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Full Field and Early Production in Ultra-Deep Waters: The 'DP-FPSO' and 'DP-EFPSO' Concepts

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Abstract

In the coming years, there will be a growing demand for Floating Production and Storage Units (FPSOs) for ultra deep waters (greater than 2000 m [6,000 feet]), as evidenced by the large number of deep water FPSOs being considered for West Africa, Brazil and possibly the Gulf of Mexico. Several standard solutions for FPSO systems exist – turret moored FPSOs, turret moored FPSOs with thruster-assistance, and spread-moored FPSOs for benign, directional environments. However, beyond certain water depths, the technical and economical constraints associated with the use of passive mooring systems may favour a fully dynamically positioned FPSO. This system can either be utilized as an early production system designed to operate on many fields, or as a full-field development solution with service life up to 25 years. The areas most suited for this application are offshore West Africa, Brazil and the Gulf of Mexico.

The paper describes a joint study undertaken by the various companies represented by the authors to develop designs for fully dynamically positioned FPSOs for ultra deep waters. Two systems have been developed – a full-field development solution for the Gulf of Mexico (DP-FPSO), and an early production system for West Africa (DP-EFPSO). The various technical challenges for both systems have been identified and solutions to them provided. The differences in environment and operation of the two systems are discussed. Results from computer simulations and model tests are also provided to illustrate system performance in mild and harsh environments, and to study the performance as a function of control strategy.

Introduction

There is a growing demand for cost-effective and reliable floating production system concepts for ultra-deep water depths (greater than 2,000 meters). Floating, Production, Storage and Offloading (FPSO) systems are a mature floating production technology that is readily adaptable to deep water. There are a number of discoveries in ultra deepwater worldwide that will require floating production units, and a need for the industry to provide technical and economical solutions to face this challenge.

One of the critical issues in the design of FPSOs for ultra deep waters is the design of the most cost-efficient station keeping system for the specified operational requirements. The capital cost of the station keeping system including its installation can increase dramatically with an increase in water depth. This is even more important when a system is used as an early production system and may be relocated to several fields over its life. In addition, seafloor congestion, poor geotechnical conditions, or short field life may result in the traditional mooring system not being an optimum solution. Thus beyond certain water depths and for certain other conditions and applications, the technical and economical constraints associated with mooring systems may favour the fully dynamically positioned FPSO.

The development of the dynamically positioned FPSO concepts described in this paper builds from the experience obtained with the BP SWOPS Vessel (MV Seillean), disconnectable turret technology for the Terra Nova field, and the latest generation of dynamically positioned drill ships specifically designed for water depths up to 3,000 meters. The BP Seillean [1] operated in the North Sea for 8 years as a dynamically positioned production platform and was recently re-deployed in deep water offshore Brazil as an early production system for the Roncador field in 1,853 meter water depth. In Brazil the Seillean has remained on station while offloading to standard and DP shuttle tankers without incident [2, 3]. The latest generation deepwater drill ships have been in operation for five years in many deepwater regions worldwide and are designed to remain on station in sea states up to the 10-Year hurricane environment in the Gulf of Mexico. In addition many thruster-assisted turret-moored FPSOs are in operation in the North Sea and offshore Canada, and have been studied for the Gulf of Mexico [4, 5].

References [6, 7, 8] present the results for a DP-FPSO concept developed by the authors over the past two years for the GoM in 2,500 meters of water. The papers provide details of vessel design (including the DP thrusters, power generation and control systems), and the disconnectable turret and riser system. A summary of results from state-of-the-art computer simulations and model test program are also provided in the papers for a variety of extreme and operating conditions to demonstrate the performance of the system for all aspects of the operations including emergency disconnection, offloading, and survival. Regulatory aspects associated to this concept and results and conclusions from a reliability and safety study performed on the system have also been presented.

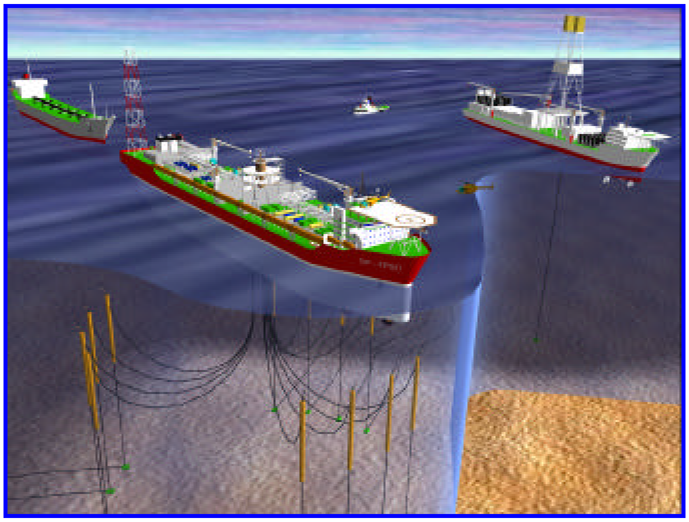

Figure 1. The DP-FPSO Concept

Early production FPSO systems have been used over the past twenty years and have either been custom-built or modification of an existing system. Currently there is a trend of developing generic FPSOs for use on several fields in Brazil and West Africa. These FPSOs may be deployed in deep water and work on several fields during their life. The DP-FPSO concept lends itself to this category of FPSO as it is very adaptable to deepwater sites and can provide cost savings due to the elimination of the mooring system and its installation. The Seillean in Brazil is an outstanding example of this concept.

This paper will summarize some of the key design details and simulations that have been performed with the DP-FPSO for the Gulf of Mexico with an emphasis on system performance and robustness. The remainder of the paper will focus on the development of an Early Production System DP-FPSO (DP-EFPSO) design, and results from computer simulations to demonstrate system performance for a variety of environmental and operating conditions.

The Full Field Development DP-FPSO Concept

The DP-FPSO system has been developed and analyzed based on a design basis developed for a hypothetical deep-water field in the Gulf of Mexico. The water depth selected was 2,500 meters, and the field was assumed to be produced from three drill centres. A total of twelve (12) risers and four (4) umbilicals were assumed to interface between the drill centres and the FPSO. The riser system consists of six (6) 12" pipe in pipe production risers, two (2) 10" water injection risers, one (1) 10" gas injection riser, one (1) 12" gas export riser, and two (2) additional 10" gas lift/injection risers. The production rate was assumed to be 125,000 barrels of oil per day, and the minimum storage capacity for the DP-FPSO was set to be 1 million barrels of oil.

