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Vessel to Vessel Fluid Transfer Line Alternatives and Costs for the Gulf of Mexico

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Abstract

The transportation of stabilized crude by shuttle tankers instead of by pipeline offers cost and market flexibility advantages. The stabilized crude is stored on an FSO for periodic offloading to shuttle tankers. Fluids are transferred between Dry Tree Units (DTUs) such as Tension Leg Platforms and Spars and the FSO by means of Fluid Transfer Lines (FTLs). Additional cost benefits can be obtained by splitting the facilities between weight sensitive Dry Tree Units and the FpSO. An overview is presented regarding the practicality, cost and selection of vessel to vessel FTLs for use in the Gulf of Mexico. Four different FTL configurations are investigated: Flexible and steel W-Wave (near-surface) risers, Flexible Free-hanging catenaries, and a Steel Catenary Riser (SCR) and Steel Lazy-Wave Riser (SLWR) combination that extends to the seabed. Installation and material costs are presented. Attention is focussed on flow assurance – especially as regards pipe sizing and insulation requirements. A base case is selected, and sensitivity studies are carried out for three vessel separations and for three water depths.

Introduction

The conclusions of the 2001 OTC paper on shuttling in the Gulf of Mexico serve as a starting point for this paper, (Ref. 1).

The conclusions were that:

- Given the current world energy market and the US demand for energy resources, deepwater exploration in the Gulf of Mexico (GOM) will continue at a rapid pace
- The active GOM exploration programs will likely identify substantial discoveries spurring field development technology.
- These discoveries will be located further from existing field infrastructure requiring additional existing infrastructure and development of new transportation systems.
- Shuttling is a proven offshore transportation technology that is in use globally operating in both benign and harsh weather conditions.
- Both pipeline and shuttling transportation systems will be essential to meet the volume requirements of the Gulf of Mexico and energy demand of the US.

The type of field layout that is particularly suited to the employment of shuttle tankers is shown in Figure 1. The goal is to minimize DTU cost by placing as much of the processing facilities on a FpSO. The storage offers the developer the option of offloading stabilized crude to a shuttle tanker – increasing infrastructure independence and lowering cost, while avoiding the need to tie into an oil export pipeline system. (There is still the need to tie into a gas export pipeline system.)

One of the keys to reducing costs is to transfer the maximum amount possible of facilities from the DTUs to the FpSO on account of the reduced cost of FpSO “real-estate.” This requires the presence of FTLs, for which there are a number of alternatives. Separations between the platforms can be significant because the FpSO must be turret moored. The separations will be of the order of 2000m or 3000m unless the vessels are coupled through their moorings. Operators are likely to have their own ideas as to the vessel separation needed for ensuring safety. The operator will want to consider a number of FTL possibilities. Detailed investigation requires simultaneous consideration of processing, flow assurance, mooring and vessel dynamics, riser behavior, installation, and of course cost. This may have to be repeated for each option. Prior to investing in such work most operators ask two questions “What will it take to ensure uninterrupted flow of the fluids?” and “What will it cost?” Only then is the typical operator likely to undertake one or more detailed investigations. The task of the designer is to shorten this process through a quick consideration of the essential features of the competing systems and of their material and installation costs. It is convenient to have some idea of how the likely choice and costs of FTLs vary with water depth and with vessel separation.

The approach followed here is to rely on static sizing achieved through the use of the ubiquitous spreadsheet. While it is fully appreciated that one can never be sure of the viability of any dynamic system until extreme responses and fatigue lives have been determined, it is felt that static sizing (and cost estimation) represents for most people the proper starting point. After static viability has been established, and an understanding of the cost drivers has been gained, then the operator can proceed to undertake a sound, rapid investigation of the dynamics.

The three most likely FTL configurations are the simple catenary riser, the W-Wave riser, and risers going to and from the seabed. A selection is shown in Figure 2. At this time, the usual choices for the materials are non-bonded flexible pipe and steel. Operators may well want to consider composite risers and non-traditional forms of flexible pipe. Most operators will probably prefer first to consider the more traditional materials.

In this study the processing has been split as shown simplistically as shown in Figure 3. As much of the process system as possible has been moved from the DTU to the FpSO.

Dry Tree Units, FSOs and FpSOs

Dry Tree Units (or Platforms) such as TLPs and Spars are often selected for deepwater field development because of the following benefits:

- Direct well accessibility for workover,
- Better reservoir testing and monitoring,
- Better flow assurance, and
- Increased recovery.

The benefits are in comparison with a typical wet tree development alternative that does not permit direct well access.

A number of Dry Tree Units (DTUs) exist in deepwater Gulf of Mexico (GOM) and several more are under design and construction. TLPs have been installed in up to 4,000ft water depth in the GOM and announced projects will extend the water depth range of TLPs to about 4,800ft. It is generally considered that mini-TLPs can be applicable in the GOM in up to 6,000ft water depth. Spars have been used in up to 4,800 ft water depth, and are considered to be applicable in the full range of water depths, up to 10,000 ft and beyond.

Oil and gas from the DTUs that are currently operating in the GOM is exported through pipelines. As developments move into deeper water, it becomes attractive to consider other alternatives such as shuttling. A robust shuttling system for first of a kind GOM application is likely to make use of a turret moored FSO and DP shuttle tankers, although a variety of other alternatives are also possible. In the present study, one or more DTUs with full process topsides are considered in the base-case field development scenario together with an FSO. Halliburton KBR's Offshore Technology Department was contracted by Conoco to carry out this work.

An FSO or FpSO provides inexpensive deck area and payload capacity compared to a dry tree unit such as TLP or Spar. Between and FSO/FpSO and a TLP or Spar, there is an order of magnitude difference in the cost to support payload in $/lb. Therefore, it is logical to consider splitting the total process/utility/drilling payload between the DTU and the FpSO so that the total cost of the overall field development is minimized. The prize associated with split facilities depends on project specific requirements such as the water depth, production rate, drilling requirements, etc. Technology and costs associated with the fluid transfer lines between the FSO/FpSO and DTU are major issues, and are the subjects of this paper. The scope of the Halliburton KBR study included a high level assessment of the prize associated with splitting the process facilities and moving some of the facilities to FSO.

Shuttle tanker offloading and the platform-to-vessel separations that are involved require consideration. These issues in turn affect riser top separation. Coupling of the moorings has been proposed (Ref. 2). Side-by-side shuttle tanker offloading is then required with its attendant uncertainty of waiting on weather. (See Figure 4.)

The ability of the turret of the FpSO to accommodate the risers was checked. Since the number of risers is not excessive (perhaps a total of four to six risers) weight and space limitations were not encountered.

Facilities Split

The facilities split approach involves using the DTU as a wellhead platform and initial gas separation facility, thus minimizing the size and cost of the platform. The unstabilized crude will then be transferred to the FSO, which now becomes a FpSO with second stage separation facilities, in addition to oil storage capability.

