

## Design and Optimization of Top Tension Risers for Ultra Deep Water

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#### Abstract

The track record of Top Tension Risers (TTRs) has been well established for deep water applications in US Gulf, Africa and Indonesia. However, future applications of this technology, particularly in the US Gulf, will consider ultra deep (3000m) and HT/HP (>>10ksi) reservoirs. In such applications the criticality and complexity of the riser design process is significantly increased and in some instances it may not be possible to achieve an acceptable configuration. The paper addresses the key design issues looking at sizing, design of key components, material selection, analysis methods and installation issues. Limitations of current technology and application envelopes requiring new methods are defined

#### Introduction

The development of deepwater oil and gas reserves constantly faces the challenge to reduce costs of all components and activities in the selected development scheme. The largest costs associated with deepwater and deep reservoirs directly results from the time taken to drill, complete and work-over the wells. This is due to the high day rate of deepwater drilling vessels and the complexity of the operations involved. The requirement to reduce the cost of these activities in ultra-deep wells increases the attraction of dry tree floating production facilities such as spars, Figure 1, and TLP's, Figure 2 where direct accessibility of the wells below the production platform is possible. For this reason it is believed that dry tree units will continue to be the favoured development approach for ultra deep water – subject to acceptable reservoir extent and characteristics.

A key aspect in the selection and design of a dry tree unit is the feasibility of the associated risers and the impact they have on the vessel specification. Increases in water depth have a direct impact on the design of the riser, primarily due to the increase in riser weight, resulting in larger tension requirements and hydrodynamic drag loading. Tension is provided through use of non-integral aircans for spars, Figure 3, or hydro-pneumatic tensioners for TLP's, Figure 4. The impact of riser weight in deep water is further compounded by deep reservoirs, which typically have high pressures, resulting in the need for larger riser wall thicknesses and hence heavier pipes to

support. This leads to the need for careful consideration of the design approach and materials used for such riser applications.

Figure 5 illustrates the existing and planned applications of dry tree production platforms. TLP's have a practical water depth limit around 5,000ft range due to the challenge of being able to provide adequate levels of tendon axial stiffness to achieve the required motion characteristics. However, design development are ongoing to determine cost effective solutions to this problem. For water depths beyond 5,000ft, Spar based dry tree units have been the preferred technology, and is being evaluated by a number of operators for water depths up to 10,000ft[5]. The limiting aspect of Spars technology for ultra deepwater applications is the ability to accommodate large aircans or hydro-pneumatic tensioners, required to support and tension heavy risers.

This paper presents an overview of the challenges faced in designing top tensioned production riser for Spars in water depths greater than 6,000ft, up to 10,000ft. The focus is on the key design issues and the availability of new technology that may enable the application of spar top tensioned risers in ultra deepwater.

#### Background

Top Tension Risers (TTRs) have been in service on floating production facilities from as early as 1984 when the Hutton Tension Leg Platform was installed in the UK North Sea, in 486ft water depth. Since that time 29 dry tree production facilities have been installed using TTRs, with either TLPs (17 platforms) or Spars (12 platforms) as the host vessel.

The first spar installation was Neptune in 1996. Whilst this was in a water depth of only 1,930ft (600m), the technology has now been successfully extended into water depths exceeding 5,000ft (1524m). The deepest spar installed to date is the Devils Tower field, operated by Dominion in 5,610ft water depth.

As exploration currently proceeds into water depths close to 10,000ft, the challenge facing the industry is how to extend production technology to meet the drilling capabilities. Not only is the water depth, and therefore additional riser weight a challenge,

but additionally in these deep waters high pressure and high temperature reservoirs are an added challenge that directly impacts riser design.

Top tension risers for dry tree arrangements may be either single or dual barrier systems, depending on a range of considerations including functional requirements, intervention and workover requirements, reservoir pressure, water depth, economics and perhaps most importantly, safety and reliability considerations.

The single barrier riser consists of a single casing and internal production tubing. This arrangement has the smallest diameter and offers the lightest solution with lowest capital cost. The disadvantage of this arrangement is the single structural barrier, which in some developments can be insufficient. A critical phase is during workover operations when the production tubing is removed leaving only a single barrier plus completion fluid. Provision of gas lift is also a challenge due to the quantity of gas in the annulus or the impact of including a dedicated annulus line.

As a result of the above issues some Operators adopt a double barrier riser where two concentric casings are used. In the event of failure of the inner casing the outer casing is designed to retain the completion fluids and hence maintain the hydrostatic balance in the well. Further, if a leak occurs in the primary barrier (inner casing) it can be detected by a pressure build up in the outer annulus. Dual barrier systems offer improved thermal performance over single barrier systems, often a key challenge in deep water.

Typically the outer riser casing, for both single and dual barrier systems, consists of a lower taper joint that connects to the subsea wellhead via a tieback connector. The taper joint either has a crossover joint above or connects directly to standard riser joints, depending on the structural performance at the base of the riser. Standard riser joints then run through the water column to 20 to 30ft below the keel of the spar. At this point the standard riser joints connect to the keel joint. The keel joint has a double machined tapered wall thickness with a keel ball at the mid point to react against the keel guide of the spar. Standard joints connect the keel joint to the surface wellhead. For dual barrier systems the inner riser casing consists of standard riser joints running from the subsea tieback connector to the surface wellhead.

With the exception of the Holstein spar, all spar developments have used aircan / stem systems for providing the required top tension to the riser system, Figure 3. For these systems a stem pipe runs through the hull of the spar and either have

integral or non-integral aircans that provide the tension to the system. The aircans and stem are guided within the hull of the spar by a series of guides that provide reaction points between the aircan / stem system and the vessel. The riser system runs up through the stem pipe with a series of centralizers to maintain the eccentricity of the riser within the stem.

The Holstein spar is novel, in that it does not use an aircan / stem system but rather has hydro-pneumatic tensioners to provide the required tension to the riser system. Figure 10 provides an illustration of the type of hydro-pneumatic tensioner used for the Holstein top tensioned risers.

The conventional construction method for riser joints uses 'weld-on' threaded connections, Figure 6, on the end of each riser joint. This limits the material yield strength to 80ksi to achieve acceptable weld performance, particularly where NACE compliance is required. This approach results in a relatively heavy riser due to material strength limitations giving a thicker wall and also the introduction of heavy couplings. Whilst weld on threaded couplings can be designed with a high strength and low stress concentration factor it is important to appreciate that the weld is normally the limiting factor with a fatigue performance of DOE E class 1.3.

An alternative construction approach is the use threaded and coupled (T&C) connections that do not require welding. This allows material yield strengths up to 125ksi and results in thinner riser wall thicknesses, allowing weight reduction to be achieved. Threaded and coupled connection have been shown to offer acceptable fatigue performance and when fitted with a suitable external environmental seal offer a lower cost and lower weight solution compared to a welded construction. The use of higher strength steel also allows in some cases the use of a smaller nominal casing size depending on downhole drift dimensions. The T&C connection with external seal is shown in Figure 7.

This construction method has been used on a number of Spar risers to-date and is proposed for a number of facilities currently under fabrication. Fatigue testing confirms acceptable fatigue performance can be achieved with T&C connections and where fatigue damage rates exceed the capacity of the T&C connection, a limited number of weld-on connections can be used. Two field developments in the GoM environment are also adopting the use of T&C connections on a single barrier riser system.