The DP-FPSO system has been designed for the environmental conditions from the Gulf of Mexico. This was selected as the first detailed design case due to its extreme environmental conditions and regulatory environment. This allows the evaluation of the system station keeping performance in an extreme hurricane environment, and also in fairly mild operational conditions. For this design effort the vessel is assumed to maintain station with all risers attached for all extreme sea states including the 10-year hurricane environment (Hs=8.6m). For extreme sea states greater than this environment the vessel will disconnect from the riser system and sail away to avoid the storm. The DP-FPSO may also disconnect from the riser system in order to evacuate the crew from the remote site if that is an operational preference.

The results obtained for the Gulf of Mexico have been verified and calibrated against model test data. A summary of key results will be presented in this paper and additional information can be found in [6, 7, 8].

Description of the DP-FPSO System. A detailed description of the vessel and DP related systems has been provided in [8] and the main design features are summarized below. The DP-FPSO system consists of the hull and topsides, a thruster-based station keeping system, and a disconnectable riser turret that allows rapid disconnection from a large number of risers, when required. Figure 1 above provides a schematic of the DP-FPSO. The main components of the DP-FPSO system are:

- **Vessel:** A 1,000,000 barrel storage vessel with production capacity for 125,000 barrels of oil per day. The FPSO has a DP-thruster station keeping system and offloads to a shuttle tanker connected in tandem. The turret location is placed at midships to minimize the motions of the turret during extreme sea states.
- **Turret:** Allows for transfer of fluids between the riser system and the vessel. The turret is designed to allow rapid disconnection from the riser system, providing the ability to sail away from a hurricane. This also provides the means of disconnecting from the riser system in case of a blackout or scheduled maintenance at a shipyard.
- **Riser System:** The riser system provides transfer of product from the wellheads to the FPSO, and is specifically designed for use in this concept with the disconnectable turret system developed.
- **Offloading Tanker:** For transporting the stabilized oil to onshore refineries. Currently conventional tankers with a capacity of approximately 500,000 barrels are considered in this study.

FPSO Vessel. The FPSO has been designed with a crude oil storage capacity of one million barrels, and is double sided and has a double bottom to comply in full with MARPOL Regulations (International Convention for the Prevention of Pollution from Ships). The vessel hull forms are typical for a new-built FPSO, with a prismatic mid-body, a sloped flat transom and triangular bow. The hull forms have been optimized to minimize wave drift forces and green water loading [9]. The turret is located amidships, to minimise the vessel motions affecting the riser system and the riser (dis)connection operations. The accommodation (and helideck) is located forward in order to provide adequate navigational capabilities, as it is envisaged that the FPSO will disconnect and sail away in extreme environmental conditions. A process plant weight of 15,000 tons is accounted for. Table 1 provides a summary of the main vessel particulars and Figure 2 shows the general arrangement of the DP-FPSO.

Table 1: DP-FPSO Vessel Particulars

Parameter	Value	Units
Length b.p.p.	260	meters
Beam	46	meters
Depth	28	meters
Storage Capacity	1,000,000	barrels
Topsides Weight	15,000	MT
Accommodation	100	p.o.b
Offloading Tanker	500,000	barrels

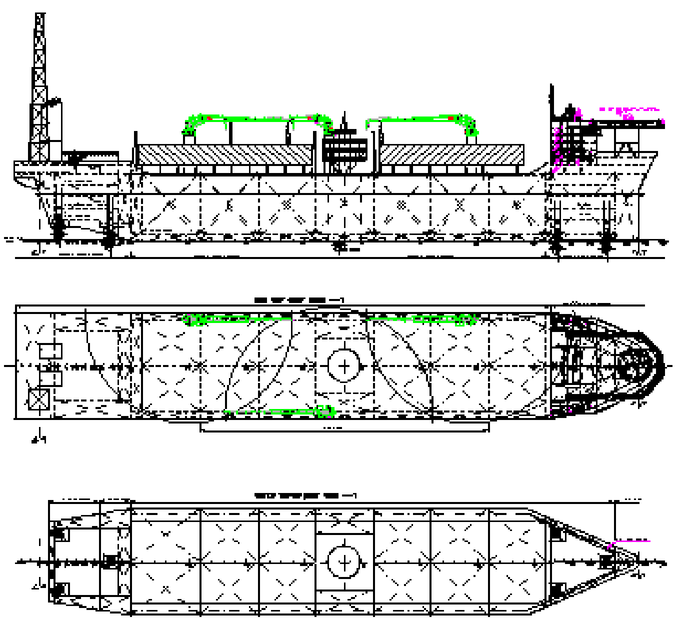

Figure 2: DP-FPSO General Arrangement

The DP-FPSO is intended to operate permanently on site during the specified service life of 20 years without dry-docking. A high uptime of the installation is desired, similar to that of a conventional turret moored FPSO. Adequate means for inspection and maintenance on site are provided. Special attention has been paid to thruster maintenance on location. The low utilization of the thrusters (normally only one forward and one aft) allows for a proper scheduled maintenance of the thrusters during mild weather (overhauling is recommended every five years).

FPSO Stationkeeping System. The DP system is sized to provide the required stationkeeping performance governed by the riser system, in the extreme design environmental conditions. The maximum allowable riser system offset is approximately 10% of the water depth (250 meters) for the current design basis. The DP system is also sized to provide sufficient redundancy in case of thruster failure or is being out of service for maintenance. The DP system is designed to be classified with DnV Notation DP AUTRO, equivalent to IMO Class 3.

For the present case study (GoM Area) the thruster system comprises six (6) azimuthing fixed pitch, frequency controlled thrusters with an anticipated capacity of 5 MW each. The thrusters are located three (3) aft and three (3) forward in individual compartments so as to fulfil the DNV AUTRO requirements.

Due to the criticality of the power generation system for a reliable and efficient operation of the DP and process systems, an optimization study has been carried out to assess the features of alternative power generation plants. The results of the study are highlighted in [8]. Although the selected power plant configuration selected is highly dependent on the degree of reliability/cost/flexibility required by the duty holder, a cost-efficient solution seems to be an integrated plant (serving the hull and topsides) fully redundant (two engine rooms, as required by DP Class), and comprising one dual fuel-gas turbine and two dual fuel-gas generators in each engine room.

The Control System and sensors for positioning required by the DP Class Notation are common to other conventional DP systems and have been described in the papers indicated above.

