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Lessons Learnt from the Evolution and Development of Multiple-Lines Hybrid Riser Towers for Deep Water Production Applications.

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Abstract

The multiple-lines hybrid riser tower which was first applied in the late 1980's in the Gulf of Mexico, and more recently to deep-water FPSO projects at the Girassol field in Angola, is now starting to be applied more widely on other deep water projects. This paper presents the lessons learnt from the design of recent hybrid riser tower applied to meet the requirements of several different deep water field developments. The paper specifically addresses the various changes made to the Hybrid Riser Tower relating to the design, fabrication and installation. The performance aspects are discussed along with information covering the overall costs associated with the use of riser towers as opposed to other single riser line concept. The paper also concludes on the possible future evolution of the HRT to meet the future ultra deep-water developments.

Introduction:

The first generation of multiple-lines hybrid riser tower (HRT), called FSPR (Free Standing Production Riser), was designed as a cost effective re-usable riser system by Cameron Iron Works in 1983 and installed in 1988 by Placid on the Green Canyon field block 29 (see reference 1). The structure was then upgraded and reinstalled on the deeper Garden Bank field (2096 feet water depth) by Enserch in 1994 (see reference 2). This early concept of HRT used the drilling technology to assemble the riser bundle with adequate buoyancy from a drilling rig; the riser tower foot and spools were connected to a subsea base manifold and flexible jumpers at the top were connected to the rig. **Refer to fig 1**. The concept proved to be cost effective and well adapted to operate in the Gulf of Mexico environment.

In 1997 Total called for a design competition to define the subsea architecture of the Girassol field (1450m WD) discovered in Angola. Stolt Offshore proposed three riser towers of what can be considered the second generation of HRT after the first experience in the Gulf of Mexico. This technological choice was mainly motivated by the stringent thermal insulation requirement imposed by the field operations and the layout (see reference 3). This second-generation design of HRT was completely designed to accommodate the specific fabrication and installation requirements associated with the Girassol field and its geopolitical environment.

The AMG consortium consisting of Stolt Offshore (67%) and Saipem (33%) was awarded the contract for designing, fabricating and installing the Umbilical, Flowline and Riser system which included the three HRTs. The Girassol field, which was designed for a production of 200,000 bbl/d is actually producing up to 260,000 bbl/d. This success encouraged Stolt Offshore to further develop the concept and use the lessons learnt from the Girassol project to improve the HRT design and take it into the third generation of HRT **refer to Fig 2**. The Greater Plutonio field operated by BP in Angola will be equipped with an HRT of the third generation. Other Contractors and Operators also consider the HRT for their deep-water field development. This accumulation of experience certainly allows to consider a possible design evolution towards the forth generation of ultra deep water HRT in beyond 2000m water depth.

HRT general design process:

The HRT is an essential component of the subsea architecture of a field and as such must satisfy the design processes for field development. The field design basis generally defines the drivers used throughout the design process:

- Transport, efficiently and reliably wellstream fluids between the subsea reservoir and the surface production system in accordance with production operating philosophy.
- Ensure that the main design parameters such as production fluid characteristics, protection and enhancement requirements, operating philosophy, environmental conditions, design life etc…are properly considered.
- Satisfy HSE, local authorities & governmental agencies, design code & standards obligations.

Basically the design engineering team will cover the following activities:

- Assess the relevant design input and implement the design methodology within the frame of the specified design codes.
- Meet the contractual performances by developing and validating the right numerical models.

- Ensure the structural integrity of the HRT throughout its development phases (fabrication, installation & operation).
- Mitigate the project risks and cost effectiveness by selecting and qualifying the most appropriate materials and solutions.

The next generation of HRT has been developed by including the experience and feedback from the Girassol Project (**refer to fig 3**) in the design of the riser components namely:

- Riser Bundle
- Buoyancy Tank
- Riser foot and spool
- Riser Anchor Base

Basic principle for optimising HRT configuration

Several totally new configurations of riser tower were investigated after Girassol mainly to reduce the cost of the Buoyancy tank and its connection to the bundle. One of these solutions consisted in eliminating the buoyancy tank to replace it by more syntactic foam distributed along the length of the riser bundle and connecting the flexible jumpers directly to the top of the bundle in a lazy wave configuration. **Refer to fig 4**.

After a closer evaluation of the applications under consideration this new configuration did not provide sufficient advantages from both a technical and commercial point to further develop it. As a result the principle of the buoyancy tank and its connection was maintained for the third generation design.

- The general configuration of an HRT, its height, distance to FPSO, length of flexible jumpers is engineered using the following parameters as input:
- Water depth.
- Environmental conditions and FPSO excursions / motions.
- Capacity of flex-element to absorb bottom angular variation.
- Minimum Bending Radius of flexible jumper in near FPSO excursion.
- Flexible bend stiffener capacity to absorb maximum angular variation resulting from the FPSO excursions and motions.

The external forces acting on the riser tower are identified below:

- Net global buoyancy of the structure,
- Reaction of flex element at riser foot,
- Loads on the buoyancy tank from the flexible jumpers
- Drag from current force profile along the riser tower.
- Wave loads on the buoyancy tank.

The mechanical equilibrium of the loads acting on the structure is used to optimise the best configuration for the HRT. **Refer to fig 5.**

Riser bundle, cross section & associated issues.

The design of the vertical riser bundle is the next activity to be considered by the engineering process.

Field layout and riser tower composition.

One of the first activities of the design process is to define the number of risers per HRT considering the following:

- the field layout & subsea architecture,
- the total production & injection fluid flow rate to transfer,
- the field development schedule,
- the economics of the field.

As with any field component the decision must be confirmed by a risk assessment to address possible delay in the HRT delivery resulting from various scenarios (procurement, fabrication or installation).

HRT flow area.

The flow area of the HRT is the sum of all the internal pipes section areas used to transport production or injection fluids. As shown throughout this paper, this value is a good and simple design parameter to describe the HRT in terms of size, performance and cost. For instance on Girassol the flow area was $0.3m^2$ and on other projects flow area of up to $0.7m^2$ were studied (**refer to fig 6**). The upper limit for the flow area value is dictated by fabrication and installation considerations.