It is noted that T&C connections are used on all dual barrier riser systems on the inner strings, with

the outer structural riser using weld on threaded connections. Whilst this is not the primary structural barrier it is the primary pressure barrier and can be subjected to significant fatigue loading at critical locations adjacent to the wellhead and vessel interface. Three development in the Gulf of Mexico use both inner and outer casings with T&C connectors.

### Key Design Issues

The key design issues associated with dry tree spar riser systems are focused around the parameters that have an affect on, and are affected by, riser weight. In ultra-deep water the riser weight is a direct function of water depth, and is further compounded by high pressure reservoir environments. It is noted that there is a common correlation between ultra deep water and reservoir depths in excess of 25,000ft below mudline and hence high shut in tubing pressures in excess of 10,000psi may be present. Such reservoirs are considered challenging when coupled with water depths beyond 5,000ft.

Combining high pressure and ultra deep water, results in the requirement for a large riser wall thickness. For dual barrier systems the inner casing must accommodate the full shut in tubing pressure and the outer casing must resist the hydrostatic collapse pressure at the full water depth. Barrier philosophy is an important issue and for the Majors the trend appears to be towards dual barrier configurations.

Reservoir pressures above 10,000psi may result in wall thickness at the limits of manufacturability, or at the very least, larger than has been previously developed for heavy wall T&C connections. Casing wall thickness greater than 1.25 inch is limited by the thickness of the coupling material and the ability to achieve the adequate through thickness material properties. Also the increased wall thickness of the internal casing can impact the riser diameter due to achieving a minimum drift requirement. This can either be as a result of the internal diameter of the casing being too small that standard tooling cannot pass through for downhole operations, requiring the inner casing diameter to increase, and hence increase riser system weight, or due to the large coupling OD that cannot fit within the ID of the outer casing, resulting in a larger outer riser which not only increases the riser weight, but may degrade the riser performance due to the additional drag diameter.

As discussed, increases in water depth and high reservoir pressure are the primary parameters that influence the riser weight. The effect of riser weight tends to have a negative 'knock on' effect on other

design aspects of the system, which affect the feasibility of the risers for ultra-deep water and/or high pressure applications. This is summarized below and illustrated in Figure 8:

- Increased tension requirement
- Increased aircan size to provide sufficient riser tension, or;
- Increased hydro-pneumatic tensioner requirements
- Impact on hull design to accommodate either tensioning system
- Increased riser costs

Large tension requirements result in the need for larger aircan volume, which can be achieved by either increasing the length or diameter of the can. It is currently considered that the limit for aircan length is approximately 230ft. This is primarily due to the following reasons:

- Desire to maintain aircan with hull hard tanks
- Installation and handling complexities

Increasing the aircan length to beyond 230ft to meet the tension requirements of conventional dry tree risers in water depths beyond 6,000ft will result in the large diameter aircan protruding beyond 50ft below the hard tank of the spar. This is not favourable, and results in complex hydrodynamic loading with the increased susceptibility to fatigue of the aircan, risers and mooring system. In particular, the exposure of 12ft diameter aircans to the high current region from 200ft to approximately 500ft below mean water level is a cause for concern with respect to VIV of the riser aircan system. VIV of the aircan is likely to lead to a detrimental influence on the riser as well as the aircan welds themselves. This issue has previously not had to be addressed as the aircans have been protected within the hard tank of the hull.

In addition, the larger drag loading on the spar will potentially increase the vessel offsets during environmental loading and increase the bending loads on the lower taper joint at the base of the riser. Further limits on aircan length are encountered due to the truss spar design that currently does not accommodate the possibility of aircans stroking through the heave plates of the spar, illustrated in Figure 1, however, it is possible that that this requirement could be engineered.

Aircans less than 230ft can easily be transported to site on barges, lifted off and lowered into the spar well slots by derrick barges already in the field for the deck lift operation. Increasing the aircan length much beyond 230ft may require the aircan to be installed in two sections due to the fact that the

aircan length capacity is a function of the derrick barge crane reach whilst maintaining a safe operating distance from the spar hull, Figure 9. Installation of an aircan in two sections presents its own challenges. There are many concerns with this operation, particularly with respect to securely supporting the bottom section in the well slot, and achieving the correct alignment of the two sections for make up of the flange connection whilst holding the upper section from the derrick barge crane. It is clear that this is a complex issue, at a connection that is likely to be fatigue critical.

It is considered that maintaining the spar riser aircans within the environmental protective hard tank of the hull is important for the design of the riser/hull interface. For longer aircans the need to increase the hard tank can be evaluated if the riser response is shown to be unacceptable, and providing that the aircan length protruding is not excessively long. An alternative is to increase the diameter of the aircan from the conventional 12 - 13ft range to 14-16ft in order to maintain the required buoyancy volume within the ~200ft section of hard tank. This has the impact of increasing the well bay spacing with the result being an increase in spar hull diameter to maintain the same spar hull buoyancy, and is considered to have a large cost impact on the fabrication of the spar. However, this may remain a viable option for developments with 6-8 wells, but is not attractive for larger field development where 12-16 risers are required.

Both options to increase aircan buoyancy volume present challenges that require substantial re-engineering of the spar to resolve the hull/riser interfaces. As an alternative, hydro-pneumatic tensioners, may be used with the following implications:

- Simplification of hull/riser interface enabling shorter time to freeze hull design arrangement;
- Increased vessel payload and associated increase in hard tank capacity;
- Reduced stroke due to tensioner effects
- Need to re-evaluate vessel hydrodynamic response due to lowering of vessel heave natural period from riser tensioner stiffness;
- Increased fatigue damage in the production risers due to large tension fluctuations;
- Need to optimise tensioner stiffness (accumulator volumes) to produce suitable balance between low accumulator volumes and riser fatigue damage;

Whilst not affected greatly by the influence of water depths, the flexible jumpers, which connect the surface trees to the production manifold is limited by pressure and temperature capacities. It is

understood that the current limit on temperature is 266 F (130 C), and pressure capacity is approximately 13,000psi depending on the internal diameter of the flexible jumper. It is also noted that combinations of high pressure and temperature restrict the capabilities of these pipes, as does the introduction of a sour environment.

### Wall Thickness Sizing

Conventional dual barrier risers have used steel grades of T95 and P110 for the inner casing with a lower grade X80 for the outer casing. Whilst the use of lower grade steel for the outer casing maintains the option to use weld-on threaded connectors, the result is riser systems that have thicker walls and are subsequently heavier, therefore requiring high top tensions.

Figure 12 through Figure 15 show a comparison of wall thickness, weight, tension requirements and required aircan lengths for the following conditions:

- 5,000ft WD, 5ksi design pressure
- 5,000ft WD, 10ksi design pressure
- 10,000ft WD, 5ksi design pressure
- 10,000ft WD, 10ksi design pressure

Each condition is assumed to consist of 13-3/8 inch outer casing and 9-5/8 inch inner casing and have an aircan outer diameter of 13 feet.

For top tension risers in 5,000ft water depth, Figure 12 shows an increase in riser wall thickness requirements of approximately 60% for the inner casing when increasing the design pressure from 5 to 10 ksi. The outer casing requirement remains unchanged since this is driven by hydrostatic collapse in the normal operating condition.

