FDPSOs: The New Reality, and a Game-Changing Approach to Field Development and Early Production Systems
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Abstract
The Azurite field development, installed in the Republic of Congo in 2009, employed the industry’s first Floating, Drilling, Production, Storage and Offloading (FDPSO) vessel to develop the field. While the FDPSO concept has been of interest within the industry for some time, the Azurite project team took the FDPSO from concept to reality.

The concept has tremendous potential as a “game changer” for field developments, whether it is employed to unlock the value of marginal fields in deepwater – even in a low oil price environment – or as an early production system. Because the concept employs a drilling rig onboard the vessel, traditional challenges regarding deepwater drilling rig day rates and availability are eliminated.

This paper summarizes development of the Azurite field as a way of providing context for evolution of the FDPSO concept. This paper also highlights other application for FDPSOs, and discusses some of the key variables that determine the suitability of the FDPSO concept for use in field developments.

Introduction
History was made in August 2009 when the Azurite field began producing offshore Republic of Congo [1]. Azurite employed the industry’s first Floating, Drilling, Production, Storage and Offloading (FDPSO) vessel to develop the field. While the FDPSO concept has been of subject of interest within the industry for some time, the Azurite project team took the FDPSO from concept to reality. It is a robust concept that has potential for much broader application, as the number of large discoveries in deepwater shrink and the industry seeks new ways to monetize stranded pockets of oil and gas.

This paper will reflect on the project technical and economic drivers that led the Azurite project team to select the FDPSO concept. This paper will also discuss other applications for FDPSOs, and identify key variables that determine suitability of the FDPSO concept for use in field developments.

Azurite: Inspiration for the Concept

Discovery and Appraisal
The Azurite Marine Field lies within the Mer Profonde Sud (MPS) block offshore Republic of Congo, just north across the border from Cabinda Block 14. Water depths across MPS range from 1100 – 2000 meters.

Azurite field was discovered in January 2005 with the Azurite Marine-1 (AZRM-1) well. The field was subsequently appraised in late 2005 and early 2006 with the drilling of AZRM-2 and AZRM-3 wells. Each of the latter two wells was sidetracked (ST). AZRM-2ST was also cored and tested. Aquifer support was found to be essentially non-existent along the producing trend, necessitating the requirement for water injection to support reservoir pressure.

Field Size Description
The AZRM-2 and AZRM-3 wells were ST to appraise the four fault blocks of the field as shown in Figure 1 below.
Concepts Considered

Azurite integrated project team began the task of identifying and evaluating of field development alternatives, as well as leading the capital project execution planning effort.

Multiple development schemes were identified and evaluated. The four main alternatives evaluated were:

- Subsea tiebacks to third party facilities
- Subsea tieback to infield FPSO
- Dry Tree Unit (DTU) producing to FPSO
- Infield FDPSO

A subsea tieback to third party facilities in Republic of Congo or Angola was considered and deemed technically feasible, with the aid of subsea boosting. However, tiebacks to third party facilities in Republic of Congo or tiebacks to third party facilities in Angola, with the associated cross-border issues, would have introduced too much schedule and political risk. Furthermore, subsea tiebacks to third party facilities did not fully support the Azurite team’s objective of establishing production operations in Republic of Congo. Hence tieback schemes involving third party facilities were not selected.

A subsea tieback to an infield FPSO was considered. This alternative represents the “classic” solution for deepwater field developments offshore West Africa. However strong market demand for deepwater floaters exposed the project to significant schedule delays. Likewise their associated day rates adversely impacted project economics.

DTU options were considered as a way to overcome the roadblock posed by the tight market for deepwater rigs. A DTU option was a possibility because the Azurite reservoir depth and areal extent permitted directional drilling from a single surface location. One alternative considered was a minimal wellhead facility with a tender assist drilling rig. This concept was successfully employed to develop the Kikeh field in Malaysia. Another alternative considered was a DTU with a self-contained compact drilling rig. In both DTU cases, processing would occur on an FPSO in the field. The option of a minimal wellhead facility with tender assist rig was ultimately rejected due to a lack of available tender rigs. The DTU with compact rig producing to an FPSO was retained as a technically viable alternative, however it was considered cost-prohibitive.

