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## **Feasibility Assessment of a Mid-Water Transfer System**

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### **Abstract**

The development of deepwater oil fields based on a production platform with dry trees, connected to a Floating Production Storage and Offloading (FPSO) vessel, has proved to be technically and economically attractive. However, a key issue for the practical implementation of this production concept is the availability of a cost-effective oil and gas transfer riser solution.

The use of conventional catenary or self-standing riser technologies is sometimes avoided by operators due to high costs and flow assurance issues. To counter these problems operators are seeking a cost-effective solution for fluid transportation between two vessels at a water depth close to the surface. This type of riser system has been used successfully in benign environments like West Africa and is now being considered for harsher environments such as offshore Brazil.

2H Offshore conducted a preliminary feasibility study encompassing installation and in-service dynamic response, to prove the technical feasibility of a system composed of a group of large diameter free-hanging flexible pipes, required to connect two platforms offshore Brazil.

The paper demonstrates that this configuration is practical and simple because it can be designed with regular flexible pipe and standard components. Additionally, it can be deployed using conventional flexible pipe laying vessels.

### **Introduction**

The design of a riser solution to connect a spread moored Floating Production Storage and Offloading vessel with a dry completion platform (Tensioned Leg Wellhead Platform - TLWP) is a complex engineering process which is being sought by operators as a novel and cost effective solution for fluid transportation.

The objective is to transfer the produced oil from the TLWP to the FPSO for processing, storage and later off-loading to a shuttle vessel. Additionally water is injected from the FPSO back to the TLWP and into the wells. This type of system has been proposed by several companies and is referred to as a "Mid-Water Transfer System", hereinafter referred to as MWTS.

Due to the increasing demand for riser solutions in deep water developments, the use of conventional catenary risers (Flexible/SCRs) or Free Standing Hybrid Riser (FSHR) technologies, are sometimes avoided due to their cost. This paper evaluates a novel and cost effective solution for fluid transportation between the two rigs, considering flexible risers which are suspended close to the water surface. This allows the use of cheaper flexible risers with low collapse pressure limits which, reduces the cost of the riser system.

2H Offshore has conducted a preliminary feasibility study to prove the technical feasibility of a system composed of a group of large diameter free-hanging flexible pipes required to connect two platforms in offshore Brazil. The study covers the installation, in-service dynamic response and slugging behaviour of the system.

## System Description

The proposed system has large diameter free hanging flexible pipes which act as jumpers to transfer the fluid from a Tensioned Leg Wellhead Platform, with dry trees, to a Floating Production Storage and Offloading vessel, as shown in Fig. 1.

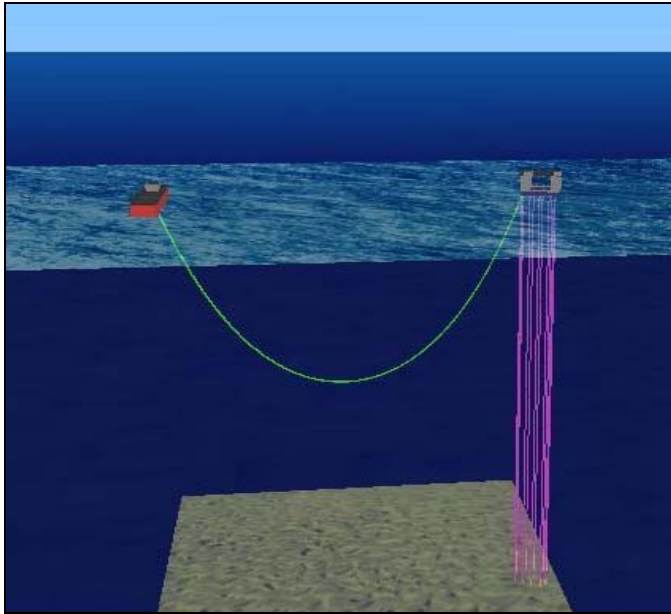


Fig 1. – Mid-Water Transfer System

The number of lines required is assumed to be four lines transporting fluids of different densities. The nominal diameter of the flexible risers considered is 16inch.

The nominal separation between the TLWP and the FPSO considered for the feasibility assessment is 1500m. This distance provides enough room so that the produced oil, after being processed by the FPSO, may be exported to a shuttle vessel by means of an in-tandem off-loading system.