The 60% increase in wall thickness for the inner casing equates to an increase of approximately 20% in the required top tension of the riser system, resulting in a corresponding increase in aircan length from 165ft to 195ft, assuming a steel aircan effective density of 280kg/m<sup>3</sup>. Whilst the top tension requirements and the aircan lengths are within current design limits this example demonstrates that by simply doubling the design pressure of the riser system, a significant increase in hardware requirements, for both the riser and aircan system occurs.

In making the step from 5,000ft to 10,000ft water depth, and maintaining the design pressure at 5ksi the increase in wall thickness is seen in both the inner and outer casing. The inner casing wall thickness increases by approximately 25% due to the increased axial tension in the system, and the outer casing increases by 35% due to the increased

external hydrostatic head and subsequent increased collapse strength requirements. The overall tension requirement is now seen to increase by approximately 150% over the 5,000ft case, with a corresponding increase in required aircan length, 412ft for the 10,000ft water depth. Increasing the design pressure to 10ksi for the 10,000ft water depth has similar effect with the overall aircan length increasing to 470ft.

As discussed earlier, these aircan lengths are beyond the 230ft limit by almost 200ft. For truss spar arrangements, this means that the aircons will protrude significantly into the truss section of the spar, resulting in additional drag loading on the spar and complex hydrodynamic response which has the potential to impact the riser performance.

### Enabling Technologies

The implication of these heavy risers in ultra-deep water is discussed in the previous sections. However, it is important to note that long or large diameter aircons, or hydro-pneumatic tensioners have huge impacts on the commercial and technical feasibility of the riser system and also the spar hull. In order to extend the use of dry tree units in water depths greater than 6,000ft and also for HPHT applications, methods for reducing riser weight is a key focus area. There are potentially a range of methods for reducing the riser weight, with varying levels of effectiveness:

- Tubing tie-back riser
- Single barrier risers
- Use of different materials
- Addition of distributed buoyancy along riser length

The tubing tieback riser with split tree has been proposed on a number of previous studies but has not to date found application in the field. A tubing riser is simply a type of top tensioned riser that only has the production tubing running through the water column, with a split tree located between the tieback connector and taper joint to provide an additional safety barrier, Figure 11 [13]. A dedicated drilling/workover riser is also required for drilling, completing and working over the wells. The main advantage of the tubing riser over conventional single or dual barrier risers is the significant reduction in weight. It is estimated that the top tension requirement of a tubing riser is 25% of that for a conventional single barrier TTR [13]. In comparison to dual barrier system the tubing riser is only 10-15% of the total tension requirement. This results in a riser system that is very attractive in ultra-deep water as aircan or tensioner requirements would be manageable and within current design capabilities.

The main disadvantage of the tubing tie-back system is that full wellbore access requires the removal of the subsea tree and reinstallation of the drilling/WO riser. This is time-consuming as the well needs to be killed and a plug set. Additionally each subsea tree requires a production control umbilical and this can complicate the riser design if run with the riser or alternatively requires separate control umbilicals with a subsea distribution system.

It is observed that the deepest spar installed to date, uses a single barrier approach with high strength steel threaded and coupled connections. The use of a single barrier system tends to be perceived as less reliable and perhaps less safe than the dual barrier option and particularly in deep water and with high pressure reservoirs where the risk weighted concerns are increased. Hence for these conditions the barrier philosophy tends towards the dual barrier approach. One option available is similar to the tubing tieback riser whereby a single casing riser is installed to reduce tension requirements, but to maintain the dual barrier philosophy a mudline tree is installed just above the tubing hanger [5]. In case of a tubing leak the mudline tree will close automatically, based on input from riser annulus pressure sensors. However, the complexity of this system is significant.

The use of single barrier riser systems, with high strength T&C connections, does not provide the level of weight saving of that seen for tubing tieback risers, but the removal of the larger diameter outer casing can reduce the riser weight by as much as 30-40%. This is primarily because non-welded T&C connections can utilize high strength materials as high as 125ksi, and higher strength materials are being researched.

Provided the system is engineered properly and that there is a reliable environmental seal, there aren't any known problems inherent to the T&C system. The fatigue tests conducted as part of the qualification program for TTRs in the GOM and Indonesia indicate that fatigue performance of the connection is more than adequate. 2H managed the TRF JIP, that focussed on full scale fatigue testing and qualification of threaded and coupled connections from three different suppliers. A total of 20 specimens were tested. The majority of the specimens taken to failure achieved the fatigue performance comparable with DNV B curve and SCF of 2.0 or below. These results exceed prior expectations and confirm that the fatigue performance of a threaded and coupled connection is as good as or even better than a good quality single sided weld. Based upon this testing program, and other qualification testing programs conducted by operators that have observed similar results, the

application of threaded and coupled connections for the outer casing string is expected to become common practice in the near future as an initial step to reducing the weight and interface loads on the top tensioned risers in water depths greater than 5,000ft.

It should be noted that there is significant increase in usage of threaded and coupled connections throughout the offshore industry. In addition to the use on TTRs, recent applications include completion risers, and high pressure drilling risers, indicating an increased level of confidence in the use of these connections. Further development and testing is also being conducted by a range of suppliers that offer these connections, to increase the wall thickness available and improve the environmental seal arrangement. This is beneficial as the industry steps into higher pressure applications where wall thickness reduction is key to minimizing riser weight.

An alternative material to high strength steel with non-welded threaded connections is aluminum alloy with yield stress ranges close to 70ksi. Aluminum alloy offers the benefit of being lightweight, the density is a third of steel, whilst maintaining good strength characteristics. Despite having thicker walls, ranging between 25-40%, aluminum alloy risers require top tensions approximately 40% less than the equivalent steel riser. The lower riser weight results in aircan dimensions that remain within the hard tanks of the hull without having to increase the aircan diameter, even in water depths up to 10,000ft. The difference of aircan length between steel and aluminum alloy riser systems is illustrated in Figure 16. It is noted that the steel riser in 10,000ft water depth is not shown but the aircan length is in excess of 400ft. Figure 16 shows that even in 5,000ft water depth the aluminum riser requires an aircan that is almost 60% shorter than the equivalent steel riser arrangement, despite the riser weight only being 40% less. This is because the application of aluminum alloy for aircan fabrication, results in a much more buoyancy efficient structure, with effective densities in the region of 150kg/m<sup>3</sup> compared to 280kg/m<sup>3</sup> for the steel version. It is considered that aluminum riser systems could be a potential enabling technology to advance dry tree technology to water depths beyond 6,000ft, however it is appreciated that for HPHT applications wall thickness requirements will increase further and may be close to manufacturing limits, partially due to temperature de-rating of the aluminum substrate.

The addition of distributed buoyancy modules along the length will also provide a mechanism for reducing riser top tension requirements. Whilst it is not advisable to use buoyancy modules such as

those used on drilling risers, due to the increased drag diameter. The approach is to use buoyant, thermal insulation material 2-3 inches thick similar to that used on subsea flowlines and production risers, such as C-Therm. This material provides the dual benefit of buoyancy and thermal insulation, which will improve the thermal performance of the system, particularly for single barrier riser arrangements.

### Case Study

The use of threaded and coupled connectors for both the inner and outer casing of dual barrier top tension risers will allow the associated use of high strength steels of up to 125ksi.

