

## THE NEXT GENERATION OF ROUND FIT-FOR-PURPOSE HULL FORM FPSOS OFFERS ADVANTAGES OVER TRADITIONAL SHIP-SHAPED HULL FORMS

**William B. Lamport, Ph.D., P.E.**  
Vice President of Operations  
OPE, Inc.  
Houston, Texas 77042  
Email: wlamport@opeinc.com

**Per M. Josefsson, M.S.**  
Senior Engineer  
OPE, Inc.  
Houston, Texas 77042  
Email: pjosefsson@opeinc.com

### ABSTRACT

*The next generation of FPSOs provides the industry a new and exciting area of creativity and optimization. The industry has recently seen the first deployments of permanently moored round-shape floating, production, storage and offloading vessels (FPSOs) with more in the design stages and projected to be under construction in the near future. One such round-shaped FPSO, currently in the later stages of design, is OPE's patented Satellite Services Platform (SSP)320 FPSO.*

*The benefits obtained by implementing the proven technologies and operational techniques from ship-shaped FPSOs into a more fit-for-purpose hull form are outlined and discussed. Important advantages of round-shape FPSOs, such as their similar motion response regardless of seastate direction and hence elimination of the need for turrets or the need to disconnect and abandon location in the event of approaching tropical storms will be reviewed. In addition, the discussions will also focus on constructability, fabrication, operability, safety and cost advantages offered by the next generation of FPSOs.*

### INTRODUCTION

Offshore oil production began in the early 20<sup>th</sup> century and by 1930 oil drilling was being undertaken by derrick systems located more than a mile offshore (although the water depth at the drill sites was still limited to less than 5m). As oil and gas exploration moved into deeper waters away from existing infrastructure self-contained floating production systems were introduced. The first floating, production, storage and offloading vessel (FPSO), Shell's Castellon, was installed in 1977 [Ref 1]. Since this time the industry has seen a large and diverse suite of different FPSO solutions, from converted tankers to purpose-built barge shaped vessels. Until recently,

most FPSOs had one thing in common; the design philosophy was based on classic ship-shaped vessels. While a ship has beneficial characteristics for transporting cargo from one location to another, with great maneuverability and little water resistance, its slender and non-axisymmetrical shape presents major disadvantages when permanently moored in one location.

One such disadvantage is that ship-shape vessels must be able to align themselves with the predominate seastate to minimize their motions and vessel stresses. The oil and gas industry mitigated this problem by developing turrets and swivels, which allowed the ship-shaped vessels to weathervane into the predominant seastate. Though swivels and turrets allow ship-shaped vessels to weathervane, they are costly, have long lead times and are typically available from only few specialized designers and fabricators. Swivels and turrets also have associated maintenance requirements and potential downtime (from leaking seals, for example).

Slender ship-shapes are subjected to significant bending loads due to hogging and sagging and, as a result, are subject to fatigue damage. In the case of converted hulls, the fatigue problem is exasperated when using hulls built after 1985 where high tensile strength steel was used extensively to reduce weight. Ship-shapes are also less efficient in storage volume per plated area than more compact shapes of the next generation round-shaped FPSOs.

To overcome short comings associated with using traditional ship-shaped vessels for FPSOs, the industry is now developing fit-for-purpose FPSOs. Unlike traditional ship-shaped FPSOs, which must weathervane into the predominate seastate to minimize water resistance and motions, the next generation FPSOs are being designed to have similar motion characteristics from all directions and to eliminate yaw excitation. This eliminates the need for a costly turret and

swivels, minimizes the bending loads and fatigue and increases the storage capacity per plated area. Round-shaped FPSOs also have the advantage of being more easily approachable by service and installation vessels with minimum collision risk. However, the next generation fit-for-purpose FPSOs are integrating proven technologies into their designs for mooring, risers and offloading systems. This limits the risk associated with a “new concept, new technology” which is important for operators in a conservative industry such as the oil and gas industry. Figure 1 shows a typical ship-shaped FPSO and the round-shaped SSP.



**Figure 1. A TYPICAL SHIP-SHAPED AND ROUND-SHAPED FPSO**

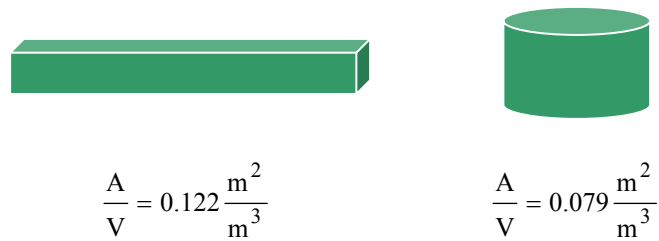
As can be seen from Figure 1, the SSP consists of a hull in form of a truncated cone, and a center column extending from the keel. At the bottom of the center column is a mass trap, which increases the natural pitch period by adding a large amount of entrapped seawater that must be moved during pitch motions. At the bottom of the keel is a bilge keel which reduces heave motions.

