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EFFECTIVE RISER SOLUTIONS FOR A DEEPWATER FPSO

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ABSTRACT

With the recent increase of discoveries in the deepwater Gulf of Mexico (GoM) and the rapid deployment of deepwater floating production systems, the design of dynamic risers to produce and export to and from these FPS has quickly evolved in complexity and variety. As one of the attractive solutions for the development of these deepwater discoveries, the Floating Production, Storage and Offloading (FPSO) system offers a serious challenge to the riser system designer.

This paper presents detailed results of a three steel risers systems design study to a turret moored FPSO system in 1,370 meters (4,500 feet) water depth in the GoM. The three riser systems considered are the Steel Lazy Wave Riser (SLWR) system, the Tension Leg Riser (TLR) system and the Single Leg Hybrid Riser (SLHR) system. The three riser concepts are shown to be feasible. The paper shows that for the diameter, number of risers and water depth considered, the SLWR is the preferred option. However, under different parameters, the TLR or SLHR may be preferred since they fully decouple the steel portion of the riser from the vessel motions via flexible jumpers. Very often, riser feasibility can only be demonstrated by doing a complete and thorough evaluation as demonstrated in the paper.

The results of this paper demonstrate that steel riser options are available and present effective solutions for use on an FPSO system in the GoM.

INTRODUCTION

With the recent increase of discoveries in the deepwater Gulf of Mexico (GoM) and the rapid deployment of deepwater floating production systems, the design of dynamic risers to produce and export to and from these FPS has quickly evolved in complexity and variety. As one of the attractive solutions for the development of these discoveries, the Floating Production, Storage and Offloading (FPSO) system offers a serious challenge to the riser system designer.

This paper presents the preliminary riser system design and cost evaluation for a new built turret moored FPSO system in 1,370 meters (4,500 feet) water depth in the GoM. The three riser system concepts considered and designed are the Steel Lazy Wave Riser (SLWR) system, the Tension Leg Riser (TLR) system and the Single Leg Hybrid Riser (SLHR) system. The evaluation involved both a technical assessment (i.e., riser performance in strength and fatigue) and a commercial assessment (i.e., cost and schedule).

To assess the technical feasibility of the risers, survival analysis was conducted using extreme hurricane conditions to check allowable stresses and to determine top termination requirements. Fatigue analyses were also performed. Both first and second order wave induced fatigue were examined along with fatigue due to Vortex Induced Vibrations (VIV). A commercial assessment was also made by developing screening-level, installed cost estimates for each riser concept, including the knock-on effect on associated systems such as the turret. The paper shows that for the diameter and number or risers and water depth considered, the SLWR is the preferred option. However, if global motions of the vessel were to become more severe, the TLR or SLHR may be preferred as they effectively decouple the steel portion of the riser from the vessel motions via flexible jumpers.

ENVIRONMENT

Typical deepwater Gulf of Mexico environmental parameters were used for hurricane conditions (10, 100 and 1,000 year hurricanes), loop/eddy current events, and everyday fatigue sea states. The 100-year hurricane conditions used for the study are summarized in Table 1. The 100-year hurricane significant wave height is 12.3 meters, with a peak period of 14 seconds. The 100-year loop current condition uses a significant wave height of 8.6 meters with a peak period of 12.3 seconds, and maximum current speeds of 2.25 meters per second. Both collinear and crossed environmental conditions were studied due to the weathervaning nature of the turret moored FPSO system.

Table 1. 100-year Hurricane Criteria

Environment Alignment	Units	Collinear	Crossed	Crossed 2	Crossed 2B
Waves					
Hs	(m)	12.3	12.3	12.3	12.3
Tp	(s)	14	14	14	14
Gamma		2.4	2.4	2.4	2.4
Direction	(deg)	0	0	0	0
Wind					
Velocity (1-hour)	(m/s)	42	42	42	42
Wind-Wave Direction	(deg)	0	35	35	30
Current					
Current-Wave Direction	(deg)	0	-15	15	45
Surface	(m/s)	1.70	1.70	1.70	1.70
30	(m/s)	1.30	1.30	1.30	1.30
60	(m/s)	0.63	0.63	0.63	0.63
90	(m/s)	0.00	0.00	0.00	0.00
>90	(m/s)	0.00	0.00	0.00	0.00

FPSO SYSTEM DESCRIPTION

The FPSO selected for this study is a new-build “tanker” with an elliptical bow and a storage capacity of approximately 2 million barrels. The vessel is turret moored in 1,370 meters water depth. Its turret was designed to accommodate up to six risers of 406.4 millimeters outer diameter (16-inch OD). Both loaded and ballast conditions were considered in the investigation of riser performance. In order to investigate the important effect of turret location on FPSO responses, different turret locations were evaluated. The turret location was optimized accounting for both vertical motions (riser design) and weathervaning efficiency (mooring/vessel design). The riser system design was performed using an optimum turret location of 100 meters forward amidships (15% LBP aft of FP (forward perpendicular)). Additional details of the mooring and turret systems are provided in [1]. The main FPSO particulars are presented Table 2.

Table 2. FPSO Particulars

Parameters	Ballast	Full Loaded	Units
Length	274.43	285.40	m
Beam	63.00	63.00	m
Depth	30.50	30.50	m
Mean Draft	8.00	19.50	m
Displacement	135,786	337,818	m^3
Vertical Center of Gravity abv. Keel	24.94	19.00	m
Vertical Center of Buoyancy abv. Keel	4.02	9.86	m
Water Plane Area	16,725	17,372	m^2
Long. Metacentric Height abv. Keel	750	346	m
Tran. Metacentric Height abv. Keel	45.20	26.83	m

PRELIMINARY RISER SIZING

Preliminary pipe wall thickness was established using API RP 1111 [2]. The pipe material was API 5L X65. An internal content specific gravity of 0.9 was used, along with a maximum internal operating pressure of 3447 kilopascals. Both the SLWR and the TLR designs assumed the pipe would be installed in a voided (air-filled) condition, with wall thicknesses governed accordingly by collapse due to external pressure. A relatively thick wall of 19 millimeters (0.75 inch) was selected for these risers. The SLHR, however, was assumed to be installed flooded and would never be in the empty/vented condition throughout its design life. As a result, its design was not governed by collapse and a thinner wall of 12.7 millimeters (0.5 inch) was selected.

STEEL LAZY WAVE RISER DESCRIPTION

The SLWR system is a compliant riser system. It provides an alternative to the Steel Catenary Riser (SCR), which is generally not feasible on a turret moored FPSO in harsh environments due to the high vertical motions at the turret which result in high stresses and fatigue damage near the touch down point (TDP) of the riser. In this study, the maximum vertical motion at the riser hang off point in the 100-year hurricane condition was approximately 23 meters (double amplitude).