For this study the facilities are considered to be inherently minimized to produce oil having a vapor pressure suitable for storage in the FpSO (Reid Vapor Pressure = 12 psia) and gas dehydrated and compressed for export via pipeline. The facilities therefore consist of the following:

- Multistage separation of oil, gas and water
- Electrostatic dehydration of the oil
- Gas Compression to an export pressure of 2000 psia
- Gas dehydration
- Water Treating for overboard disposal
- Power Generation and distribution
- Typical utility systems – fuel gas, compressed air, cooling water, heating medium, etc

All stages of oil and water separation and treating downstream of inlet separator are moved to the FpSO. The oil and water separated in the inlet separator are pumped to the FpSO at a pressure to maintain the transfer line free of gas. The oil may require heating to prevent deposition of wax in the transfer line. Gas compression and treating is also moved to the FpSO. The facilities on the DTU are minimized to those required to support a minimum operation. Several utility systems must be duplicated.

There are a total of three Fluid Transfer Lines:

- FTL #1 – 8" ID oil / water line from DTU to FpSO operating at 1350 psi
- FTL #2 – 10" ID wet gas line from DTU to FpSO operating at 1000 psi
- FTL #3 – 3" ID fuel gas line from FpSO to DTU operating at 500 psi

The chief process properties of the three lines are given in Table 1.

Base Case and Sensitivity Cases

The base case is considered typical for "typical" Gulf of Mexico developments in the 1,524m (5,000 ft) water depth ranges. The platform separation (DTU center to FpSO turret center) of 2,000 m closely matches values considered appropriate for such fields. The remaining water depths and vessel separations were chosen to span likely values, with the additional goal of causing step changes to take place in the form of flow assurance requirements, riser configurations and installation vessel capabilities. Two greater water depths were selected for the sensitivity cases: 2,286 m (7,500 ft) and 3,048 m (10,000 ft). The smaller separation of 700 m was selected to cover the case of side-by-side offloading (see Ref. 2). The larger separation of 3,000 m was selected to be representative of an existing case: Liuhua. The possibility exists of coupling the two vessels in the 700m separation case. The size of the low frequency vessel separation envelope can then be decreased.

The dimensions of the base and sensitivity cases are shown in Table 2. The dynamic vessel characteristics are summarized in Table 3. This table shows both the full watch circle radius (one half of the dynamic excursion of the vessel) taking all frequencies into account, and the mean offset when the vessels are acted upon by extreme events such that both vessels are displaced in the same direction. The table reflects the assumption that in depths of 5000ft TLPs will be selected for the DTU. At this time it is likely in depths of 7500ft and greater a spar would be selected.

Since we wanted to investigate the cost impact of selecting a system with a short nominal separation, we modified the 700m separation case dynamic vessel motions to simplistically represent a coupled mooring. Faced with an infinity of possibilities, generic values were selected for the three depths. To keep the number of cases within reason (and realistic) minor changes were made to plausible vessel motion characteristics so that the riser separations are similar at each water depth. This of course means that watch circle diameter as a percent of water depth has to be reduced as shown. The cost associated with this has not been taken account into the economics presented.

Separation Distances

The basic geometry of the system is arrived at through consideration of safety and operations (minimum acceptable vessel separation distances), moorings and vessels, and risers. The starting point is a drawing of the basic geometry of the system. An example is shown in Figure 5. The figure can easily be modified to suit the specific needs of the user.

The mean vessel separation, Sep is defined as the distance between the center of the DTU and the center of the FpSO turret. DTUwr and FpSOwr are the watch circle radii of the two vessels. For purposes of initial sizing it is convenient to group first and second order vessel motions into a single variable per vessel representing the dynamic envelope, in this case DTUdd and FpSOdd. These values are associated with an extreme environment. Mean offsets are implied by the fact that the extremes of each dynamic motion envelope take the vessel to the edge of its respective watch circle. The mean offset is typically given by an expression such as

Mean DTU offset = DTUwr – DTUdd/2.

In our sizing activities we have assumed that the mean offsets of the two vessels will be in the same direction.

DTU center to FpSO turret center separations are given by:

MaxL = DTUwr + Sep – FpSOwr + FpSOdd
MinL = DTUwr– DTUdd + Sep – FpSOwr
MaxR = – DTUwr+ DTUdd + Sep + FpSOwr
MinR = – DTUwr + Sep + FpSOwr – FpSOdd

Vessel separations (between nearest perpendiculars) are given by equations of the form:

MinVSepR = MinR – DTUo2 – FpSOs

Riser top separations are given by equations of the form:

MinRSepR = MinR – DTUo2

The target minimum vessel separation distance for the 2000m and 3000m mean separation distances is approximately 1350m. The minimum vessel separation distance for the case of a 700m mean separation distance will be considerably smaller – of the order 350m to 400m (assuming coupled moorings). The consequences of this need to be taken into account when specifying procedures, and perhaps through the specification of increased station keeping equipment.

An example of the results of such consideration is shown in Table 4. The table presents the results of the consideration of the vessel separations and motions shown in Table 2 and Table 3.

Processing and Insulation

FTL #1: Oil/Water from DTU to FpSO: Liquid is heated to keep operating temperature above wax deposition temperature. (Maximum reported wax appearance temperature is less than 90 deg F.) Operating pressure in the liquid transfer line is maintained above the bubble point to prevent gas breakout.

FTL #2: HP Wet gas from DTU to FpSO: Wet gas is transferred at temperature above hydrocarbon dewpoint and hydrate formation temperature.

Temperature distributions and pressure drops were calculated for each of the three riser configurations shown in Figure 2. The resulting FTL or riser inner diameters (IDs) are shown in Table 5. The required Overall Heat Transfer Coefficients (U-values) are shown in Table 6. None of the flexible risers required insulation beyond that supplied by the layers of the standard designs. Insulation was required for the oil/water and wet gas steel risers.

Fluid Transfer Line Alternatives

Catenary risers. The first alternative is a simple flexible catenary joining the DTU and the FpSO. Catenary risers have the distinct benefit (from static considerations at least) that the configuration will be insensitive to internal fluid density changes as long as a suitable weight in water is chosen when the pipe is empty.

In this paper the flexible pipe analyses are based on rough bore products, as they are the most universally used flexible pipe products. Rough bore is the most conservatively priced product and can be used to identify an envelope to be used during early development costing and planning stages of field developments. The non-bonded flexible pipe properties as supplied by Halliburton Wellstream are given in Table 7 and Table 8. These values were used in all platform to vessel flexible riser sizing activities. When the bottom of any flexible riser exceeded a depth of 500m, the design was switched to the 1000m depth collapse pipe design. “Simple” steel catenary risers were not considered due to lack of time.

During the static sizing a rule-of-thumb was applied that the maximum angle from the vertical at the ends should not exceed 45 degrees. When one riser was located over another, the static sizing was carried out so that the sagbend of the lower riser was about 100m below that of the upper riser.