Disconnectable Turret and Riser System. The disconnectable turret and riser system is an important component of the DP-FPSO. The turret allows the vessel to weathervane about a single point to minimise environmental loads and motions of the vessel as a function of the environment intensity and duration. This allows the optimisation of the thruster system, power consumption, and the motions of the vessel. The turret also allows fluid-transfer from the earth-fixed riser system to the ship-fixed production and storage system. Another important element of the turret-riser system is the ability to rapidly disconnect the vessel from the riser system when required. The controlled disconnect (de-pressurizing and flushing risers) takes approximately 4 – 12 hours, while the emergency disconnect is designed to allow total disconnection in 5 minutes.

The turret design for the DP-FPSO has been based on the experience with the Terra Nova disconnectable turret mooring system [10]. Details of the disconnectable turret and riser system concept developed for the DP-FPSO application are provided in [8].

Summarizing the disconnectable turret design, the system consists of an integrated design of the risers and turret that results in a stable system when disconnected. The concept utilizes single leg hybrid risers [11] and a buoy that supports the flexible jumpers when disconnected from the FPSO. The buoy reaches stable equilibrium at 225 meters below the surface and can survive extreme environmental conditions like the loop current and 100-year hurricane. Figure 3 presents an elevation view of the disconnectable riser turret and the main components of the system. This concept has been extensively verified by simulation and a model test program that also focused on disconnect and reconnect of the system.

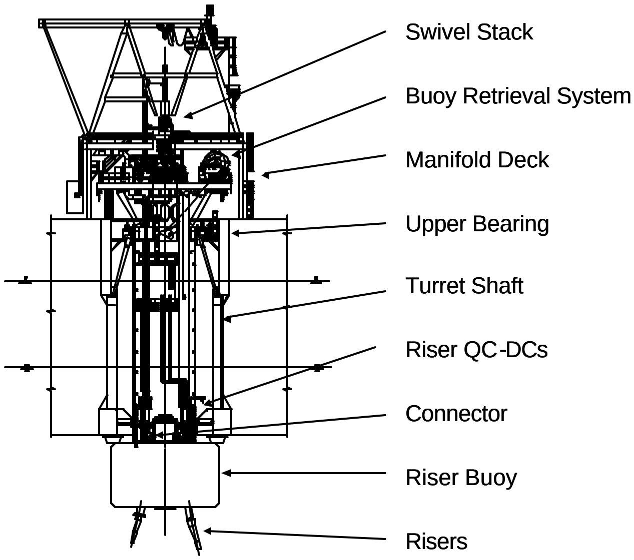

Figure 3: Elevation View of DP Turret Concept

A reliability and risk evaluation has been performed on the DP-FPSO concept and details are provided in [8]. The main conclusion is that the concept can be considered to have sufficient reliability to serve as a full-field development system. Although the risk for loss of position is higher than for a moored FPSO, the ability to disconnect and abandon the site together with the better control of the heading during offloading, provides unique advantages to this concept compared to a conventional turret moored FPSO.

Computer Simulation and Model Test Verification. For the DP-FPSO an extensive model test program and simulation study was performed in 2003. These are described in some detail below as they form the basis of the performance evaluation of the DP-EFPSO. For a more detailed description reference is made to [6, 7, 8].

Computer Simulations. Prior to the model test program DP capability analyses and initial simulations were performed using the time domain simulation program DPSIM. DPSIM is used to study the behaviour of dynamically positioned vessels, exposed to wind, irregular waves and current. DPSIM predicts the mean and low frequency motions in the horizontal plane and provides thruster forces and estimates of power consumption. Based on these simulation results the model test program was optimized and initial DP control settings were established.

Current loads were based on current load coefficients of a similar shaped FPSO and a constant current velocity. Wind loads were calculated using wind load coefficients of a FPSO with similar hull shape and topsides and assuming a NPD wind spectrum formulation. For the second order wave loads a diffraction analysis was performed on the DP-FPSO. All of this data, including thruster characteristics and positions, were used as input into DPSIM and simulations run for the various environmental conditions.

A standard PID controller was used to calculate the required thrust. The initial control settings for surge, sway and yaw were determined as follows: Spring Coefficient: Maximum. Total thrust / max allowable excursion; Damping Coefficient: 70% of critical damping; and Integrating Coefficient: zero. A large number of simulations were performed to optimize the control coefficients. As sway and yaw are highly coupled, a good balance has to be found between these coefficients.

The calculated thrust by the controller was allocated over the available thrusters using a thruster allocation routine based on LaGrange multipliers and minimizing the total consumed power. Three different allocations were used: Full DP, with all six thrusters active; Maximum single failure (CL fore and aft thrusters inactive). The third allocation simulates a maximum single failure in light sea states, when only four thrusters are used to maintain position (and the other two are out of service, e.g., for maintenance).

Model Test Program for GoM DP-FPSO. Early 2003 an extensive model test program on the DP-FPSO (GoM) has been completed in Marin's deep water Offshore Basin. The tests were performed at a scale of 1 to 60. The modelled water depth in the basin was 600 meters. The DP-FPSO model was equipped with a disconnectable buoy and six azimuthing thrusters, in a thruster layout with three thrusters both forward and aft.

The thrusters were controlled using a dedicated real-time full DP-system ('RUNSIM'), including an extended Kalman filter. Using this control system the DP-FPSO was free to choose any heading set point in order to minimize the motions or power consumption. The DP-FPSO was kept in position using conventional DP with a fixed heading set point. The turret was equipped with a heading control system, allowing the buoy to maintain its earth-fixed orientation independent of the DP-FPSO heading.

An equivalent riser system for 2,500 meters water depth was installed in the basin. The riser system consisted of four (4) truncated vertical riser towers (each modelling 3 individual risers), up to 250 meters below the water surface. Each riser had a cylindrical air can to obtain the required pretension. The connection between the top of the air can and the disconnectable buoy was made with flexible jumpers. The design of the riser system was such that after disconnection from the FPSO the buoy dropped to a depth of 250 meters below the water line, to avoid excessive current loads. Figure 4 shows the DP-FPSO model used in the model tests.

The model test program focused on Gulf of Mexico environmental conditions. The environments were simulated by generating waves, wind and current in the model basin. The following conditions were considered:

- Operational (90% and 99% exceedance sea states)
- Loop current condition
- 10-year winter storm
- 10-year hurricane
- 100-year hurricane
- Squalls
- Offloading to 500,000 bbls shuttle tanker

Details are provided in References [6, 7, 8].