The SLWR configuration was optimized early by examining riser performance in the extreme sea states, and by minimizing the amount of buoyancy required on the riser. The parameters of interest were maximum and minimum effective tensions and maximum Von Mises stresses. The riser analysis was performed using the program Orcaflex [3]. Table 3 presents the SLWR configuration. The optimum riser configuration was developed by changing the hang-off angle as well as the location and distribution of buoyancy. The sensitivity analyses showed that it is preferable to place the wave (formed by the hump and sag bend portions of the SLWR) as close as possible to the seabed, and have enough buoyancy to maintain the “wave” shape up to the extreme far position. The nominal hang-off angle of the SLWR is 10 degrees and the top termination is to a specially designed flexible joint. Figure 1 shows the SLWR configuration in the near, mean and far positions.

Table 3. SLWR System Configuration

Outside Diameter	16 inch	
Wall Thickness	0.75 inch	
Bare Pipe Section		
outside diameter	0.406 m	1.333 ft
inside diameter	0.368 m	1.208 ft
weight in air empty	182.0 kg/m	122.3 lb/ft
weight in seawater empty	49.1 kg/m	33.0 lb/ft
Buoyant Pipe Section		
outside diameter	0.85 m	2.79 ft
inside diameter	0.37 m	1.21 ft
foam density	475 kg/m^3	29.7 lb/ft^3
weight in air empty	390.0 kg/m	262.0 lb/ft
weight in seawater empty	-191.7 kg/m	-128.8 lb/ft
Riser Configuration		
length of upper catenary	1550 m	5085 ft
length of buoyant section	450 m	1476 ft
length of lower catenary	245 m	804 ft
top/tdp horizontal distance	1370 m	4495 ft
total net buoyancy (foam)	108 mt	239 kips

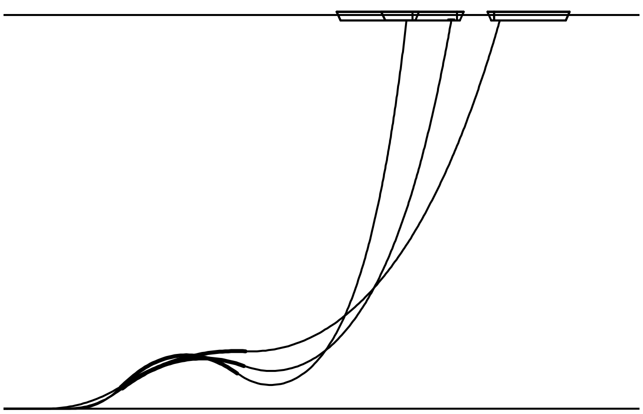

Figure 1. SLWR in near, mean and far positions

TENSION LEG RISER DESCRIPTION

The TLR system is a hybrid decoupled riser system. Figure 2 shows a 3D picture of the TLR system. As can be seen on the figure, the TLR system provides a means of decoupling SCRs from the motions of the FPSO via flexibles (more details on the licensed TLR system can be found in [4], [5] and [6]).

Figure 3 shows an Orcaflex elevation view of the TLR model as analyzed. For this particular study, three SCRs depart on each side of the buoy. Table 4 presents the TLR system properties. The "H" shaped buoy is an open bottom structure designed to equalize internal and external pressures. The buoy is located approximately 145 meters below mean water level, at a horizontal distance of about 220 meters from the turret. The buoy is tethered to the seafloor with four SPR3 sheathed spiral strand tendons. The tendons are secured to the seafloor using suction piles. The SCRs depart from the buoy at a 5.5 degrees angle from the vertical. They are terminated at the buoy using a tapered stress joint. The tapered stress joint is 50 millimeters (2 inch) thick at the top and 19 millimeters (0.75 inch) thick at the bottom, with a total length of approximately 9.5 meters (31 feet). It is designed to accommodate a rotation of ±6 degrees.

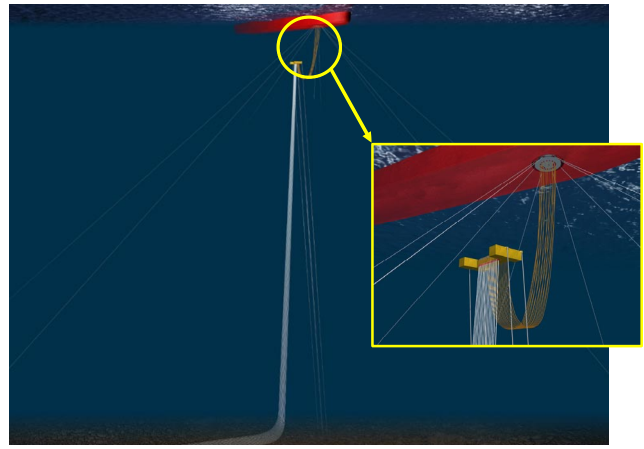

Figure 2. TLR system

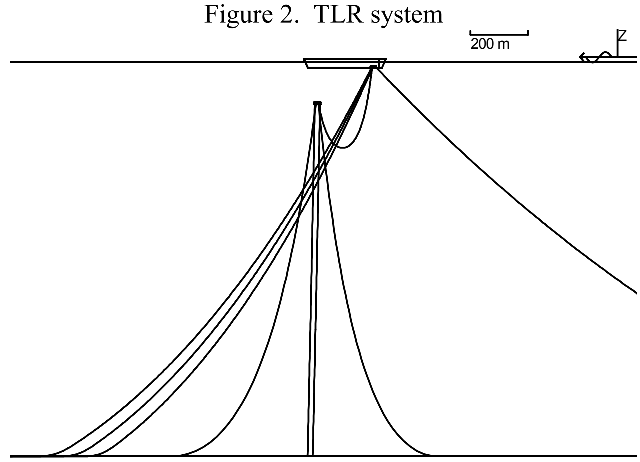

Figure 3. TLR System Layout

Table 4. TLR System Configuration

Outside Diameter	16 inch	
Wall Thickness	0.75 inch	
SCR Properties		
outside diameter	0.406 m	1.333 ft
inside diameter	0.368 m	1.208 ft
weight in air empty	182.0 kg/m	122.3 lb/ft
weight in seawater empty	49.1 kg/m	33.0 lb/ft
Buoy Properties		
net buoyancy	2038 mt	4492 kip
displacement	2621 mt	5776 kip
steel weight	582 mt	1283 kip
diameter	6.8 m	22.5 ft
side length	20.5 m	67.4 ft
cross length	27.4 m	89.9 ft
porch length	20.5 m	67.4 ft
Tendon Properties		
number	4	4
length	1220 m	4003 ft
diameter	76 mm	3 inch
submerged weight	24 kg/m	16 lb/ft
breaking strength	636 mt	1402 kips
Other Properties		
buoy/turret separation	220 m	722 ft
length of SCR	1400 m	4593 ft
length of flexible jumper	500 m	1640 ft
SCR hang off porch elevation	-145 m	-476 ft