Until full designs are undertaken, there is a natural concern regarding the viability of catenary risers, as nominal vessel separations increase from, say 2000m to 3000m. From the viewpoint of static analysis, as long as dynamic flexible risers have been employed in water depths comparable to the maximum depth of the sagbend, there seems no *a priori* reason to reject such a riser as being infeasible.

Near Surface W-Wave Risers. The second alternative for the near-surface FTLs is flexible (Ref. 3) or steel W-Wave risers (Ref. 4). Both flexible pipe and steel risers were sized statically. Time constraints precluded the investigation of risers supported at their centers by means of tethered buoys.

The static design of a single W-Wave riser is based on achieving minimum pipe length (and thus cost) with due consideration for the following:

- Need for sufficient depth to reduce wave particle motions to acceptable values.
- Need for adequate clearance between the top of the buoyed arch and passing vessels.
- Need for sufficient tension to avoid excessive lateral motion.
- Requirement for axial tension to be below that causing pipe design problems.
- Combinations of end tension and angles relative to vessels must be below those causing problems for bend stiffeners
- Forces at pipe ends should be below those causing problems for turret and end fittings.

The outside diameter of the distributed buoyancy is initially selected to keep the net buoyancy of buoyed section approximately equal to the weight in water of bare pipe. The vertical excursions of the top of the buoyed arch associated with changes in internal fluid density must be controlled. This is achieved through a suitable combination of pipe weight in air, pipe outside diameter, buoyed length and net buoyancy per unit length. This consideration was addressed by arbitrarily requiring that the top of the buoyed arch be no closer to the surface than ½ of the 100-year return period hurricane design wave. This depth (at which particle motions are reduced to 4% of that at the surface) is 93 m.

If more than one W-Wave riser is present, then clearance between the risers becomes an issue. The value of 100 m seems to be a reasonable starting point for preliminary design. Consequently all static design took place by requiring that the top of the buoyed arch came no closer to the surface than 100 m when the internal fluid density was at its design minimum. Thought must be given to what happens when a riser that is operated with gas as the pipe is filled with water – for example during hydro testing. At such a time the configuration of the W-Wave riser may become close to that of the simple catenary. Two examples of W-Wave sizing are shown in Figure 6.

Risers to and from the seabed. The principal alternatives for risers to and from the seabed are combinations of steel and flexible pipe in traditional configurations (primarily free-hanging catenaries and Lazy-Waves). At the time of writing (February 2002) there is no known track record for 8” ID or greater in depths of 5000ft (1524m) although flexible pipe manufacturers are giving a high priority to the qualification of pipe in these depths. In this paper attention is focussed on steel risers going to the seabed.

There are two main challenges (apart from flow assurance, installation and cost). Challenge #1 is to achieve a satisfactory fatigue life. Challenge #2 is to provide the axial force on the seabed needed to avoid movement associated with displacement of the vessels.

Challenge #1 is addressed somewhat simplistically for the purpose of obtaining riser sizes and costs by assuming that an SCR could be made to work for a DTU consisting of a TLP or spar. At the FpSO it was assumed that a configuration having an appropriate distribution of buoyancy and weight would be needed. A Lazy-Wave riser configuration was selected and sized.

The cost of meeting challenge #2 was on of the focuses of this work. The desired separation beween the DTU and the FpSO (2000m to 3000m for uncoupled moorings) is of same order as the depth. Consequently there will be little pipe on the seabed, and it will be difficult to provide a sufficient length of pipe to generate the needed friction force. (The use of piles has not been investigated but may prove cost-effective.) As it turned out a stable configuration could not be found for such separations, and the nominal separation between the vessels had to be increased to some 6500m to 7500m. Uncertainty in the value of the axial coefficient of friction between steel pipe and the seabed is a concern. Another alternative that was not investigated due to lack of time is that of adding weight to the pipe. An example of the sizing is given in Figure 7. In this spread-sheet based sizing heave has been exaggerated. In the final configuration the riser will not touch the seabed when the FpSO is in the Near position, and the buoyant section will not become horizontal in the Far FpSO position.

Selection and Summary of Riser Cases. The challenge has been to come up with a reasoned, manageable set of cases. As mentioned earlier, advantage was taken of the fact that the moorings are likely to be selected keeping in mind both riser requirements and vessel separation. The result has been that the platform to vessel riser cases are independent of water depth. Flexible catenaries were considered to be the most practical option for the 700m separation case. Flexible catenaries, flexible W-Wave risers and steel W-Wave risers were all investigated for the 2000m and 3000m separations. The cases considered are given in Table 9. The catenary riser sizing was based on two assumptions. The flexible 10" wet gas line will be placed 100m or so above the 8" oil/water line (since it is more expensive to design the 10" line for collapse), and the 3" fuel gas line will be strapped to the 10" wet gas line.

The W-Wave risers were sized with slightly different assumptions: The 3" fuel gas line will be strapped to the 8" oil/water line, and the 10" wet gas line will be located 100m below these lines. This is because should the gas in the 10" line become air filled (a density not far removed from the operational density of 3.6 lb/ft^3) the top of the arch must come no closer to the sea surface than 100m. When the 10" ID riser is filled with water for hydro-testing one cannot prevent the two sagbends from dropping to a depth of about 700m. (This is about 500m below the minimum depth of the arch top when the line is empty). Clearly this particular riser configuration warrants closer investigation. No problems were encountered, empty or full with the 3" fuel gas line, or with the 8" oil/water line, whose internal fluid density is not expected to fall below 46.5 lb/ft^3.

We were unable to achieve viable SCR/Steel Lazy-Wave Riser (SLWR) combinations even for the 3000m separation case using only seabed friction and horizontal forces from the opposing riser to compensate for horizontal forces of the individual risers. Thus there was only one separation studied for each water depth since of course the three FTL alternatives have to have the same top separations. It should be mentioned that a 3" ID flexible fuel gas riser could theoretically be designed for the 10000ft case. Details of the three indirect platform-to-seabed to vessel riser cases considered are given in Table 10.

Results

Results are presented in Table 11 and Table 12. The main purpose of these tables is to provide the input for the cost estimation process. They are included so that anyone who wishes to perform their own cost estimation will have the necessary numbers. (Space limitations precluded listing the information needed to estimate the size and cost of the various bending control devices that are needed.)

In Table 11 two points are interesting. The flexible pipe vertical loads and buoyant uplift requirements are less than those for the equivalent steel pipe. (However the buoyant effect of the insulation on the steel pipe has not been considered.) This is because the flexible pipe has a larger OD; it thus in effect supplies its own additional buoyancy. The large loads associated with the Wet Gas riser are those associated with the FTL full of water, and as stated earlier, it is not possible to compensate passively for this weight due to operational considerations.

Table 12 also contains some noteworthy features, chief of which perhaps is the fact that the platform to vessel separations needed to stabilize the SCR and SLWR configurations are seemingly independent of depth. The length of pipe that never lifts off the seabed and connects the two risers decreases with increasing water depth. This is due to the fact that the watch circles of each vessel, as a percent of the depth, decreases with depth. Loads clearly are considerably higher than for the direct platform to vessel cases. This is partly a consequence of the increased pipe sizes required to keep arrival pressures at the prescribed values.