A key challenge when defining the system configuration is the definition of the optimum length of the flexible risers. They must be long enough to not be pulled taut during extreme offset conditions, but also sufficiently short that no point of the riser may pass below the riser collapse limit of 614m below the mean sea level, due to structural limitations of the 16” flexible pipe considered.

Additionally, during far offset conditions where riser top angles are high, the tension in the risers is also high and must remain below the allowable limits for the flexible pipe.

Two internal fluids are considered: production fluid with density of  $276\text{kg/m}^3$  and injected water with a density of  $1025\text{kg/m}^3$ .

## Riser Length Optimization

The maximum length of riser that can be installed without the sag bend depth exceeding 614m is investigated. As the bollard pull of the installation vessel is limited, a relatively long riser is required to reduce as much as possible the riser top angle, and hence the effective horizontal component of tension at the vessel. Reducing the horizontal component of tension is necessary as high levels of tension inhibit the Laying and Support Vessel (LSV) during deployment, and also exert excessive loads on the mooring lines of the floating units during operation.

As illustrated in Fig. 2, during far vessel offset conditions, the tension in the flexible riser increases significantly as the top angle at the vessel increases. This is because the vertical component of tension must be large enough to support the weight of the riser at any given hang off angle. As the hang off angle increases, whilst the vertical component of tension remains constant, the horizontal component must increase to maintain equilibrium. As such, the risers must not only be long enough not to be pulled taut during extreme vessel offsets, but they must also be long enough so that the tension in the riser does not exceed operating limits.

Whilst maximum riser tensions are reduced with increased riser length, the maximum length of riser allowable is defined by installation limits. The riser must not be so long as to hang deeper than 614m below the water line. The maximum sag bend depth occurs during installation at the last stage of installation immediately before the riser is pulled in by the FPSO. Preliminary static installation analysis is conducted to define the maximum length of riser permissible not to exceed this maximum depth limit.

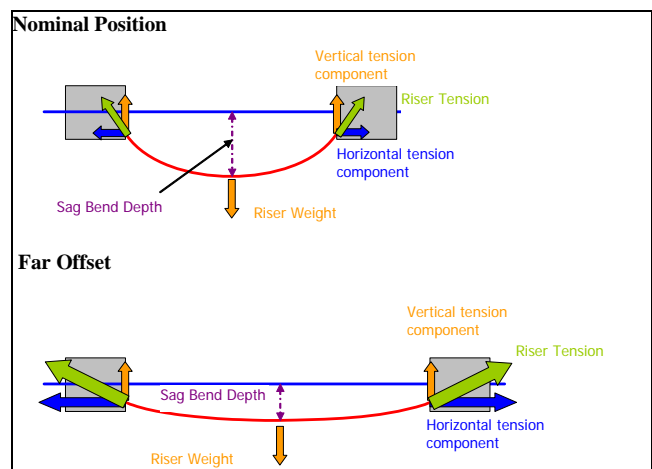
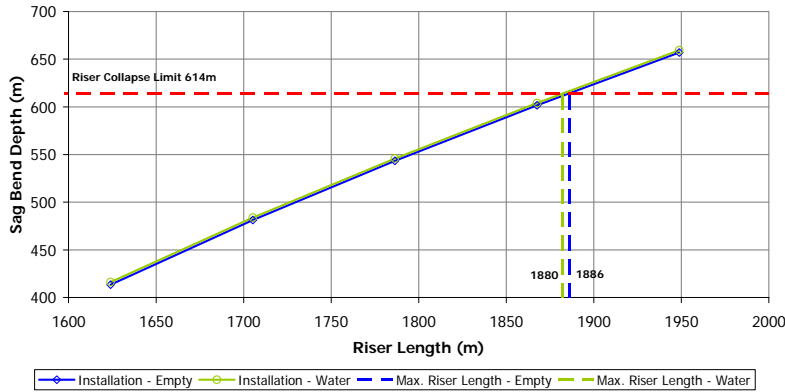


Fig 2. – Catenary Riser Tension with Vessel Offset

Analysis is conducted considering the final installation stage when the separation between FPSO and the stern of the LSV is 150m, and the pull-in head of the riser is 150m below the water line.