Figure 12 shows the result of increasing the material grade for both the inner (95ksi increased to 125ksi) and outer (80ksi increased to 125ksi) casing of a 10,000ft, 10ksi design pressure top tension riser. The wall thickness of the inner casing reduces by approximately 25% whilst that of the outer casing reduces by 8%. The smaller reduction of the outer casing wall thickness is due to the wall thickness being driven by the collapse condition.

The reduction in wall thickness has a corresponding effect of reducing the top tension requirement and hence the aircan length by approximately 15% to a required length of 416ft, compared to 470ft for a conventional T95 / X80 design.

This reduction in aircan length is significant as it could result in the ability to design the spar to accommodate these aircans without increasing the depth of the keel (overall height of the vessel).

It can be seen from the above that there are savings to be made by the use of high strength (125ksi) steels in top tension riser. The savings are seen both in terms of riser and aircan hardware and in required vessel size.

Further savings could also be seen by the use of an alternative material for the aircans of the riser system. For example the use of an aluminum alloy for the aircans would reduce the effective density of the aircans from 280kg/m<sup>3</sup> to 150kg/m<sup>3</sup>. This reduction in effective density equates to a reduction in required aircan length, for the 10,000ft, 10ksi condition, from 416ft to 354ft.

### Summary and Conclusions

In conclusion it is predicted that dry tree riser systems will continue to be selected for ultra deep developments, particularly in the Gulf of Mexico. This is in contradiction to the apparent wisdom in which it may seem impractical to extend the

wellheads to the surface in increasing water depth. However, the time taken to drill and complete these wells and the current and future day rate of deep water mobile offshore drilling units will continue to make dry tree systems commercially attractive.

If these ultra deep and high pressure dry tree systems are to be successful, significant development in riser technology is considered necessary. The complexity of such riser systems will be such that caution should be exercised in costing, planning and engineering such systems and the belief that they are simple extensions of proven technology should be avoided.

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Figure 1 – Spar Dry Tree Production Platform [7,8]



Figure 2 – Tension Leg Platform (TLP) [9,10]

