

# **Catenary and Hybrid Risers for Deepwater Locations Worldwide**

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## **INTRODUCTION**

Floating production systems offer the most practical method for developing medium and deep water oil and gas reserves. A wide range of tethered and catenary moored production vessel designs have evolved including TLP, SPAR, tanker, deep draught floater, semi submersible, and their derivatives. As water depth increases the cost of the riser system, used to transport production fluids from the seabed to these production vessels, becomes a higher proportion of the total field development cost. Consequently, it is increasingly important that proper attention is paid to the design and selection of the riser system early in the design loop.

The riser systems currently implemented on deeper water production systems are mostly adaptations of shallow water concepts. However, a number of new riser concepts have been developed in recent years that offer technical and commercial advantages over the systems typically used in shallow water. The following paper discusses two of these systems and the factors that affect selection of one system over the other. Riser system evaluation and selection is a complex process. It is not sufficient to simply compare hardware costs and a full evaluation of the impact of the riser system on the overall development cost, schedule and risk is required.

## **CURRENT STATUS**

The term 'deep water' is a fast moving target. The industry is now seriously considering technology for water depths up to 2000m whilst only 4 years ago 500m was widely considered 'deep'. Whilst TLPs are well suited to deepwater and are feasible in water depths down to 2000m, experience has shown their capital cost is high and development schedule long. Consequently they are suited to large field developments using a high number of completions.

The success of catenary moored floating production systems in recent years has firmly established the technology within the industry. It offers a fast track, low capex solution which greatly enhances field economics. These floating production systems have largely used flexible risers which is a natural extension of proven shallow water technology. In general this approach has been successful and flexible pipe suppliers have developed the capability to design, manufacture and install riser systems to meet the demands of the market. However, the cost of flexible pipe is relatively high and there are technical limitations to the maximum diameter, operating pressure and temperature. Additionally, availability is limited to a small number of qualified vendors.

It is predicted that there will be increasing use of floating production systems in the future not only for small medium depth developments but also for larger, deep water developments. Examples are the BP Foinaven and Schiehallion fields, West of Shetland. These developments place significant demands on the riser systems, large numbers (25), large diameter (12 inches), high depth (500m), long life (25 years) coupled with an extremely harsh environment. These developments push current flexible riser technology to the limit and as a result the riser system forms a high proportion of the hardware costs.

Flexible riser technology is being progressed due to the demand for improvements in pressure ratings, diameters, depth of application and materials for sour service. However, the improved specifications result in higher costs due to more complex manufacturing processes and more exotic materials. Consequently, alternatives to flexible risers have been eagerly pursued. The advent of low cost, high speed computing and advanced computational techniques has allowed new riser geometries to be considered and their response evaluated. Some major advances in rigid riser system design have been achieved which will be instrumental in reducing the cost of future deepwater developments.

## RISER DEVELOPMENTS

Two riser concepts which offer alternatives to flexible risers for deep water floating production, and have significant potential, are the hybrid riser and steel catenary riser systems, both recently implemented in the Gulf of Mexico.

### Hybrid Risers

The hybrid riser was the first practical alternative to the full depth flexible riser to be installed and implemented. In principle it is a vertical steel bundle of pipes supported by external buoyancy. Compliance is provided by the use of short flexible pipe jumpers which are located near the surface to accommodate relative motions between the top of the riser and vessel.