SINGLE LINE HYBRID RISER DESCRIPTION

The SLHR is also a hybrid decoupled riser system. The main riser section is decoupled from the motions of the FPSO using flexibles. Figure 4 presents the general description of the SLHR and its components. The SLHR is composed of a vertical rigid pipe that is tensioned using an air can. The riser system is terminated at the seabed with a stress joint and is anchored with a suction pile via a Stab and Hinge Over (SHO) assembly. A gooseneck at the top of the riser provides the connection between the steel portion of the riser and the flexible jumpers. Table 5 presents the SLHR configuration for this study. Buoyancy for each vertical riser is provided by an air can with a displacement of 283 metric tons and net buoyancy of 227 metric tons, located 145 meters below the water surface. The tension factor (top tension/wet weight of the riser) used was 1.8. The riser base is located 200 meters from the FPSO center. The flexible jumpers are 400 meters long.

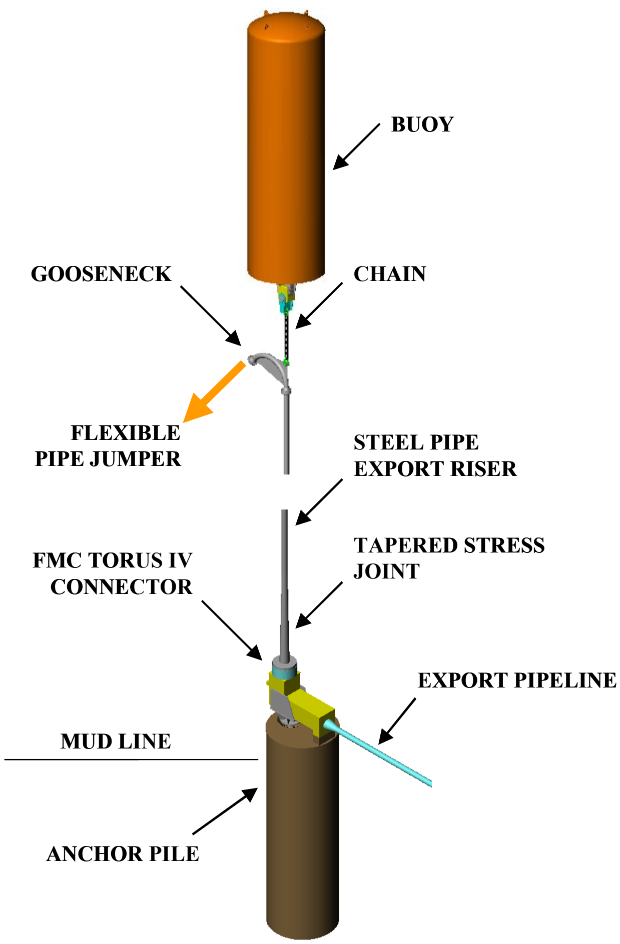

Figure 4. SLHR Components

Table 5. SLHR System Configuration

Outside Diameter	16 inch	
Wall Thickness	0.5 inch	
Riser Pipe Properties		
outside diameter	0.406 m	1.333 ft
inside diameter	0.381 m	1.250 ft
weight in air empty	123.3 kg/m	82.9 lb/ft
weight in seawater empty	123.3 kg/m	123.3 lb/ft
Air Can Properties		
diameter	5 m	16 ft
length	14 m	46 ft
net buoyancy	227 mt	500 kips
displacement	283 mt	625 kips
weight	57 mt	125 kips
volume	276 m^3	9763 ft^3
Riser Configuration		
length of riser pipe	1220 m	4003 ft
length of flexible jumper	400 m	1312 ft
buoy elevation (bottom)	-145 m	-476 ft
anchor point/turret separation	200 m	656 ft
Static Results		
top tension	204 mt	449 kips
bottom tension	90 mt	199 kips
tension factor	1.8	1.8

The SHO assembly is shown in Figure 5. The assembly is lowered in the vertical position during installation after which the stab assembly stabs into a cylindrical pile. The hinge module then rotates 90 degrees into the operation phase as shown on the figure. The use of the SHO assembly minimizes the hardware required at the seabed to connect the riser system to the pipeline. However it requires a lay away (first hand) installation method for the pipeline.

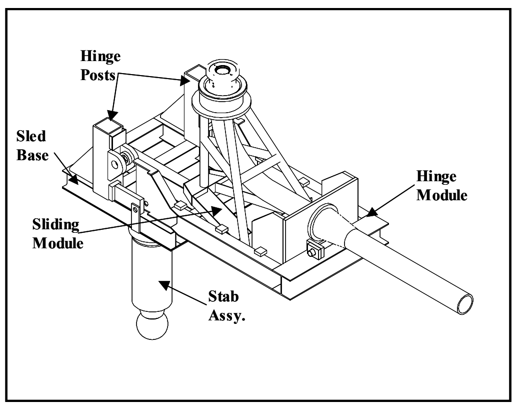

Figure 5. Stab and Hinge Over Assembly

As an alternative, a simple two-flowline hub structural arrangement can be used at the riser base. The center hub is for the riser attachment and the outboard hub is for a flowline U-jumper connection to a Pipeline End Termination (PLET). The riser base uses a retrievable structure interface with a suction pile to resist riser loads. Figure 6 shows the SLHR base structure.