Figure 4: DP-FPSO model

Comparison of Simulations versus Model Tests. Analysis of the model test results provided input to the simulations. Drag coefficients of the disconnectable buoy and damping coefficients of the DP-FPSO were derived from the model tests and used as input to the simulation program. A comparison was made between the simulations and the model tests for each environment tested in the model test program. The comparison was made for the standard deviation of surge, sway and yaw as well as mean power consumption for a range of FPSO headings. An example is shown in Figure 5, where 'MT' denotes the model test results and 'sim' the simulation results.

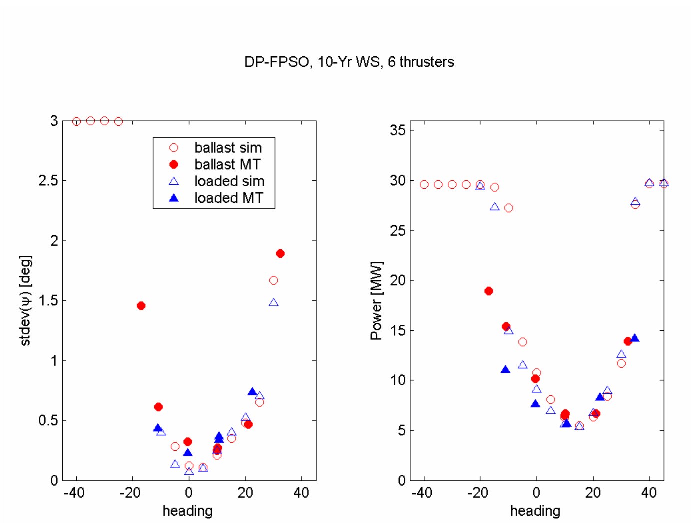

Figure 5: Comparison of Model Test Results and Simulations

The comparison showed good agreement between the simulations and the model test results. With this 'tuned' simulation program the workability of the DP-FPSO was assessed for Gulf of Mexico, West Africa and Brazil scatter diagrams. Results of this analysis are presented in [8].

Cost Comparison between DP-FPSO and Turret Moored FPSO. This subsection provides a brief summary of the CAPEX cost comparison study performed earlier. Additional details are provided in [8].

Using the design basis for the DP-FPSO, the design of a conventional turret moored FPSO with a 3X3 polyester anchor leg mooring system was developed for 2,500 meters of water in the GoM. The same riser system was assumed to be applicable to both systems. Both designs were examined in parallel and based on the differences between the two the following groups were identified to estimate the relative CAPEX costs for each system.

- **Hull Systems Group:** This group includes the modifications that need to be made to the hull for the DP-FPSO option (thruster support systems, maintenance, etc. etc.) and the turret system for both systems.
- **Stationkeeping Group:** This includes the off-vessel anchor leg components for the conventional turret mooring system, and the DP-thruster system for the DP-FPSO.
- **Lower Turret Group:** This includes all components of the turret system from chaintable to the upper bearing. For the DP-FPSO this also includes the costs of the riser buoy, the retrieval system, the QC-DC system for the risers, and related piping.
- **Power Generation and Control Group:** This includes the additional power generation requirements and redundancy required for the DP-FPSO as compared to a conventionally moored FPSO.
- **Commissioning and Installation Group:** This includes concept specific commissioning costs and the installation and hook-up of the anchor leg system for the conventional turret moored system.
- **Services and Administration Group:** This includes all engineering, management, procurement and mark-up costs associated with the conventional or DP-FPSO specific items described above.
- **Maintenance and Inspection Group:** This includes the inspection and maintenance costs for the conventional anchor leg system and the DP-thruster systems.
- **Other System Specific Operational Expenses:** This category covers all other concept specific operational costs like fuel for thruster system, additional marine crew for DP-FPSO option, etc.

Figure 6 presents the relative CAPEX in normalized US dollars for the various groups listed above. It can be seen that for this particular example the difference between the two CAPEX estimates is less than 5% implying that for this example the relative CAPEX for the two systems are similar. Note that for the DP-FPSO the CAPEX should be insensitive to water depth based on the groupings considered above. For the conventional turret moored FPSO the cost of stationkeeping and the installation will increase with water depth. This indicates that for the design basis considered the 2,500-meter water depth is close to a threshold water depth over which the DP-FPSO may be cost effective.

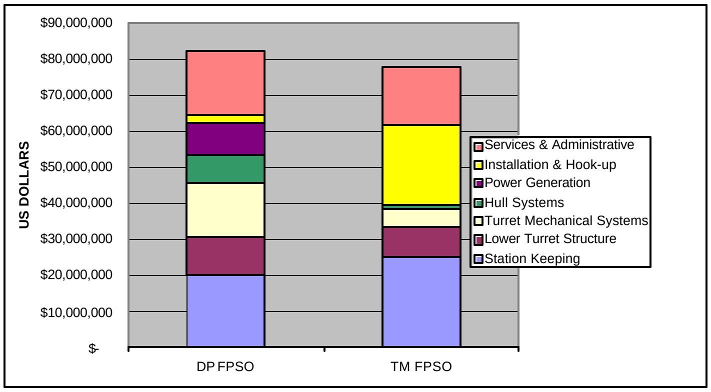

Figure 6: Relative CAPEX estimate for DP-FPSO and Turret Moored FPSO

The Early Production System – the DP-EFPSO

A fully dynamically positioned FPSO shows the most promise as an early production system where it may be deployed on several fields during the course of its life for short durations of time (5 – 7 years). As can be seen from the comparison made in the previous section this is where the maximum cost benefit is possible (especially due to mooring system installation and re-deployment costs) and maintenance of the thruster system can be performed in dry dock in between assignments.

The DP-EFPSO system has been developed and analyzed based on a design basis developed for a hypothetical deep-water field in West Africa. The water depth selected was 2,500 meters. A total of six (6) risers and three (3) umbilicals were assumed to interface with FPSO. The riser system consists of four (4) 12" production risers, one (1) 10" water injection riser, and one (1) 8" gas injection riser. The production rate was assumed to be 80,000 barrels of oil per day, and the minimum storage capacity for the DP-EFPSO was set to be 1.5 million barrels of oil based on typical West Africa export parcel sizes of 1 million barrels.

The DP-EFPSO system has been designed for the environmental conditions typical of West Africa. The West Africa environment consists mainly of swell from the south west and infrequent but intense wind squalls. Excluding the wind squalls, the long wave periods and low wind speeds result in relatively light conditions for dynamic positioning. On the other hand, to minimize FPSO roll motions it may be necessary to orient the DP-EFPSO the vessel heading into the swell, requiring additional power. The most challenging environmental condition is the wind squall as it can be unpredictable in intensity and direction.