Cost Comparisons

A cost model has been developed that includes the procurement and installation of the flexible riser and steel riser solutions in all configurations. Some of the principal cost assumptions are shown in Table 13. These rates have been factored down to reflect the complexity of the installation and short lengths of line. Risk was not considered during the cost estimation process. In future studies of this nature we plan to base such work on risk-adjusted costs.

The results of the cost estimation are contained in Figure 8. The cost impact of vertical loads has not been taken into account. Although the vertical load will impact structural costs, in many situations the vertical load can take the place of ballast -- as long as the loads are not too eccentric. Figure 8A is the simplest configuration with a single flexible pipe catenary for a vessel separation of 700m. The reader will note the procurement cost is about one third of the overall cost with the installation cost forming the remainder.

Figure 8B extends this to include buoyancy for the W-Wave flexible and steel riser configurations for a separation of 2000m. The single catenary increases mainly due to the increased procurement cost as the installation cost changes only marginally. The use of buoyancy in the W configuration reduces the overall length of the riser, which reduces the pipe cost. However, the reduction is more than offset by the cost of the buoyancy. The steel W-Wave riser is clearly the least expensive due to low procurement cost and despite the higher installation and buoyancy costs.

Figure 8C increases the separation for these configurations to 3000m. The effect is to reduce the percentage difference between the three cases as the steel configuration increases for both installation and buoyancy costs.

Finally Figure 8D compares the costs for the same SCR + SLWR configuration in 5,000ft, 7,500ft and 10,000 ft water depths. The separations between the hosts for each case are not significantly different. What is surprising is the dramatic effect of the use of buoyancy at depth for the SLWR system. The buoyancy becomes by far the largest cost component in the system. The slight differences due to increased procurement and installation time are not noticeable on the scale shown compared with the increases in buoyancy costs.

Conclusions

The cost comparison provided in Figures 8A-D lead to the following conclusions:

1. The seabed options are by far the most expensive for all separations considered. It is abundantly clear that there is a need to come up with more creative ways of reducing touch down problems associated with SCRs in deep water. The considerable cost of syntactic foam in deep water is only part of the problem. Schemes have been proposed in which the SCRs are made lighter in the touch down region (but not positively buoyant), and heavier above the touch down region. (See also Ref. 5.)
2. Steel W-Wave risers offer the potential for cost savings of several million dollars compared to flexible catenary or W-Wave risers. However, technical uncertainties related to fatigue life are greater for the steel W-Waves. Procurement times are also likely to be longer. Nevertheless, the potential cost saving is of a sufficient magnitude to develop this technology further.
3. The flexible catenary configuration is likely to be of lower cost than the flexible W-Wave configuration. Further study is needed to determine the separation distance at which the crossover between the competing configurations occurs.
4. FTL cost savings of 2-4 million dollars can be achieved if the separation distance is reduced from the base case 2000m to a “close-coupled” 700m. However, the close-coupled configuration requires side-by-side offloading (see Ref. 2). It is well known that side-by-side offloading has a lower operating sea-state limit resulting in larger offloading downtimes. The lower separation distance increases the collision risks associated with human errors, mechanical failures or environmental surprises during shuttle tanker approach and departure. Therefore a full evaluation of life cycle cost-benefit may well result in a rejection of this option for GOM application.
5. Increasing the separation from the base case 2000m to 3000m results in an increase of FTL cost of 2 to 4 million dollars. Such amounts are not inconsequential. Nevertheless, at perhaps 1% of the total development cost, operators may well prefer to select the vessel separation with which they feel comfortable, and pay the additional riser cost. We conclude that the sensitivity of FTL costs to separation distances is small. Therefore the appropriate separation distance can be chosen with regard to other factors and considerations, including risk assessment.

This study serves as a reminder of how careful integration of flow assurance, cost estimation, and engineering design early in the planning cycle will lead to a beneficial focussing of effort. Configuration optimization and dynamic evaluation of likely candidates can then proceed in a timely and cost-effective manner.

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Table 1 – Design Basis

Split Processing Case FTL #1: Oil/Water from DTU to FpSO Flow rates Pressure at DTU Weight density Temperature	 55,000/20,000 1,350 46.5 130	 BPD Psig Lbf/ft3 Deg. F
FTL #2: HP Wet gas from DTU to FpSO Flow rate Pressure at DTU Weight density Temperature	 200 1,000 3.6 130	 MMscfd psig Lbf/ft3 Deg. F
FTL #3: Fuel gas from FpSO to DTU Pressure at FPSO Weight density Temperature	 500 1.55 130	 psig Lbf/ft3 Deg. F
Axial seabed friction coefficient	0.400	
Horizontal distance between FpSO turret center and stern perpendicular	200	Meters
Horizontal distance between FpSO and shuttle tanker– not used in 700 m mean vessel separation case	60	Meters
Shuttle tanker overall length – not used in 700 m mean vessel separation case	200	Meters
DTU width (TLP or spar)	100	Meters

Table 2 – Mean Nominal Separation Distances and Water Depths

	Nominal Vessel Separation		
Water Depth	**700 m**	**2000 m**	**3000 m**
1,524 m (5,000 ft)	√	BASE CASE	√
2,286 m (7,500 ft)	√	√	√
3,048 m(10,000 ft)	√	√	√

Table 3 – DTU and FpSO Offsets Expressed as Percent of Water Depth

					FpSO		
Water depth	DTU Type	Watch Circle Radius	Approximate Mean Offset Coupled	Approximate Mean Offset Uncoupled	Watch Circle Radius	Approximate Mean Offset Coupled	Approximate Mean Offset Uncoupled
1,524 m (5,000 ft)	TLP	9.00 %	7.90 %	6.8 %	12.0 %	9.0 %	6.0 %
2,286 m (7,500 ft)	Spar	7.50 %	6.91 %	5.8 %	10.0 %	8.0 %	6.0 %
3,048 m(10,000 ft)	Spar	5.36 %	5.25 %	4.5%	8.0 %	7.0 %	6.0 %

Table 4 – Vessel Separations, Riser Top Separations and Associated Vessel Locations

Mean vessel separation	700	2,000	3,000	700	2,000	3,000	700	2,000	3,000
Water depth	Min vessel separation			Min riser top separation			Max riser top separation		
1524	371	1,353	2,353	571	1,813	2,813	729	2,087	3,087
2286	366	1,355	2,355	566	1,815	2,815	734	2,085	3,131
3048	363	1,357	2,357	563	1,817	2,817	737	2,083	3,205
* with respect to DTU watch circle center				DTU center location* associated with min separation			DTU center location* associated with max separation		
				-104	137	137	104	-137	-137
				-145	-94	-94	145	94	94
				-157	-111	-111	157	111	111
** with respect to FpSO watch circle center				FpSO turret center location** associated with min separation			FpSO turret center location** associated with max separation		
				-183	0	0	183	0	0
				-229	-229	-229	229	229	229
				-244	-244	-244	244	244	244

Table 5 – Required Inner Pipe Diameters (approximate) in inches

	Mean DTU center to FpSO Turret Center Separation								
Separation	**700 m**			**2,000 m**			**3,000 m**		
	Oil & water	Wet gas	Fuel gas	Oil & water	Wet gas	Fuel gas	Oil & water	Wet gas	Fuel gas
W-Wave*	8	10	3	8	10	3	8	10	3
Double catenary*	8	10	3	8	10	3	8	10	3
To seabed at:									
1,524 m (5,000 ft)	9	10	4	--	--	--	--	--	--
2,286 m (7,500 ft)	--	--	--	11	11	4	--	--	--
3,048 m(10,000 ft)	--	--	--	--	--	--	11	11	4

* Dimensions assumed constant regardless of depth of seabed.