Faced with deepwater rig shortages and the desire to make a step-change improvement in project economics, the project team conceived of the FDPSO alternative. Figure 2 shows the overall view of the Azurite field development.
FDPSO Feasibility
The FDPSO concept has tremendous potential as a “game changer” for the oil and gas industry for deepwater field developments, whether it is employed to unlock the value of marginal fields in deepwater – even in a low oil price environment – or as an early production system. Because the concept employs a compact drilling rig onboard the vessel, traditional challenges regarding deepwater drilling rig availability and expensive day rates are eliminated.

Field development economics heavily favor an FPDSO concept when reserves can be produced from a single location. However the concept still has application for fields with multiple drill centers. The FDPSO can be located over the drill center containing the majority of a field’s reserves, and other drill centers can be tied back to the FDPSO.

FDPSOs have been discussed and the concept developed in the marketplace since the 1990’s but, until Azurite, never became a reality. While it sounds relatively novel, the technology involved is not new. Combined drilling and production platforms are commonplace, as are deepwater drill ships. Thus extending these time-tested concepts to drilling from an FPSO did not represent a quantum leap.

Both wet and dry tree FDPSO solutions have been studied in industry, however the Azurite team opted to focus its efforts on a wet tree solution because it represented less of a technological step-out. With the wet tree FDPSO, the moon pool is located in the center of the vessel in order to minimize rig motions. A base suitable for mounting a modular drilling rig is installed. Wells are drilled from the vessel and completed subsea.

Drilling from a FDPSO requires either a spread-moored solution or drilling in a continuous dynamic positioning mode. Benign environments and uni-directional seas permitted the use of a spread-moored FDPSO. Motions studies for Azurite confirmed that the relatively benign West Africa seastates, dominated by a long-period swell from the southwest, permitted drilling operations to continue even during a 10-year event.

A FDPSO concept hazard identification (HAZID) review was held prior to final consideration of the FDPSO as an acceptable option. The HAZID team included facilities engineers from the Azurite team, drilling engineering and field supervisor representatives from Kikeh Team, and drilling contractor HSE and engineering representatives. No high risks were identified that could not be mitigated through layout restrictions or the implementation of specific operating procedures.

Other Applications for the FDPSO
As the previous discussion suggests, market supply and demand forces and the operator’s own strategic aims in Republic of Congo led the team down a path to the logical conclusion of employing a FDPSO. However the concept is certainly not limited to Azurite. The concept can easily be extrapolated to other uses: in fields with marginal reserves, as an early production system, as part of a phased development, and in fields where other storage and offloading infrastructure are already present.

Marginal Field Development
As a 2002 study by Matthew Simmons [2] noted, 116 of the world’s largest oil fields produce 47% of the world’s crude oil supply. In contrast, over 4,000 fields produce the remaining 53% (ref. Figure 3). While the report is somewhat dated and
does not reflect recent discoveries in the Gulf of Mexico and Brazil, Simmons’ work points to the reality that the vast majority of new discoveries produce less than 100,000 barrels per day.

We do not suggest that a 100,000 barrel per day field defines a marginal field, as many other factors play into the equation, some of which are technical and some non-technical.

As tornado diagrams like the one shown in Figure 4 normally indicate, non-technical factors such as oil price and fiscal terms oftentimes have the greatest effect on field development economics [3].

As far as technical factors go, subsurface factors such as recoverable reserves, well productivity, and well count also drive economics. As well counts increase, so do drilling costs as a percentage of the overall field development capital cost. Likewise, intervention costs and operating expenses increase.

Setting aside then the ability to re-negotiate fiscal terms as well as technical and non-technical factors beyond our control, the key to making marginal fields economic lies in our ability to find a step-change improvement in capital cost and operating expense. In the case of the FDPSO concept, operators can move away from the cost-prohibitive deepwater semi-submersible drilling rig rates and towards day rates approaching that for a conventional land based drilling rig.