The flexible riser is considered both empty and sea water filled. The riser configuration is assessed considering no current or wave loading.



**Fig 3. – Maximum Installable Riser Length**

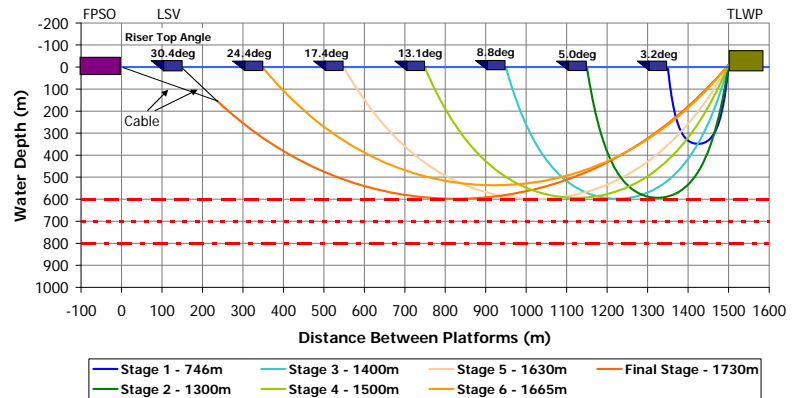
installed empty. When the riser is full of sea water this value increases to close to 280tonnes. Tensions at the LSV Hang off are marginally smaller than those at the TLWP due to the smaller elevation of the hang off point and the geometry of the risers.

The maximum top angle at the LSV when the sag bend is at its collapse limit is 30degrees for both internal fluids. At the TLWP, the maximum top angle at the hang-off is 26degrees. Whilst the analysis shows that the riser geometry is identical regardless of the internal fluid, the effective tension at the vessel hang offs varies significantly depending on the internal fluid, but not riser length. The maximum static tension of 290tonnes occurs at the TWLP hang-off when the riser is water filled. This value is 37% of the tensile capacity of the riser which is 781tonnes.

**Riser Installation**

One of the main advantages of the free-hanging flexible configuration in comparison with steel-based solutions is that the flexible pipe handling and installation can be performed using conventional vessels with a laying tension of around 270 tonnes and a bollard-pull limit of 20tonnes.

Static analysis is conducted considering 7 different stages during installation, as shown in Fig. 4. The sag bend is always maintained close to or above 600m water depth and the top angle at the LSV is shown for each stage. During the final stage considered, the riser is hung off from the installation vessel on a cable and the pull-in head is 150m below the water level. The riser installation is considered for both empty and sea water filled conditions.

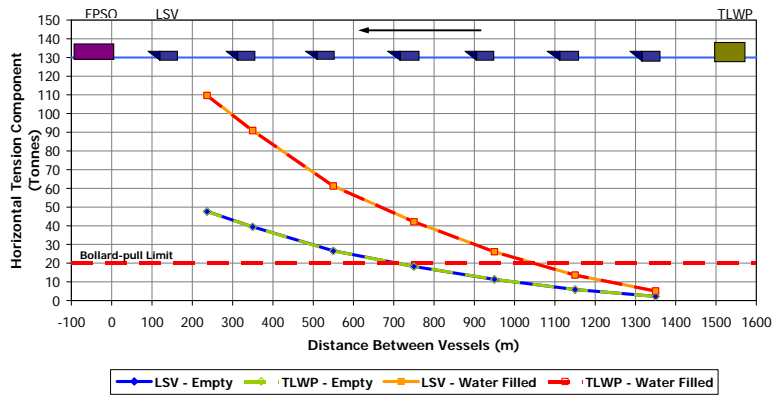


**Fig 4 – Flexible Riser Installation Stages**

The analysis shows that the hang-off angle at the installation vessel increases as it drifts apart from the TLWP. These angles are greater than 3degrees for most installation stages. In the final stage before the pull-in to the FPSO, the maximum top angle is 30.4degrees, as shown in Fig. 4. For all installation stages the riser effective tension at the hang-off is always less than the 781tonnes riser failure limit, even if the riser is considered water filled. However, the component of horizontal tension at the LSV in the final installation stage, considering an empty riser, is approximately 50tonnes which is 2.5 times the vessel bollard-pull limit of 20tonnes, as illustrated in Fig. 5. If the riser is installed water filled the horizontal tension component is 110tonnes, or 5.5times the bollard pull capacity of the vessel. Due to the catenary nature of the hanging flexible, the hang off tension at both the LSV and TLWP are equal during each stage of the installation.