Table 6 – Required U-values (BTU/HR/FT^2/^{o}F) based on ID

	Mean DTU center to FpSO Turret Center Separation								
Separation	**700 m**			**2,000 m**			**3,000 m**		
	Oil & water	Wet gas	Fuel gas	Oil & water	Wet gas	Fuel gas	Oil & water	Wet gas	Fuel gas
W-Wave*	3.4	3.3	NA	3.4	3.3	NA	2.2	3.0	NA
Double catenary*	3.4	3.3	NA	3.4	3.3	NA	2.2	3.0	NA
To seabed at:									
1,524 m (5,000 ft)	1.4	1.5	NA	--	--	--	--	--	--
2,286 m (7,500 ft)	--	--	--	1.4	1.4	NA	--	--	--
3,048 m(10,000 ft)	--	--	--	--	--	--	1.2	1.3	NA

* Values assumed constant regardless of depth of seabed.

Table 7 – Representative W-Wave Flexible Riser Pipe Properties (non-insulated)

Riser Name	Nominal ID		OD		Weight/meter Empty in Air		Weight/meter SW* full in Air		Weight/meter SW full in SW	
	mm		mm		kgf/meter		kgf/meter		kgf/meter	
Maximum depth (m)	500	1000	500	1000	500	1000	500	1000	500	1000
8” Oil & water	203.2	203.2	280.2	285.4	106.6	110.0	142.4	147.6	79.2	82.0
10” Wet gas	254.0	254.0	338.2	344.2	135.7	154.0	191.7	209.6	99.6	114.2
3” Fuel gas	76.2	76.2	129.8	133.3	28.8	31.7	33.8	36.9	20.2	22.6

* SW = Seawater

Table 8 – Representative W-Wave Flexible Riser Pipe Properties and Limits (non-insulated)

Riser Name	Storage Radius		Failure Tension		Bending Stiffness, EI		Axial Stiffness, EA		Collapse Depth	
	meters		kN		N.m^2		kN		meters	
Maximum depth (m)	500	1000	500	1000	500	1000	500	1000	500	1000
8” Oil & water	1.82	1.85	2997	2835	25707	29151	389676	326836	882	1294
10” Wet gas	2.20	2.25	3408	3918	53741	58587	405106	505405	801	1247
3” Fuel gas	0.84	0.87	983	1012	1666	1819	119575	124077	834	2575

Table 9 –Particulars for Cases Involving Direct Platform to Vessel Fluid Transfer Lines

		Flexible Pipe			Steel Pipe	
Case	Vessel Separation (Nominal)	Nominal Internal Diameters*	Catenary	W wave	Pipe ODs*	W wave
1	700m (coupled)	3", 8", 10"	Yes			
2a,b,c	2,000m (uncoupled)	3", 8", 10"	Yes	Yes	4.5", 10.75", 12.75"	Yes
3a,b,c	3,000m (uncoupled)	3", 8", 10"	Yes	Yes	4.5", 10.75", 12.75"	Yes

* Fuel gas, Oil and water, Wet gas

Table 10 – Particulars for Cases Involving Indirect Platform to Vessel Riser via the Seabed

Case	Water depth	SCR + SLWR	Vessel Separation (Nominal)	Pipe ODs*
4	5,000ft	yes	6,500m	4.5", 10.75", 12.75"
5	7,500ft	yes	7,122m	4.5", 12.75", 12.75"
6	10,000ft	yes	6,630m	4.5", 12.75", 12.75"

* Fuel gas, Oil and water, Wet gas

Table 11 – Design Results for Cases Involving Direct Platform to Vessel Fluid Transfer Lines

Fuel Gas Riser		**5000ft water depth (same for 7500ft and 10000ft)**						
		700m separation (coupled)	**2000m separation (uncoupled)**			**3000m separation (uncoupled)**		
		Flexible solution	Flexible solutions		Steel solution	Flexible solutions		Steel solution
Description	units	Catenary	Catenary	W-catenary	W-catenary	Catenary	W-catenary	W-catenary
Pipe length	m	827	2,368	2,280	2,280	3,503	3,380	3,370
Pipe steel weight	Tonnes				750			1,108
Buoyancy requirement	KN uplift			93	143		167	221
Buoyed length	m			480	497		743	770
Syntactic foam wt density	lb/ft3			23.0	23.0		23.0	23.0
Pipe OD for coating calcs	m				0.115			0.114
Vertical load on DTU	kN	82	262	143	199	388	226	285
Vertical load on FpSO	kN	82	262	143	199	388	226	285

Water / Oil Riser		**5000ft water depth (same for 7500ft and 10000ft)**						
		700m separation (coupled)	**2000m separation (uncoupled)**			**3000m separation (uncoupled)**		
		Flexible solution	Flexible solutions		Steel solution	Flexible solutions		Steel solution
Description	units	Catenary	Catenary	W-catenary	W-catenary	Catenary	W-catenary	W-catenary
Pipe length	m	860	2,460	2,280	2,280	3,640	3,380	3,370
Pipe steel weight	Tonnes				2,565			4,242
Buoyancy requirement	KN uplift			433	546		701	969
Buoyed length	m			530	535		830	837
Syntactic foam wt density	lb/ft3			23.0	23.0		23.0	23.0
Pipe OD for coating calcs	m				0.274			0.273
Vertical load on DTU	kN	334	990	500	628	1,464	735	980
Vertical load on FpSO	kN	334	990	500	628	1,464	735	980

Wet Gas Riser		**5000ft water depth (same for 7500ft and 10000ft)**						
		700m separation (coupled)	**2000m separation (uncoupled)**			**3000m separation (uncoupled)**		
		Flexible solution	Flexible solutions		Steel solution	Flexible solutions		Steel solution
Description	units	Catenary	Catenary	W-catenary	W-catenary	Catenary	W-catenary	W-catenary
Pipe length	m	827	2,368	2,380	2,300	3,503	3,480	3,380
Pipe steel weight	Tonnes				3,478			5,842
Buoyancy requirement	KN uplift			323	356		517	776
Buoyed length	m			338	320		553	577
Syntactic foam wt density	lb/ft3			23.0	23.0		23.0	23.0
Pipe OD for coating calcs	m				0.325			0.324
Vertical load on DTU	kN	404	1,326	1,046	1,195	1,962	1,488	1,848
Vertical load on FpSO	kN	404	1,326	1,046	1,195	1,962	1,488	1,848