Table 2 provides a summary of the various types of environmental conditions assumed. As can be seen from the table the DP-EFPSO will experience extreme waves (swell) and extreme wind squalls. For this design effort the vessel is assumed to maintain station with all risers attached for all extreme sea states, and offload in environments (except wind squalls) up to the 10-year return period. Due to the fairly unique nature of the West Africa environmental conditions the majority of results in the latter sections will focus on the performance of the DP-EFPSO.

Table 2: West Africa Environment assumed for DP-EFPSO study

Sea State	Hs [m]	Tp [s]	γ [-]	μ_{waves} [deg]	Vw [m/s]	μ_{wind} [deg]	Vc [m/s]	μ_{CUR} [deg]
Workability	According to WoA scatter diagram							
100-Yr return	4.5	15.0	6	SSW	7.5	S	0.3	E
10-Yr return	3.8	13.6	6	SSW	7.5	S	0.3	E
Squall	1.5	12.0	6	SSW	0-30	Var	0.3	E

Description of the DP-EFPSO System. Similar to the previous concept discussed, the DP-EFPSO system consists of the hull and topsides, a thruster-based stationkeeping system, and a disconnectable riser turret that allows rapid disconnection from the riser system. The main differences are the location selected for the operation, the size of the FPSO, and the location and design of the turret system. The main components of the DP-EFPSO system are summarized below.

FPSO Vessel. For this application, the DP-EFPSO has been designed with a crude oil storage capacity of 1.5 million barrels, and is double sided and has a double bottom to comply in full with MARPOL Regulations. The vessel hull forms are similar to those of the DP-FPSO, however some modifications have been made (reduced freeboard, deletion of the forecastle and poop deck) due to the milder environment in which the Unit is envisaged to operate. An external turret with above water riser connection is located at the bow, to allow for easy construction, weathervaning DP operating mode, to provide easy access to the riser connectors and a proper visualization during the (dis)connection operations. Like the DP-FPSO, the accommodation (and heli-deck) is located forward in order to provide adequate navigational capabilities. A process plant weight of 10,000 tons is accounted for in the design. Table 3 provides a summary of the main vessel particulars and Figure 7 provides a general arrangement of the DP-EFPSO.

Table 3: DP-EFPSO Particulars

Parameter	Value	Units
Length b.p.p.	294	meters
Beam	52	meters
Depth	30	meters
Storage Capacity	1,500,000	barrels
Topsides Weight	10,000	MT
Accommodation	80	p.o.b
Offloading Tanker	1,000,000	barrels

The DP-EFPSO is intended to operate permanently on site for typical durations for early production (6-7 years) without dry-docking. A high uptime of the installation is desired, similar to that of a conventional turret moored FPSO. Means for inspection and maintenance on site are similar to those of the DP-FPSO.

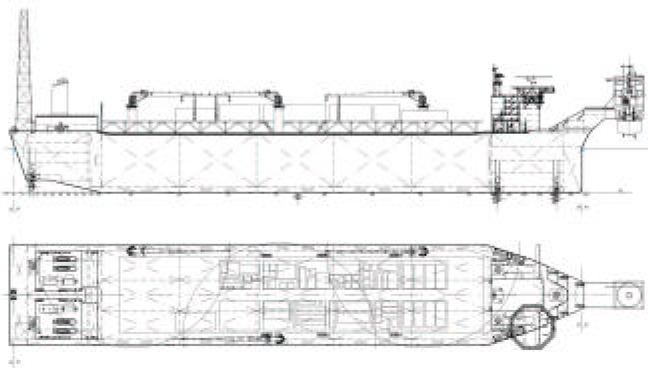

Figure 7: DP-EFPSO General Arrangement

FPSO Station-keeping System. The DP system is sized to provide the required stationkeeping performance governed by the riser system, in the extreme design environmental conditions. The maximum allowable riser system offset is approximately 10% of the water depth (250 meters) for the current design basis. The DP system is also sized to provide sufficient redundancy in case of thruster failure or is being out of service for maintenance. The DP system is designed to be classified with DnV Notation DP AUTRO, equivalent to IMO Class 3.

For the present case study (West Africa Area) the thruster system comprises five (5) azimuthing fixed pitch, frequency controlled thrusters with an anticipated capacity of 5 MW each. The thrusters are located two (2) aft and three (3) forward in individual compartments so as to fulfil the DNV AUTRO requirements. This configuration has proved to be the most suitable for operation in weathervaning DP mode (see analysis and simulation results below).

The power generation plant, control system and sensors are similar to those of the DP-FPSO and are not described in this paper.

Disconnectable Turret and Riser System. The disconnectable turret and riser system has been based on the work performed for a GoM FPSO. Due to the lower seastates and vessel motions, and a fewer number of risers, an external turret is suitable and a less expensive option. The design of the turret is very similar to the internal turret developed for the DP-FPSO. The turret is then designed to accommodate the riser and umbilical system, and the riser buoy connects to the bottom of the turret, suspended above the waterline. When disconnected the buoy is designed to support the risers at the design stable equilibrium point (typically 50 – 100 meters below the surface). The method of operation and equipment used for the DP-EFPSO turret is similar to that for the DP-FPSO, including controlled and emergency disconnect times.

As another option the riser buoy could be eliminated (especially if the number of risers is very few) and each jumper disconnected individually from the turret and dropped or lowered. As can be seen from the analysis presented later the DP system can maintain the vessel on position for all 100-year environments even with the maximum failure of two thrusters. This implies that the probability for disconnection is very low and thus may allow the use of a system where risers are disconnected and reconnected individually.

Control Modes and DP strategy. For the DP-EFPSO two different DP control modes are considered. In both cases a minimum power thruster allocation is used to allocate the required thrust to each thruster. The first is conventional DP with heading control. In this mode a heading is selected by the DP-operator (DPO) based on the environmental conditions. A significant change in environment requires that the DPO manually adjusts the heading setpoint to maintain on position. This is important when sudden changes in the environment occur, e.g., when squalls occur. The second DP mode considered is the weathervaning mode. In this mode the FPSO is allowed to weathervane into waves, wind and current and thus find an optimum heading by itself. When the environment changes the FPSO will follow the environment without human interaction. In [12] it has been shown that this DP mode leads to good position keeping with low power consumption, provided the control point is located sufficiently forward of midship and sufficient thruster power is available forward of midship. However, in some cases the weathervaning mode may result in undesirable roll motions or large sway excursions, for instance if the resulting FPSO heading is beam to the swell or the waves [13]. This may happen in conditions where wind or current dominate the total environmental load on the FPSO. In these cases it may be desirable for the DPO to switch to conventional DP until the environment allows switching back to weathervaning DP.