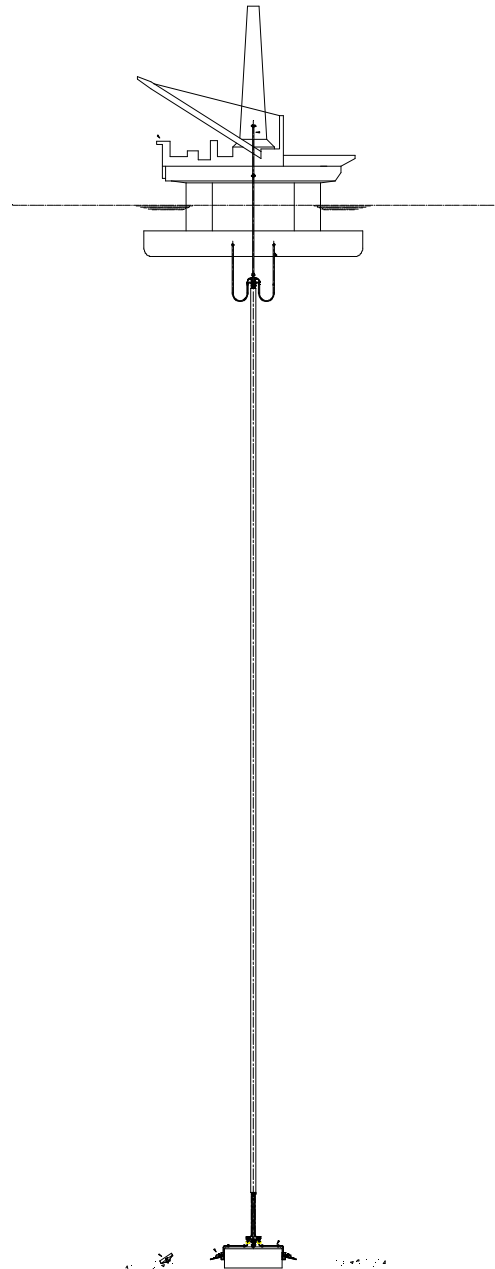
The first hybrid riser was installed on Placid's Green Canyon development and recently refurbished and extended for use on Ensearch's Garden Banks development [4]. The main section of the hybrid riser consists of a central structural tubular, around which syntactic foam buoyancy modules are attached. Peripheral production and export lines run through the buoyancy modules and are free to move axially in order to accommodate thermal and pressure induced extension. The central structural member is connected to the riser base by way of a hydraulic connector and stress joint. The peripheral lines are attached to hard piping on the base, which provides connection to the subsea flowlines, and terminates in goosenecks some 30 to 50m below the water surface. Flexible piping is attached between the goosenecks and porches on the pontoons of the semisubmersible production vessel, providing the flowpath to the vessel whilst accommodating relative movements between the rigid riser section and the platform.

The hybrid riser implemented by Ensearch is run offshore in a manner similar to that used for drilling risers. This process is costly due to modifications required to the installation vessel and long installation durations which limits the feasibility of the concept particularly for harsh environments where weather windows are short. However, bundle construction and installation by tow-out has been investigated [1] and shown to offer substantial savings in cost and installation time, offering improved scope for application of the concept in greater water depths. It has also been shown that the concept may be used with a ship-shaped vessel. A range of hybrid riser designs have evolved based on beach fabrication with tow out and upending at the offshore site using offset and non offset arrangements. Study work has shown these arrangements are technically feasible and cost effective. [1].

### Steel Catenary Risers

The Auger platform is the first floating production facility to implement steel catenary risers, 2 off 12inch lines being used for oil and gas export. In this arrangement, the riser forms an extension of the flowline which is hung from the platform in a simple catenary. Relative rotational movement between riser and platform is accommodated using a flex-joint. Hard piping mounted on the outside of the hull, is used to transport fluids from the process facilities above sea-level to the riser connection to the platform on the pontoon. In this application, the benefits of the catenary riser compared to the vertical tensioned arrangement include a fixed valve stack and elimination of the riser base. Perhaps more important, is the reduction in wellbay deck space required.

The steel catenary risers implemented on Auger and proposed for the Mars and Ram-Powell TLP's, can be seen as a direct alternative to flexible lines. They may be used at larger diameters, higher pressures and temperatures and may be procured more easily. Steel lines are cheaper than flexibles and may be used in greater water depths without a



disproportionate increase in cost. The ability to use larger diameters can reduce congestion at the vessel, which may simplify turret design on ship-shaped vessels and porch construction

on semi-submersibles. The larger diameters may also enable greater production flow rates to be achieved, thus offering better use of the production vessel. The opportunities for developing high pressure, high temperature fields are also improved by the development of steel catenary risers though their use in shallower water depths is limited.