Table 12 – Design Results for Cases Involving Indirect Platform to Vessel Riser via the Seabed

Fuel Gas Riser		**5000ft water depth**	**7,500ft water depth**	**10,000ft water depth**
		6,500m	7,122m	6,630m
		Separation	Separation	Separation
Description	units	SCRs+buoy	SCRs+buoy	SCRs+buoy
Total pipe length	m	8,670	10,453	11,359
Static pipe length on seabed	m	4,679	4,473	3,930
Pipe steel weight	Tonnes	2,248	2,710	2,945
Buoyancy requirement	KN uplift	119	179	170
Buoyed length	m	209	313	297
Syntactic foam wt density	lb/ft3	30.50	37.80	41.30
Pipe OD	m	0.114	0.114	0.114
Pipe ID	m	0.094	0.094	0.094
Vertical load on DTU	kN	527	793	1,001
Vertical load on FpSO	kN	494	737	953
Water / Oil Riser		**5000ft water depth**	**7,500ft water depth**	**10,000ft water depth**
		6,500m	7,122m	6,630m
		Separation	Separation	Separation
Description	units	SCRs+buoy	SCRs+buoy	SCRs+buoy
Total pipe length	m	8,214	9,788	10,561
Static pipe length on seabed	m	2,997	2,441	1,881
Pipe steel weight	Tonnes	8,858	17,942	21,547
Buoyancy requirement	KN uplift	966	1,921	1,934
Buoyed length	m	441	542	496
Syntactic foam wt density	lb/ft3	30.50	37.80	41.30
Pipe OD	m	0.273	0.324	0.324
Pipe ID	m	0.238	0.273	0.267
Vertical load on DTU	kN	2,541	5,844	7,742
Vertical load on FpSO	kN	2,202	5,266	7,248
Wet Gas Riser		**5000ft water depth**	**7,500ft water depth**	**10,000ft water depth**
		6,500m	7,122m	6,630m
		Separation	Separation	Separation
Description	units	SCRs+buoy	SCRs+buoy	SCRs+buoy
Total pipe length	m	8,129	9,788	10,561
Static pipe length on seabed	m	2,631	2,442	1,881
Pipe steel weight	Tonnes	12,307	17,942	21,547
Buoyancy requirement	KN uplift	1,471	1,921	1,934
Buoyed length	m	489	542	496
Syntactic foam wt density	lb/ft3	30.50	37.80	41.30
Pipe OD	m	0.324	0.324	0.324
Pipe ID	m	0.283	0.273	0.267
Vertical load on DTU	kN	3,657	5,844	7,742
Vertical load on FpSO	kN	3,135	5,266	7,248

Table 13 – Base Case Costs (sample)

Cost Center	**Depth rating (if applicable)**			
	500m	1000m	2000m	3000m
3” Flexible	$250 /m	270 /m		
8” Flexible	$725 /m	785 /m		
10” Flexible	$842 /m	922 /m		
Syntactic foam buoyancy	$4.0 / lbs uplift	$8.55/ lbs uplift	$12.0/ lbs uplift	$13.5/ lbs uplift
Pipe coating	$175 / m based on 30mm thickness for 10” line			
Reel lay vessel rate	$150,000 / day and average lay rate of 5000m per day*			
J-lay vessel day rate	$200,000 / day and average lay rate of 1200m per day*			

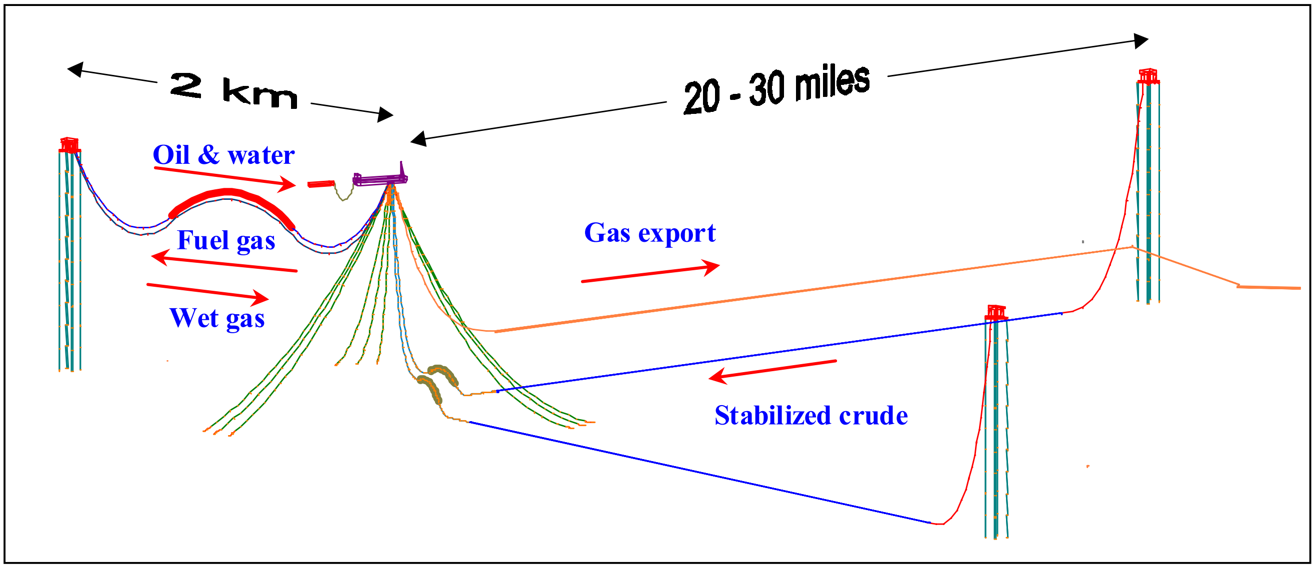

Figure 1 – Generic Field Layout for FpSO / Shuttle Tanker Development Case (simplistic)

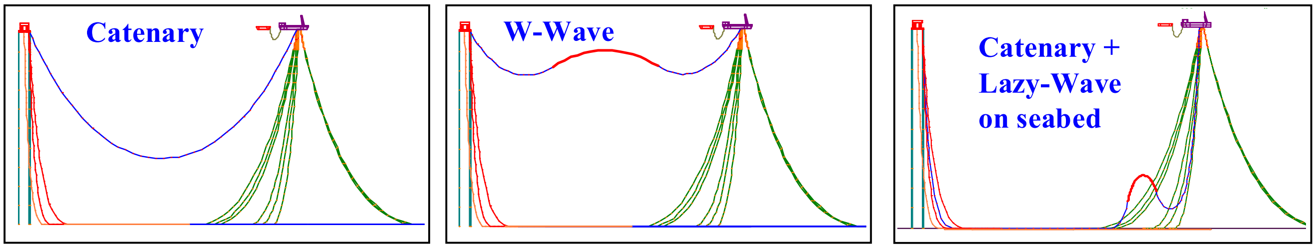

Figure 2 – Representative Fluid Transfer Line and Riser Configuration Alternatives