Cross-section design and sizing.

The wall thickness of the pipe is the next parameter to size. This is a relatively straightforward process mainly relying on design codes (internal pressure or external collapse). Once the core pipe has been sized the quantity of foam to provide adequate buoyancy during installation can be defined. In the third generation of HRT the idea of using the syntactic foam as thermal insulation has been abandoned for technical and economical reasons. As a result the riser pipes are now distributed at the periphery of the cross section and the production risers are independently thermally coated. This configuration also simplifies the fabrication process of the riser tower. **Refer to fig 7**.

Central core pipe.

The core pipe is structurally, the ‘back bone’ of the HRT and as such is designed to accommodate installation and in-place loads as well as providing sufficient fatigue resistance to the structure. The core pipe is generally dimensioned to prevent the rest of the bundle piping from being affected by in-place or installation fatigue damage.

The core pipe can also be used for fluid transfer in a similar fashion as steel catenary risers where functions of fluid pressure containment and structural integrity are combined.

Quantity of syntactic foam along the bundle

The mass of the steel structure along the bundle (pipes and clamps) defines the quantity of syntactic foam to integrate in the bundle cross section to provide the required level of positive buoyancy required to tow and upend the HRT. This quantity of syntactic foam has been optimised by installing the entire riser pipes empty as opposed to the Girassol project where the water injection pipelines in the bundle were installed flooded for stability reason at fabrication yard and during towing operation.

The foam elements consist of two half shelf tight together around the core pipe by mean of bolts fitted in the foam. This constitutes an improvement compared to the Girassol design where kevlar straps had to be used and pre-tensioned to compensate for the foam compression at depth and avoid seawater circulation inside the bundle.

Compression load in the core pipe.

The combination of the bundle buoyancy attached to the core pipe and the weight of the risers suspended from the buoyancy tank may generate a compression load along the upper part of the core pipe when the HRT is in the vertical configuration. This compression load happens right after the offshore upending operation and before the buoyancy tank is fully de-ballasted. **Refer to fig 8**. Excessive compression load could jeopardise the installation operation by affecting the structural integrity of the HRT. The compression load is directly proportional to the amount of buoyancy in the bundle and guiding clamp for the riser are distributed along the bundle to prevent the core pipe from buckling. A finite element numerical model developed with Abacus software is used to properly size the core pipe and the taper joint. **Refer to fig 9**.

The riser guide design is a simple steel structure fitted on the core pipe and holding the pipes laterally but letting them slide axially.

Hydrodynamic and riser clamp distribution.

Since the riser pipes are now located to the outside of the bundle and exposed to the complex action of seawater flow, extensive hydrodynamic testing and analysis have been conducted to validate this design. Model tests have been performed to establish various hydrodynamic coefficients such as drag & uplift coefficients. Various numerical models use these coefficients to assess the VIV (Vortex Induced Vibration) phenomenon, global HRT excursion and fatigue analysis during towing. The hydrodynamic behaviour of the HRT has been checked both globally along the bundle length and individually along each riser pipe. The results of the numerical analysis are used to optimise the distribution of the riser guiding clamp and define maximum clearance between the clamp and the risers. **Refer to fig 10**.

Special features: gas lift and monitoring.

The flow assurance of the HRT deserves special considerations. By adopting an individual thermal protection on each production line a lot of design challenges experienced on the Girassol project have now disappeared and more particularly the natural internal convection inside the bundle. However the new design had to address the problem of managing the thermal protection / expansion of the gas lift lines. In the Girassol design this issue was resolved by placing the gas lift lines inside the bundle in contact with the production steel pipe. Both the gas lift and production pipe were thermally insulated and were expanding in a similar way, as heat was transferred between them.

With the new design two alternatives were considered:

- Keep the Girassol approach and put the gas lift line in contact with the steel production pipe within the thermal coating of both pipes so that they can expand in a similar fashion.
- Disassociate the gas lift from its production pipe and mechanically protect the gas lift line from reservoir fluid ingress by means of remotely controlled isolation valves located as close as possible to the injection point.

The first option was really challenging for both the thermal insulation design and the fabrication process. As a result a manifold to operate a series of isolation barrier valves between the production pipe and the gas lift line is provided as insulation barrier. This manifold is also designed to be retrievable by ROV.

An expansion loop integrated along the gas lift piping system integrated inside the riser foot structure is designed to absorb the differential thermal expansion between the two pipes.

The new HRT design integrates a control umbilical to operate the gas lift manifold in which HRT monitoring functions have also been integrated:

- Strain gauges to measure tension.
- Temperature sensors etc….

Pipe material selection.

The concept of the HRT is particularly well suited when field operations or the nature of the reservoir fluid requires selecting special materials to address corrosion and erosion issues. The use of clad pipe, CRA or pipe with internal liner is an issue manageable by the fabrication yard. The flexibility offered by the HRT mainly results from the fact the structure is build onshore in a controlled environment to guarantee the quality of the final product. This removes substantial project risk exposure compared to other solutions, such as SCRs, where the structures are fabricated offshore.

Syntactic foam qualification program.

The syntactic foam is now only used as permanent buoyancy and not as insulation material any more; this has greatly simplified the foam qualification program and its fabrication process. Carbon fibre macrospheres have been added to the foam material. The fabrication process of the syntactic foam material should be more reliable and simpler compared to the Girassol solution.

For a given temperature, the syntactic foam must now be qualified for ageing, compressibility at water depth and water absorption over its design life. An extensive testing program has been carried out with several suppliers to anticipate the foam behaviour over a long period of time. The result of these tests will be used to account for the reduction in buoyancy into the buoyancy tank volume.

Buoyancy tank & connections to the bundle and flexible jumpers.

Connection of the bundle with the buoyancy tank

The fabrication engineering team worked out a solution to connect the buoyancy tank to the bundle in dry condition on the fabrication yard which definitely removes any incentive to develop a design where the tank is linked by means of tether to the bundle.