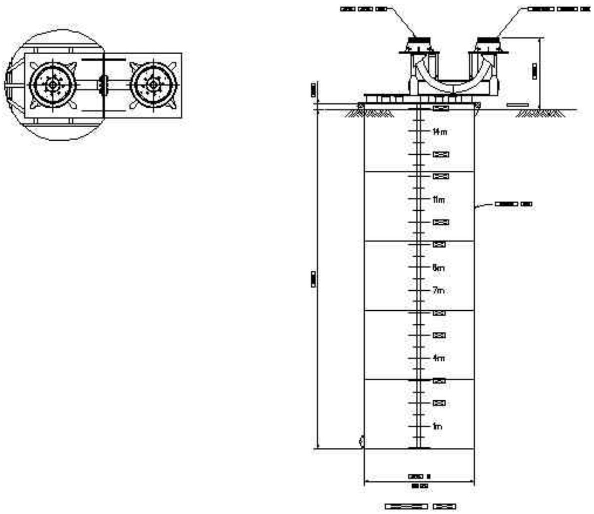

Figure 6. SLHR Base Structure

The inverted U-Jumper is a single bore pipe spool with connector hubs on either end. The inverted U-jumper connects the riser base hub to the hub connector on the PLET. It features large radius elbows to permit pigging. U-jumpers are typically between 12 and 21 meters (40 and 70 feet) long to allow for pipe flexibility during installation without making the jumper too long to be unwieldy to handle. U-jumper connections include ROV actuated hydraulic flowline connectors with a retractable guidance system that can raise or lower the connector for access to the connector gasket or allow for pivoting the jumper assembly around one of the hubs during installation. Figure 7 presents a typical inverted U-jumper.

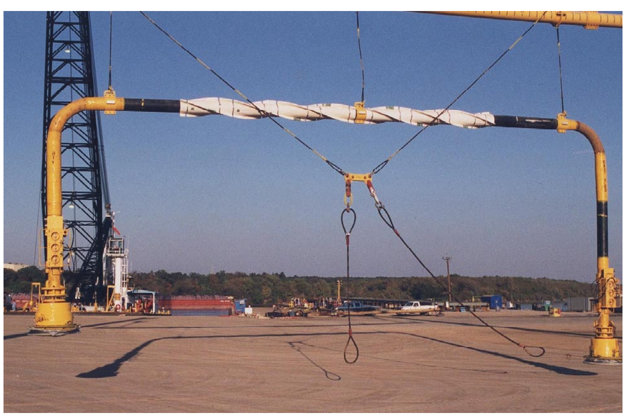

Figure 7. Inverted U-Jumper

The PLET sleds are used to provide connection points to pipeline segments. They are mudmat mounted flowline hubs that are physically attached to the end of a pipeline. The inverted U-jumpers connect the PLET sleds to the SLHR base. Figure 8 shows a PLET sled. This arrangement allows for a second hand installation method.

Figure 9 shows the SLHR in the near, mean and far positions.

Figure 8. Pipeline End Termination Sled

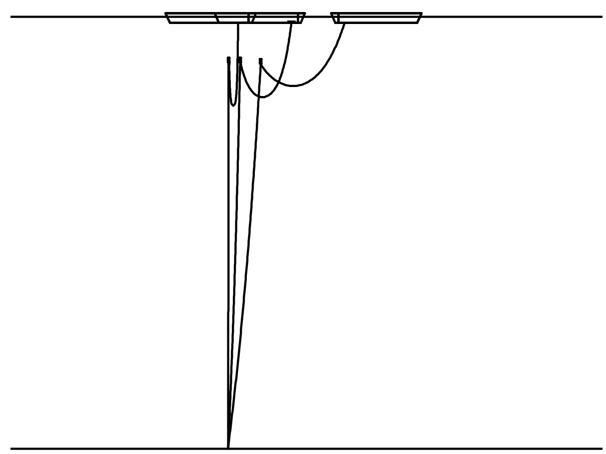

Figure 9. SLHR in near, mean and far positions

SURVIVAL ANALYSIS

Methodology

The survival analysis was performed using the program Orcaflex. The risers were designed to API RP 2RD [7].

In the survival (or strength) analysis, the performance of each riser system under extreme storm conditions (including 100-year loop and 1,000-year events) was analyzed for different offset cases. The slow drift extreme offsets of the FPSO were obtained using the global analysis program SPMsim [8] which provides a fully coupled frequency domain analysis of turret moored vessels, mooring and riser systems. RAOs were used to simulate the wave frequency motions of the vessel around the low-frequency offset. Design cases also included accidental conditions such as a damaged mooring line. Both ballast and fully loaded draft conditions were investigated. Finally, interference between risers and/or flexibles was also investigated.

Since the maximum motions of the vessel are mainly driven by the extreme waves, the survival analysis was performed using regular waves. The regular wave height and period were selected to represent both the extreme waves, and the most-probable maximum wave-frequency motions of the vessel. In order to verify the conservatism of the regular wave analysis method, a few governing design cases were analyzed using random waves. The random wave analysis was conducted by using a JONSWAP Spectrum (gamma of 2.4) and by generating for each environmental condition a series of five 3-hour wave elevation time series using different random seeds. The analysis was then performed around the maximum waves of each time series.

The design of the flexible jumpers for the SLHR and TLR investigated maximum tension, maximum compression and minimum bending radius (MBR) and checked these parameters against manufacturer specifications. For a flexible jumper with inside diameter 368.3 millimeters (14.5 inches, to roughly match the inside diameter of the steel portion of the riser for pigging requirements), manufacturer limits for maximum tension, maximum compression, and MBR are 218 metric tons, 10 metric tons, and 4.5 meters respectively.

Along with an inertia coefficient of 2.0, a drag coefficient of 0.7 was used in the bare portion of the risers, assuming no strakes. Sensitivity runs were also performed using higher drag coefficients.

Results

Static analyses performed for the SLWR with the riser filled with air, oil and water showed that the when the buoyancy section of the riser is being installed, the riser cannot be installed voided as excessive departure angles would occur on the lay vessel. Table 6 shows some static results for the SLWR.

Table 6. SLWR Static Results

SI Units

Parameter	Units	Near	Mean	Far
Offset	(m)	-170	0	170
Top Tension	(mt)	208	214	231
Top Angle	(deg)	6.5	10	16
MBR	(m)	161	256	450
Max Stress	(kPa)	2.71E+05	1.81E+05	1.23E+05
Arc length of TDP from top	(m)	2180	2205	2280

A sample of the results from the survival analyses for each of the three riser systems studied is provided in Table 7.

Figure 10 shows a typical effective tension range graph along the arc length of the SLWR system. Note the large tension range at the top and the relative small tension range at the TDP, which indicate a good decoupling effect between the riser TDP and the FPSO motions at the top.

