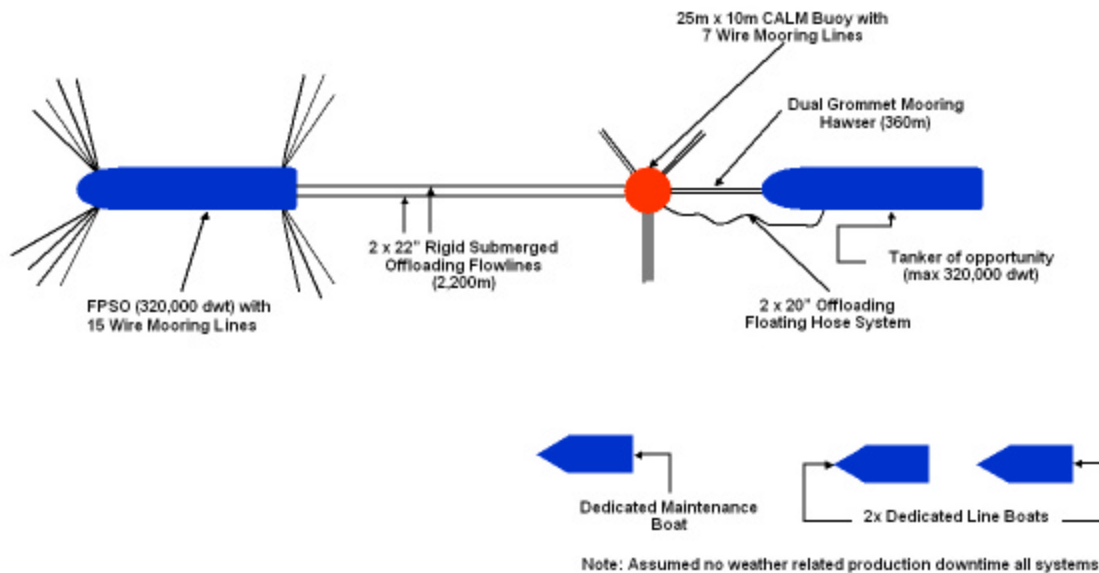
The disadvantages of the turret system are:

- The tandem offloading requires heavy tug assistance, and
- The bounded turret envelope limits the flexibility in the number of risers

## Case 2 Spread Mooring System with Remote Offloading and Near Surface Termination of Offloading Flowlines

The spread-moored system is typically installed with the FPSO's bow towards the prevailing environment. This makes the FPSO susceptible to waves incident at large relative wave angles which increases the probability for substantial FPSO motions, especially roll. Therefore, the spread-moored system normally has a larger number of lines with increased component size than an equivalent turret moored (Case 1) FPSO.

### Case 2 – Spread Moor (Remote Offloading) Near Surface Termination of Offloading Flowlines



The FPSO spread mooring system would be fifteen (15) lines with the top chain section of 150 meters of 119mm R4 studless, center wire section of 2,000 meters of 119mm SPR2 unsheathed, and the bottom chain section of 150 meters of

114mm R4 studless with a required pretension of 140 metric tons. The suction piles would be designed to a maximum intact load of 475 metric tons and a maximum damaged load of 575 metric tons at a force angle of twenty-eight degrees.

The offloading lines would be two-twenty two inch (2-22") rigid flowlines with floats of 2,200 meters length each, running from the FPSO to the CALM terminal located one nautical mile away. The offloading lines are exposed to possible damage from fatigue due to wave forces, especially at their connection points to the CALM.

The large distance required between the FPSO and the offloading point (one nautical mile or 1,850 meters) and the weight of the large suspended flowlines result in large reaction loads at the CALM buoy. These loads are compensated by designing an asymmetric mooring system to react to the horizontal load, and increasing the displacement of the CALM to support the risers and mooring load. This results in a CALM system that has a displacement approximately four to five times that of a conventional CALM. The heavy rigid flowlines also affect the motions of the CALM and must be accounted for when assessing the dynamic response of the CALM system.