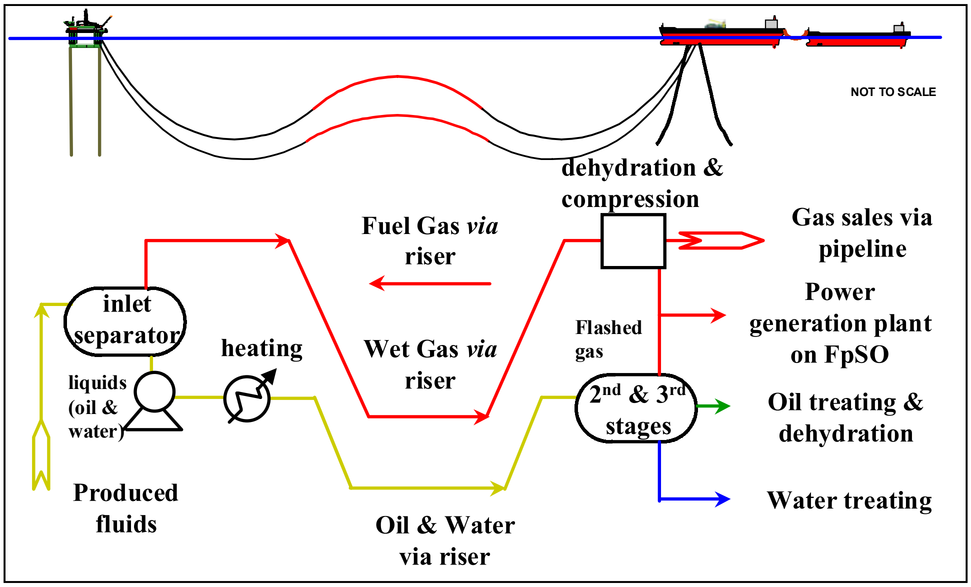

Figure 3 – FPSO Facilities Split (fuel gas line system and riser not shown)

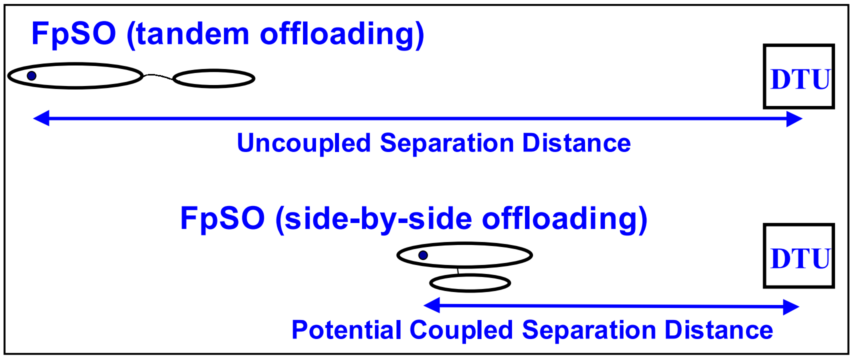

Figure 4 – Shuttle Tanker Offloading Nomenclature

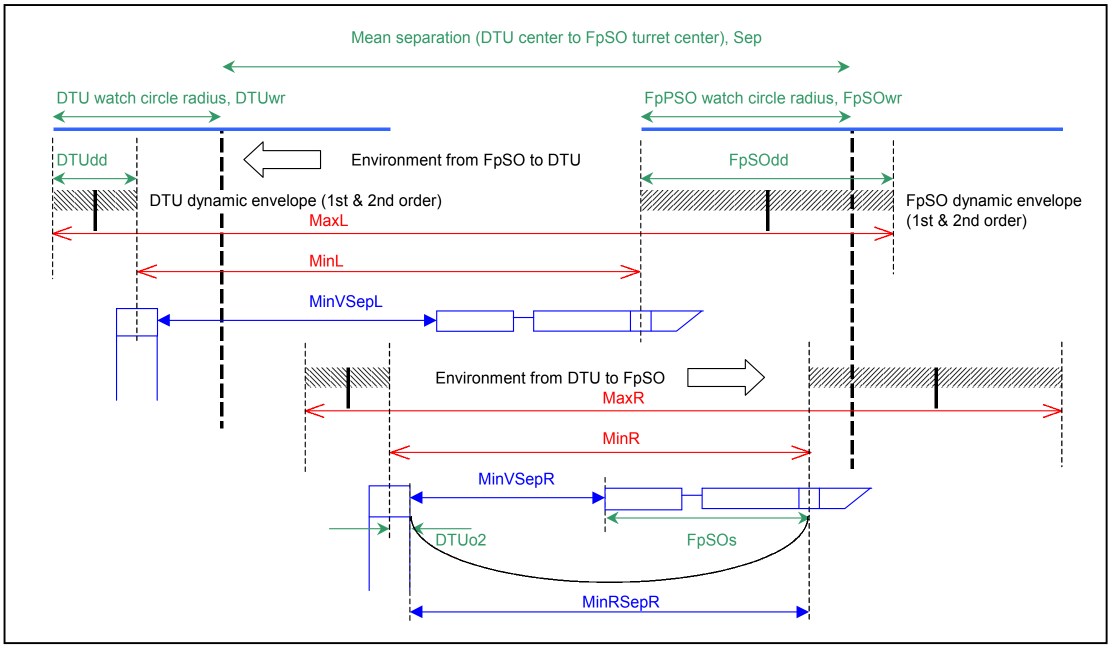

Figure 5 – Vessel and Riser Geometry

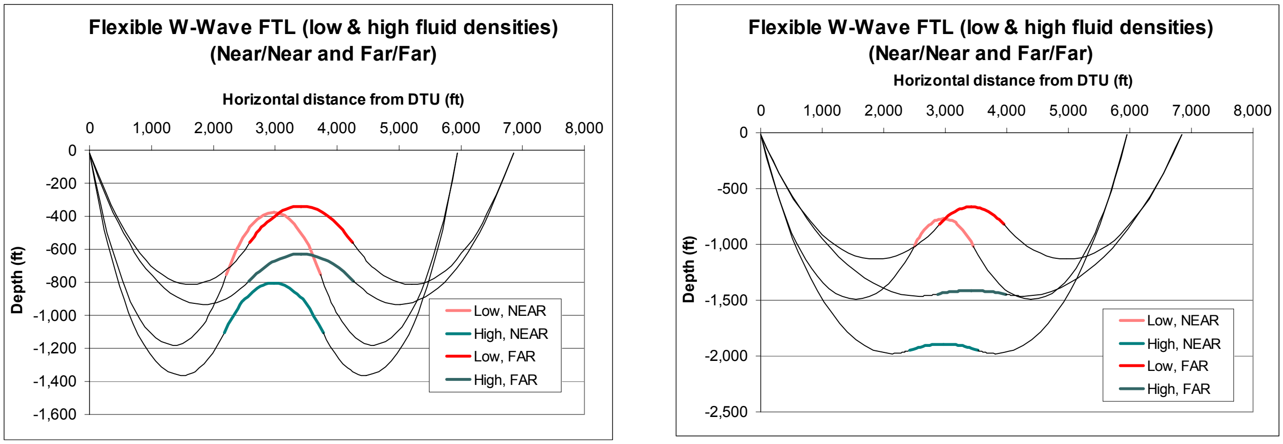

Figure 6 – W-Wave Riser Configurations for 2000m Separation: Oil/water FTL and Wet Gas FTL