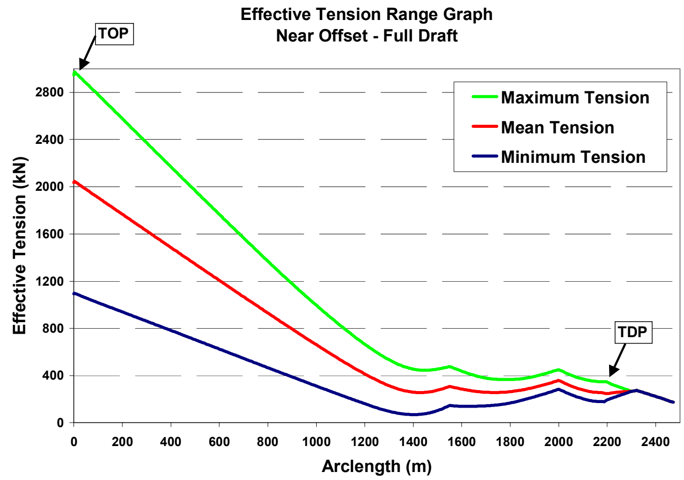

Figure 10. SLWR Effective Tension Range Graph

Survival analysis for the SLWR showed that there are no compression loads in the riser and that the utilization ratio (maximum stress/yield stress) is kept below the allowable limits. The ballast condition produced slightly greater extremes than the fully loaded condition. Table 7 also provides information for the flexjoint design. The angle ranges are within the capabilities of typical single-action flexjoint designs.

The results of the TLR survival analysis show that the steel part of the riser meets all the design requirements. Note the small difference between the maximum and minimum top tension that indicates the riser is fairly well decoupled from the FPSO motions, allowing for a quasi-static design of the SCRs. The hang-off angles, measured from the vertical axis of the buoy, are well within the limits of an acceptable stress joint design. Results for the flexible jumpers are not presented due to space limitations but were also found to be within acceptable limits. The TLR buoy mooring tendons were also checked. The minimum intact safety factor is 2.80 and the minimum for a damaged tendon condition is 1.31. Should a tendon fail, the buoy will tilt due to the asymmetry of the vertical loads. Should the resulting transient and mean rotations from a failed tendon be determined to be excessive for the risers or the jumpers, an eight-leg mooring could be designed (two tendons at each corner), which will greatly reduce the maximum tilt.

Results of the SLHR survival analysis also show that all parameters are kept within acceptable limits except for stresses at the bottom of the riser. These results confirm the requirements for a stress joint at the base of the SLHR system (the stress joint was not accounted for in the Orcaflex model). Angle variations at the base are within the limits for a stress joint. Similar to the TLR, the results show how well the SLHR concept decouples the vertical steel riser from the FPSO motions. Results for the flexible jumpers are not presented but were found to be acceptable, thus no integrity issues exist for the system.

Table 7. Survival Analysis Results

Case						Top Tension		Minimum Tension	Relative Angle Variation*		Utilization Ratio
Riser System	Draft Condition	Environment Alignment	Storm	Vessel Offset	Intact or Damaged Mooring	Max	Min	Min	Max	Min	
						mt	mt	mt	deg	deg	
SLWR	Full	Collinear	100 Yr Hurricane	Near	Damaged	303	112	7	9.4	0.0	0.60
			Irregular Waves			290	126	11	7.5	0.0	0.60
	Ballast	Collinear	100 Yr Hurricane	Near	Damaged	310	104	5	9.9	0.3	0.61
			Irregular Waves			269	146	15	8.0	0.0	0.59
	Full	Crossed	100 Yr Hurricane	Far	Damaged	319	130	18	14.3	0.8	0.45
	Ballast	Crossed	100 Yr Hurricane	Far	Damaged	325	119	14	15.1	1.2	0.47
	Full	Crossed 2	1000 Yr Hurricane	Near	Intact	306	101	2	13.9	0.8	0.69
	Ballast	Crossed 2	1000 Yr Hurricane	Near	Intact	327	92	0.0	15.4	0.6	0.70
TLR	Full	Collinear	100 Yr Hurricane	Near	Damaged	202	181	>0	4.4	5.3	0.71
	Full	Crossed	100 Yr Hurricane	Far	Damaged	200	180	>0	4.0	4.9	0.74
	Full	Crossed 2	1000 Yr Hurricane	Near	Intact	206	189	>0	5.6	7.2	0.56
SLHR	Full	Collinear	100 Yr Hurricane	Near	Damaged	213	193	101	0.6	0.1	0.56/0.24
	Full	Crossed	100 Yr Hurricane	Far	Damaged	216	196	104	4.0	3.7	0.45/1.05
	Full	Crossed 2	1000 Yr Hurricane	Far	Intact	229	183	118	4.0	3.4	0.47/1.00

* From vertical, at top (SLWR), top (SCR) and bottom (SLHR).

FATIGUE ANALYSIS

The fatigue damage to each riser system consists of contributions from three main sources:

- First order wave fatigue induced by wave loading and associated FPSO motions;
- Second order (or low frequency) fatigue induced by the low frequency vessel motions; and
- Vortex Induced Vibrations (VIV) fatigue induced by current and vessel motions.

Additional fatigue damage may accumulate during the installation of the riser systems.

A safety factor of 10 was used for the wave induced fatigue damage, and 20 for the VIV induced fatigue damaged. When combined together with their respective safety factors, the total predicted fatigue life from wave induced and VIV induced fatigue should be greater than the design life, which is 30 years for this study.

The adequacy of each riser system to resist fatigue was assessed by computing separately damage induced by first order wave action, damage induced by second order (low frequency) wave induced motions and damage induced by VIV. Damage from these three main sources was combined to obtain a minimum fatigue life for each riser. Fairly conservative assumptions and parameters were used to conduct this fatigue analysis. The fatigue was evaluated for all risers in operating configurations, with an intact (undamaged) FPSO mooring system.

Wave Induced Fatigue Analysis Methodology

Two wave scatter diagrams composed of 12 and 13 sea states were successively used for the fatigue analysis. For the first order fatigue analysis, the fatigue damage induced by each sea state of the wave fatigue scatter diagram was evaluated by running a twenty minute time domain simulation to determine the stresses along the entire flowline. The standard deviation of stress was then used to calculate the fatigue damage for that particular sea state using the Rayleigh damage formulation shown below:

$$D = k \cdot N \cdot (f \cdot \sigma)^m$$

$$k = \frac{(2 \cdot \sqrt{2})^m}{a} \cdot \Gamma(m/2 + 1)$$

where:
D = damage
f = thickness modification factor
σ = RMS hot spot stress
a = constant relating to the *S-N* curve
m = negative inverse slope of the *S-N* curve
N = total number of cycles
Γ = gamma function

The fatigue S-N curve used to estimate the fatigue damage of the flowlines is the DNV E curve, along with a stress concentration factor of 1.1. The NPD wind spectrum was used, and the irregular waves in the scatter diagram were modeled using a JONSWAP spectrum with a gamma of 1.0.