The rigid flowlines must be designed to require no change-out for the life of the field (30 years) due to the great expense and offloading downtime that would be experienced if this were required. As the flowlines are directly connected to the CALM, they respond dynamically to any motions the CALM itself may exhibit in response to the wave environment and are thus susceptible to the accumulation of fatigue damage. Detailed analysis of this complex system has shown that the fatigue life of the flowlines attached to a large displacement CALM can have unacceptable levels for a twenty plus year application.

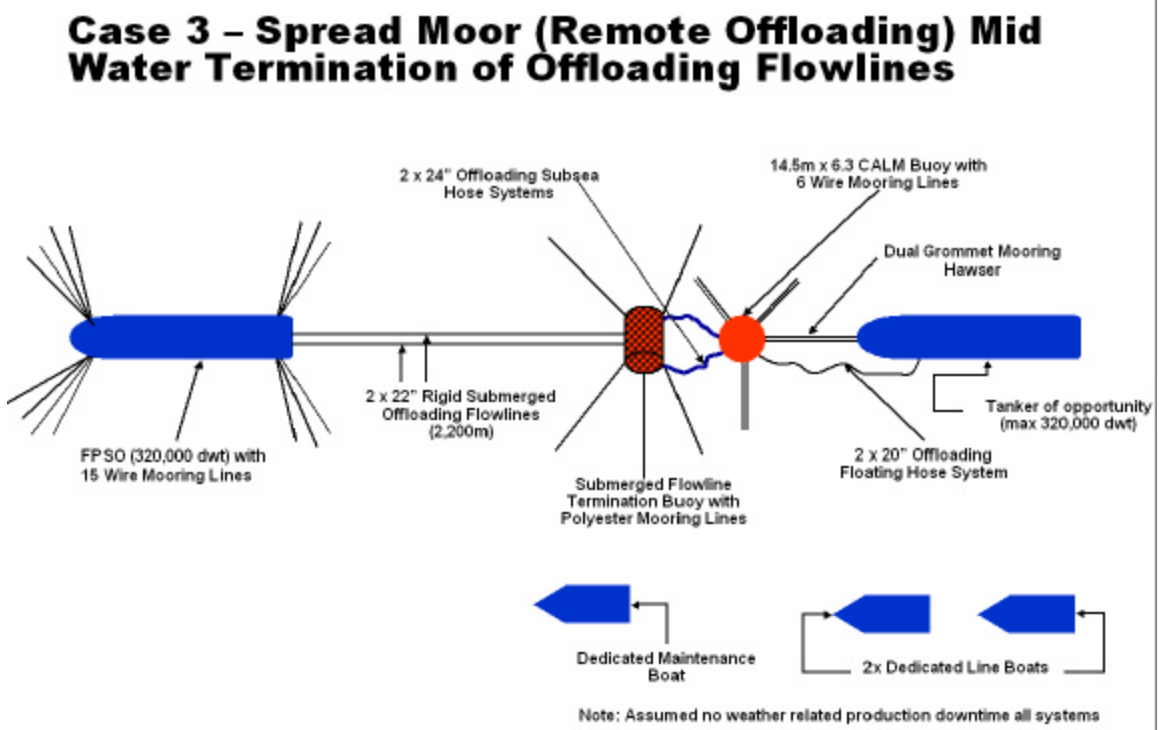
The CALM would be 25 meters diameter with a height of seven (7) meters and weigh approximately 700 metric tons. The CALM mooring system would be seven (7) lines with the top chain section of 180 meters of 78mm R4 studless, center wire section of 1,345 meters of 70mm SPR2 unsheathed, and the bottom chain section of 50 meters of 78mm R4 studless with a required pretension of 150 metric tons. The suction piles would be designed to a maximum intact load

of 260 metric tons and a maximum damaged load of 350 metric tons at a force angle of twenty-eight degrees.