The design of the interface between the core pipe and the buoyancy tank is a simple and robust taper joint typically consisting of:

- 40 inches pipe with a constant wall thickness of 32mm (1.25 inch).

- Forged transition cone to connect with the 20 inches central core pipe of the bundle.

Design and sizing of the buoyancy tank.

The buoyancy design and sizing process has basically been unchanged from the Girassol concept. The buoyancy tank is sized to provide sufficient uplift forces at riser foot for the flex element and compensate the global submerged weight of the HRT structure. Spare buoyancy to cover potential loss of buoyancy for both tank and syntactic foam must also be accounted for by the design.

Both the water depth and the flow area value as it is defined in previous section directly impacts the size of the buoyancy tank. The buoyancy tank shape has been simplified and optimised compared to the Girassol design. The outer diameter of the tank has been sized to cope with the minimum draft at fabrication yard facilities.

Special devices on buoyancy tank.

The following features of the buoyancy tank have been improved mainly to facilitate fabrication and installation scopes:

- The goosenecks at the top of the tank,
- the receptacle structures for the flexible jumpers,
- the integration of the gas lift control umbilical,
- the ROV ballasting panels along side the tank,
- a temporary working platform to provide handling facilities during the post fabrication testing program.

An entry point for coil tubing to allow access down to the riser bottom for methanol injection in case of hydrate formation has been provided and incorporated in the gooseneck design.

Riser foot.

The riser foot design of the new HRT has been simplified compared to the Girassol design. Since the HRT is now towed sub-surface the temporary protection door panels have been removed. The standard vertical flange connections and associated interface structure for the MATIS^{TM} connection tool has been preserved from the original Girassol design. The original buoyancy pressure tank integrated to the Girassol riser foot has been replaced by syntactic foam designed for the water depth pressure. The riser foot structure now also integrates the gas lift expansion loop, the gas lift manifold and control umbilical.

Riser base.

The riser base is basically dimensioned to sustain the following loads:

- Nominal tension of the riser bundle to guarantee an appropriate inclination angle of the HRT compatible with the characteristics of the flex-element and the riser jumpers.
- The potential tension increase resulting from removing fluids from some the riser pipes.

The flow area value and water depth impact the design and size of the riser base. When the overall weight of the riser base is beyond the installation spread capacity, the riser base structure has to be split into a suction anchor and additional ballast weights.

The receptacle for the flex-element has also been inclined to better optimise the design of the bundle connection to its base.

Fabrication

Having to encapsulate the pipes inside the foam elements in a continuous mode to ensure reliable thermal protection, with open cell foam material and rubber seals to place, made the fabrication process on Girassol complex. The connection of the buoyancy tank to the bundle was performed in wet condition in the Bay of Lobito using a cofferdam structure, a marine spread and a tailor made catamaran pontoon.

The fabrication of the new HRT design is now simplified **refer to fig 11**:

- The riser bundle are made by sections of 250m approximately and butt welded together to reach the entire length. This is made possible because the riser pipes are now distributed at the periphery of the bundle cross section with sufficient room for the welders to perform the connection.
- The buoyancy tank will now be delivered with the taper joint and the top bundle section already connected. The buoyancy tank can be then connected directly to the bundle in dry condition inside the firing line. This method is considered safer and more cost effective.

The preparation and the testing of the HRT prior to installation has also been simplified by initiating the buoyancy tank first and keeping the riser foot in the firing line to conduct the testing program. The goosenecks are pre-installed at the top of the buoyancy tank and temporary facilities are provided on the buoyancy tank itself to ensure the minimum intervention operations required by the program.

Installation

The installation method used on Girassol proved to be reliable and efficient and will be conserved in its principle for the next generation of HRT. However for bundle with a large outside diameter and under specific meteocean conditions a sub-surface tow method has to be considered. **Refer to fig 12**.

Performance and Economics

The basic cost break down for a multiple-lines HRT covering, engineering & management, procurement, fabrication & installation is presented **on fig 13**; for the sake of comparison the same graphic has been provided for steel catenary risers system (see reference 4).

The HRT is an integrated riser system developed to commercially and technically compete with other single riser lines system (Steel Catenary Riser or Flexible lines). The ratio performance versus price is an important factor to consider in the decision making process.

Like any other riser system, the cost equation can be expressed through the following simplified equation:

$$\text{Cost} = K + \Psi(\text{Fla, wd, Cplx})$$

K is a coefficient relatively independent from the design parameters; K generally represents the mobilisation cost of the resources.

Ψ(Fla, wd, Cplx) is a tri-dimensional function which reflect the relationship of the cost with some parameter impacting the HRT components design.

Fla: is the flow area of the cross section as defined in the previous section.

Wd: is the water depth

Cplx: represent the number of technological complexities to be integrated into the system. These complexities generally covers the following technical features:

1. Passive thermal protection (pipe in pipe or plastic coating),
2. active heating,
3. material selection (clad pipe, CRA, internal liner etc…),
4. gas lift,
5. riser monitoring,
6. flow activation or
7. any additional specific requirements which may be required by the operator.

The Ψ(x,y,z) function incorporates project cost such as engineering & management, procurement, fabrication and installation and also considers all the components of the HRT, including the connection to the static flow line system and the special technical features listed above. The size of these components are themselves a direct function of the Flow area (Fla) alone or the water depth (wd) alone or both combined, this dimensioning relationship combined with project costs ultimately define the Ψ function.

On fig 14 the comparative graphic representation of the cost equation for both HRT and single riser lines provides a better understanding on how the cost evolve as a function of the three main driving parameters (Fla, wd, Cplx).

The curves can be explained by the fact that incorporating more riser pipes or increasing the length of the riser bundle or integrating more technical features do not affect the fabrication and installation cost in the same proportion as it does for single riser lines. When increasing the size, depth and complexity of the design, the HRT solution benefits from a leverage effect which reduces fabrication and installation costs compared to other single line riser solutions.

The graphic also shows that for a shallow, small flow area and with no specific technological requirement the single riser line systems are without any doubt commercially more attractive compared to the HRT. But the cost break-even point can be quickly reached once the water depth or the flow area or the technological requirement increases. It is also worth mentioning that for extreme field operation requirements the HRT has definitely a higher technical and commercial potential performance compared to single riser lines.