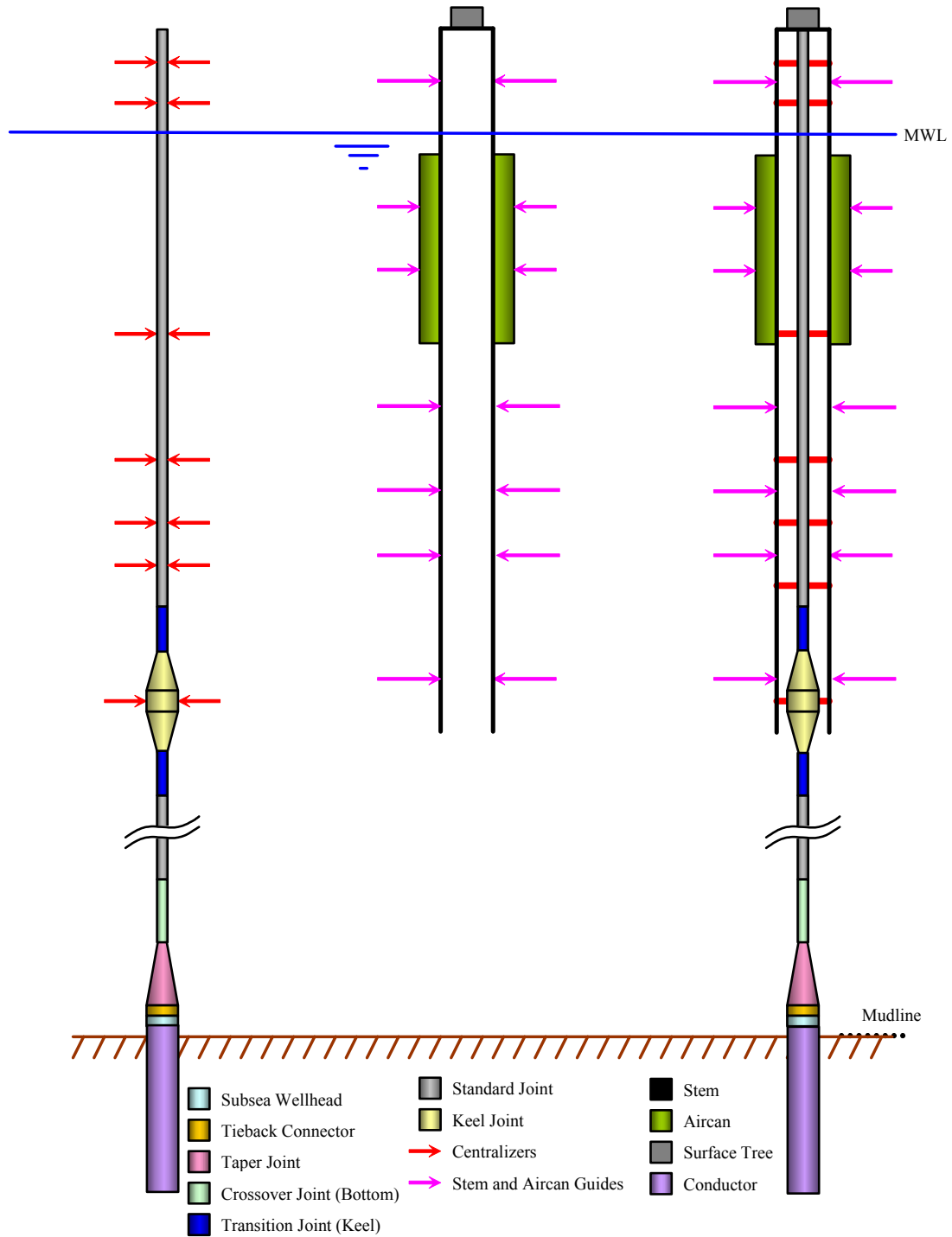


Figure 3 - Typical Spar Top Tension Riser System

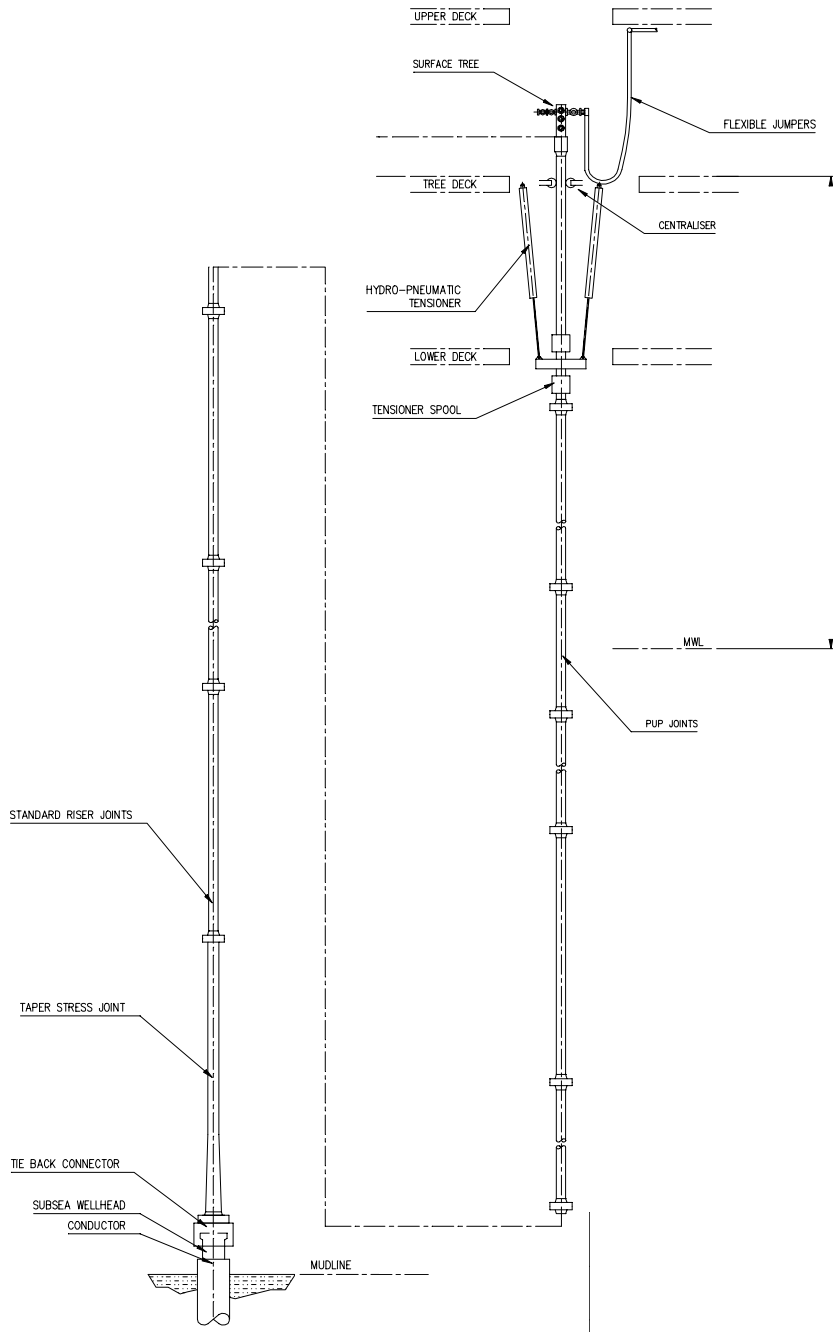


Figure 4 - Typical Gulf of Mexico TLP Top Tension Riser System

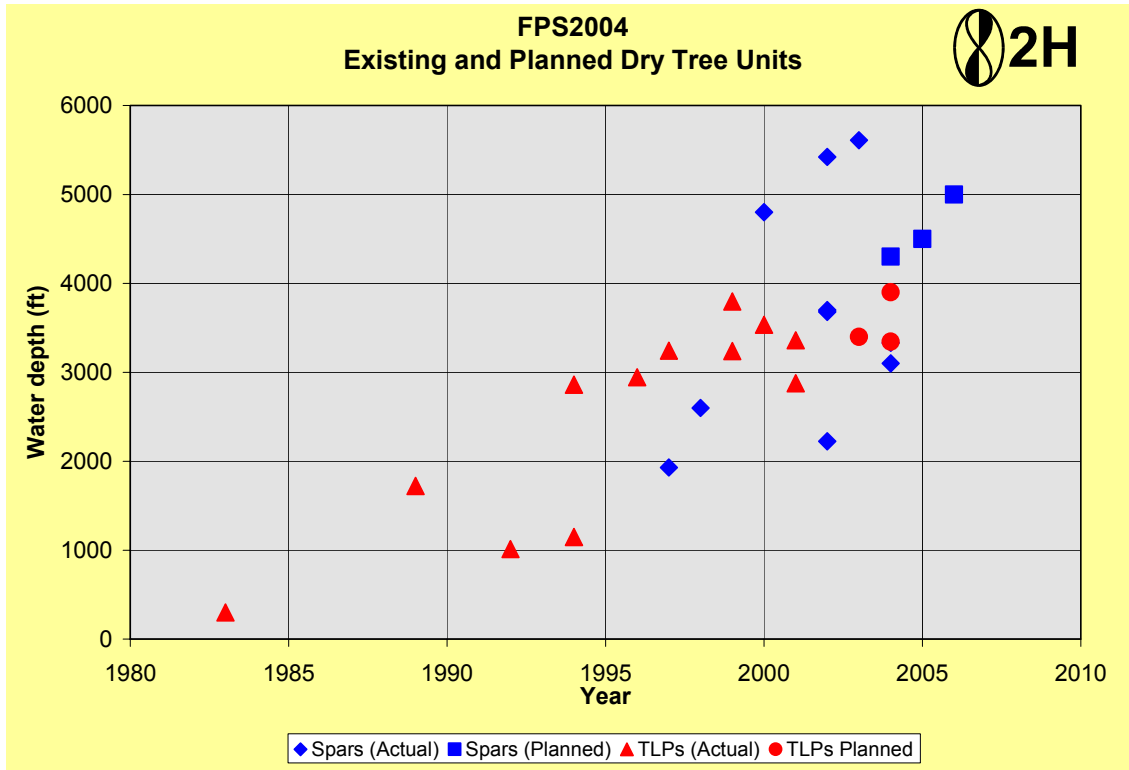


Figure 5 – Existing and Planned Dry Tree Units [4]