**Early Production System (EPS)**

The cost of today’s conventional offshore field development is staggering, with capital costs alone routinely exceeding $1 Billion, even for fields in relatively shallow water producing less than 100,000 barrels of oil per day.
As noted previously, reserve size, well productivity, and well count have a significant influence on project economics and therefore are often at or near the top of most NPV tornado diagrams. Consequently, reducing subsurface risk in offshore field developments is of paramount importance.

For operators with portfolios that are robust enough to support the associated capital cost, operating expense, and continued utilization, the employment of a FDPSO is an attractive solution:

- Early revenue generation from EPS or extended well tests
- Less expensive exploration and appraisal campaigns (day rate of the FDPSO versus the day rate of a deepwater semi-submersible drilling rig)
- Gain information on subsurface performance in order to optimize future full-field development
- Rather than pre-investing in a full field development solution and finding that results do not match predictions, the FDPSO can be re-deployed elsewhere. Thus the concept acts as an effective hedging mechanism.

**Phased Development**

Operators of blocks that contain multiple prospects or discoveries, many of which might be considered sub-economic on a stand-alone basis, will also find that the FDPSO with subsea trees offers tremendous advantages over conventional development schemes.

If you have a portfolio of prospects with sufficient chance of geologic success (e.g., operating in a known geologic basin), then a more bullish approach may be warranted.

Operators that discover a marginal field in an area with multiple prospects will normally require multiple prospects be drilled and appraised before an investment decision can be made. Thus cycle time, from initial discovery to first oil, is significantly impacted as each field is studied, reservoir models are built and analyzed, and multiple discovery and appraisal wells are drilled.

A FDPSO, employed in tandem with a semi-submersible drill rig, is a good fit to exploit the resources of blocks containing numerous marginal prospects and/or discoveries.

As Figures 5 through 7 indicate, following initial discovery and appraisal of Field #1 by the semi, field production can then commence via the FDPSO. As the semi-sub drills exploration and appraisal wells at Field #2, and as subsea hardware is ordered for the new field, plans can commence to relocate the FDPSO to Field #2 for development well drilling. If reserves remain at Field #1 that can still be economically produced, Field #1 can be tied back to Field #2. In a similar manner, as the semi-sub drills exploration and appraisal wells at Field #3, and as subsea hardware is ordered for the new field, plans can commence to relocate the FDPSO to Field #3 for development well drilling. If reserves remain at Field #1 that can still be economically produced, Field #2 can be tied back to Field #3.

Depending on the distance between the fields subsea boosting may be required to produce the incremental reserves. This possibility must be taken into account, and sufficient pre-investment made in each field to permit such future modifications.

Subsea tiebacks can be achieved via spare hub(s) on the production manifold. If a looped system is desired to enable dead oil circulation and round-trip pigging, the tieback can be via dedicated flexible risers to the FDPSO host.

![Figure 5 – Production from Field #1](image-url)
The impact of multiple tiebacks and differing fluid characteristics will have an impact on the existing FDPSO topsides and must not be overlooked or excluded from evaluation of field development economics. However, such a technical and commercial evaluation is beyond the high-level scope of this paper.

In the context of this discussion on phased developments, it is also worth noting that a FDPSO with subsea trees will have a distinct advantage over a FDPSO with surface trees. Once the wells are drilled, the FDPSO can easily be relocated, whereas a FDPSO with surface trees must remain on station until the end of the field’s economic life.