A total of 5 different riser lengths from 1624m to 1949m are considered. For both internal fluids the maximum riser length that can be installed is interpolated from the plot shown in Fig. 3. The analysis shows that the maximum riser length which can be installed is approximately 1885m regardless of the internal fluid density. The slight difference in sag bend depths is due to the water filled riser stretching slightly due to its increased self-weight.

For this configuration the maximum nominal effective tension at the TLWP hang-off is approximately 120tonnes if the riser is



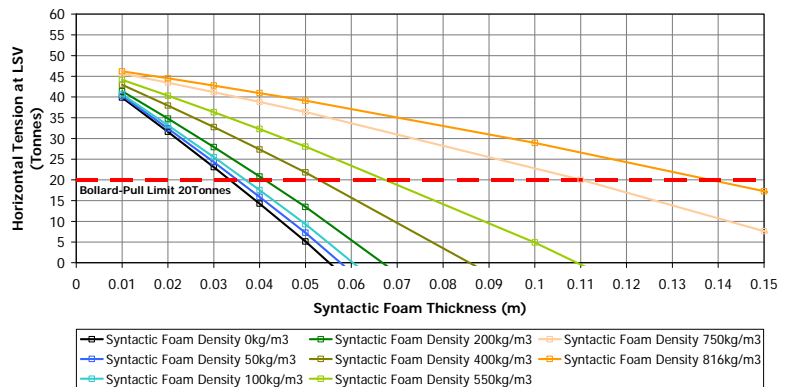
**Fig 5. – Horizontal Tension at LSV and TLWP Hang-off during Installation for Empty and Water Filled Risers**

The final stage is considered for the preliminary calculation because the maximum top angle and consequently maximum horizontal tension, occur during this stage of the installation. The hang-off angle at the vessel is fixed by the riser length and associated geometry, but the effective tension must be large enough so that the vertical component of tension will support the self weight of the riser. If the self weight of the riser can be reduced, vertical component of tension will also reduce, as will the overall effective tension and consequently the horizontal component of tension.

The hanging riser segment considered hangs in a catenary of approximately 1885m length and a weight in water per meter of 105kg/m when empty. The pull-in head is 150m below the water level and the top angle at the riser connection with the LSV cable is 30.4degrees to the horizontal and the horizontal tension (bollard-pull at the LSV) is 48tonnes. To make the installation operation feasible the horizontal tension in the riser extremity considered needs to be reduced until the horizontal component of tension is below the bollard-pull limit of 20tonnes. The top angle of 30.4degrees and the riser segment length of 1885m remain constant regardless of the amount of buoyancy on the riser.

The horizontal tension at the LSV for a range of syntactic foam densities and thicknesses considered is illustrated in Fig. 6. For a density of 750kg/m<sup>3</sup>, which is representative of the density of syntactic foam used in offshore activities, the minimum thickness required is 0.11m (or 110mm).

The horizontal tension at the LSV is reduced from 50tonnes to 20tonnes if the additional layer is considered. The component of horizontal tension at the LSV just reaches the bollard-pull limit of the LSV in the final installation stage.



**Fig 6. – Syntactic Foam Layer Thickness Optimization**

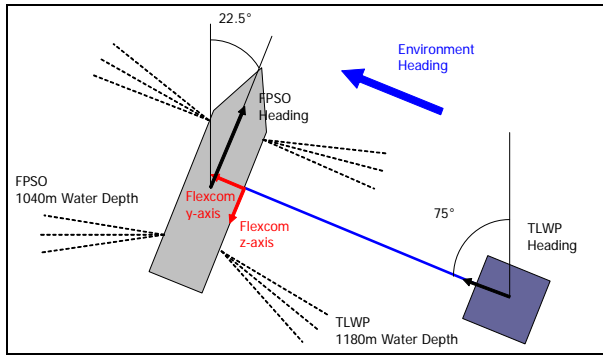
This study indicates that installation is feasible for the planned riser configuration and installation vessel if the riser is installed empty and is coated by an additional layer of syntactic foam with a minimum thickness of 0.11m and density of 750kg/m<sup>3</sup>. In practice a thicker layer will be required to allow the vessel additional thrust capacity.