Steel catenary risers are well suited for use with tethered platforms such as TLP's. Platform motions due to wave action are mostly lateral, with a small degree of vertical movement or set-down from the inverted pendulum action of the tethers. Consequently, the nominal catenary shape does not change significantly. Large water depths, such as found on Auger, are also beneficial in that dynamic excitation from wave action at the surface is damped as it travels to the seabed. The concept is being taken a stage further by Petrobras, who intend implementing a 10inch steel catenary riser for gas export from the Petrobras XVIII semisubmersible floating production facility in the Marlim field. In this configuration, the riser is exposed to the heave and pitch induced heave motions of the platform. While the magnitude of the extreme dynamic motions are not particularly severe, typically less than 5m, due to the relatively mild environmental conditions of Marlim, platform drift motions significantly larger than those experienced with a TLP, up to 15% of water depth, must be accommodated. This is an important development, which paves the way for more widespread use of steel catenary risers with catenary moored production vessels.

Variations on the steel catenary riser arrangement of Auger and Marlim are currently proposed [2, 3] which use buoyancy and weights to shape the riser, giving steep and lazy wave arrangements similar to those used for flexible lines. These concepts improve the ability of the riser to resist dynamic loads and vessel motions and enable greater offsets to be tolerated. Feasibility of these concepts has been demonstrated in diameters up to 30inches, for harsh environments, where platform heave motions up to 30m and vessel offsets up to 25% water depth must be accommodated.

## **HYBRID VERSES STEEL CATENARY**

The scope for using hybrid and steel catenary risers in water depths less than 300m is limited and conventional flexible riser systems are likely to continue to provide the most suitable solution for some time. However, many benefits can be realised by consideration of the rigid riser options for water depths from 300m up to 2000m. As direct alternatives to the flexible riser systems, hybrid and steel catenaries offer distinct advantages in terms of cost and service. Both systems can give installed cost reductions of over 40% compared to a flexible riser system, which can increase with increasing water depth. Vessel loads for both hybrid and steel catenaries are lower than equivalent flexible systems. For high pressure, high temperature (HP/HT) developments or sour service conditions, concerns regarding the use of flexible lines can be alleviated with steel catenaries or a hybrid riser. The critical components in each system, namely the flex-joint for the steel catenary and flexible lines for the hybrid riser, are located near the surface where they are accessible and readily replaceable.

Development work on hybrid and steel catenary risers is well advanced. Results have confirmed the feasibility of both systems [2,3] for use with tanker and semi submersible production vessels in a wide range of environments and water depths. The question that is now asked is which of the two systems is the best and what factors dictate the selection of one of the systems over the other?.

A hardware cost analysis is normally the first step in evaluating alternative riser systems however, the process is rarely so simple and in addition it is necessary to compare installation, operating, and decommissioning costs. It is also important to assess the impact of the riser system on vessel design and field layout and determine any limitations it

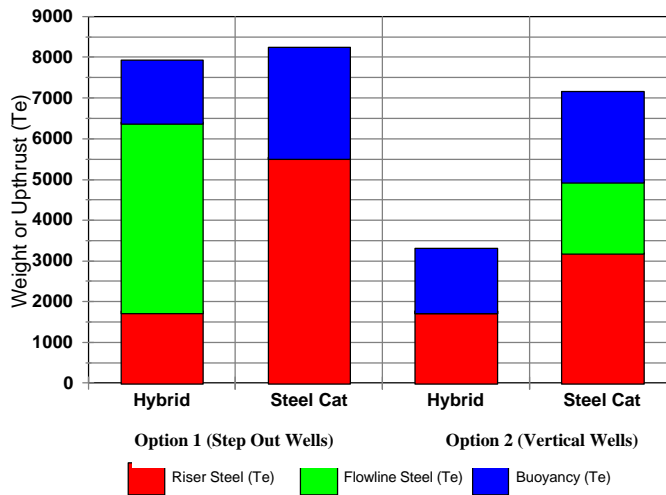
imposes which may affect commercial, reliability or safety issues.

In the following sections the key factors affecting selection of hybrid or steel catenary systems are discussed. Two field arrangement options are considered; the first with subsea wells located outside the production vessel mooring pattern and the second in which the wells are located directly below the production vessels, allowing simultaneous production, drilling and workover. See Figures 1 and 2 respectively. Other development parameters are common and are summarised in the following table.