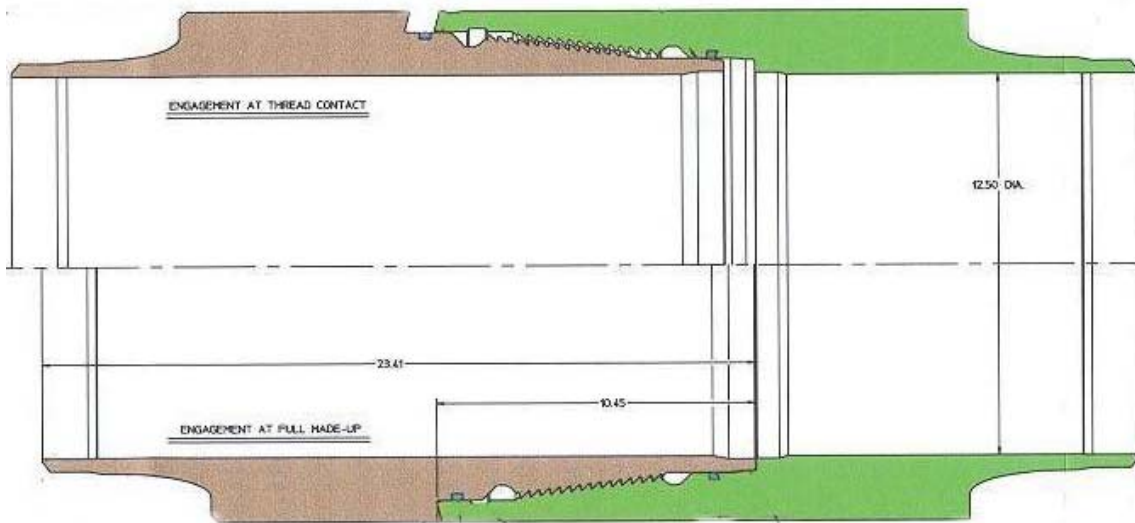


Figure 6 – Typical Weld-on Threaded Connection

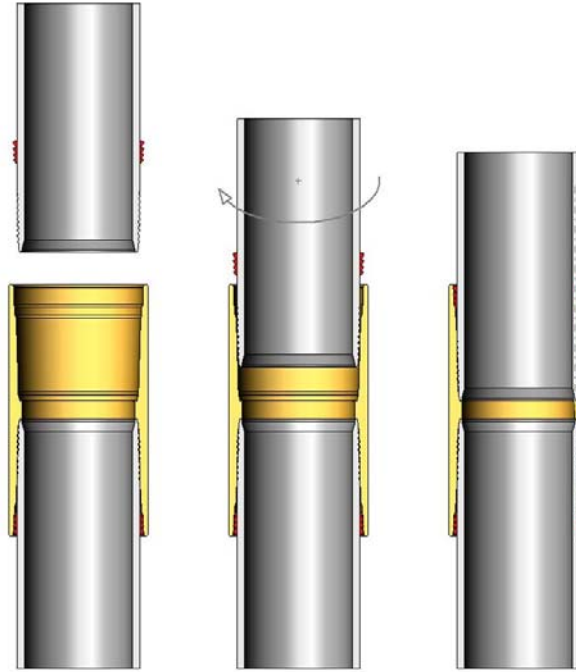


Figure 7 – Threaded and Coupled Connections

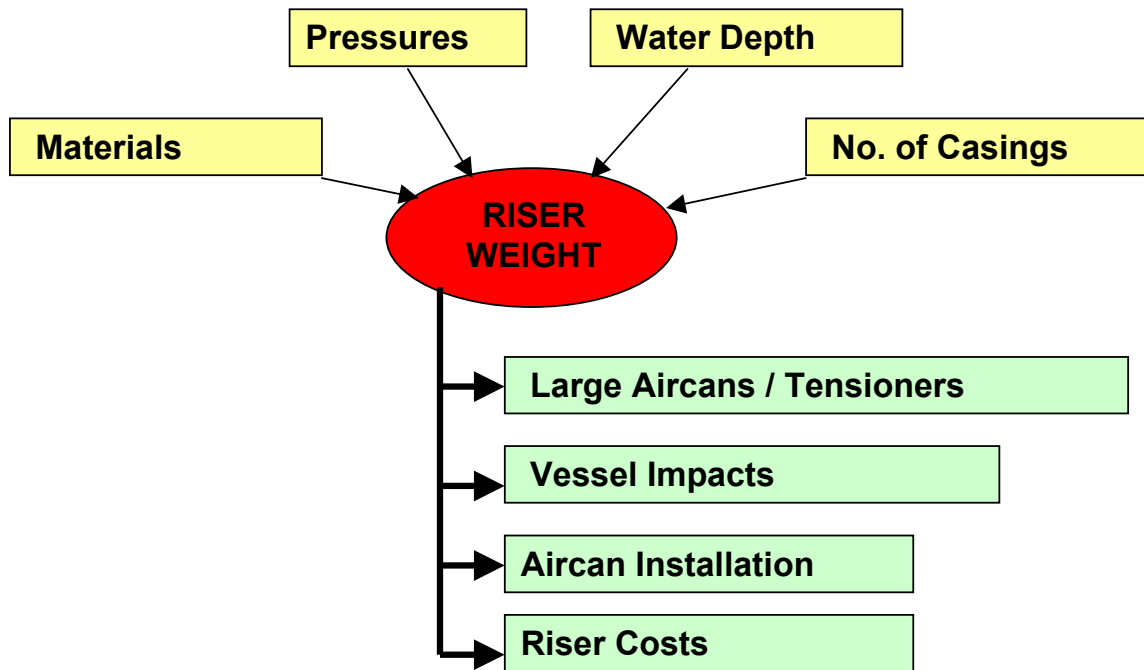


Figure 8 – Summary of Parameters Affecting and Affected by Riser Weight



Figure 9 – Spar Aircan Installation

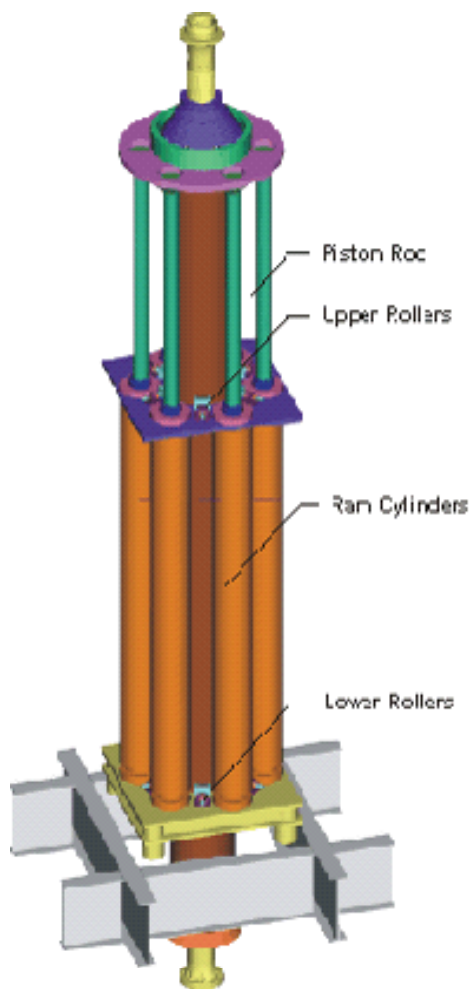


Figure 10 - Ram Style TTR Tensioner System [12]

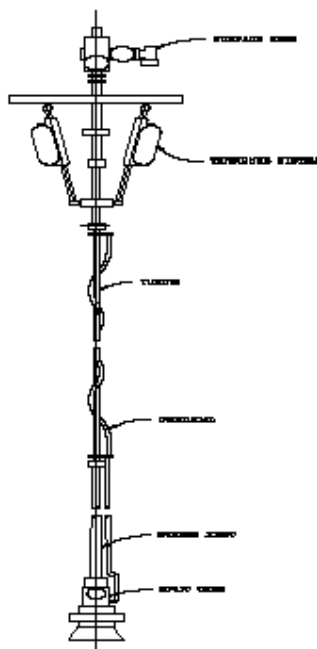


Figure 11 – Schematic Configuration of a Tubing Riser[13]

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Field Name	Operator	Water Depth (m)	Water Depth (ft)	Date	Spar/TLP	Location	Nos Wells	Prod Dual Single	Prod OD WT	Welded / T&C	Coupling Supplier
Auger	Shell	872	2,860	1994	TLP	GOM	32	Dual	10.75x0.469 6.625x0.719	Weld On	
Boomvang	Kerr McGee	1,128	3,700	2002	Spar	GOM	6	Single	9-5/8 OD	Weld On	
Brutus	Shell	910	2,985	2001	TLP	GOM	8	Dual	13-5/8 OD 11-3/4 OD	Weld On	
Devils Tower	Dominion	1,710	5,610	2003	Spar	GOM	8	Single	11-3/4x0.734	T&C	Grant Prideco
Front Runner	Murphy	1,015	3,330	2003	Spar	GOM	8	Dual	13-3/8x0.534 9-7/8x0.625	T&C	Grant Prideco
Genesis	ChevronTexaco	792	2,599	1998	Spar	GOM	20	Dual	13-3/8 OD 9-5/8 OD	T&C	
Gunnison	Kerr McGee	945	3,100	2004	Spar	GOM	3	Single	10-3/4 OD		
Heidrun	Statoil	351	1,150	1995	TLP	Norway	30	Single	9-5/8 OD	Forged End Pipe	
Holstein	BP	1,311	4,300	2003	Spar	GOM	21	Dual	14-7/8 OD 11-7/8 OD	VG C'pling / T&C	
Hoover Diana	ExxonMobil	1,463	4,800	2000	Spar	GOM	8	Dual	13-3/8 OD 9-5/8 OD	Weld On	
Horn Mountain	BP	1,653	5,422	2002	Spar	GOM	12	Dual	12-3/4x0.440 9-5/8x0.435	Weld On & T&C	RTI VAM
Hutton	Sevmorneftegaz	148	486	1984	TLP	UK North Sea	32	Single	9-5/8 OD	Forged	
Jolliet	ConocoPhillips	536	1,760	1989	TLP	GOM	20	Single	9-5/8 OD		
Mad Dog	BP	1,372	4,500	2005	Spar	GOM	16	Dual	13-3/8 OD 10-3/4 OD	Weld On & T&C	RTI
Magnolia	ConocoPhillips	1,432	4,700	2004	TLP	GOM	-	Single	11-3/4 OD	Weld On	
Marco Polo	Elpaso	1,311	4,300	2003	TLP	GOM	6				
Marlin	BP	988	3,240	1999	TLP	GOM	5		10-3/4 OD	Weld On	