The offloading floating hose system would be 2 x 20" lines at approximately 360 meters length from the FPSO to the tanker of opportunity (maximum size 320,000 dwt). The mooring of the tanker of opportunity will require the assistance of two dedicated line boats with the addition of a dedicated maintenance boat for the complete Case 2 system.

### Case 3 Spread Mooring System with Remote Offloading and Mid Water Termination of Offloading Flowlines

The Case 3 spread moored is the same as the Case 2 system except for the changes described in the paragraphs below.



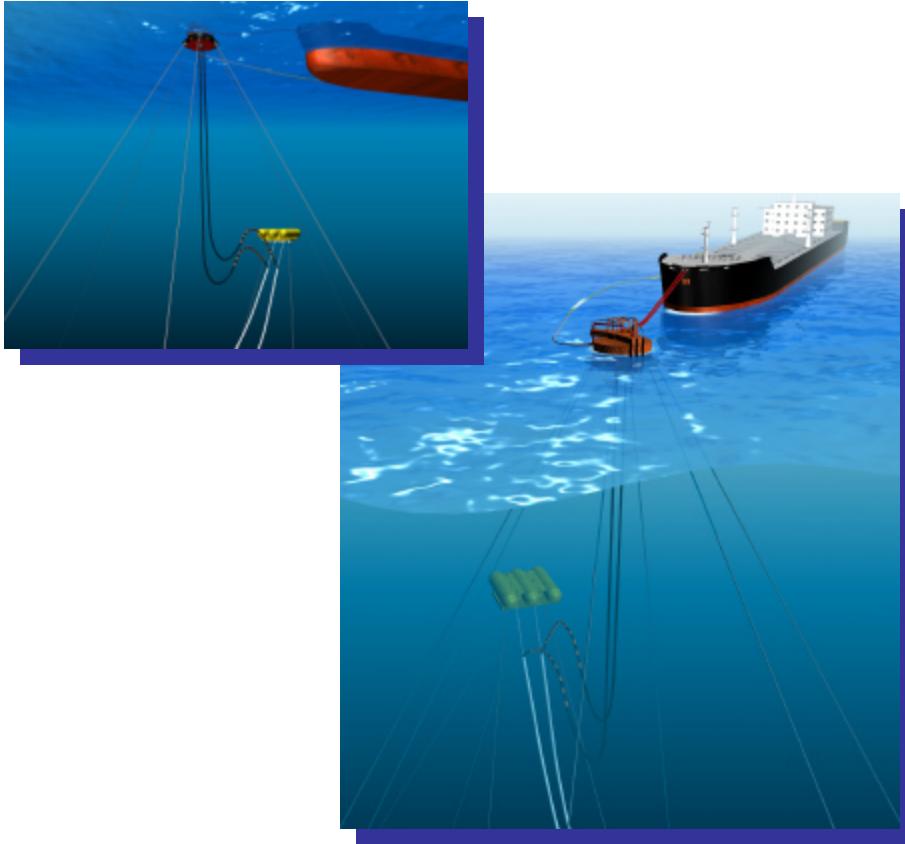
The offloading lines would be two-twenty two inch (2-22") rigid flowlines with floats of 2,200 meters length each, running from the FPSO to the Flowline Termination Buoy (FTB). The flowlines are connected to the FTB via a specially designed gooseneck flowline termination assembly that allows connection of the

flowline to the FTB with an adjustable chain element. The chain segment eliminates the need for expensive flexjoints at the flowline/FTB interface, and allows for easy installation of the flowline. Marine hoses or flexible pipe (depending on required diameter) are connected from the gooseneck to the CALM in a lazy wave configuration. Ball valves and breakaway couplings can also be provided at the marine hose-gooseneck interface if required.

The FTB will be submerged approximately 75 meters below the water surface. It consists of three (3) tanks, each containing three (3) compartments and is relatively insensitive to density changes in the fluid in the flowlines (e.g., from oil to water). The FTB mooring system would be four (4) lines with the top chain section of 100 meters of 58mm R4 studless, center wire section of 1,075 meters of 62mm SPR2 unsheathed, and the bottom chain section of 20 meters of 58mm R4 studless with a required pretension of 45 metric tons. The suction piles would be designed to a maximum intact load of 80 metric tons and a maximum damaged load of 110 metric tons at a force angle of twenty-eight degrees.