**HULL EFFICIENCY AND STRUCTURAL BEHAVIOR**

One way to minimize FPSO fabrication costs is to reduce the plated area (i.e., reduce steel tonnage) for a given storage capacity. In general, for any type of simple body, the shorter the longest distance between two points is, the smaller the surface area per volume. A simple example is illustrated in Figure 2 where a rectangle having typical length, width and height ratios for a ship-shaped FPSO is compared with a cylinder of typical ratios for a round-shaped FPSO. Both bodies have the same volume, but as can be seen in the figure, the surface area is about 50% larger for the rectangle. This illustrates one of the major advantages of a round-shape FPSO; it can have less plated area for a given storage volume, which minimizes the steel tonnage and associated costs with the plated shell structure of the hull. These savings are even further amplified when one considers that new-built FPSOs require a double hull.

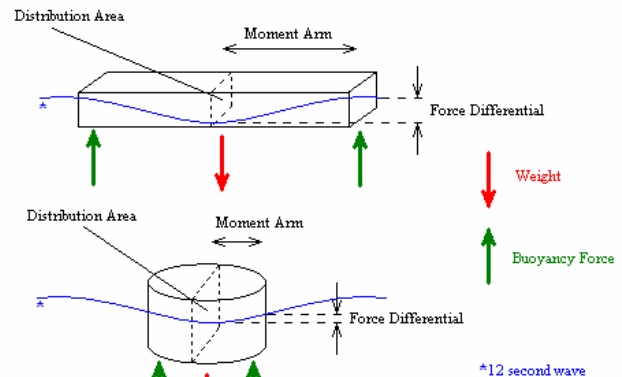
Another driver of structural steel weight in traditional ship-shaped FPSOs is the hull stiffening required to meet the strength and fatigue loading to resist repetitive hogging and sagging bending loads. It is well known [Ref 2] that a major

concern with converted tankers is crack propagation and fatigue



**Figure 2. AREA TO VOLUME RATIO COMPARISON OF A RECTANGLE AND CYLINDER**

in structural connections. Mitigating these problems can require significant structural stiffening and frequent inspections. Extreme bending loads and stresses are significantly higher in a long slender body, such as a traditional ship-shaped FPSO, as compared to a more compact body such as the round-shaped FPSOs. Figure 3 is helpful in illustrating this phenomenon.



**Figure 3. FORCES, BENDING MOMENT AND STRESSES IN A RECTANGLE AND CYLINDER SUBJECTED TO WAVE LOADING**

Consider the two bodies shown in Figure 3 to be under the influence of a typical long period wave. The figure shows the wave when the trough passes the midpoint of the vessels. As the figure indicates, the center of gravity (i.e. the midpoint) is supported by very little buoyancy for the ship-shape with the buoyancy being concentrated at the bow and the stern of the vessel. This means that the buoyancy forces at the bow and the stern (the arrows pointing upwards) will be significantly larger for a ship shape than for a round shape, where the buoyancy is more evenly distributed along the vessel due to the more compact shape. Due to the lower buoyancy concentration at the bow and the stern and the shorter moment arm (midpoint-to-bow/stern distance), the bending moment arm is smaller than

a comparable traditional ship-shaped FPSO. As a result the reduction in bending moments comes from both the reduction in buoyancy force differential between the center and bow/stern and the reduction in moment arm for a round-shaped vessel.

The vessel's ability to "take load" is determined by the section modulus. In general, round-shaped FPSOs have a deeper depth than traditional ship-shaped FPSOs, and as a result, the cross-sectional area is larger and hence the unit has a larger section modulus. Therefore, even if the bending moments are the same, they would create lower stresses for a round-shaped unit than for a ship-shaped vessel.

In summary, three major components; reduced buoyancy variation, shorter moment arm and larger section modulus lead to reduced stresses and hence improve the strength behavior of a round-shaped FPSO when compared with a traditional ship-shaped FPSO. For waves with short wave periods, the distances between the wave crests will be shorter and the variations depicted in Figure 3 will be smaller. These waves, however, have smaller wave heights and hence generate smaller loads.

## MOTIONS

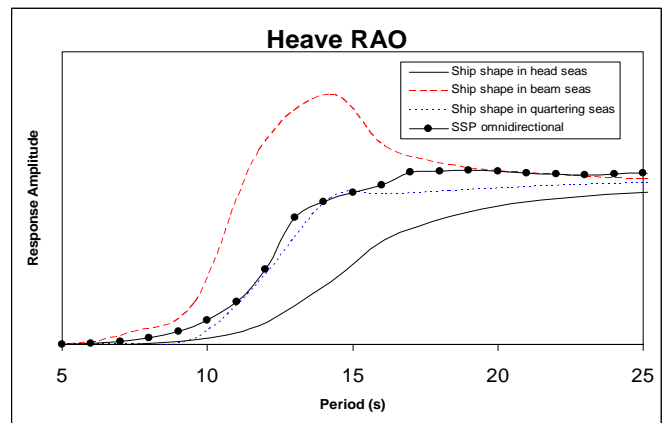
The motions characteristics for the various next generation round shape FPSOs vary, but they have the common benefit of having motions essentially independent of seastate direction and minimal yaw excitation due only to mooring and riser asymmetry whereas ship-shape motions vary considerably from head to beam seas. Unlike a typical ship-shape, round vessel motions can be described by three degrees of motion; roll/pitch, heave and surge/sway. As a result, the next generation round shape FPSOs eliminates: 1) the need for an expensive turret and swivels and 2) riser clashing and clearance issues associated with turrets.