Numerical Analysis Results for the DP-EFPSO. For the DP-EFPSO a similar simulation study was performed, using the numerical model as developed for the DP-FPSO, but using updated data for wave, wind and current loads. Offshore West Africa is considered the main area of operation for the DP-EFPSO. Therefore the simulation study focussed on different environmental conditions:

- 100-Year return swell
- 10-Year return swell
- Squall event
- Offloading
- Workability based on WoA wave scatter diagram

Two different DP control modes are considered, conventional DP (using a fixed heading) and weathervaning DP, where the FPSO is free to rotate around its turret location.

100-Yr return and 10-Yr return swell condition. First the two DP modes are compared in 100-Year return and 10-Year return swell conditions. Table 4 shows the simulation results with current at 90° to the swell direction. For the simulations with conventional DP the FPSO heading is selected into the swell to minimize roll motions. All simulations were performed for the maximum single failure condition, with one thruster forward and one thruster aft out of operation. The table shows the standard deviation of surge motion and heading during the simulation, and the power required to maintain station.

Table 4: DP Performance in 100-Yr & 10-Yr Swell Simulations

Sea State	Loading condition	Conventional DP			Weathervaning DP		
		σ_X	σ_ψ	Power	σ_X	σ_ψ	Power
Units		(m)	(deg)	(MW)	(m)	(deg)	(MW)
100-Yr swell	Ballast	0.48	0.01	680	0.91	1.61	1112
	Loaded	0.50	0.01	745	1.35	1.52	1918
10-Yr swell	Ballast	0.42	0.01	693	0.80	1.13	827
	Loaded	0.44	0.01	758	1.07	1.44	1617

The results show that position keeping in a 100-Yr return swell condition is not a problem, even when a maximum single failure occurs. Based on the above results there seems to be no merit in using weathervaning DP control algorithms. The main reason is that the mean drift force due to the swell is very small and the DP-EFPSO will align itself in between waves and current. The low frequency varying drift force due to the swell cause large surge, sway and yaw motions in this condition.

Squall events. For DP-EFPSO performance in squalls only the ballast condition is considered. Due to the larger wind area this condition is the most conservative. For all simulations a squall is considered where the DP-EFPSO is initially with its heading into a 1.5 m swell and 10 m/s wind. Current is beam to the FPSO at 0.3 m/s. During the squall the wind speed increases from 10 m/s to 30 m/s, while at the same time the wind direction changes from head on to beam wind. Squalls with varying ramp-up times have been tested in the simulations. Both intact and maximum single failure (one thruster forward and one aft failed) condition are considered. The results are shown in Table 5.

Table 5: DP Performance in Squalls - Maximum Excursion

wind speed	type	ramp-up time	Max Failure	Intact
10 – 30 m/s	constant	5 min	150 m	16 m
10 – 30 m/s	constant	10 min	21 m	11 m
10 – 30 m/s	constant	15 min	7 m	7 m
10 – 30 m/s	NPD spectrum	10 min	112 m	13 m
10 – 36 m/s	Slow varying	30 min	5 m	5 m

Figure 8 shows the response of the DP-EFPSO in the worst condition of Table 5, for a squall ramping up from 10-30 m/s in 5 minutes. Although the maximum excursion is 150 m this is still within limits of the riser system. This simulation was performed with a maximum single failure, i.e. two thrusters out of operation. In intact condition squall performance is excellent and only small excursions occur, even in the most extreme conditions.

Squall simulations have also been performed with the DP-EFPSO on conventional DP. These simulations show that the DP-EFPSO is able to maintain its position, provided that the DPO changes the heading of the FPSO into the wind in time. If the change of heading is started too late, the FPSO will not be able to turn into the wind and drift off may occur. Figure 9 shows the response of the DP-EFPSO in a 30 m/s squall ramping up in 5 minutes. In the left figure the heading is turned into the wind 2 minutes after start of the squall. Position keeping is very good in this case. In the right figure the change of heading is started 3 minutes after the start of the squall, i.e., only one minute later than the former case. In this latter case the DP-EFPSO is not able to turn into the wind and position is lost. This is considered a 'drift off'.

This analysis shows that using weathervaning DP it is possible to maintain position in the most severe squall conditions. When positioning is done using conventional DP with heading control a prompt response of the DP-operator is required to keep the FPSO on position in squalls.

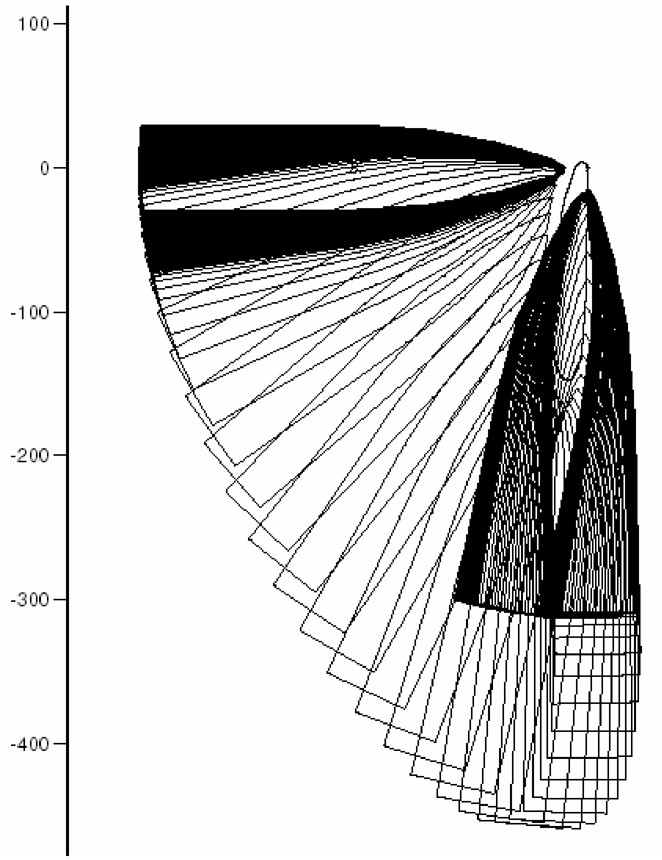

Figure 8: Response of Weathervaning DP-EFPSO in Squall

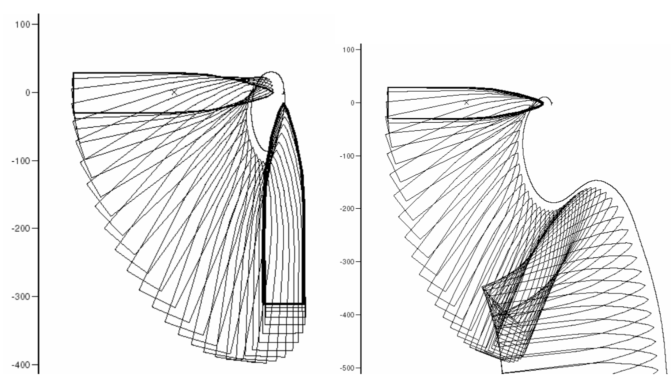

Figure 9: Response of DP-EFPSO in Squall on Conventional DP for (a) 2 min. and (b) 3 min. Response Times