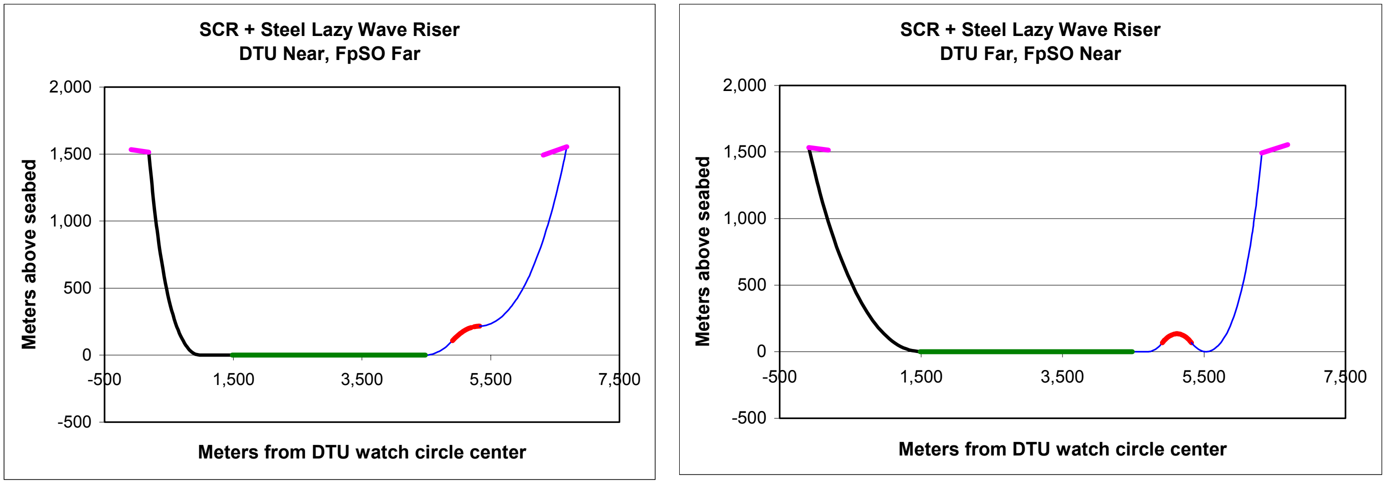

Figure 7 – Wet Gas Riser Combinations in for 5000ft Water Depth Case (note exaggerated DTU and FpSO heave)

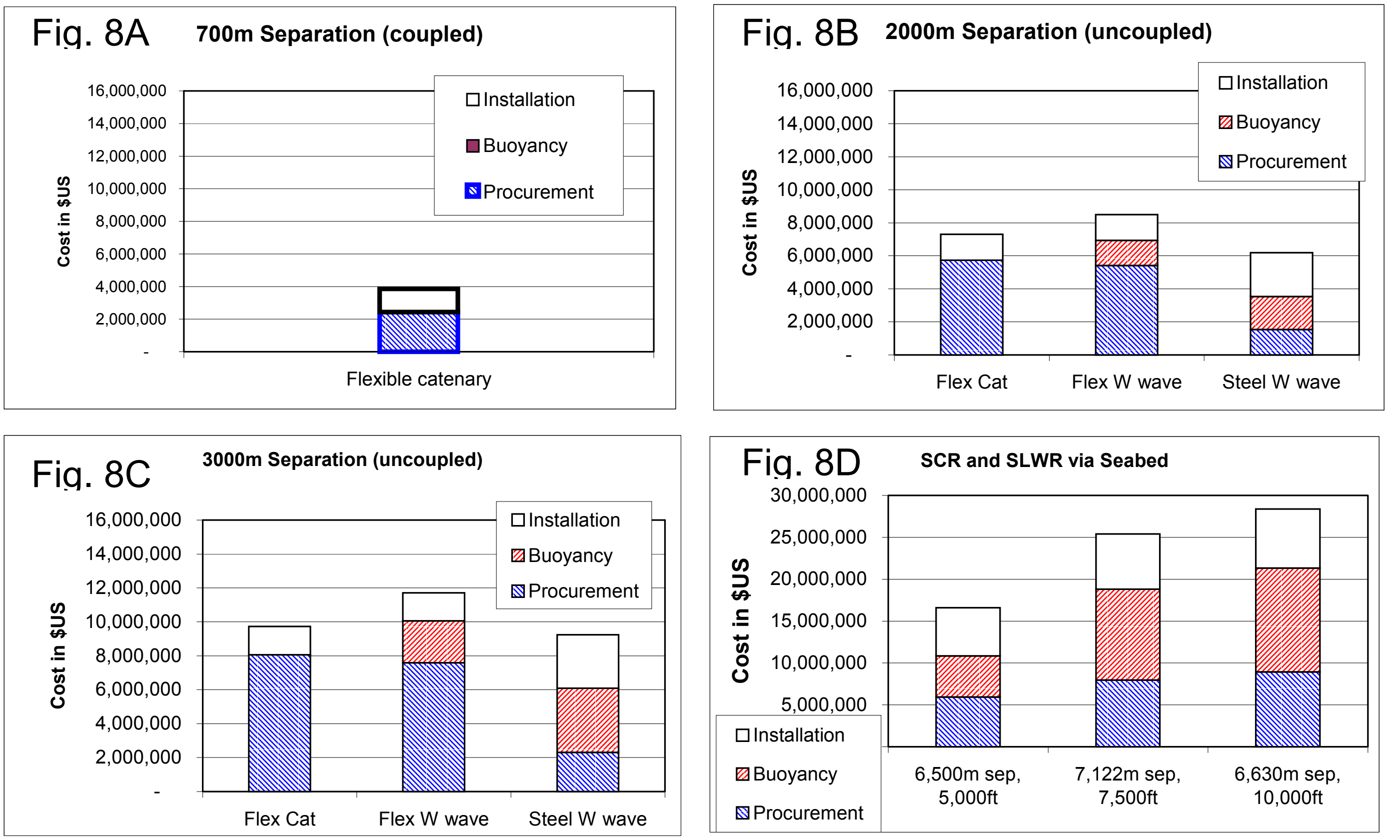

Figure 8 – Riser Cost Comparison (costs of moorings and vertical loads not included)