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Field Name	Operator	Water depth (m)	Water Depth (ft)	Date	Spar/TLP	Location	Nos Wells	Prod Dual Single	Prod OD WT	Weld On / T&C	Coupling Supplier
Mars	Shell	896	2,940	1996	TLP	GOM	24	Dual	7-5/8 OD 4-1/2 OD	Weld On	
Matterhorn	TotalFinaElf	869	2,850	2003	TLP	GOM	8	Single	10-3/4 OD	Weld On	
Medusa	Murphy	678	2,223	2002	Spar	GOM	8	Dual	13-3/8 OD 9-7/8 OD	T&C	Grant Prideco
Nansen	Kerr McGee	1,120	3,675	2001	Spar	GOM	8	Single	9-5/8 OD	Weld On	
Neptune	Kerr McGee	588	1,930	1996	Spar	GOM	16	Single	9-5/8 OD	T&C	Grant Prideco
Prince	Elpaso	457	1,500	2001	TLP	GOM	9	Single	10-3/4 OD		
Ram/Powell	Shell	980	3,214	1997	TLP	GOM	20	Dual		Weld On	
Red Hawk	Kerr McGee	1,615	5,300	2004	Spar	GOM	2				
Snorre A	Hydro	335	1,100	1992	TLP	Norway	36	Single	9-5/8 x 12.5mm	Forged End Pipe	
Ursa	Shell	1,225	4,018	1999	TLP	GOM	12	Dual	2 designs: 14.0x0.750 10-7/8x0.608 & 13-5/8x0.625 10-3/4x0.545	Weld On	
W.Seno	Unocal	1,021	3,349	2003	TLP	Indonesia	24	Dual	7.0x0.408 13-3/8x0.480	T&C & Weld On	