**FDPU**

Operators in mature, established producing regions with existing infrastructure will find that the basic FDPSO concept is adaptable. Total’s Moho-Bilondo deepwater field offshore Republic of Congo, shown in Figure 8, utilized a Floating Production Unit (FPU), as existing storage and offloading infrastructure was already available.
In a similar fashion, the FDPSO concept can be adapted; hence the name ‘FDPU.’ A suitable hull form serves as the platform for drilling and production operations. Crude oil and associated gas can be exported via pipeline for storage and offloading via existing infrastructure. The primary advantage of a FDPU over a more conventional dry tree development lies in the inherent buoyancy offered by the hull. Other concepts like tension leg platforms (TLP) are extremely weight-sensitive and so the ability to execute future topsides expansions are limited.

**Key Variables that Determine FDPSO Suitability**

In the context of field development, prudent practice demands identification and evaluation of multiple field development alternatives. The list of alternatives need not be exhaustive and can be narrowed based on experience and suitable analogues.

To determine whether a FDPSO is suitable as the cornerstone for a field development, its technical and commercial viability must first be established. A number of variables or “uncertainties”, with their corresponding interdependencies, factor into the determination of FDPSO suitability. For simplicity, we have identified key variables that determine suitability of the FDPSO concept for use in field developments. Many of these variables, along with their interdependencies, are represented in the ‘strawman’ influence diagram shown in Figure 9.

We note that the need for storage and offloading remains a key variable in the selection of a FDPSO over other alternatives. Some of the other key variables or uncertainties are described further below.

**Water Depth**

The FDPSO concept is robust over a range of water depths. We believe that a natural lower bound water depth for the FDPSO is in the range of 300 ft, corresponding to the depth at which jackup drilling rigs are numerous and therefore become an attractive alternative. In these water depths, either subsea wells or dry tree solutions employing fixed jackets, in conjunction with an in-field FPSO, will compete with the FDPSO concept. The number of wells to be drilled, and the need to conduct routine intervention, will influence this decision.

In water depths greater than 400 ft (effectively outside the range of jackup drilling rigs) but less than 1,000 ft, fixed jackets or compliant towers outfitted with a drill rig – again in conjunction with an in-field FPSO – will also compete with the FDPSO concept. As with the lower bound water depth cases, the number of wells to be drilled and the need to conduct routine intervention will influence this decision.

With respect to a maximum water depth, we note that 7000 ft roughly corresponds to the maximum water depths for which flexible production risers have been qualified. For the FDPSO to move over each well for direct vertical access, and to accommodate additional displacements due to seastates, flexible production risers are taken as a requirement for this discussion. Beyond 7000 ft, however, the FDPSO concept still has application. Flexibles would need to be qualified on a case by case basis. An alternative approach that permits employing the FDPSO concept in deeper water is to utilize a riser tower, with flexible jumpers in the shallow part of the water column that accommodate movement of the vessel.
Geographical Region & Seastates
A principal enabler for the FDPSO concept in West Africa is the relatively benign environment and directionality of seastates. Persistent swells emanate from the southwest, and this condition effectively serves to fix the FDPSO bow heading in order to minimize roll during drilling and production operations.

To confirm viability of the FDPSO concept across other geographic regions, we evaluated the response of a taut-moored very large cargo carrier (VLCC) hull FDPSO in 7000 ft water depth for a variety of seastates, as described in Table 1 below.

Table 1 – Key Worldwide Metocean Parameters

<table>
<thead>
<tr>
<th>Location</th>
<th>1yr sea state</th>
<th>10yr sea state</th>
<th>100yr sea state</th>
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<tr>
<td></td>
<td>Hs (ft)</td>
<td>Tp (sec)</td>
<td>Hs (ft)</td>
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<tr>
<td>West Africa</td>
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<td>Gulf of Mexico</td>
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<tr>
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<td>Bay of Bengal</td>
<td>10.8</td>
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</tr>
<tr>
<td>Arabian Sea</td>
<td>12.1</td>
<td>9.6</td>
<td>15.8</td>
</tr>
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Suitability of the FDPSO concept for drilling purposes was based on vessel response to 1 year sea states. Vessel response was then compared to mobile offshore drilling unit (MODU) drilling operation limitations for the 1-year condition (refer to criteria outlined further below). Suitability of the concept for continuous production operations was also considered, taking into account 10 and 100 year seastates.