**In-Place Riser Response**

Static analysis during operational conditions is carried out for both production and water injection risers. Static analysis considers near, far and nominal vessel offsets and no current loading on the riser. Dynamic analysis during operational conditions is also conducted considering a 100year wave and 10year current, and 10year wave and 100year current aligned in-plane with the riser, as shown in Fig. 7.

Consequently, the analysis shows that this riser configuration cannot be installed by the planned LSV vessel. In order to make installation feasible, the riser will need to be installed empty and its self weight in water made lighter.

A reduction of the submerged weight of the riser can be achieved with an additional syntactic foam coating. A preliminary calculation, considering a total of 8 different syntactic foam densities from 0 to 816kg/m<sup>3</sup>, is conducted to determine the required thickness of syntactic foam which reduces the submerged weight of the riser and the horizontal component of tension at the LSV to an acceptable level.



**Fig 7. – Platform Headings and Environmental Loadings**

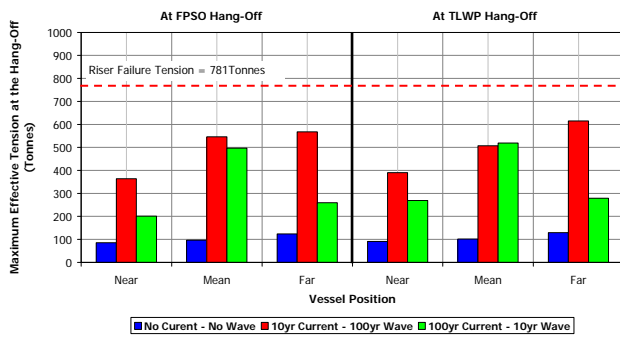
Extreme waves are selected based on the highest wave heights experienced in the Campos Basin offshore Brazil. Extreme currents which have the highest mean velocity over the top 350m of the water depth in the Campos Basin are also selected. In this analysis, it is conservatively assumed that both current and wave loading are approaching in the plane of the flexible lines.

In-place riser response is assessed considering 100year vessel offsets of 115m. This is approximately 10% of water depth, which is 1150m at the FPSO location. Because the probability of the TLWP having a 100year offset at the same time as the FPSO is highly unlikely, and the TLWP offset is most likely to be in the same direction as the FPSO, the TLWP is conservatively assumed to remain in its nominal position whilst only the FPSO is offset both towards (near) and away (far) from the TLWP.

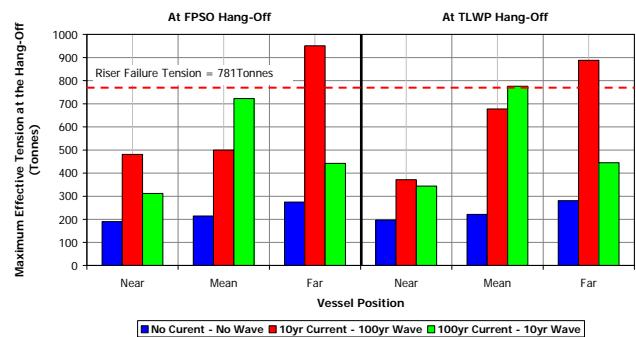
Analysis is carried out with and without the minimum required thickness of 750kg/m<sup>3</sup> syntactic foam needed to adequately install the riser, in order to verify if the buoyancy modules must be removed after installation.

The maximum effective tension at the FPSO and TLWP hang-offs for static and dynamic conditions are shown in Fig. 8. The slight difference between the effective tension at the TLWP and at the FPSO for static conditions is caused by the higher elevation of the TLWP hang-off.