This evaluation does not consider the economics brought by the HRT to the other field architecture components such as the surface support system, mooring system, first oil schedule etc…

The high local content value and the transfer of technology associated with the HRT solution have also to be considered in the early stage of the decision making process.

Future design evolution towards ultra deep water

The previous section showed the potential of the HRT to meet the more stringent technical requirements of deep water at a competitive cost. When considering ultra-deep water development field there will only be few technical issues to review in order to bring the HRT design to a viable commercial solution. The technical aspects to be reviewed are:

- Qualification of the reliability of the syntactic foam produced industrially to meet ultra deep hydrostatic pressure for extended period of time. Presently syntactic foam is currently used by the drilling industry up to 3000m for their operations. Syntactic foam formula has been developed to sustain hydrostatic pressure up to 10,000 meters.
- Integration of an active heating system to compensate the heat lost of reservoir fluids due to the Joule-Thomson and potential energy effect along the vertical column. Active heating systems have been developed and their integration into the HRT structure is not considered problematic at this stage.
- Optimise the size of the buoyancy tank and the riser base to meet installation and fabrication constraints by providing an appropriate split of buoyancy between the top tank and the syntactic foam elements along the bundle.
- Compression load generated on the central core pipe by the buoyancy distribution along the bundle. This problem is now well understood through validated numerical model and solution can be found.

Summary and Conclusions

The review of the lessons learnt from the evolution and development of multiple-lines Hybrid Riser Towers for deep-water production applications has shown that the HRT design has significantly evolved from the Girassol Project. This evolution is driven by simplification, reliability, efficiency and cost reduction and progressively, as new project realizes their objectives, establishes an industrial standard for the HRT product. The HRT is also a process component capable of integrating dedicated functions and devices to improve the efficiency of the production. This review is instrumental to better appreciate the full potential of the concept both from a technical and commercial point of view. It is clear that there is a range of applications particularly suited to the concept and the development of ultra deep fields will make operators and contractors realise the benefits and the flexibility the HRT concept can bring to field operations. Further more the relative simplicity of the concept make it particularly attractive for the local economy, generally eager to develop its own industrial infrastructure and know how.

Nomenclature:

AMG: Alto Mar Girassol
CRA: Corrosion Resistance Alloy
FPSO: Floating Production Storage and Offloading
FSPR: Free Standing Production Riser
HRT: Hybrid Riser Tower
MATIS: Modular Automatic Tie-In System
ROV: Remotely Operated Vehicle
SCR: Steel Catenary Riser
VIV: Vortex Induced Vibration

Acknowledgement

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We also wish to thank Sonangol for being an instrumental parterner in the success of the HRT in Angola.

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Figure 1: Green Canyon free standing production riser