Parameter	Description
Water Depth	850
No Risers	10
Diameters	12 inches
Rating	5000psi
Max Vessel Offset	20% Water Depth
Environment	Northern North Sea
Vessel	Semi or FPSO

**Hardware Costs**

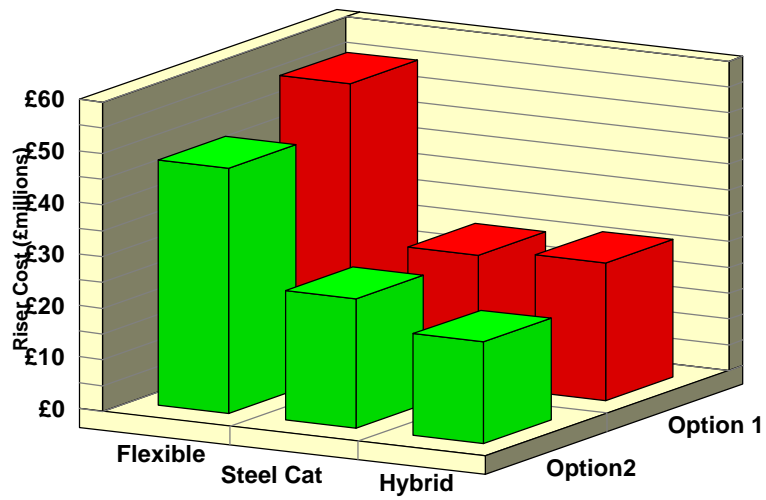
The cost of riser and flowline steel and external buoyancy for a deep water development forms a high proportion of the total riser hardware cost, typically 60-80%. The following graph summarises steel weight and buoyancy upthrust estimates for hybrid and steel catenary arrangements for the two field arrangements.



**Graph Showing Steel Weight and Buoyancy Upthrusts for Riser Options**

The following table presents the total riser hardware costs based on typical steel and buoyancy costs. The costs also include the cost of other equipment such as riser bases, coatings, flexible jumpers, flex joints, flowline porches etc. The table also presents, for comparison, budgetary costs for equivalent flexible riser and flowline systems.

Option	Hybrid ( millions)	Steel Catenary ( millions)	Flexible ( millions)
<b>Option 1</b> Step Out Wells	26.57	25.27	66.7
<b>Option 2</b> Vertical Wells	19.63	25.06	57.6



## **Summary of Riser Hardware Costs**

It can be concluded that the hybrid and steel catenary riser total costs are similar for field development option 1 using step out wells. It should be noted however, that buoyancy would not be required for option 1, steel catenary risers, in many locations worldwide where vessel offset are less than 20% waterdepth, which results in a 50% hardware cost saving. For field development option 2, using wells directly below the platform, the hybrid riser has a significantly lower hardware cost. It can be concluded that both the hybrid and steel catenary systems offer significant hardware savings over the flexible riser system.

### **Fabrication Costs**

The number of welds required in each system is proportional to the steel weight. The steel catenary riser due to its more dynamic response and fatigue sensitivity may also require a higher weld quality along a proportion of the length, particularly near the touch down point, to achieve the required fatigue life. The steel catenary riser may also be assembled offshore using threaded couplings [5] thus eliminating the need for welding. Riser joints can be either manufactured using premium or weld on couplings. Both methods have a higher connection cost than welding but can allow the use of a lower cost installation vessel and improved fatigue details.

The hybrid riser is fabricated onshore at a beach site whilst the steel catenary may be fabricated offshore from a J lay vessel or onshore at a reeling site. The cost of providing these facilities/vessels will of course be different in both cases and must be considered in conjunction with the installation costs. The cost of beach site mobilisation and demobilisation, in the case of the hybrid, is dependent on geographical location. The requirements include temporary shelter, winches, and a levelled beach section on which to support the riser.

### **Installation Costs**

Installation costs are particularly difficult to estimate accurately due to variance in mob/demob durations and vessel day rates. For commercial reasons it is advantageous to use low specification vessels which have a higher availability rather than specialist vessels in order to achieve shorter mobilisation and lower day rates.

Following launch from the beach the hybrid riser is installed as a single pre-commissioned structure by a towing operation with upending at site and connection to the preinstalled riser base. Low specification vessels are suitable and short installation schedules can be achieved. Typically a riser may be towed at 4 knots, allowing installation within a 600km radius to be completed in 5-7 days. The riser may be pre-installed prior to the production vessel offering improved schedule flexibility over the steel catenary riser which must be installed after the production vessel. If the hybrid riser is used with step out wells (option1) it is necessary to mobilise a pipe lay vessel to install flowlines. This significantly adds to the total installed cost. However, it should be noted that the flowlines do not need external buoyancy, and therefore installation is significantly quicker than for buoyant catenaries.