The minimal yaw excitation in combination with the favorable motion characteristics regardless of seastate direction and the large freeboard allow round-shaped FPSOs to remain on location during severe storms, even extreme hurricanes, while traditional ship-shaped FPSOs generally abandon location. This means a ship-shaped FPSO needs to shut-in production, disconnect the riser turret, abandon location, weather the storm, return to location, reconnect the turret and restart production, while a permanently moored round-shaped FPSO only needs to shut-in production, survive the storm and restart production. The need to abandon location for a traditional ship-shaped FPSO, therefore, results in significantly more production downtime and the associated loss of revenue.

The heave response of a round-shaped FPSO is highly dependent upon the hull form, but in almost all cases, the round-shaped FPSO incorporates a bilge keel to suppress the heave. Some round shape units, such as the Petrobras MonoBR [Ref 3] improves the heave motion by having a large moon pool in addition to a bilge keel, effectively reducing the water plane area and hence increasing the natural heave period by reducing the restoring force. In the case of the SSP, heave response is controlled by two damping components; diffraction

damping from the sloped sides of the hull and viscous damping from the bilge keel shown in Figure 3.

In the case of the SSP, the heave motions can roughly be described as similar to a traditional ship-shape in quartering seas. Figure 4 shows the heave Response Amplitude Operators (RAOs) for a Gulf of Mexico 100-year hurricane wave for the SSP320 and a typical ship-shaped FPSO with similar storage capacity in head, quartering and beam seas. The SSP heave response is a function of the bilge keel design which, as mentioned previously, is designed to suppress heave motion. While for a nominal bilge keel size, the motion response of the SSP is higher than for a ship-shape in head seas, the motions are significantly better than a ship in beam seas. The heave response of the SSP can be further improved by improvement of the bilge keel design. It should be noted that the fully loaded condition, which gives the highest motion response (i.e. the worst case), for the SSP has been chosen for comparison in both RAO plots.

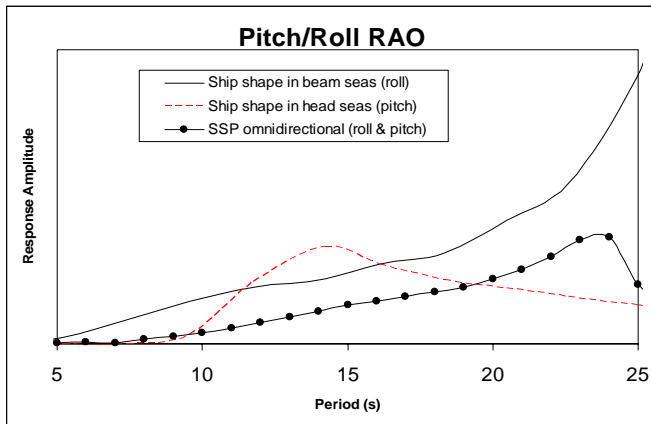


**Figure 4. HEAVE RAOS FOR SSP320 UNDER WORST LOADING CONDITION AND A TYPICAL SHIP-SHAPED FPSO IN HEAD, QUARTERING AND BEAM SEAS**

Figure 5 shows the roll and pitch RAOs for a Gulf of Mexico 100-year hurricane wave for the SSP and a typical ship-shaped FPSO in head and beam seas. For any loading condition other than fully loaded, the SSP320 has better motion performance. The SSP center column design can be "tuned" for a certain environment allowing the corresponding pitch period to be moved further away from the wave period, should this be necessary. For a West Africa environment for example, the entrapped mass increases the natural pitch period by more than 20% compared to a hull-only configuration, and decreases the pitch response by up to 50% for the long wave periods typical of West Africa.

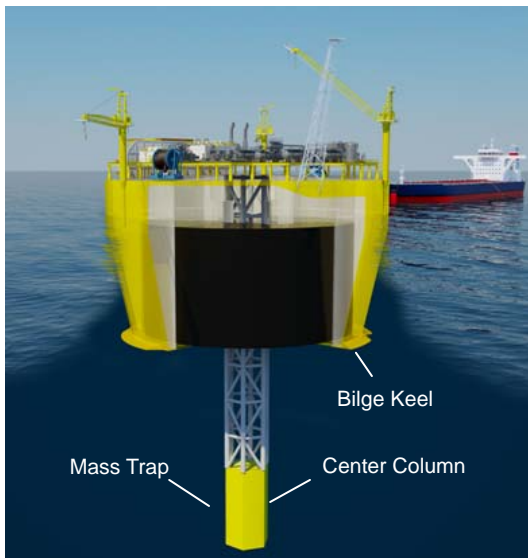
As discussed previously, the distance between the bow and stern of a traditional ship-shaped FPSO is normally significantly greater than for a round-shaped FPSO. As a result, the variation of vertical bow and stern motions as compared to motions at the center of rotation, as plotted in

Figure 4, will be larger for a ship-shaped unit than for a round-shaped FPSO.



**Figure 5. ROLL AND PITCH RAOS FOR SSP320 UNDER WORST LOADING CONDITION AND A TYPICAL SHIP-SHAPED FPSO IN HEAD AND BEAM SEAS**

For round shape FPSOs, another factor that controls the natural pitch period is the keel-to-mass-center distance. The greater this distance is the longer the natural pitch period. This method of improving pitch response, however, may have an adverse effect on the stability of the vessel. However, with the SSP and its unique center column, the natural pitch period can be tuned to a favorable value without having any negative effect on the stability of the vessel. This allows the SSP to have minimal capsizing potential yet maintain good motion performance.