From the above analysis it is clear that the squalls govern the design of the DP-thruster system in terms of number of thrusters, etc. However, the system designed also has a means to disconnect rapidly to avoid severe weather or in case of exceeding the offset limits when connected.

Offloading. An important aspect for an FPSO is offloading to a shuttle tanker. In the model test program for the DP-FPSO this has been extensively tested for various offloading sea states. Position keeping during offloading proved feasible in the maximum single failure condition up to Hs 4 m. For the DP-EFPSO offloading simulations were performed in the 10-Year return swell condition in both ballasted and loaded condition. The effect of the shuttle tanker, including some fishtailing, was taken into account by a time varying hawser load acting on the stern of DP-EFPSO. All offloading simulations were run in the maximum single failure condition (2 thrusters lost, 1 aft and 1 forward). Table 6 shows the results for conventional DP and weathervaning DP. Using conventional DP the FPSO heading is selected into the swell.

Table 6: DP Performance in Offloading Conditions

FPSO LC	Shuttle LC	Conventional DP			Weathervaning DP		
		σ_X	σ_ψ	Power	σ_X	σ_ψ	Power
Ballast	Loaded	0.42	0.01	693	0.80	1.13	827
Loaded	Ballast	0.44	0.01	758	1.07	1.44	1617

These results show that position keeping during offloading in a 10-Yr return swell condition with a maximum single failure (2 thrusters) is not a problem. Like in the 100-Yr return and 10-Yr return swell conditions described earlier the yaw motions and power consumption are somewhat higher using weathervaning DP than when using conventional DP with heading control. Figure 10 below shows positioning of the DP-EFPSO in loaded condition during offloading using conventional DP (left) and weathervaning DP (right).

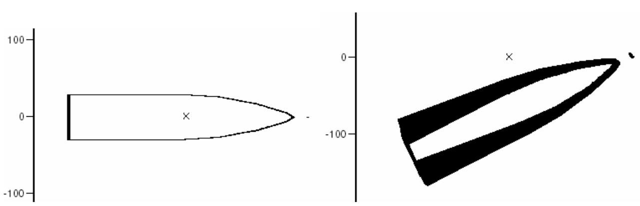

Figure 10: Position Keeping of DP-EFPSO during Offloading

As the DP operator has the freedom to choose between the two DP modes, this gives him flexibility to select the mode that gives the best overall performance, taking into account FPSO motions, power consumption and relative position of the shuttle. Furthermore, using conventional DP with heading control the DP-EFPSO can be brought in a favourable heading for the shuttle while approaching.

Workability. The workability of the DP-EFPSO in West of Africa environments was assessed for the maximum single failure condition for both loaded and ballasted condition. To determine the workability of the DP-EFPSO simulations have been performed for a typical West of Africa wave scatter diagram for both conventional and weathervaning DP. For each cell in the wave scatter diagram a simulation was performed in waves, wind and current. The wind direction was set at 30° to the wave direction and wind speed was chosen according to the Kruseman relation. The current was set as 0.5 m/s at 90° to the wave direction, with an additional small wind driven component. The 0.5 m/s mean current velocity is assumed to be the 99% exceedance current velocity.

In each simulation the mean required power as well as position accuracy is computed. If the excursion in the simulation exceeds the riser offset limits position keeping is considered not feasible in that sea state. Figure 11 shows iso-lines of mean power consumption. The overall workability is defined as the cumulative probability of sea states where position keeping is possible. The total downtime is defined as the cumulative probability of sea states where position keeping is not possible. The figures show the required power to maintain in position for both conventional DP and weathervaning DP for the loaded condition. Table 7 shows a summary of the workability analysis. In all conditions the workability is 100%, even with a maximum single failure.

Table 7: DP-EFPSO Workability

FPSO loading condition	Conventional DP		Weathervaning DP	
	Max power	Workability	Max power	Workability
Ballast	3.40 MW	100%	1.22 MW	100%
Loaded	13.62 MW	100%	1.27 MW	100%

In this workability analysis the mean power consumption for the DP-EFPSO in conventional DP mode is considerably higher than for the weathervaning mode. The main reason for this is the relatively high current which runs perpendicular to the swell direction. Using conventional DP with heading into the swell a large current force must be counteracted by the DP system. Using weathervaning DP the FPSO finds the optimum heading with much lower power consumption. However in this DP mode the roll motions of the FPSO may be more unfavourable.

For ballast condition the power consumption for conventional and weathervaning DP is almost the same. The figures above show that for the loaded condition the power consumption using conventional DP is higher. This would favour the choice of weathervaning DP in this case. In all sea states position keeping is possible in a maximum single failure condition. As mentioned before, the choice of DP mode depends also on the vessel roll motions, which are not taken into account in these simulations.

Based on these simulations and the probabilities given in the scatter diagram the probability density function of power consumption can be determined. The results for ballasted and loaded condition are combined, assuming that both loading conditions occur 50% of the time. The results are shown in Figure 12.