Steel catenaries and flowlines are installed using J or reel pipelay vessels, DP semi or DSV with workover derrick. These may have a day rate 2-3 times those used for the hybrid tow-out operation and additionally, the duration to install 12 steel catenaries may be 30-50 days depending on depth, amount of buoyancy on each riser, number of seabed tie-ins and requirements for respooling.

For the field arrangement option 1, using step out wells, the steel catenary risers have the advantage that they are laid directly to the subsea completion eliminating the need for additional flowlines. However, when the wells are located directly below the vessel as in option 2 additional flowlines are required to extend the end of each catenary riser back under the vessel. Additionally each catenary riser must be terminated at individual foundation structures, the installation of which increases the installation duration by approximately 30 days.

In summary the installation cost of the hybrid riser is generally lower than the installation cost of the steel catenary system even when the cost of the hybrid riser foundation and launch from the beach site are considered. Typical installation costs are estimated at 5million and 10million respectively. If the development uses step out wells the cost of installing the hybrid system will approach that of the steel catenary riser system.

### **Development Schedule**

The hybrid riser is a large single assembly and has a longer development schedule than equivalent steel catenary risers. Whilst engineering and analysis schedules are similar, procurement, site set-up, fabrication and assembly of the hybrid riser is likely to be longer. In the case of the steel catenary risers it is probable that all risers will not be required in the

first season and installation may be spread over 2 or 3 seasons which relaxes the procurement schedules. It is possible that a steel catenary riser may be designed and procured, ready for installation, inside 12 months whereas the hybrid may take over 18 months depending on geographical location.

### **Simultaneous Drilling/Workover and Production**

If the production vessel has drilling facilities and wells are located directly below the vessel, simultaneous drilling/workover and production is possible. This is particularly suited to the hybrid riser arrangement whereby the drilling template is integrated with the riser base structure. This arrangement is adopted on Ensearch Garden Banks Block 388. Steel catenary risers are less well suited as the natural shape of the catenary takes the riser termination away from the vessel and additional flowlines are required to extend the risers back underneath the vessel which is costly, Option 2. However, there is an advantage in that this leads to a reduced risk of clashing between the drilling/completion riser and production risers. This arrangement is being considered on the Norsk Hydro Visund development.

If a development has 24 completions and field life of 20 years, typical drilling and workover rig costs are estimated around 100 million, depending on future rig rates and workover frequencies. If deep water rig rates increase and/or a development is predicted to have a high workover frequency, well access from the production vessel can significantly reduce through life costs.

### **Vessel Payload**

The nominal steel catenary total top tension for the system costed above is estimated at 2000 Te with a maximum tension of 2800 Te. This compares with a total payload for the hybrid riser of approximately 200-300 Te (tether and flexible jumpers). For an FPSO this payload differential may not be important but may become more so for a semi-submersible.

### **Riser Diameter**

The steel catenary can be designed with diameters up to 30 inches, depending on water depth and vessel motions. The maximum individual line diameter for the hybrid solution is approximately 16 inches, which is largely dictated by the availability of large diameter surface jumper hoses. Consequently if line diameters greater than 16 inches are required then manifolding is necessary. This can present pigging problems and introduce additional hardware and installation costs.

### **Number of Risers**

The maximum number of catenary risers that may be installed from a single vessel is limited by deck, pontoon or turret porch space. Typically the maximum number of risers may be up to 50 for a spread moored vessel or 30 for a turret moored vessel (depending on diameter). The hybrid riser has a slightly lower limit determined by practical fabrication requirements and congestion of the flexibles at the upper goosenecks. A limit of approximately 25 off 10-12 inch diameter risers is suggested however, a larger number of smaller diameter lines is feasible ie. 30 to 40 off 6 inch lines.

The effect of riser numbers on riser hardware cost is significant. For larger numbers the hybrid riser becomes more cost effective than the steel catenary system as the high cost items such as the riser base, tether and site mob/demob are spread over a higher number of lines. Conversely, smaller line numbers favour the steel catenary riser configuration.