**Figure 6. VIEW OF THE SSP320 SHOWING DOUBLE HULL, CRUDE CARGO TANKS AND CENTER COLUMN**

If a vessel is exposed to a steady current of high velocity, vortices may be shed by the hull in a harmonic pattern. These vortices can cause the vessel to surge/sway or roll/pitch, a phenomenon known as Vortex Induced Motion (VIM). Due to the slenderness of a ship-shaped unit, these motions could

become unpredictable if the current was coming beam on to the vessel. The impact of VIM is a design issue that must be considered when evaluating turret-mooring (which mitigates the problem) versus a spread-mooring (which might be feasible if the extreme currents have some certain degree of directionality to them). For a round shape unit, the vortex pattern is practically independent of flow direction. For the SSP, the varying diameter throughout the water column ensures that the vortices are shed at different frequencies, eliminating the potential for a clear lock-in phenomenon at a natural surge/sway or roll/pitch period. This VIM-suppressing design feature is unique to the SSP.

### FREEBOARD

Since the water plane area for a given storage volume is smaller for a round-shaped FPSO than for a ship-shaped, a round-shaped unit can be designed to have significantly larger freeboard than a ship-shaped vessel. A typical converted tanker may have as little as 6m freeboard in the fully loaded condition, while the SSP320, for example, never has less than 18m. This increased freeboard reduces the risk of green water. As shown in Figure 7, the traditional ship-shaped FPSO tends to “dive into” the wave whereas for the SSP the center column induces surge-pitch coupling for long waves, shifting the center of rotation of the SSP downward, and causing the SSP hull to pitch “away” from the wave. In other words; although the mean pitch during all operational conditions is zero, for hurricane waves, the maximum pitch amplitude is smaller in the direction facing the oncoming waves, hence increasing the freeboard towards the waves. This further reduces the potential for green water on the deck.



**Figure 7. SSP VERSUS TRADITIONAL SHIP-SHAPED FPSO RESPONSE UNDER 100-YEAR GULF OF MEXICO HURRICANE WAVES [Ref 4]**

### STABILITY

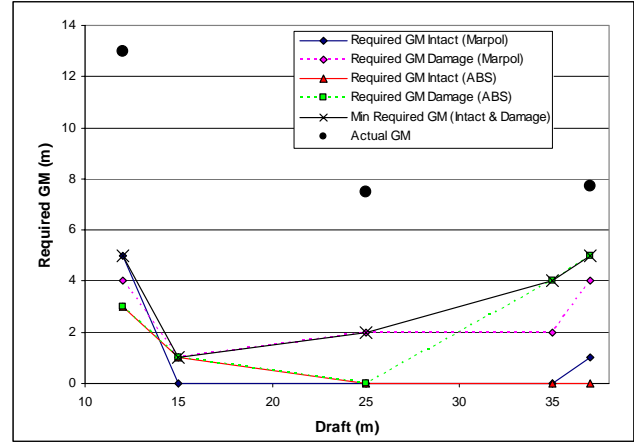
The stability criteria applicable to all FPSOs, as stated by MARPOL and ABS, are given in MEPC Resolution 139(53) as amended by Resolution 142(54) “Guidelines for Application of MARPOL Annex I Requirements to FPSOs and FSUs” – July 2005 and ABS “Rules for Building and Classing Mobile

Offshore Drilling Units”. The MARPOL side penetration criterion requires that a steady heel angle of less than or equal to 25° must be maintained for an extreme side penetration. The extreme side penetration distance is taken as the smaller of 38ft (11.5m) and one-fifth of the breadth (B/5) of the vessel at the deepest draft.

Ship-shaped FPSOs need active ballasting in order to maintain stability and operability while loading and offloading. As with any major operational procedure, active ballasting poses safety issues with respect to control systems/piping problems as well as the human error factor, in addition to adding CAPEX and OPEX costs. Some round shape units require active ballasting to maintain good motions as well, but the SSP design eliminates the need for an active ballast system and a pre-specified tank filling sequence. Elimination of the active ballast system requirements for the SSP is possible due to the hull configuration, i.e. short distance between the bow and the stern and sloped sides. Regardless of loading sequence, the weight from the crude oil tends to be concentrated towards the middle of a round-shaped unit, as compared to the more distributed weight in a traditional ship-shaped unit. As a result, the static moments that are associated with list and other imbalances are minimized in a round-shaped FPSO such as the SSP. As mentioned previously, this design also minimizes hogging and sagging for a round shape FPSO such as the SSP thus reducing associated fatigue problems.

In order to meet and exceed all stability criteria without having to utilize an active ballast system, the inner hull of the SSP was moved to the position shown in Figure 6. This unique design feature keeps the crude cargo tanks out of the damage zone. This means that only the double hull tanks and not the crude tanks become flooded during a catastrophic hull penetration. This has two major benefits; minimizing the risk for crude release during a catastrophic event and minimizing the list associated with a hull penetration. Damaged stability analysis of the SSP320, as shown in Figure 6, with a six tank configuration indicated the SSP320 is able to maintain good stability even in the damaged condition with the static heel angle being significantly less than the MARPOL specified limit of 25°. As shown in Figure 8, all minimum metacentric height requirements were exceeded by at least 50%.