The second order fatigue damage was evaluated by conducting a quasi-static analysis using second order vessel motions for each sea state of the scatter diagram. Second order vessel motions were estimated with SPMsim using statistics from 3-hour simulations conducted for each sea state. The RMS stresses along the riser were determined for each sea state using the mean and 1-sigma low frequency offsets.

Wave Induced Fatigue Results

First and second order wave-induced fatigue results for the SLWR are presented in Table 8. Both fully loaded and ballast cases were examined. The minimum fatigue life of 680 years occurs at the TDP. The ballast load case results in a riser fatigue life approximately half that of the fully loaded condition. A third case, the ballast case in the crossed environmental condition, assumes all the waves are incident 20 degrees off the bow. This case was analyzed to check sensitivity to the vessel weathervaning performance and to recognize that the waves will seldom be directly on the bow. For this case, the effect of the non-collinear waves did not have much impact on the minimum fatigue life since the touchdown point controls the design. However, the non-collinear waves noticeably affect the fatigue life at the hang-off point due to the increase in roll response, as the waves become more quartering. Low frequency motions contributed very little to the total damage.

Table 8. SLWR Wave Fatigue Analysis Results

Parameter	Unit	Analysis Case		
Draft Condition		Full	Ballast	Ballast
Flexjoint Stiffness	(kN.m/deg)	30	48	48
Shortest element	(m)	5	2	2
Environment		collinear	collinear	crossed
Offset Direction		far	far	far
Soil Stiffness	(kN/m/m^2)	200	200	200
Friction Coefficient		0.5	0.5	0.5
Cd		0.7	0.7	0.7
SCF		1.1	1.1	1.1
WF damage	(1/years)	6.59E-04	1.36E-03	1.37E-03
% of total damage	(%)	99	98	93
LF damage	(1/years)	7.24E-06	2.99E-05	9.73E-05
% of total damage	(%)	1	2	7
Total damage	(1/years)	6.67E-04	1.39E-03	1.47E-03
Total Life	**(years)**	**1500**	**718**	**680**
Location		TDP	TDP	TDP

Figure 11 shows total fatigue along the length of the riser for the ballast condition and collinear waves. Note that the total fatigue life at the top termination, in the buoyancy section and at the touchdown point are approximately the same, indicating a well-optimized riser configuration.

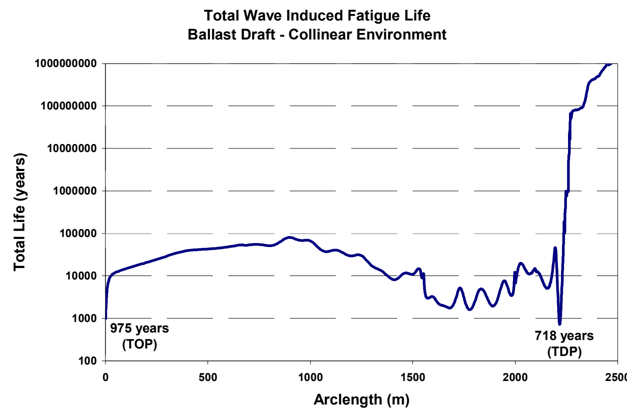

Figure 11. Wave Induced Fatigue Life Along SLWR

A sensitivity analysis was performed to evaluate the response and sensitivity of the SLWR to various input parameters, including soil vertical stiffness, number of sea state bins selected, drag coefficient, flex-joint stiffness, length of elements used in critical regions, buoyancy length, vessel heading, vessel draft, slow drift, and riser heading.

The sensitivity study showed a relatively important sensitivity to drag coefficient and element size. The sensitivity to drag coefficient showed that an increase from a Cd of 0.7 to a Cd of 1.2 resulted in a decrease of 20 percent in RMS stress near the TDP region. This result shows that for the SLWR, the drag term acts as damping for the lower part of the riser, which is not subject to wave loading. Therefore, selecting a low drag coefficient for the analysis should lead to conservative estimates of the fatigue damage of the system. This is also the recommendation in the DNV Offshore Standard for Metallic Risers [9]. The DNV guidelines state that in areas where drag is acting as a forcing mechanism a high value of the drag coefficient should be selected, and in areas where drag is acting as a damping mechanism a low value of the drag coefficient should be selected.

Figure 12 shows the sensitivity of the fatigue damage to the finite element mesh used. The figure shows an increase of 20 percent in fatigue damage when the smallest element in the TDP region is reduced from a 5-meter element to a 2-meter element. This result shows that a proper selection of the finite element mesh is critical when conducting detailed fatigue analysis of these riser systems.

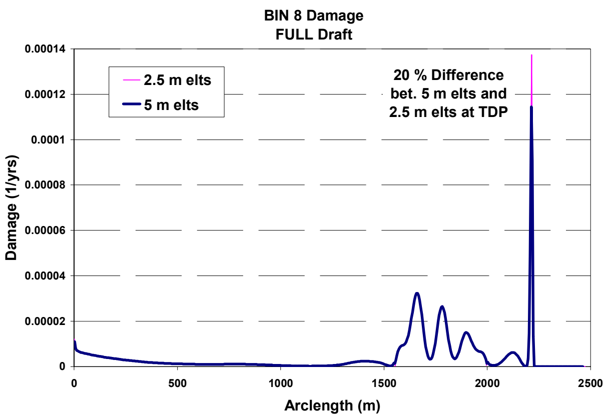

Figure 12. Fatigue Sensitivity to Element Size

Figure 13 presents the riser response sensitivity to flexjoint stiffness. The only impact is seen at the top of the riser (first element), with an increase in damage approximately proportional to the increase in flexjoint stiffness.

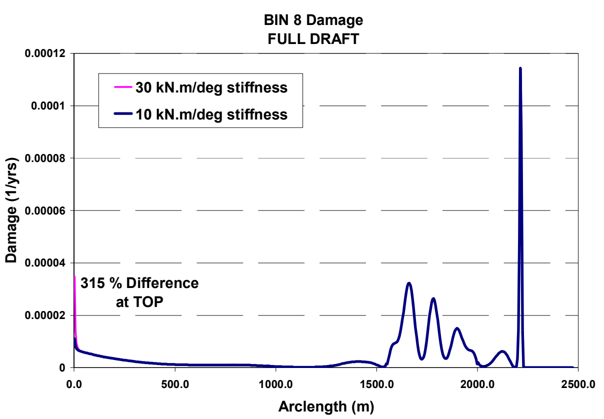

Figure 13. Fatigue Sensitivity to Flexjoint Stiffness

The minimum fatigue life calculated for the TLR steel catenary risers is 7,800 years. The minimum fatigue life occurs at the TDP. This large fatigue life also demonstrates the efficiency of the TLR system in decoupling the steel catenary risers from the FPSO vessel motions.