Figure 2: HRT Third Generation design

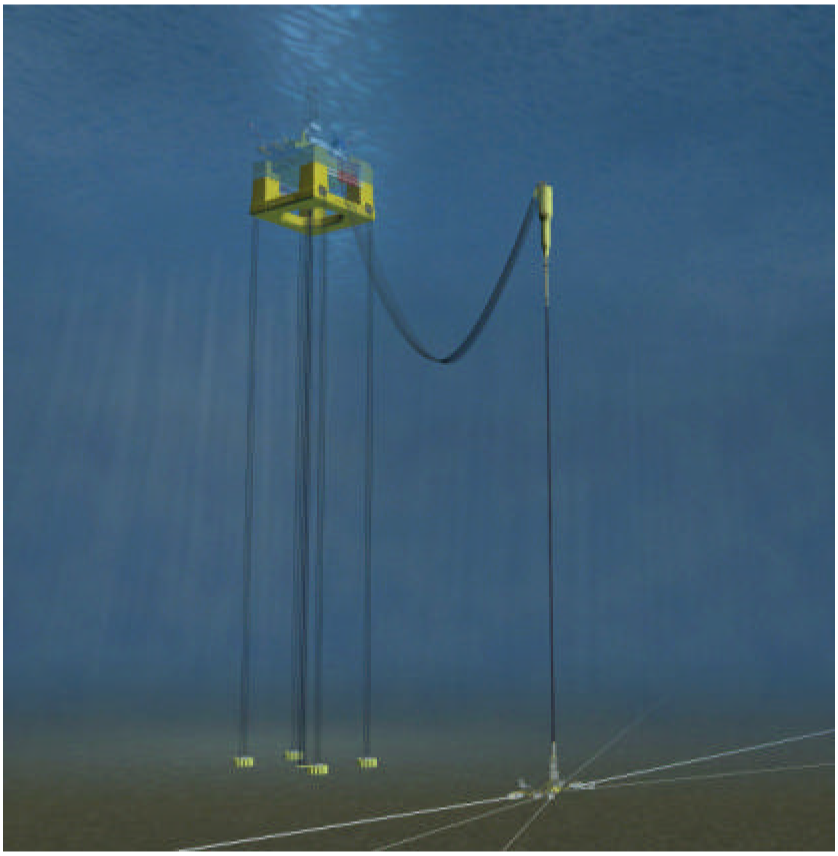

Figure 3: HRT components top and bottom sections on the Girassol Field

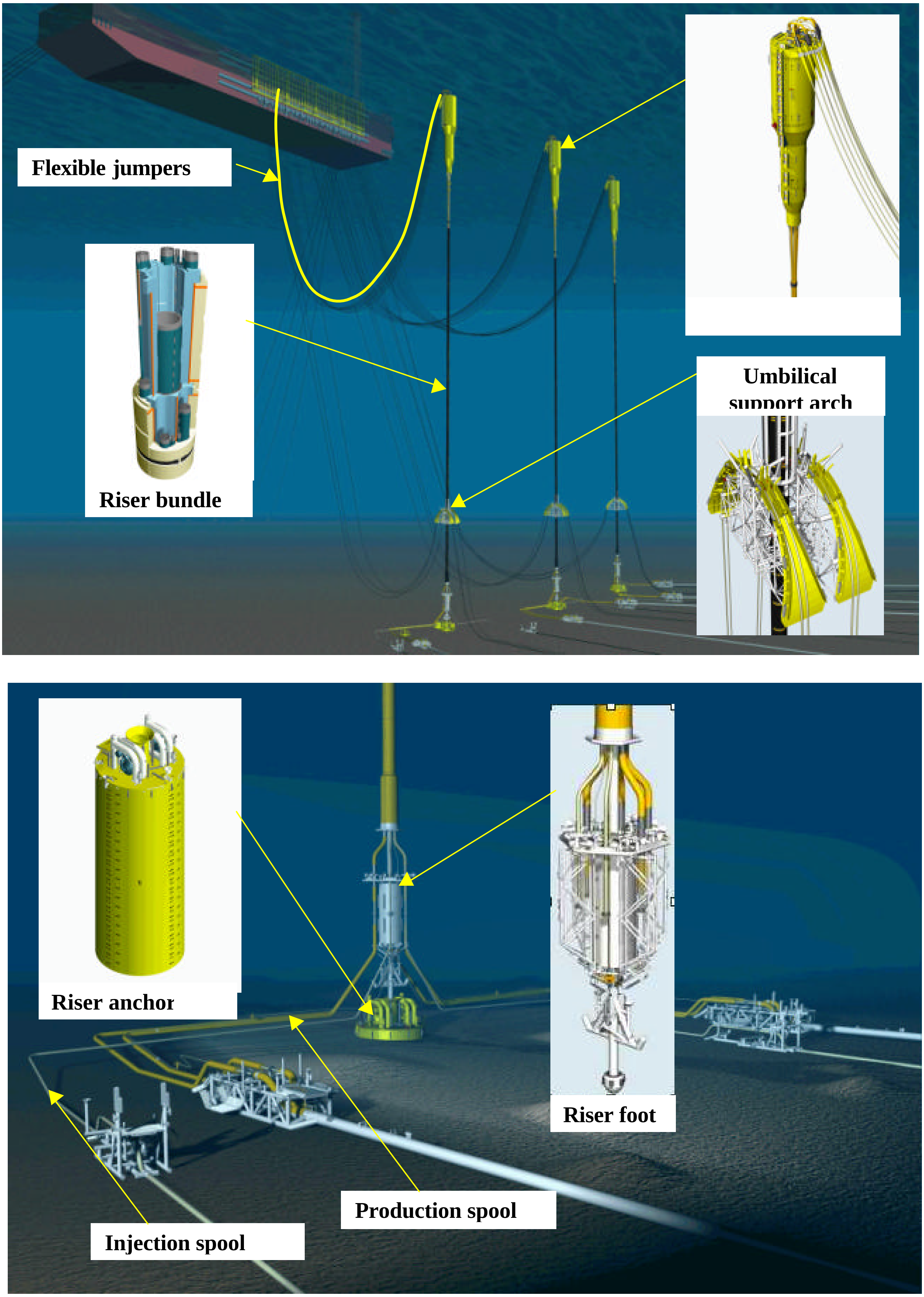

Figure 4: alternative HRT configuration

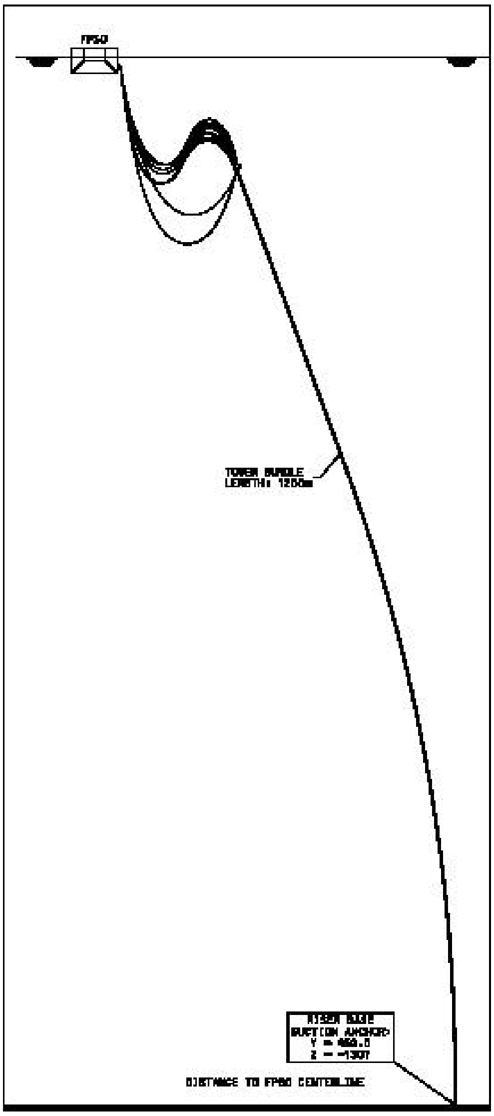

Figure 5: Loads entering into the equilibrium of the HRT

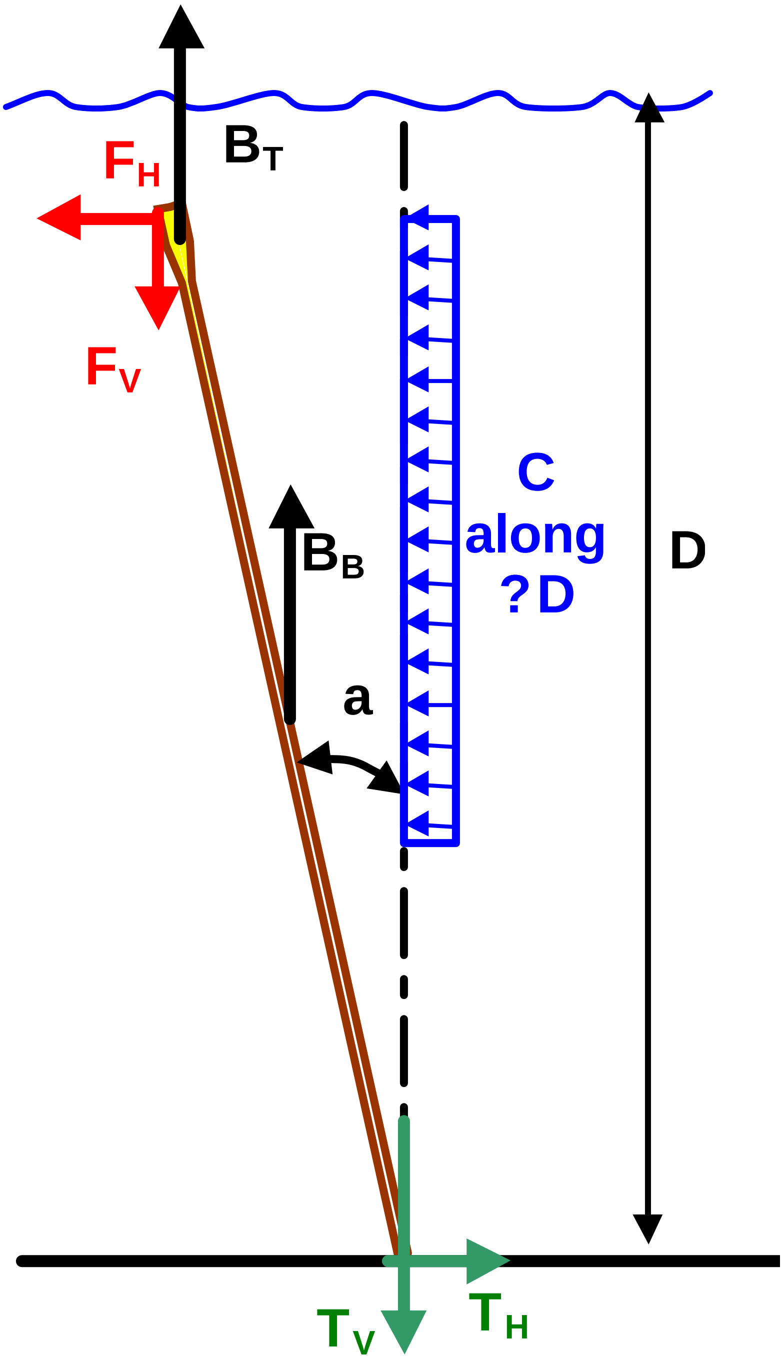

Figure 6: Flow area value and associated design parameters

HRT characteristics	Flow area value: 0.3 m^2	Flow area value: 0.7 m^2
Buoyancy tank mass	390T	600T
Buoyancy tank displaced volume	1200 m^3	1900 m^3
Riser base mass	330T	560T
Bundle linear mass	1650kg/m	2500kg/m
Compression load in the central core of the bundle.	3000 kN	5500 kN