### **Geographical Locations**

The geographical location of the field may be an important factor in riser selection. Remote locations can result in high mobilisation and installation costs in the case of the steel catenary riser, particularly if numerous respooling trips are necessary. For the hybrid riser a remote location may increase tow out durations and induce higher initial fatigue damage but this may not have a significant cost impact. However, fabrication at a remote beach site may be more problematic and result in higher set up, fabrication and launch costs.

### **Environment**

Both the hybrid and steel catenary systems are suitable for harsh and mild environments. Costs increase with increasingly harsh environments due to the need to use higher quantities of buoyancy and tension in both options. In the case of the catenary riser higher flex joint angles need to be provided and for the hybrid larger tethering tensions, jumper hose lengths and bend restrictors are necessary.

For mild environments such as Brazil and West Africa where vessel motions are small, provided offsets are kept to less than 20% water depth, simple catenary configurations may be adopted. This greatly reduces the catenary hardware and installation cost due to elimination of riser buoyancy. In such cases the steel catenary riser system will always be less expensive than the equivalent hybrid riser although vessel payloads can become significant.

### **Vessel Type**

The hybrid and steel catenary can be configured for use with tanker and semisubmersible vessels. A limiting factor with the hybrid riser is the diameter of the turret (if turret moored) which can limit the layout of the flexible jumpers. A small turret diameter combined with a harsh environment can prevent acceptable jumper response being achieved. Additionally, interference with the turret mooring lines can be difficult to prevent. However an offset riser may be used, though the increased jumper lengths would add cost. In conclusion, the hybrid riser is more suited to semi submersible applications where longer jumper hoses can be configured whilst the steel catenary is well suited to both applications.

### **Emergency Disconnect**

The hybrid riser offers the capability to disconnect the vessel and move off station leaving the riser free standing. This may be important in locations that suffer from short term severe environments such as hurricanes where the vessel mooring system cost may be significantly reduced by allowing the vessel to disconnect during extreme events. A similar approach, but with disconnection at the base and with the riser retrieved into the vessel moonpool, may be adopted in areas suffering from iceberg impact.

### **Seabed Layout**

The steel catenary riser concept generally adopts a touchdown point between 1 and 2 times the water depth away from the vessel depending on configuration. Additionally, sufficient flowline length on the seabed is required to resist high back tensions and movement of the flowline across the seabed. This may require relatively long lengths of pipe to be laid on the seabed before the lay direction of the riser/flowline can be changed. If a large number of risers are arranged radially around the vessel the result is relatively large coverage of the seabed. Additionally, the risers must be located in corridors to prevent interference with the mooring lines.

The seabed layout of the catenary risers is thus an important factor to be considered and the vessel must be located a sufficient distance away from the subsea completions/manifolds to facilitate the anticipated riser and flowline geometries. If the subsea completions or manifolds are located to one side of the vessel, additional flowline length may be required to route the risers to their final seabed terminations. Additionally, if more than one line needs to be routed to a single manifold, additional riser/flowline length will be required to route risers which are laid radially from the vessel to the same subsea termination. This requirement needs to be included when comparing the hardware and installation costs developed above which make no allowance for additional flowline lengths in Option 1.

Conversely, the hybrid riser arrangement allows a very compact subsea arrangement to be configured and mooring line interference is eliminated. Flowlines can be laid with first or second end connection at the riser base. Irrespective of the final location of each flowline, a compact arrangement can be achieved with minimum flowline length. The riser base may also incorporate a drilling template allowing subsea completions to be located on the riser base.

### **Mooring System and Interaction**

The steel catenary can be configured to assist mooring of the vessel. At extreme offsets high back tensions and top angles can be generated which contribute to the stiffness of the mooring system. As a result it may be possible to realise a reduction in the specification and cost of the mooring line components.

The hybrid riser does not provide any significant increase in the mooring stiffness or interaction with the vessel response.

### **Vessel Offset**

The steel catenary riser can be designed to accommodate relatively large vessel offsets. Simple catenary systems are limited to approximately 15% water depth depending on environment however, buoyant arrangements can accommodate offsets up to 25%.

The hybrid riser is generally only suitable for offsets up to 20% water depth and at larger offsets, problems can arise with the jumper response depending on environment and vessel response. Consequently, a stiffer mooring system may be required for the hybrid riser than the steel catenary riser.