Another advantage of the SSP hull tank compartmentalization is that the crude tanks extend from the bottom of the hull all the way up to the deck, which increases the keel-to-mass-center distance, hence decreasing the metacentric height and increasing the natural pitch period, and thus further lowering the SSP pitch response.



**Figure 8. MINIMUM REQUIRED VERSUS ACTUAL GM FOR SSP320 DRAFTS RANGING FROM BALLASTED TO FULLY LOADED**

### TANK COMPARTMENTATION

Sector-annular cylindrical crude tanks (pie-shaped tanks with inner radial truncation) typically found in round shape FPSOs offer a major advantage over typical rectangular shaped crude tanks found in traditional ship-shaped FPSOs; where sloshing is not a significant factor in determining maximum tank size. Figure 9 shows the sloshing natural period versus filling ratio for a SSP320 tank and a rectangular tank with a typical height for a ship-shaped FPSO. The rectangular tank was chosen to fit within a hull of a ship-shaped FPSO and has a volume such that the same filling ratio for the pie shaped and the rectangular tank gives the same volume. The first natural sloshing frequency for a rectangular tank is given by:

$$\omega_1 = \sqrt{\pi \frac{g}{a} \tanh\left(\pi \frac{h}{a}\right)} \quad (1)$$

where  $g$  is the gravitational acceleration,  $a$  is the length of the tank in the direction of sloshing and  $h$  is the fill height in the tank.

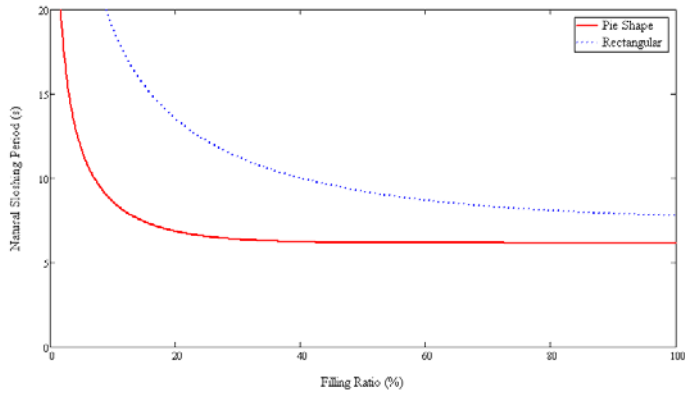
For a sector-annular cylindrical tank (pie-shaped) the first natural sloshing frequency is given by:

$$\omega_1 = \sqrt{\frac{g\lambda_1}{a} \tanh\left(\frac{\lambda_1 h}{a}\right)} \quad (2)$$

where  $g$  is the gravitational acceleration,  $a$  is the outer radius of the tank,  $h$  is the fill height in the tank and  $\lambda_1$  is the first (i.e. smallest) solution to the following equation:

$$J'_{1/2\alpha}(\lambda)Y'_{1/2\alpha}(\lambda b/a) - J'_{1/2\alpha}(\lambda b/a)Y'_{1/2\alpha}(\lambda) = 0 \quad (3)$$

where  $J$  is the Bessel function of the first kind,  $Y$  is the Bessel function of the second kind,  $b$  is the inner radius of the tank and  $\alpha$  is the angular extent of the tank.



**Figure 9. NATURAL SLOSHING PERIODS FOR PIE-SHAPED VERSUS RECTANGULAR TANK OF EQUAL VOLUME**

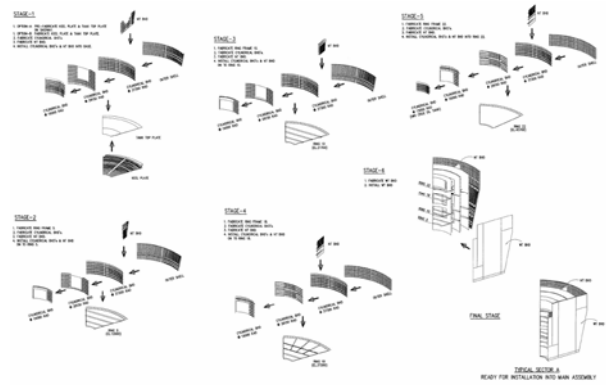
The plot clearly indicates a lower natural sloshing period for the pie shaped tank. A low natural sloshing period will be away from the peak wave periods in severe seastates, hence eliminating excitation, which will result in lower sloshing forces. In addition to the lower natural period, a pie shaped tank provides more damping from the sides due to the triangular shape as compared to a rectangular shape where the sides are perpendicular to the sloshing wave. For this reason, ship-shaped FPSOs usually utilize smaller tanks. This results in the need for additional steel and the associated costs. The number of tanks and maximum tank sizes for round-shaped FPSOs are typically not controlled by sloshing loads but determined based on stability criteria and operational and maintenance requirements.