Figure 7: Bundle cross section

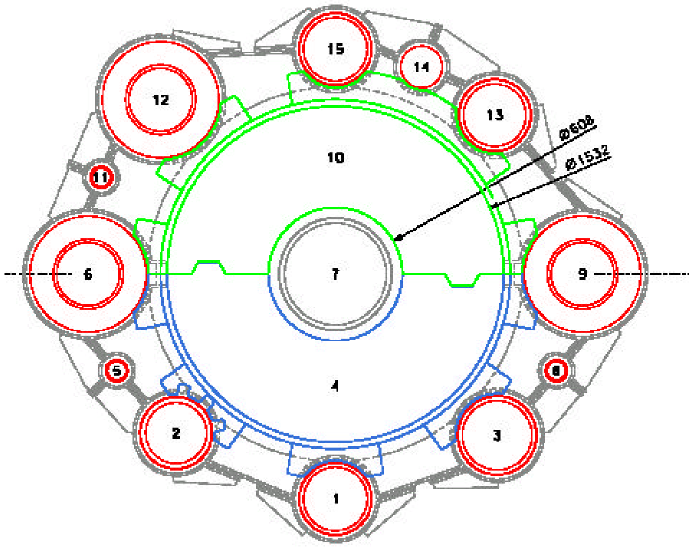

Figure 8: Core pipe put into compression after upending operation

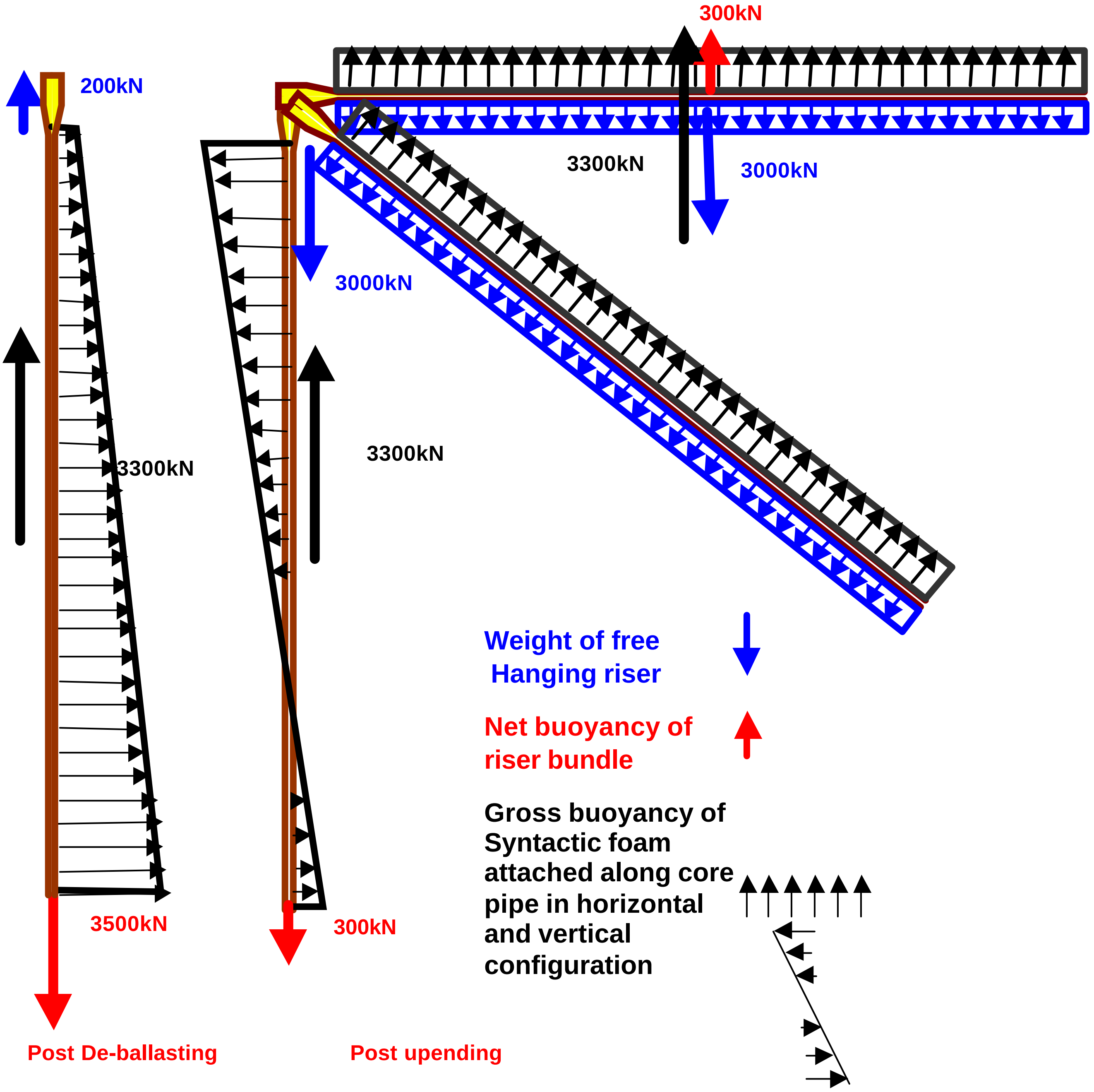

Figure 10: Stress along core pipe

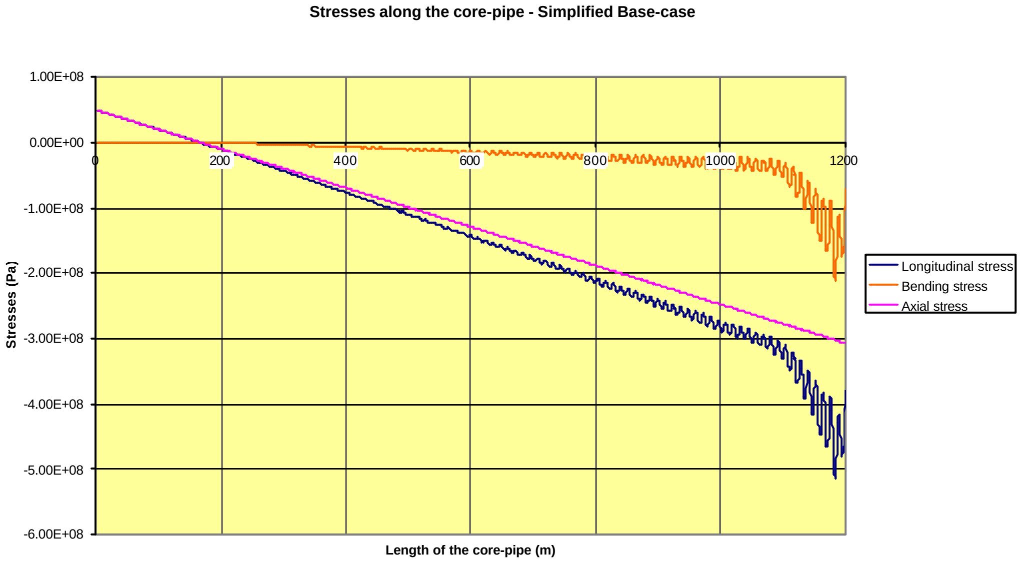

Figure 10: Bundle General assembly

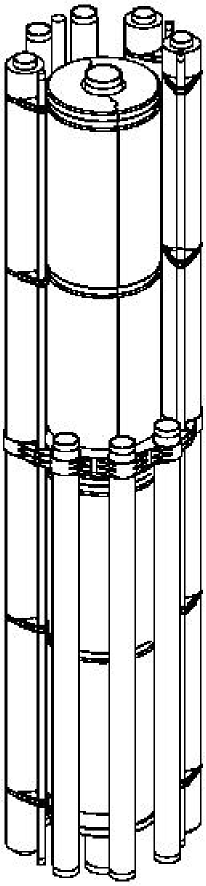

Figure 11: HRT new fabrication process