We note that directionality of seastates was not taken into account in this preliminary analysis. Conservatively, we assumed that seastates can emanate from any direction. For simplicity, wind and current were also not included as part of this analysis.

Drilling Operation Limitations
Acceptance criteria are based on drilling operation limitations. Vessel offset due to sea conditions is generally not a concern, because the FDPSO’s mooring system actively adjusts to correct for offset. Therefore the remaining criteria to satisfy are heave and pitch/roll. Heave is limited operationally to the stroke capacity of the drilling riser tensioners. We
therefore assume that a 25 ft maximum heave response provides a reasonable upper bound. Pitch and roll are effectively limited by API Recommended Practice 16Q to a resultant 2.0° angle in order to permit continuous drilling during a one-year seastate.

**FDPSO Response During Drilling Condition**

Global performance of a FDPSO with a conventional VLCC hull shown in Figure 10 was assessed in frequency domain. Wave frequency linear analysis was performed to obtain response amplitude operators (RAOs) of motions for each wave period and wave heading. The FDPSO response to an irregular wave was obtained on the basis of RAOs using a JONSWAP spectrum. Results of this analysis are summarized in Tables 2 and 3 below.

![Figure 10 – FDPSO Hull Model for Global Analysis](image)

**Table 2 – FDPSO Response for Head Seas ±25° – Values around Mean Offset**

<table>
<thead>
<tr>
<th></th>
<th>1yr sea state</th>
<th>10yr sea state</th>
<th>100yr sea state</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>West Africa</td>
<td>Gulf of Mexico</td>
<td>South Atlantic (Brazil)</td>
</tr>
<tr>
<td>Surge (m)</td>
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<td>0.23</td>
<td>1.14</td>
</tr>
<tr>
<td>Sway (m)</td>
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<td>0.18</td>
<td>0.51</td>
</tr>
<tr>
<td>Heave (m)</td>
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<tr>
<td>Roll (deg)</td>
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<tr>
<td>Pitch (deg)</td>
<td>1.66</td>
<td>1.12</td>
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</tr>
<tr>
<td>Yaw (deg)</td>
<td>0.36</td>
<td>0.21</td>
<td>0.68</td>
</tr>
</tbody>
</table>

![Table 2 – FDPSO Response for Head Seas ±25° – Values around Mean Offset](image)
Taking into account drilling and operational considerations, the results summarized in Tables 2 and 3 above indicate that the FDPSO concept remains viable for West Africa. Beyond West Africa, the concept also has application in some areas of the South China Sea that are not subject to typhoons, such as deepwater Sabah, Malaysia.

The FDPSO concept struggles in other geographic regions considered, however this result is in part due to the use of a conventional VLCC hull for the analysis. The FDPSO concept may still have application elsewhere, however a hull that is purpose-built for the environment will be required. Such an analysis is beyond the scope of this paper.

**Reservoir Characteristics and Directonal Drilling Capability**

Subsurface characteristics are key variables that collectively help determine the feasibility of the FDPSO concept for a particular field:

- reservoir depth
- areal extent
- degree of compartmentalization
- reservoir permeability
- directional drilling

Reservoir depth and areal extent, as well as operator directional drilling capabilities, will impact the well count and tree locations at the mudline. Likewise the degree of compartmentalization and reservoir permeability will impact well count.

Shallow and/or areally ‘large’ structures are difficult to drain from a single drill center. Hence in some cases a more conventional FPSO development employing subsea trees is in order. However, if a ‘critical mass’ of reserves can be produced from a single drill center, then the FDPSO concept still has merit, and the remaining reserves can be viewed on an incremental economic basis as subsea tiebacks to the FDPSO (ref. Figure 11). The overall split in well count between those that can be drilled by the FDPSO, and those that must be drilled by the semi-sub, as well as the differential between semi-submersible rig rates and FDPSO rig rates, will drive this decision.