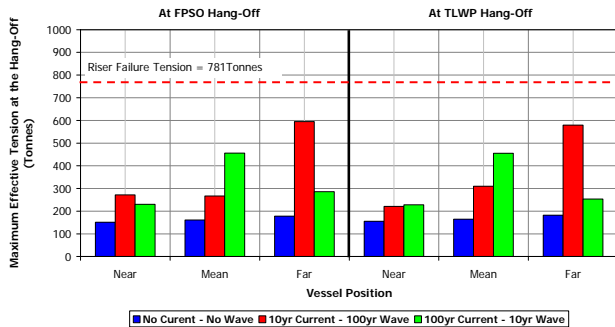
The analysis shows that for the production riser with buoyancy modules installed, the maximum effective tension during far vessel offsets is 615tonnes at the TLWP hang-off and remains 21% below the riser failure tension limit. However, during far offset conditions the effective tension in the water injection riser exceeds the maximum allowable tension of 781tonnes, and a maximum dynamic effective tension of 951tonnes occurs at the FPSO hang-off for the water injection riser, which exceeds the allowable limit by 22%. The analysis shows that whilst applying a coating with a density of 750kg/m<sup>3</sup> and a thickness of 0.11m is sufficient to allow the riser to be installed, its dynamic response is unacceptable if it is a water injection riser. If buoyancy modules are removed the maximum effective tension found is 615tonnes at the FPSO hang-off and remains below 11% the riser failure tension limit. The reason why the maximum in-place dynamic tension in the water injection riser is larger when it is coated in buoyancy is because of its increased drag diameter. The larger riser resists being pulled through the water by the vessel, and consequently the dynamic tension during wave loading is increased.



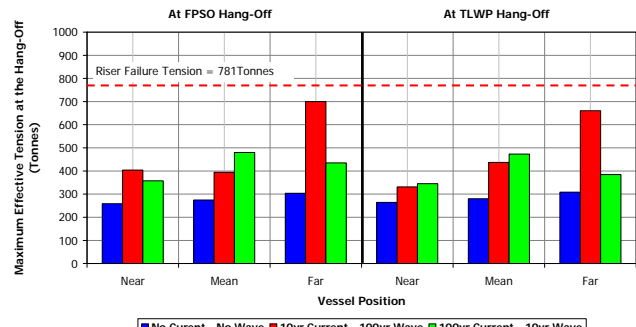
(a) Production Riser – With Buoyancy Modules



(b) Water Injection Riser – With Buoyancy Modules



(c) Production Riser – Without Buoyancy Modules



(d) Water Injection Riser – Without Buoyancy Modules

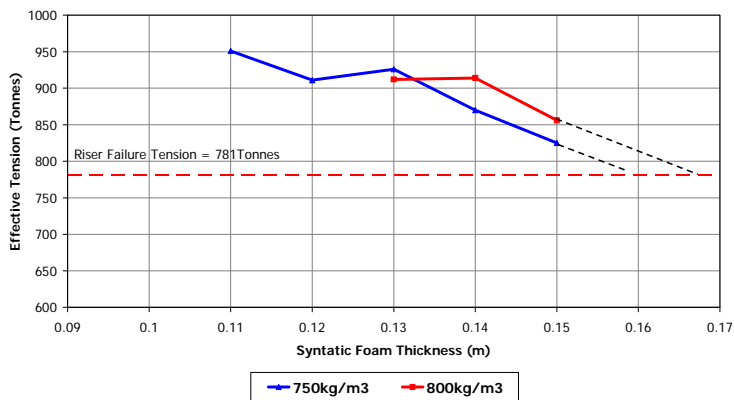
**Fig.8 – Maximum Effective Tension at FPSO and TLWP Hang-Offs**

## Water Injection Riser Buoyant Coating Optimization

In order to maintain acceptable horizontal loading on the LSV during installation, the riser self weight must be reduced by applying buoyancy, however if an additional buoyant coating is applied to the riser, the increase in drag loading can cause excessive tensions at the riser hang-off during extreme storm conditions and far vessel offsets.

Therefore two options are available to make the system work. The first would be to reduce the density of the buoyant layer, thus requiring a smaller thickness, which will reduce the drag loading during dynamic conditions. The second option is to maintain the density of the buoyant layer, but make it thicker in order to significantly reduce the weight in water of the riser. The first option is considered unfeasible, unless buoyancy material with a density lower than  $750\text{kg/m}^3$  is available, and that can also be used at depths upto 600m. Whilst the second option will increase the dynamic drag loading, if the coating is thick enough, the self weight of the riser will be so small that the dynamic drag loading will not be enough to exceed the breaking pull limit of the flexibles. Consequently this method is investigated further, as described in the following paragraphs.