### **Aggressive Completion Fluids**

If very aggressive production fluids are present such as high concentrations of hydrogen sulphide along with high pressures and temperatures, the steel catenary may be preferred to the hybrid riser due to higher resilience of the flex joint over the flexible jumpers. It is also possible to fit inconel bellows units inside the flex element to prevent production fluids from contacting the elastomer components.

### **Cost Schedule**

The hybrid riser has a higher capital cost than the steel catenary solution as it is necessary to fabricate and install the hybrid riser bundle as a single unit. The steel catenary risers may be installed as they are required, dictated by the drilling program and installation schedule. This allows first oil to be achieved with a relatively small number of risers with the balance purchased and installed in the second season.

### **Risk**

As the hybrid riser is installed as a single pre fabricated item, there is always the risk that if there are problems during tow and installation, significant costs and schedule delays may be incurred. As the steel catenary risers are installed as individual lines, the effect of a single item failure is less significant on the overall project. To overcome this the hybrid riser may be split into two smaller units, at a small additional cost, which alleviates the concerns of having all eggs in one basket.

### **Upgradeability Future Proofing**

Spare and contingency lines must be included in the hybrid riser during the initial design and fabrication phase which adds significant cost as it is difficult to add lines once the riser is installed. The steel catenary riser is more flexible with respect to upgradeability since individual lines can be added or replaced at any time with little or no impact on the other lines. A prudent development scenario may consist of a hybrid riser for the main development and steel catenary risers for contingency and additional lines.

### **Artificial Lift**

As water depths increase the effect of the internal hydrostatic pressure at the base of the riser becomes more significant on well productivity. There is increasing advantage, in terms of production rate enhancement, of reducing the back pressure by injecting gas to lift the fluids in the riser. In deep water this can offer a similar effect to injecting gas into the production tubing in the well bore but without the high cost impact on completion design.

Gas can be readily injected into the production lines at the base of the hybrid riser and maximum effect is achieved due to the vertical orientation of the lines which resists slugging, minimising pressure losses. Conversely the steel catenary is less well suited to gas injection due to the relatively large distance of the base from the vessel and the catenary configuration which may tend to cause slugging in the arch and sag bend. Additionally, the distribution of gas to each of the riser bases which are remote from the vessel can be expensive, requiring either piggy back lines or separate gas distribution lines and manifolds.

### **Decommissioning Costs**

Decommissioning costs may be significant in the case of all riser systems. The hybrid riser may be the simplest in that the riser can be removed as a single unit. However, this will leave the riser base and possibly flowlines which will be costly to remove. The steel catenary riser may be relatively slow and time consuming to remove if the complete seabed needs to be cleared. A lower specification vessel than used for installation may be considered as overstressing and buckling of the riser during removal would not be an issue.

## **CONCLUSIONS**

Recently implemented steel catenary and hybrid riser systems offer alternatives to flexible riser systems which are conventionally used on floating production systems. In water depths less than 300m their use is limited, but in larger water depths the benefits of these alternative riser systems can be significant. Cost reductions in excess of 50% and improved performance for HP/HT service applications can be achieved.

Riser systems have a key role in determining seabed layout, export options and vessel selection and need to be carefully considered during the initial design phases if a fully optimised system is to be developed and maximum benefit of the latest riser configurations is to be achieved.

The preceding cost data for the field arrangements considered shows that the hardware cost of the hybrid and steel catenary riser system is similar for field developments using step out wells but that the hybrid riser offers cost savings for field arrangements where the wells are located below the production vessel. The hardware cost of each system is sensitive to a large number of design parameters which must be evaluated for each application.

The hybrid riser has a lower installation cost than the steel catenary but its design is relatively complex with all lines incorporated in to a single assembly. Replacement or addition of lines is difficult or impossible once the riser has been installed. Conversely, the steel catenary offers maximum development flexibility.

In conclusion, there are no clear rules for selection between the hybrid or buoyant steel catenary risers with many factors affecting final selection. However, it is clear that the hybrid riser is particularly cost effective for developments where the wells are located below the production vessel. The steel catenary riser system is attractive where the field layout has a number of remote step out wells. It is probable that future developments will exploit the advantage of both systems and use a combination of hybrid and steel catenary risers. Initial development of wells close to the production vessel may be achieved using a hybrid riser and step out wells tied back during later development phases using steel catenaries. Steel catenaries may also be used for export functions.

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