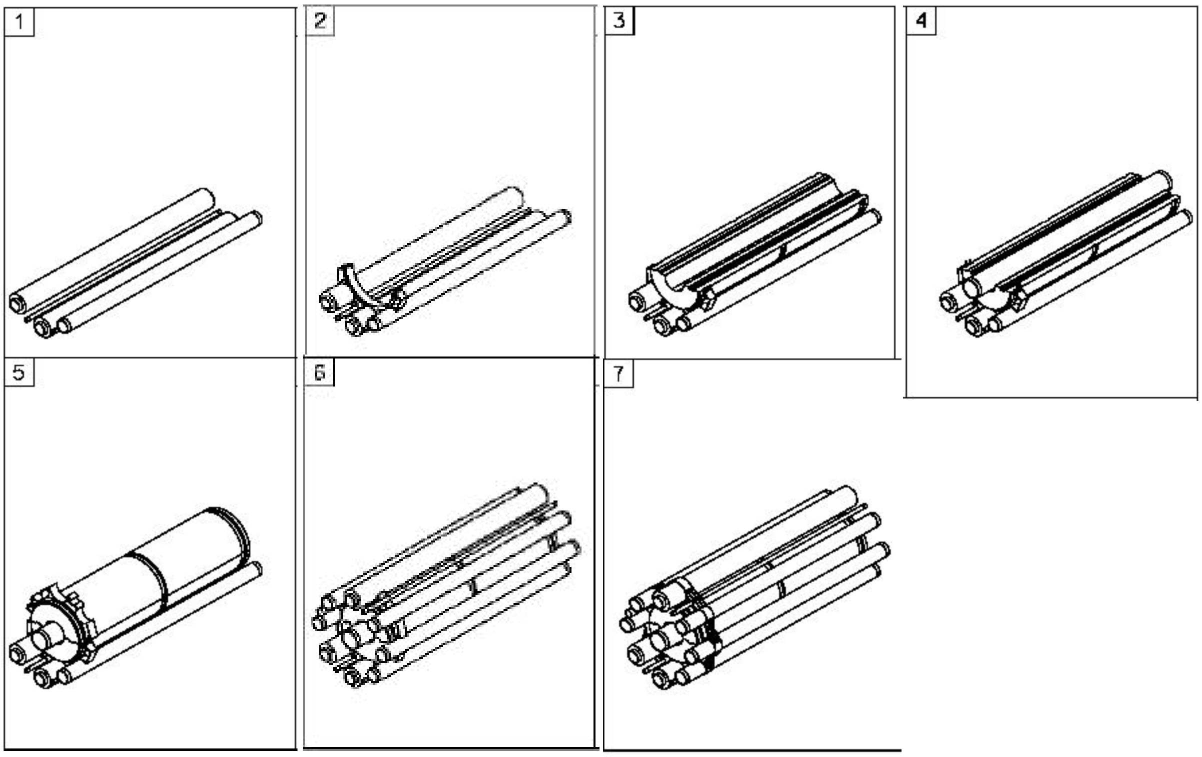

Figure 12: Subsurafce tow configuration

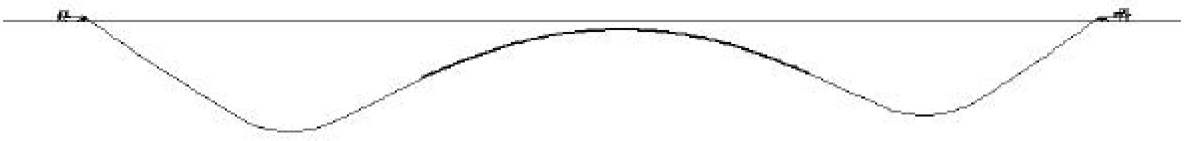

Figure 13: Hydrodynamic analysis and testing of the HRT bundle

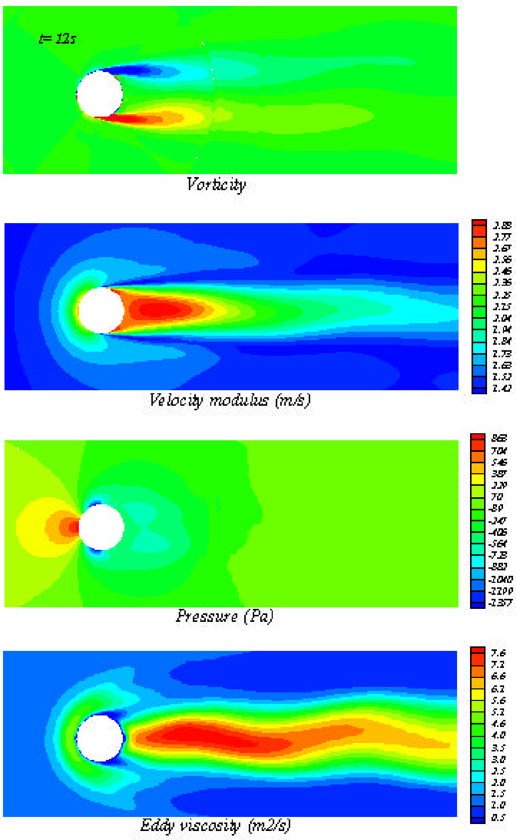

Figure 13: Cost break down

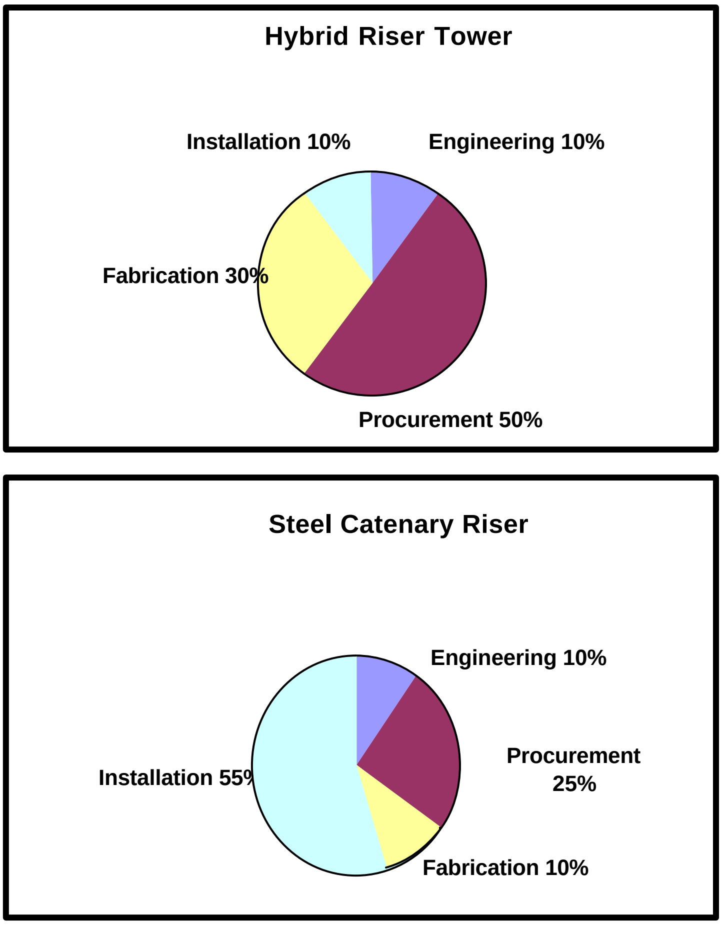

Figure 14: Cost evolution as a function of flow, depth and complexity