The minimum wave fatigue life for the SLHR riser was found to be 7,858 years. The minimum fatigue life occurs at the base of the riser. Again, the stress joint was not included, thus the minimum fatigue life would be much better since the first weld could be moved outside the fatigue sensitive zone at the base. This high fatigue life also demonstrates the efficient decoupling effect between the steel riser and the FPSO vessel motions.

Vortex Induced Vibration (VIV) Fatigue Analysis

The fatigue damage due to VIV was examined for the three risers using the program Shear 7 versions 4.0 and 4.1 [10]. The SLWR will be mainly discussed here since it is the more interesting case. A pinned-pinned beam model was assumed with mode shapes imported from a Finite Element Analysis (FEA) program. The currents at the site were represented as eddy conditions for 25 percent of the year, and background currents were assumed for the remaining 75 percent of the year. Bottom currents were also included in the current data. A total of 38 current bins were used to conduct the VIV fatigue analysis.

The SLWR mode shapes were independently calculated and verified using three different programs: Shear 7 and two FEA analysis programs. Figure 14 presents the natural periods for the SLWR for both the in plane and out of plane modes. As can be seen on the graph, the natural periods between the two planes only differ for the first few modes. Figure 15 presents the modal curvatures for mode 25 and 50.

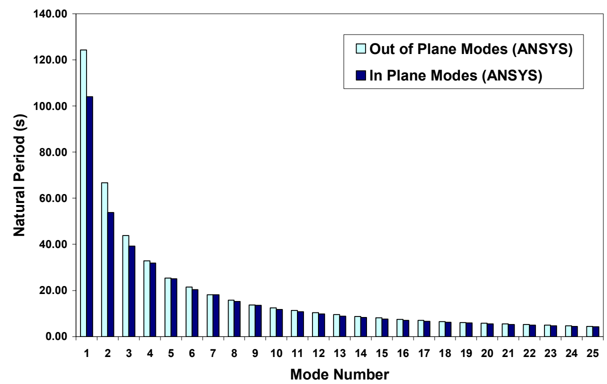

Figure 14. SLWR Natural Periods

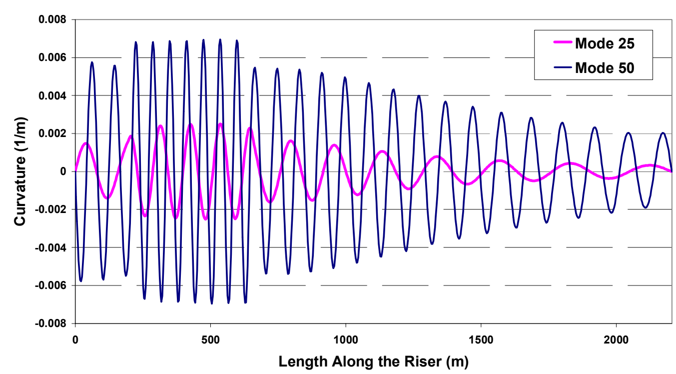

Figure 15. SLWR Modal Curvatures

Input parameters used and results for the SLWR VIV analysis are presented in Table 9. Results show a very low fatigue life for the SLWR without the use of VIV suppression devices (such as strakes). The minimum fatigue life obtained with the input parameters and current bins considered is 15 years when using a mode cutoff of 0.1 (multi mode response) and 3 years when using a very high mode cutoff parameter of 0.9 (single mode response). The minimum fatigue life occurs in the buoyancy section. The loop currents cause 80 percent of the damage. For the strouhal number, a value of 200 indicates that Shear 7 will internally calculate the Strouhal number using a rough cylinder strouhal curve (Strouhal number vs. Reynolds number).

Table 9. SLWR VIV Fatigue Analysis Results

PARAMETER		ANALYSIS CASE			
Mode Shape FE Program		**Stress**	**Stress**	**Stress**	**Stress**
Mass/Tension file		**no**	**yes**	**yes**	**yes**
Strouhal Number		200	200	0.22	0.22
Vr Two Sided Bandwidth		0.4	0.4	0.4	0.4
Mode Cutoff		0.1	0.1	0.1	0.9
Multi-Mode Reduction Factor		1	1	1	1
Lift Coefficient		shear 7	shear 7	shear 7	shear 7
Added Mass		1	1	1	1
Structural Damping		0.003	0.003	0.003	0.003
SN Curve		E	E	E	E
SCF		1.1	1.1	1.1	1.1
Loop Currents Damage	(1/years)	5.21E-02	5.23E-02	6.10E-02	3.04E-01
% of total damage	(%)	78	79	81	97
Background Currents Damage	(1/years)	1.43E-02	1.43E-02	1.43E-02	9.85E-03
% of total damage	(%)	22	21	19	3
Total damage	(1/years)	6.63E-02	6.65E-02	7.53E-02	3.14E-01
Total Life	**(years)**	**15**	**15**	**13**	**3**
Location		Buoyancy	Buoyancy	Buoyancy	Buoyancy

Some sensitivity analyses were also performed by comparing the total fatigue life (for the 20 loop current bins) using the last three versions of Shear 7 (versions 3.0, 4.0 and 4.1). The results showed a ratio of 4 between the fatigue damage from version 3.0 and the fatigue damage obtained from version 4.0 and 4.1. Table 10 presents a comparison of the excited mode numbers as well as the RMS amplitude of vibration for one loop current bin for the three Shear 7 versions compared. The highest mode excited is mode 88. At VIV scale, the differences between the last two versions of Shear 7 are limited, and the results of this sensitivity analysis did not change the conclusions previously obtained.

Table 10. Sensitivity to Shear 7 Version

Loop Bin 220	Number of Excited Modes	Excited Mode Numbers	Max rms A/D
Version 3.0	24	21,22,34,60,62,63,65,66,68,69,70,71,72,74-84	0.32
Version 4.0	15	12,13,72-84	0.203
Version 4.1	14	11-14,74-77,82,84-88	0.18

For robustness check, the VIV fatigue life under continuous exposure to the 100-year loop or the 10-year loop with bottom currents was also evaluated. Results are presented Table 11 and show very low fatigue lives. These results confirm the need to add strakes in order to increase the minimum VIV fatigue life of the SLWR to acceptable levels.