Top Tension Riser Wall Thickness Comparison

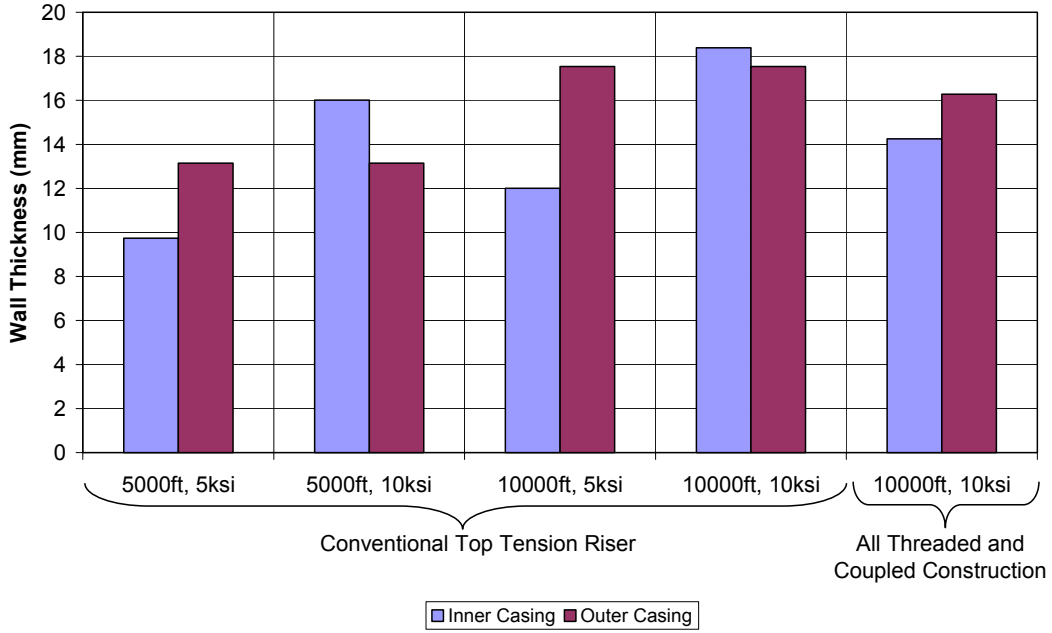


Figure 12 - Wall Thickness Comparison



Top Tension Riser Mass per Length Comparison

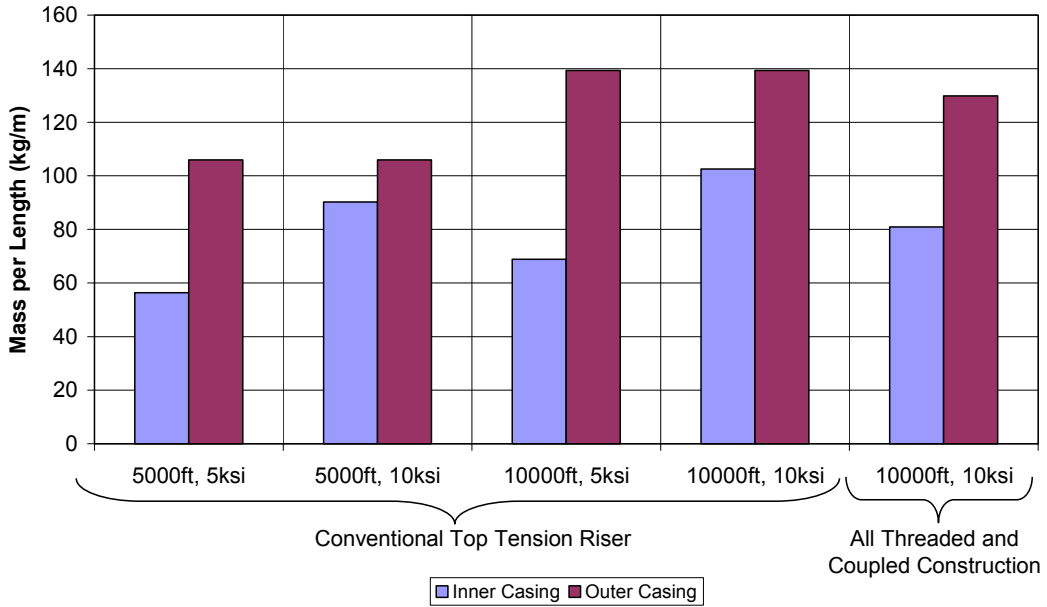


Figure 13 - Mass per Length Comparison



Top Tension Risers  
Tension Requirement Comparison

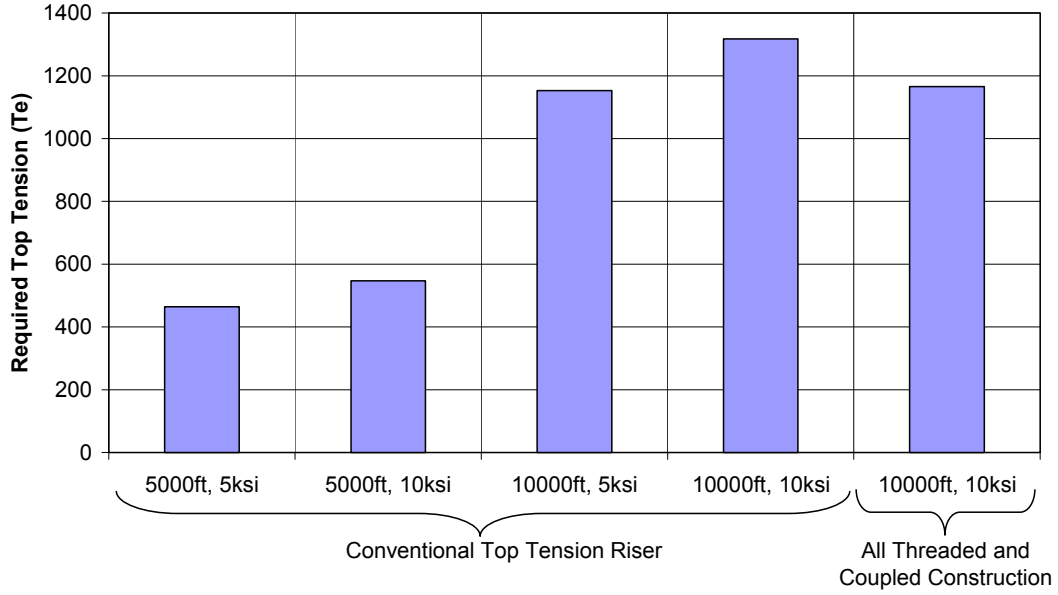


Figure 14 - Tension Requirement Comparison



Top Tension Risers  
Comparison of Required Aircan Lengths

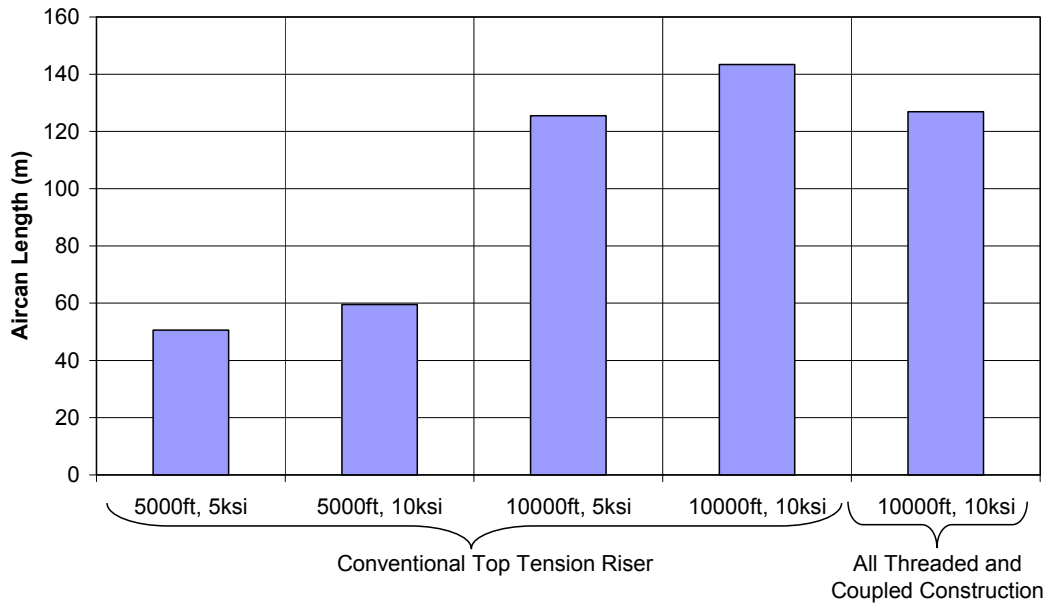


Figure 15 - Aircan Length Comparison

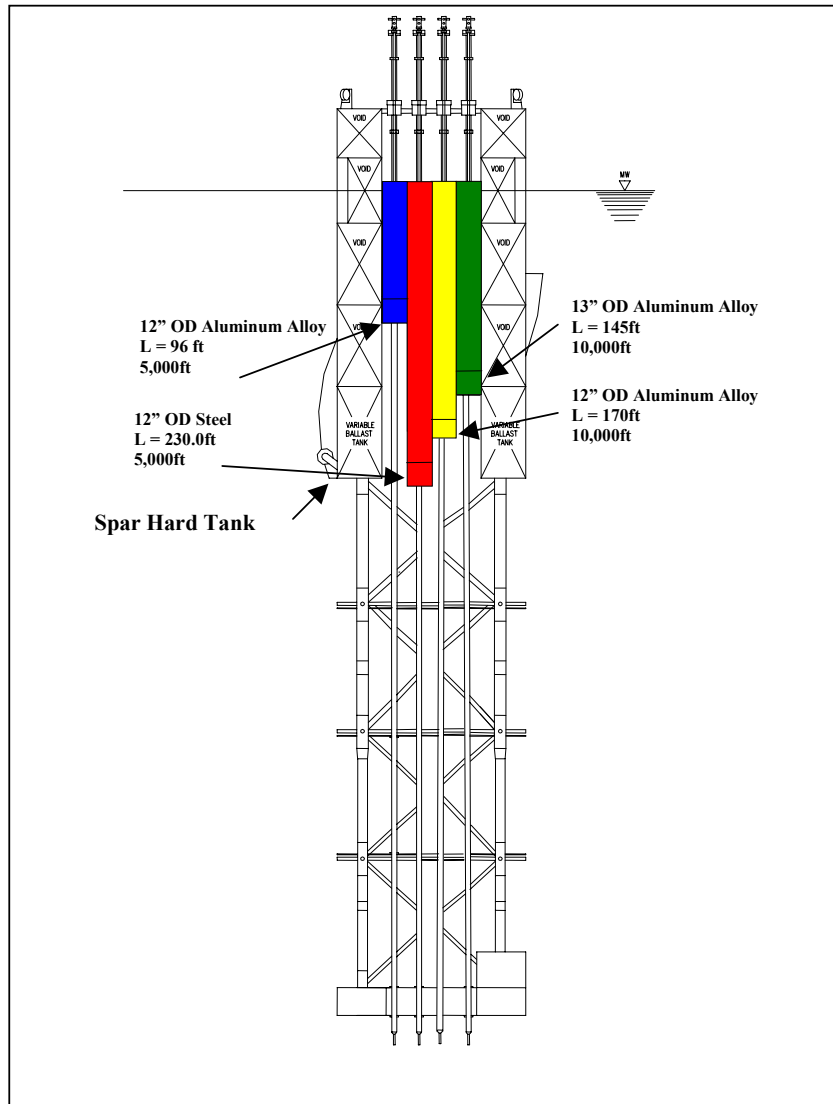


Figure 16 – Aircan Length Comparison between Steel and Aluminum Risers