In-place extreme storm sensitivity analysis, considering a total of 6 different syntactic foam thicknesses from 100mm to 150mm and two different foam densities of 750 and  $800\text{ kg/m}^3$  installed along the riser length, is conducted with the objective of verifying the feasibility of these densities and thickness during operation. The maximum effective tension for operational conditions is shown in Fig. 9.



**Fig. 9 – Maximum Effective Tension at FPSO Hang-off during Extreme Storm Conditions (10year Current and 100year Wave) - Different Buoyancy Layer Densities**

For a buoyancy density of  $750\text{kg/m}^3$  a coating thickness of at least 0.11m is required in order for the riser to be installed. Although the maximum effective tension with this configuration is 951tonnes during operational conditions, considering far vessel offset, and a 10year current and 100year wave. This limit is above the allowable tension limit of 781tonnes. From extrapolation of results for  $750\text{kg/m}^3$  foam, acceptable dynamic tensions can be obtained if the syntactic foam thickness is increased to more than approximately 0.16m.

For a buoyancy density of  $800\text{kg/m}^3$  a coating thickness of at least 0.13m is required in order for the riser to be installed. However, the maximum effective tension with this configuration is 915tonnes during operational conditions, considering a far vessel offset, and a 10year current and 100year wave. This limit is also 22% above the allowable tension limit of 781tonnes. From extrapolation of results for  $800\text{kg/m}^3$  foam, acceptable dynamic tensions can be obtained if the syntactic foam thickness is increased to more than approximately 0.17m.

The analysis indicates by reducing in the water injection riser self-weight, by increasing the buoyant coating layer, decreases the maximum effective tension during in-place extreme storm conditions and makes the system feasible. However, the dynamic drag loading on the system is increased as the larger diameter riser resists being pulled through the water by the vessel. The effect of drag loading on riser dynamic response needs to be investigated further, and will be dependant on the vessel RAO response during storms.

## Conclusions and Recommendations

From the studies conducted the key conclusions are:

- The MWTS concept is feasible;
- The installation is limited by the LSV bollard pull of 20 tonnes and the riser collapse limit of 614m;
- In order to make installation feasible, the riser will need to be installed empty and its self weight in water made lighter. A minimum buoyancy layer thickness of 0.11m is required a syntactic foam density of  $750\text{kg/m}^3$  is considered;
- In-place extreme storm riser response is limited by the riser failure tension of 781 tonnes;
- Hang-off tensions under extreme storm conditions are acceptable for the production riser if the buoyancy layer considered for installation is maintained;

- Tensions in the MWTS system are acceptable during operating conditions if a buoyancy coating of  $750\text{kg/m}^3$  with a thickness of more than 0.16m is applied to the water injection riser;
- Tensions in the MWTS system would also be acceptable during operating conditions if the buoyancy modules/coating can be removed after installation;
- It is possible to reduce the thickness of the syntactic foam layer and still keep the MWTS installation and operation feasible if the distance between floating units can be reduced marginally.

The results obtained from this preliminary feasibility study and summarized in this paper indicate that the MWTS concept based in a flexible free-hanging configuration is technically feasible from the stand point of installation and operation of the flexible pipe, however, there are still operational issues to overcome. Therefore, it is recommended that additional analytical studies that take into account some relevant factors that can attenuate the overall and horizontal component of effective tension in the pipe, such as: the possible reduction of the distance between the floating units to values in the order of magnitude of 1300m or less; and the eventual reduction in the diameter required of the risers, for instance from 16" to 12", with substantial reduction on riser dead weight and possible increase in the collapse resistance of pipe, resulting in the possibility to use the pipe in deeper location and consequently leading to smaller top angles.

As well as taking into account the improvements mentioned above, complimentary studies will enable other essential structural verifications to be assessed, such as: dynamic extreme storm response analysis taking into account all design load combination cases required by design codes; determination of reaction loads on the supporting floating units; interference analysis in multiple MWTS systems; First order fatigue analysis; VIV fatigue analysis; slugging response and fatigue; and detailed installation analysis

## References

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