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Table 11. Continuous 100-yr Loop Event Exposure

Riser without Strakes		Units	St=200 no cat file	St=200 with cat file	St=0.22 with cat file	St=0.22 c=0.9 with cat file
100 Yr. Loop	Damage	(1/years)	2.67E+00	3.03E+00	1.73E+02	1.27E+02
	Fatigue Life	(days)	**137**	**120**	**2**	**3**
10 Yr. Loop+Bottom	Damage	(1/years)	1.30E+01	1.21E+01	5.72E+00	3.32E+00
	Fatigue Life	(days)	**28**	**30**	**64**	**110**

With the specified safety factor of 10 on wave induced fatigue, 20 on VIV induced fatigue and a service life of 30 years, the VIV induced fatigue life needs to be approximately 1,100 years. Using Shear 7, further analyses were conducted to estimate the extent of strakes required. It was determined that approximately 1,000 meters of strakes would be required. A large portion of the strakes would be covering the buoyant section of the riser.

Results for the VIV analysis of the SLHR are presented Table 12. The minimum fatigue lives of the SLHR with and without strakes are presented. As seen on the table, 300 meters of strakes near the top of the riser increase its minimum VIV fatigue life to 1,290 years. An increase of the SLHR tension factor can be used to improve its VIV fatigue life. The selection of the SLHR tension factor should therefore consider its impact on the VIV fatigue damage as buoyancy cost (larger air can) is usually lower than the cost of VIV suppression devices such as strakes.

Table 12. SLHR VIV Fatigue Analysis Results

Environment		Units	Background and Bottom Current	Loop and Bottom Current	Combined
Flowline w/o Strakes	Damage	1/Yr	3.06E-04	2.46E-03	2.76E-03
	Fatigue Life	Yr.	3268	407	**362**
Flowline w/ 300m of strakes	Damage	1/Yr	2.93E-04	4.82E-04	7.75E-04
	Fatigue Life	Yr.	3409	2075	**1290**

INSTALLATION AND COST EVALUATION

Installation procedures were developed for the three riser concepts to confirm feasibility and estimate installation costs. The J-lay method was assumed for installing the steel riser sections, and reeling was assumed for installing the flexible jumpers for the TLR and SLHR systems. Installation procedures detailed in two DeepStar studies ([4] and [11]) which investigated the SLWR, hybrid tower, and TLR, are similar to what would be used to install these risers, with the exception that the SLHR system would be J-layed and transferred to a porch on the installation vessel, using a crane. The jumper and air can would then be connected to the gooseneck. While flooding the air can, the riser would be lowered and connected to the subsea connector, upon which the buoyancy tank would be deballasted.

Cost for engineering, procurement, fabrication, installation, and project management were estimated for each of the three riser systems designed. A nominal cost impact on the turret was included for the SLWR due to much greater riser hang-off loads. Results show that for this application, the SLWR was the lowest cost option. The SLHR and TLR have cost estimates 32 percent and 38 percent higher than the SLWR cost estimate respectively. However, under different parameters, the SLHR or TLR may be more cost competitive. For example, the TLR becomes more attractive as water depth increases, and as the number and the diameter of risers increase.

CONCLUSIONS

The paper presents key technical results from a comprehensive study on the preliminary riser system design for a new built turret moored FPSO system in 1,370 meters (4,500 feet) water depth in the Gulf of Mexico. Three riser systems were considered and designed: the Steel Lazy Wave Riser (SLWR) system, the Tension Leg Riser (TLR) system and the Single Leg Hybrid Riser (SLHR) system.

The detailed feasibility study included survival and fatigue analyses. First and second order wave induced fatigue analyses and VIV induced fatigue analysis were performed for each riser system. Numerous sensitivity cases were investigated. Installation methodologies were also assessed and screening level cost estimates were developed for all riser systems. The paper demonstrates that all three riser systems are feasible. The three riser systems can be installed with little modification to existing equipment. Table 13 presents a non-exhaustive summary of the various strengths and weaknesses of each of the three riser systems studied. The paper shows that for the diameter and number or risers and water depth considered, the SLWR is the preferred option. However, the SLWR is the most sensitive riser system to the environment with relatively marginal fatigue and extreme response performances. Under different parameters, or if global motions of the FPSO were to become more severe, the TLR or SLHR may be preferred as they effectively decouple the steel portion of the riser from the vessel motions via flexible jumpers.

The paper illustrates that a number of effective steel riser solutions are available for use on deepwater turret moored FPSOs in harsh environments, each with its advantages and disadvantages. The preferred riser solution depends on many factors such as water depth, number and size of risers, metocean conditions, vessel motions, turret location, turret loading, field layout and footprints, soil conditions, seabed topography and flow assurance requirements. Economics usually drive the riser selection, but risk is also important and must be considered in the process.

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Table 13. Strengths and Weaknesses

Strengths	Weaknesses
SLWR	
• Feasible riser system with FPSO in GoM • Lowest cost of three riser systems studied • Minimum required installation vessels • No subsea connections required • Simplest installation operation • Fairly insensitive to FPSO vessel offsets	• Stress and fatigue sensitive due to vessel vertical motions at turret • Stress and fatigue hot spots at touchdown point, turret hang-off and buoyancy locations • High turret static and dynamic hang-off loading increases cost impact on turret • Requires use of costly flexjoints • Requires use of costly (syntactic foam) buoyancy • Relative uncertainty of long term response of syntactic foam buoyancy modules used for such application • Requires flooded riser pipelay • Highly Sensitive to amount of distributed buoyancy
TLR	
• Feasible riser system with FPSO in GoM • Quasi-static behavior of SCRs • High fatigue resistance to wave induced FPSO motions • Low turret hang-off loading • Allows use of low cost (air can) buoyancy • Variable buoyancy accommodates future riser installations	• Higher cost riser system • Jumper design (length) sensitive to FPSO vessel offsets • Maximum required installation vessels • Possible leak path at subsea connections • Buoy stability sensitive to failed tendon condition. SCR yielding during rotation • Foundation sensitive to high deballast condition loading
SLHR	
• Feasible riser system with FPSO in GoM • High fatigue resistance to wave induced FPSO motions • Low turret hang-off loading • Allows use of low cost (air can) buoyancy • Wall thickness not governed by collapse allows for thinner wall thickness	• Higher cost riser system • Stress hot spots at riser base • Jumper design (length) sensitive to FPSO vessel offsets • Possible leak path at subsea connections • Significant seabed hardware required (pile, PLET, U-jumpers, hydraulic connector)

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