**CONSTRUCTION BENEFITS**

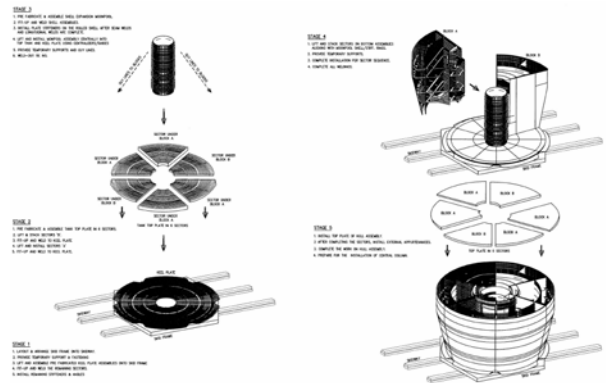
Due to simple block construction, most round-shaped FPSO fabrication can take place in virtually any fabrication yard in the world. This means added flexibility when selecting a fabrication contractor offering an advantage over traditional ship-shaped FPSOs, which require a dry dock and thus must be built in a ship yard. Given the current backlog in most ship yards, this flexibility not only increases competition but may also offer schedule advantages for a round-shaped FPSO over traditional ship-shaped FPSOs.

Figures 10 and 11 show schematics of how in principle round-shaped FPSO construction may be performed. The particular sequences shown in Figure 10 and 11 are merely an example preferred by one particular fabricator for one particular fabrication yard. However, the construction sequence clearly shows the repetitive nature of the construction

process. It should be noted that there are several different fabrication options, which could be used for the construction of a round-shaped FPSO, which are dependent on installation equipment and fabrication yard size. For example, the section-attachment method in the Figure 10 and 11 could be substituted by simple bottom-to-top fabrication.



**Figure 10. REPETITIVE CONSTRUCTION OF ROUND-SHAPED FPSO TANK SEGMENTS**

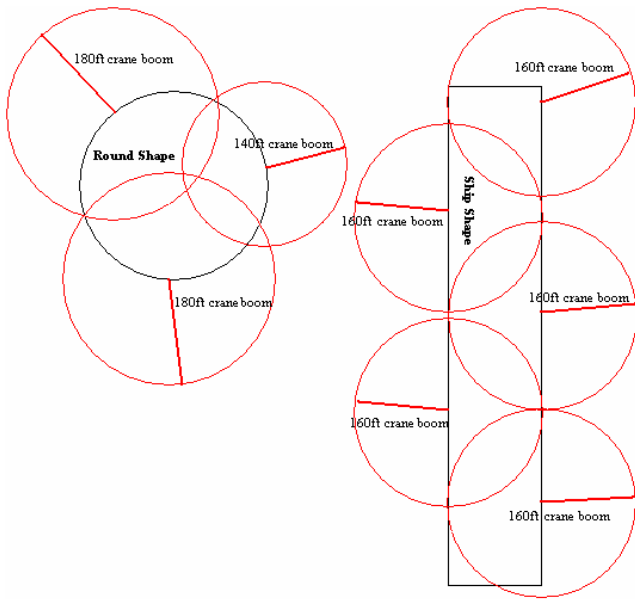


**Figure 11. ONE POSSIBLE ROUND HULL CONSTRUCTION SEQUENCE**

**TOPSIDES ARRANGEMENTS**

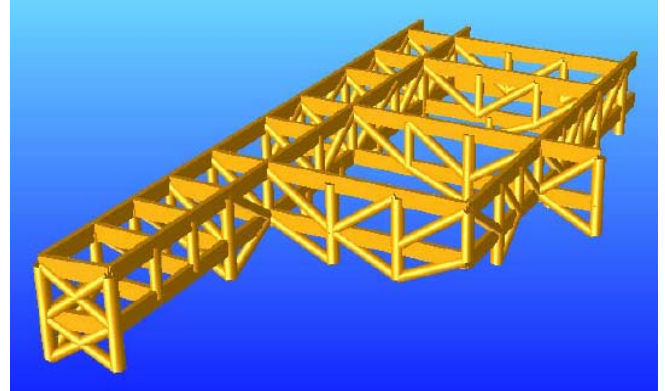
Typically the longest horizontal distance between two points on a round shape unit is less than half that of a traditional ship-shaped unit of the same storage capacity. This significantly reduces the length of piping and cable runs. The round shape FPSO also offers more flexibility in topsides arrangements than traditional ship-shape FPSOs where modules must be aligned along the axis of the deck. On a round-shaped FPSO for example, an operator can have a topside arrangement similar to those used for years on fixed platforms, Spars and tension-leg platforms (TLPs).

Crane accessibility is also better on a round-shaped FPSO than a traditional ship-shaped FPSO. As shown in Figure 12, the SSP320 deck layout is designed so that each point on the deck can be reached by one or more of three cranes; two 180ft boom cranes and one 140ft boom crane. To accomplish the same coverage for a similar capacity ship-shaped unit, at least five cranes with booms exceeding 160ft would be required. This is not cost efficient and as a result ship-shaped units make extensive use of monorails.



**Figure 12. TOPSIDES CRANE ACCESSIBILITY OF A ROUND VERSUS SHIP-SHAPED FPSO**

Figure 13 shows the module support frame for one quadrant of the SSP320. The module support frame offers greater flexibility in the module integration phase. Its design allows modules to be pulled/winched into location from the periphery of the SSP320, thus minimizing the need for extremely large shore cranes (with extended reach and height) and minimizing the need to turn the SSP320 at the quayside to facilitate exact module lifting/placement.