The FTB would then be connected to the CALM by two-twenty four inch (2 x 24") offloading sub sea hose systems. The FTB has been designed to provide a reliable support in the event of accidental damage of an anchor leg or loss of one compartment in its buoyancy tanks. Once installed, the FTB does not require an active ballasting system to maintain its position.

The CALM would be 14.5 meters diameter with a height of six (6.3) meters and weigh approximately 400 metric tons. The CALM mooring system would be six (6) lines with the top chain section of 180 meters of 58mm R4 studless, center wire section of 1,345 meters of 62mm SPR2 unsheathed at 1,345 meters and the bottom chain section of 50 meters of 78mm R4 studless with a required pretension of 45 metric tons. The suction piles would be designed to a maximum intact load of 80 metric tons and a maximum damaged load of 110 metric tons at a force angle of twenty-eight degrees.



The two buoys are independently moored, with standard marine hoses or flexible jumpers connecting the flowlines at the FTB to the CALM using a configuration that is flexible enough to effectively de-couple the two buoys. Motions of the CALM on the surface do not affect the flowlines, as in Case 2, and the FTB is deep enough to minimize the effect of wave loading. This drastically reduces dynamic loading on the flowlines from the offloading system and results in a significant reduction in fatigue damage of the flowlines.

Because the FTB is positioned 75 to 100 meters below the surface, the wave kinematics of the local wave approach is zero, while those for the swell waves are reduced by 90 percent. The taut mooring system, coupled with the weak environmental loading on the FTB-flowline system, results in very small motions of the FTB.

In addition to reducing the fatigue damage of the flowlines, the proposed offloading system also enhances the integrity of the flowline support/offloading system by reducing the risk of the tanker of opportunity or support vessel colliding with the offloading system and its impact on the flowlines. With the FTB and flowlines 75 meters below the surface there is no risk of collision between tankers of opportunity and the flowlines themselves. If a collision does occur between the tanker of opportunity and the offloading CALM, the damage is localized to the CALM and has no effect on the flowlines. The use of a conventional marine terminal allows for easy replacement without the concern of supporting the flowlines in the absence of the offloading CALM, as would be in Case 2 (larger displacement CALM buoy-flowline system).

Another important advantage of the FTB system over the large displacement CALM buoy (Case 2) is the lower hawser loads during offloading. For a given tanker of opportunity and environment, the maximum hawser load varies as a function of the offloading CALM size (due to the change in motions). The maximum dynamic hawser loads for a large displacement CALM can be significantly higher than for a smaller CALM. This can have a major impact on the offloading efficiency of the system, as the bow stoppers on most tankers of opportunity are limited to a 200 metric ton maximum load. In some sea conditions this implies that the hawser loads for the larger displacement CALM could exceed the tankers bow stopper capacity while the hawser load for the FTB-CALM system will not, thus allowing offloading to continue.

The Case 3 offloading system also allows greater optimization of the product export system (flowline and pumping equipment on board the FPSO) compared to Case 2. This is due to the reduction of dynamic response of the flowline and the insensitivity of the FTB system to changes in flowline loads.

## **CASE STUDY COST COMPARISONS**

### **CAPEX**

The financial analysis performed in this paper provides a comparison between the three FPSO mooring and offloading systems and is considered to be accurate within +/- 15%. As the Case 1 (Turret Mooring System) contains various sub-systems and has certain performance characteristics, it is important to identify similar sub-systems required for Case 2 and 3 (Spread Moored

Systems) and to ensure that each system has the desired motion and offloading performance.