**Production Rates**

Desired oil and gas production rates will have some influence as well on whether the FDPSO concept is suitable for use, as higher field production rates generally imply higher well count. The influence of well count on FDPSO suitability is discussed further in the following section.
Well Count and Subsea Tree Spacing

Refer to Figures 12 and 13. Using Azurite as a suitable analogue, a radial array resulted in an efficient layout and ensured direct vertical access to each tree at the mudline. For purposes of this paper, a radial array will also be assumed as the optimal subsea arrangement.

Well count and subsea tree spacing are driven by reservoir areal extent and depth, as well as limitations on directional drilling. In our experience each operator has a different comfort level with respect to drilling of deviated wells; and in fact each individual within a particular operator organization will have a different comfort level. In order to avoid this subjective discussion, this paper focuses on the number of trees that can be reasonably arranged in a radial array drill center.

We begin with the simplifying assumption that a FDPSO will be allowed to displace horizontally by a maximum of 5% of water depth, in order to achieve direct vertical access over each tree at the mudline. This figure is subjective but considered to be reasonable based on flexible production riser limitations.

For the 7000 ft water depth case mentioned previously, this translates to a drill center with diameter of 350 ft (107 m), Assuming a minimum of 15m spacing between trees in the radial array and making allowances for export flowlines and umbilicals, a maximum of 18 trees can be supported by the FDPSO.

We note that the 18 well-count is a technical result of the subsea layout. As a practical matter, if the field development required up to 18 trees, the field development economics might dictate another solution, e.g. a tension leg wellhead platform (TLWHP) producing to an FPSO. However, it should be noted that in the case of Azurite (with 6 producers + 4 water injectors), the FDPSO solution was deemed to have superior economics in comparison to a similar TLWHP + FPSO combination. Where the actual breakover point occurs, and tips the scale in favor of another concept, is beyond the scope of this paper.

MODU Rig Rates and Availability

As was the case with Azurite, market supply and demand forces weighed heavily on the decision to pursue an alternative development strategy, rather than the more conventional FPSO + subsea wells development scheme that is common to West Africa.

Back in 2006, a time period following discovery and appraisal when field development alternatives were identified and evaluated, most deepwater semis were fully booked on long term charters. Those that were available came at a premium, with day rates exceeding USD 500,000 per day. The ability to employ a platform-based drilling rig – and not be subject to MODU availability or pricing variability – drove the Azurite project team towards an alternative solution; either a TLWHP or the FDPSO concept.

Fast-forwarding in time to 2010, we note that even with the sustained downturn in crude oil prices, from highs that approached USD 150 per barrel back in 2008, worldwide demand for deepwater semi-submersibles remains high. A cursory view of published rig rates suggests rates will remain in the $400K+ per day rate range for the foreseeable future.
Figure 12 – Azurite Drill Center Layout (1400m Water Depth)

Figure 13 – FDPSO Drill Center Layout for 7000 ft Water Depth Relative to Azurite Layout
Conclusion
This paper illustrated some of the project technical and economic drivers that led the Azurite project team to select the FDPSO concept. Looking beyond the specifics of Azurite, this paper also identified some of the key variables that determine suitability of the FDPSO concept for use in field developments.

Regardless of application, Azurite has shown the way forward. The possibilities and permutations are many. The step change in economics afforded by the incorporation of a drilling rig onboard a conventional FPSO brings new hope to fields of similar geometry and in similar environments that heretofore were considered marginally economic or uneconomic. The FDPSO concept also has application as an early production system, in advance of full field developments. Drilling and production can commence, generating revenue while at the same time generating valuable data regarding reservoir performance. The FDPSO can also be an integral component of phased development schemes.

Thus the FDPSO has proven to be a robust concept that can add significant value – both in terms of reduced cost and information gained on reservoir performance information that permits further field development optimization. Against the backdrop of today’s lean economic times, and as the number of large discoveries in deepwater shrink and the industry seeks new ways to monetize stranded pockets of oil and gas, the concept will no doubt receive much more scrutiny.

References