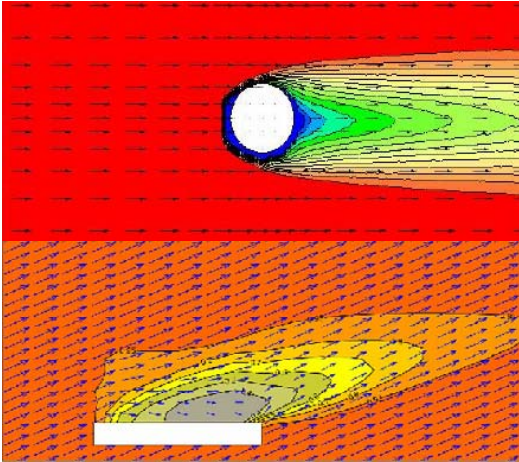
**Figure 13. TOPSIDES MODULE SUPPORT FRAME FOR ONE QUADRANT OF THE SSP320**

**OFFLOADING BENEFITS**

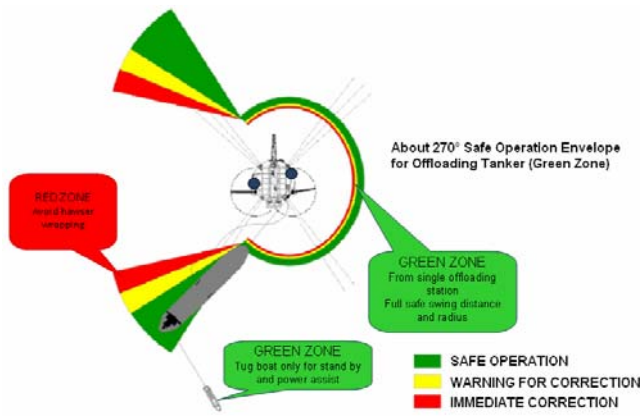
The independence of seastate direction on round-shaped FPSO motions also has significant benefits for offloading. The round shape provides significant shielding from waves, winds and current. Figure 14 shows current induced velocity fields on the leeward side of the vessel for a round-shaped versus a traditional ship-shaped FPSO. The figure clearly shows that for a round-shaped FPSO, a predictable and smooth velocity field pattern is generated as the current flows around the vessel, whereas for a ship-shaped FPSO, an asymmetric pattern develops on the leeward side. The resulting flow pattern on the leeward side of a round-shaped FPSO minimizes fish-tailing and the collision risk when compared to a traditional ship-shaped FPSO.

By utilizing an offloading reel station with the hose and mooring hawser attached on a pinned connection (which allow for horizontal rotations) on a 90° trackline system at the periphery of the SSP, an approximately 270° large operating envelope, as shown in Figure 15, can be ensured where the offloading tanker-of-opportunity can stay shielded on leeward of the vessel without requiring a dynamic positioning (DP) system.

In the case of the SSP320, wave heights are reduced up to 33% on the leeside of the SSP; wind speeds are reduced up to 60% even 250m leeward of the SSP, and current is reduced up to 25% [Ref 5]. Although a ship-shaped FPSO has great potential for shielding in beam seas, an offloading operation would become risky due to the unpredictable nature of the wave and current flow around a long slender body. In beam seas, the ship-shape also experience large wind, wave and current forces, with a potential for significant drift forces and motions as a result. In case of the SSP, if the seastate direction should change during offloading, the offloading tanker would simply rotate along the offloading trackline of the SSP and stay in the shielded area. For a ship-shape FPSO, the shielded field could change significantly during directional changes in the seastates.



**Figure 14. EXAMPLE OF SHIELDING FROM CURRENT ON A ROUND SHAPE VESSEL VERSUS A TRADITIONAL SHIP-SHAPED VESSEL**



**Figure 15. OFFLOADING ENVELOPE FOR THE SSP**

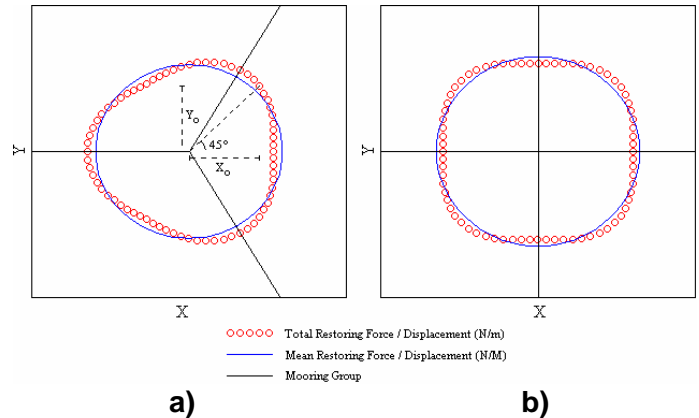
### MOORING SYSTEM

A moored ship-shaped FPSO is either turret moored or spread moored. If the FPSO is turret moored, a three-group mooring configuration can be implemented, but this still requires a costly turret. If the FPSO is spread moored, the geometry of the ship-shaped FPSO prevents the utilization of three mooring groups and four groups need to be used. A round shape unit has no such limitations, and as a result, an optimal three-group mooring system can easily be implemented without the need for a turret. The same readily available chain sizes, fairleads and other standard mooring equipment can be used for a round-shaped FPSO as is currently used for ship-shaped FPSOs.