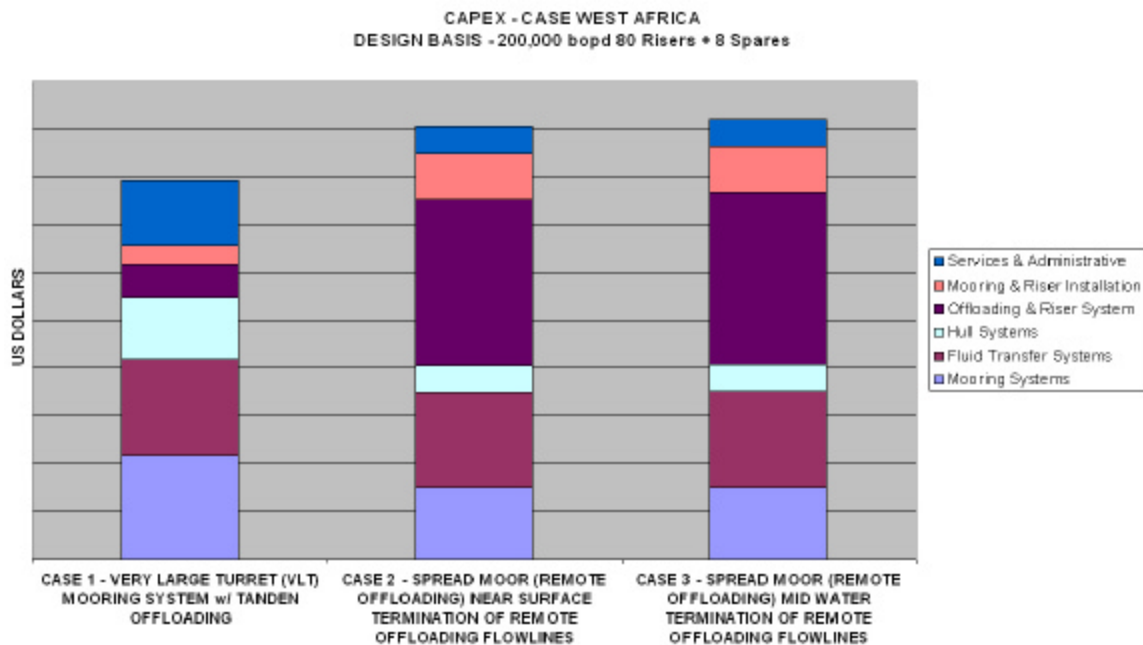
The various sub-systems and components were identified to determine the appropriate CAPEX of the common sub-systems between the three mooring and offloading cases which included engineering, management, fabrication/assembly, commissioning and installation costs. For the purpose of this paper the CAPEX costs were accumulated for the following sub-systems based on present costs with typical profit and overhead rates.

- Mooring System: This includes all systems of the mooring to vessel load-transfer system including anchor leg components, fairleads and chain stoppers, the turret structure, mooring installation equipment, etc.
- Fluid-Transfer Systems: 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: This includes mooring system specific modifications for the hull, e.g., the turret moon pool, fairlead supports, bending shoes, bilge keels, etc.
- Topsides Systems: 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 the turret system, modifications to topsides to accommodate the selection of either system, etc.
- Offloading System: This includes the specific offloading system components required for each mooring system. This includes offloading system related equipment on board the FPSO, such as offloading pumping system, and remote offloading systems, such as CALM and FTB, and associated flowlines.
- Mooring and Offloading System Installation: This includes all installation costs for installing and hook-up the FPSO to its moorings and remote offloading system if required.



- Service and Administrative: This includes all engineering, management, procurement and overhead costs associated with the three cases specific items described above

## CAPEX Summary



The CAPEX Summary shows that the new designed Very Large Turret (VLT) Mooring System with Tandem Offloading has the lowest CAPEX with the two Spread Moored Cases having approximately the same cost.