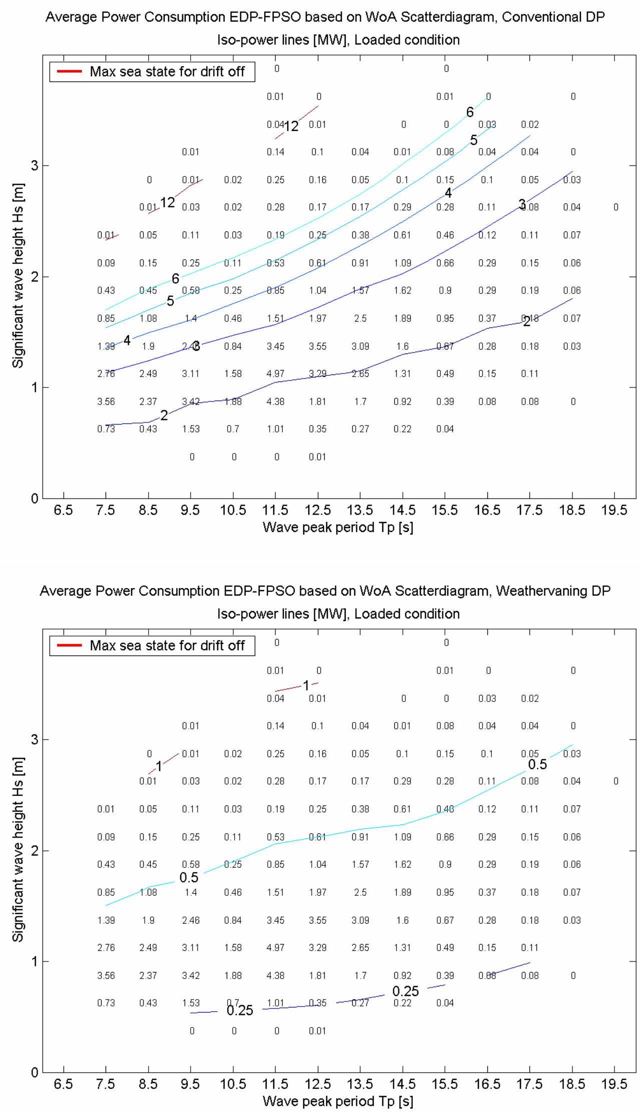

Figure 11: Required Power for (a) Conventional DP and (b) Weathervaning DP

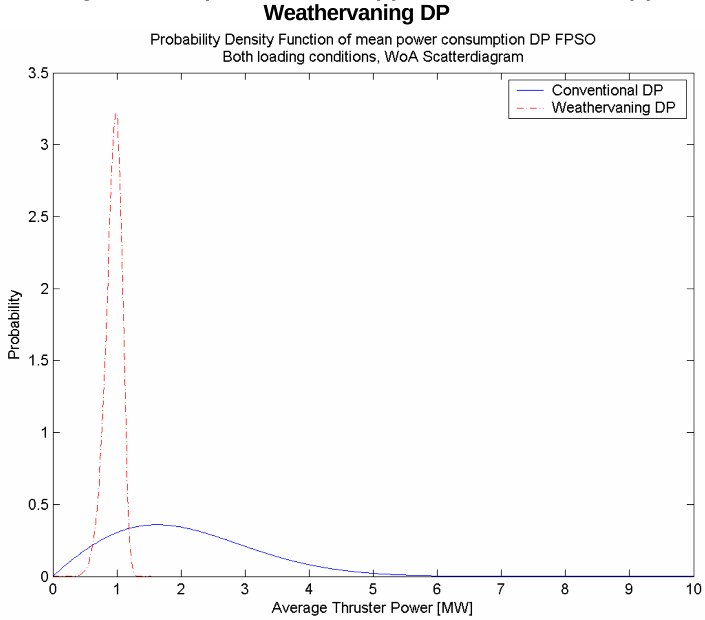

Figure 12: Probability of Power Consumption

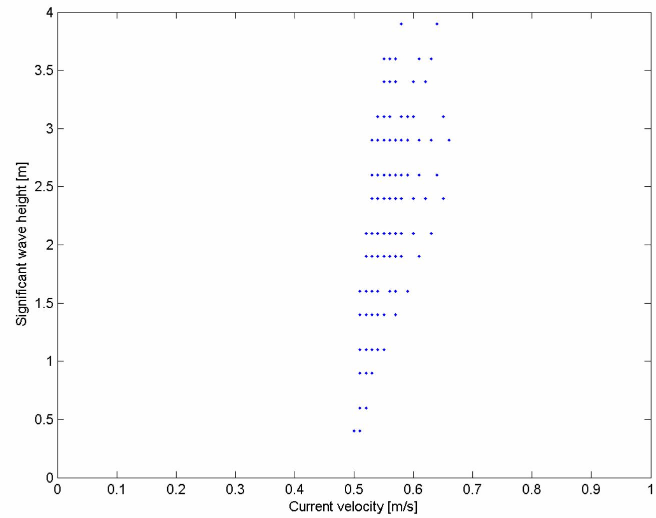

Figure 13: Joint Probability Distribution of Hs – Vc used

The probability density function of power consumption shown in Figure 12 is governed by the current used in the simulations, as the mean wave drift forces and wind loads are fairly low. Figure 13 shows the distribution of current velocity versus wave height, as used in the simulations, based on a mean current component of 0.5 m/s and a small wind driven component. The resulting current speed varies between 0.5 and 0.7 m/s. Using different current speeds will affect the results of the simulations.

Summary and Conclusions

The DP-FPSO and DP-EFPSO concepts proposed in this paper provide innovative and cost effective solutions to meet the challenges of ultra deepwater production by utilizing existing and proven technology in the offshore industry. Both systems have been comprehensively analyzed for stationkeeping performance and the systems have been designed to result in a robust system with adequate redundancy and the ability to disconnect from the riser systems if necessary. Past papers by the authors have also reported on the risk and reliability studies conducted with the design of the power generation, DP control and thruster systems to ensure a system with reliability very similar to a conventional passively moored system.

The analyses presented in this paper focus on the performance of the DP-EFPSO system in West Africa. The simulations show that the vessel can maintain position for all extreme conditions considered (both 100-year swell and squall), with the intact or damaged thruster system (2 thrusters failed), and offloading in seastates up to the 10-year swell. This shows that the probability of disconnection will be very low for the design and conditions considered. Power consumption analyses have shown that most of the time the power required by the DP system represents a small fraction of the total power required by the process plant and vessel systems. The average thruster power required for the area is of about 1 to 2 MW, which is small compared to the peak power requirements of approximately 60 MW for a floating production system.

Although it is not possible to make a definitive statement about the difference in CAPEX/OPEX for a DP-FPSO compared to a conventional passively moored FPSO, the cost estimate studies performed within the framework of this study suggest that for full-field applications, the threshold water depth may be around 2,500 m, beyond which the full-field production FPSO for the Gulf of Mexico (DP-FPSO) could be a competitive solution. For early production systems operating on several fields in West Africa over its 20-year life the threshold water depth is probably lower.

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