Figure 16 shows the result of simplified mooring analysis for two mooring systems; one mooring system with three groups and one mooring system with four groups. The plots in Figure 16 indicate the total restoring force from all mooring

groups in the x-direction and y-direction per displacement length of the unit. For example, in Figure 16 a) the total restoring force from all mooring groups in the x-direction is  $X_0$  if the vessel is displaced one unit length in the direction of positive  $45^\circ$ . The circles indicate the mean total restoring mooring force of all directions.

Considerable simplifications were used in the analysis (for example, the mooring groups were described as linear springs), but the indicated trends are accurate.



**Figure 16. TOTAL RESTORING FORCE PER UNIT DISPLACEMENT FOR A THREE VERSUS FOUR GROUP MOORING SYSTEM**

As can be seen in Figure 16a and b, the most critical direction (i.e. the direction that will provide the least restoring force per unit length displacement) is parallel to a mooring group, but in the opposite direction. That means that the largest displacement of the vessel will occur if the seastate direction is from the anchor towards the vessel parallel to and along a mooring group. For such a case, the total restoring mooring force comes essentially solely from the mooring group parallel to the seastate direction with the anchors pointing towards the oncoming waves, wind and current. If four groups of three mooring lines (a total of twelve mooring lines) would be utilized, three mooring lines (i.e. one mooring group) would need to be sized to take the maximum drift loads from the vessel, while if three groups of four mooring lines (also twelve mooring lines) would be utilized, four mooring lines would take the same drift loads. Hence, they could be smaller and therefore less expensive. This also presents benefits in the case of a failed mooring line. For the 3 groups of 4 lines configuration, the restoring mooring force would be reduced by 25% in such a case, while for the 4 groups of 3 lines, it would be reduced by 33%. However, it should be noted that the round-shaped units experience higher drift and current loads than a ship-shaped in head seas, hence requiring a heavier and more costly mooring system than a ship-shaped unit that utilizes a turret. On the other hand, a turret represents a significant extra cost.

## RISER DESIGN

The round shape and the absence of a turret provide flexibility in riser spacing with a reduced risk of clashing. The short bow-to-stern distance ensures minimum force imbalance from the weight of the risers. On turret moored ship-shaped FPSOs, the risers are generally located within the turret, which usually is at the bow of the vessel. This location on the vessel can experience quite large vertical motions due to heave combined with pitch. For spread-moored ship-shaped FPSOs, the risers are usually located around the middle of the vessel to reduce the vertical motion due to pitch. For a round-shaped FPSO such as the SSP, the risers may be located anywhere on the periphery.

As mentioned previously, a round-shaped unit does not need to disconnect, but only shut-in production, during an extreme event, which minimizes production downtime, while a ship-shaped FPSO needs to shut-in production, disconnect the riser turret, abandon location, weather the storm, return to location, reconnect the turret and restart production.

In West Africa environments, the SSP320 has motions comparable to spread moored ship-shaped FPSOs. A riser study [Ref 6], based on the RAOs of the vessel confirmed that, depending on water depth, environmental conditions and riser sizes, SCRs, lazy wave SCRs or Free-Standing Hybrid Risers are feasible options for production, service and export risers.

## SUMMARY AND CONCLUSIONS

A comparison of next generation round fit-for-purpose hull form FPSOs and traditional ship-shaped hull forms with respect to hull efficiency, structural behavior, motions, freeboard, stability, tank compartmentation, construction, topsides arrangement, offloading, mooring systems and riser design were discussed. Most FPSOs, to date, have used traditional ship-shape hull forms due to their ready availability. However, as the existing supply of convertible tankers diminishes, the industry must turn to new hulls or fit-for-propose hull forms.

When observing and comparing the design premises for FPSOs and tankers, one significant restriction that applies only to tankers is that a tanker must have great maneuverability and small water resistance to efficiently transport goods. This is not a design requirement for FPSOs.

The next generation of round shape FPSOs presents several significant advantages over the traditional ship-shaped units. Due to the more efficient storage shape and the smaller bending loads, a round shape is structurally more efficient with steel weight savings as a result. The pie-shaped tanks in round-shaped units create smaller sloshing forces than the rectangular tanks found in ship-shaped units, providing additional savings in structural reinforcement. For a round-shaped FPSO, the motions are similar from all directions with little to no yaw excitation. This eliminates the need for a costly turret and swivels, provides increased flexibility in riser spacing and provides the operator with the option to stay on location during

extreme events, further reducing costs and lost revenue associated with extended shut-ins.

The round shape FPSO allows for larger freeboard, which in combination with the short bow-to-stern distance decreases the risk of green water on the deck, as compared to a ship-shaped unit that “dives into” the waves. The simple block construction and repeatable fabrication enables construction in almost any fabrication yard worldwide. This means added flexibility when selecting a fabrication contractor whereas traditional ship-shaped FPSOs require a dry dock and thus must be built in a ship yard. Given the current backlog in most shipyards, this flexibility not only increases competition but may also offer schedule advantages for a round shape FPSO.

The round-shaped units have the benefits of traditional offloading CALM buoys “built into” the structure with regards to shielding and reducing fish-tailing and minimizing collision risk. As a result, offloading can be done using tankers-of-opportunity without the need for a DP system tanker or a dedicated CALM buoy, thus providing an opportunity for significant CAPEX saving.

The industry has only recently seen the first deployments of round-shaped FPSOs (although more concepts are currently under development), and given the advantages of round-shaped FPSO, the future seems likely to hold a large and diverse set of round-shaped FPSOs.

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