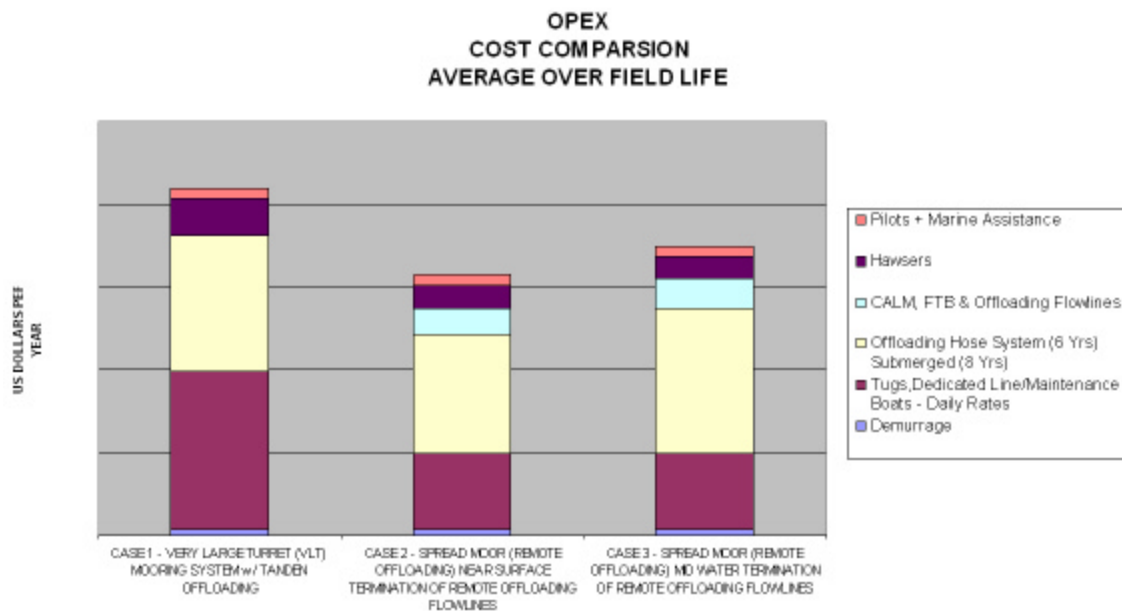
## OPEX

The operational costs (OPEX) of the three cases are also estimated within +/- 15% accuracy, again focusing only on the costs that are specific to the mooring and offloading systems selected. They also assume an inflation rate of 2% per year and average cost over the field life of thirty years. The OPEX estimates are based on:

- Demurrage: tankers of opportunity demurrage time and charges

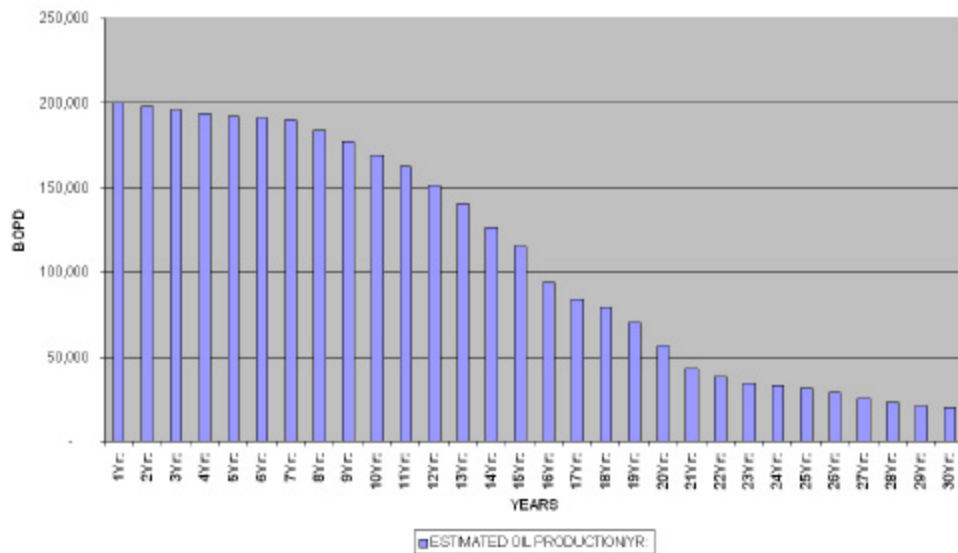
- Maintenance and Inspection: This includes all maintenance and inspection requirements for the mooring system specific components including the requirements for the remote offloading system.
- Offloading Tugs, Dedicated Line/Maintenance Boats and Pilots: This includes the costs for offloading assistance 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 for each of the three cases.

## OPEX Summary



The OPEX Summary is the average cost comparison of the average cost over the field life of thirty years. Case 1 (Very Large Turret) is the most expensive per year due to the tug assistance requirements. Case 3 Spread Mooring is the next most expensive due to the additional maintenance and expenses of maintaining the FTB and submerged hoses and Case 4 Spread Mooring is the least expensive.

## Case Oil Production - West Africa 200,000 BOPD Over 30 Years



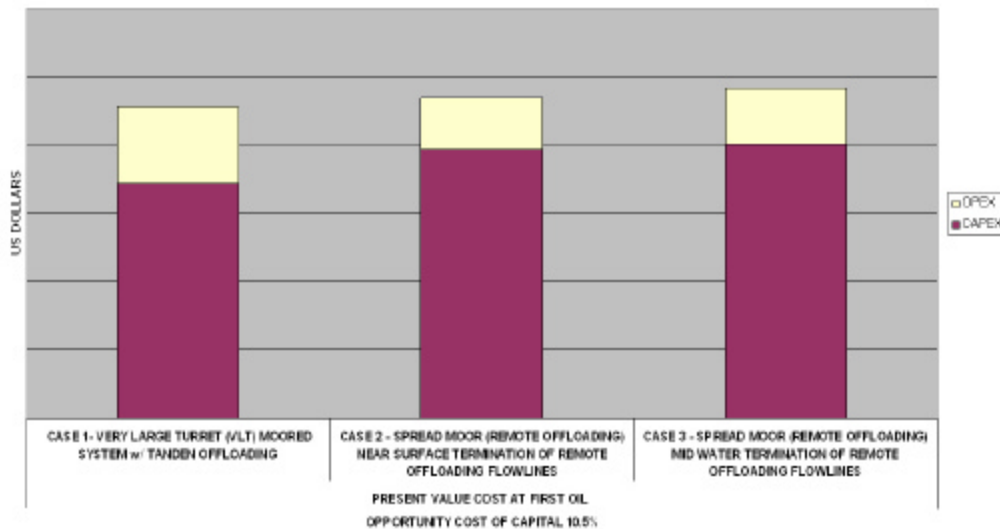
### Present Value

The Present Value (PV) of the three cases serves as a method of comparing the total cost of the mooring and offloading 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.

The results shows that Case 1 is the least expensive followed by Case 2 and then Case 3, but the total cost difference among the Cases is very small compared to the total cost of the Cases.

# Present Value Summary

CASE - WEST AFRICA



## CONCLUSION

This paper provides an overview of the comparison among the three Cases, describing the advantages and disadvantages of each Case.

The three Cases demonstrated that when making a cost and performance comparison, the true total cost of the FPSO Mooring and Offloading systems must account for CAPEX, OPEX and system performance over the life of the field.

The results of this case study indicate that for an average deepwater West Africa production field, cost is not the most important factor to consider in the selection of mooring and offloading systems. This is because the costs differences are fairly small compared to the total cost of each case. Other factors to consider include the risk of the tanker of opportunity or support vessel colliding with the FPSO in Case 1, or with the offloading system and the flowlines in Case 2.

The study demonstrates that Case 3 presents the least risk because with the FTB and flowlines submerged 75 meters below the surface, there is no risk of collision between the tanker of opportunity and the flowlines themselves. This is why we would recommend Case 3 "Spread Mooring System with Remote

Offloading and Mid Water Termination of Offloading Flowlines” for the average deepwater West Africa based on the design parameters presented in this paper.

## **References**

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