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COMPLIANT VERTICAL ACCESS RISER – RISK ASSESSMENT STUDY

FINAL REPORT

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ABBREVIATIONS

AHT	Anchor Handling Tug
AHV	Anchor Handling Vessel
API	American Petroleum Institute
AUV	Autonomous Underwater Vehicle
BM	Bending Moment
BOP	Blow Out Preventor
CAPEX	Capital Expenditure
CFR	Code of Federal Regulations
CT	Coiled Tubing
CTDESP	Coiled Tubing Deployed ESP
CTR	Cost, Time, Resource Sheets
CVA	Certified Verification Agent
CVAR	Compliant Vertical Access Riser
D	Diameter
DDCV	Deep Draft Caisson Vessel
DGPS	Differential Global Positioning System
DNV	Det Norske Veritas
DOT	Deep Offshore Technology
DP	Dynamic Positioning
DVA	Direct Vertical Access
ESP	Electric Submersible Pump
FBE	Fusion Bonded Epoxy
FE	Fatigue Enhanced
FMECA	Failure Mode, Effect, and Criticality Analysis
FPSO	Floating Production Storage Offloading
FPU	Floating Production Unit
GOM, GoM	Gulf of Mexico
GOR	Gas to Oil Ratio
GRE	Glass Reinforced Epoxy

HC	Hydro Carbon
HCR	Highly Compliant Rigid
HDPE	High Density Polyethylene
HPHT	High Pressure High Temperature
HSS	High Strength Steel
ID	Inner Diameter
IR	Inner Riser in Dual casing riser
ISO	International Organization for Standardization
JIP	Joint Industry Program or Joint Industry Project
JSA	Job Safety Analysis
LF	Low Frequency
LSP	Lower Safety Package
MBR	Minimum Bending Radius
MIT	Massachusetts Institute of Technology
MM	Multi Mode
MMS	Minerals Management Services
MODU	Mobile Offshore Drilling Unit
MTP	Mudline Tree Package
OD	Outer Diameter
OR	Outer Riser in Dual casing riser
OS	Offshore Standards
OSI	Oil States Industries
OTC	Offshore Technology Conference
PARLOC	Pipeline and Riser Loss of Containment
PLEM	Pipe Line End Manifold
PP	PolyPropylene
QA/QC	Quality Assurance/ Quality Control
QRA	Quantitative Risk Analysis
ROV	Remotely Operated Vehicle
RMS	Root Mean Square
RP	Recommended Practice; Return Period
RPSEA	Research Partnership to Secure Energy for America

SCF	Stress Concentration Factor
SCR	Steel Catenary Riser
SCSSV	Surface-controlled Subsurface Safety Valve
SIT	System Integration Test
SM	Single Mode
SMD	Shut-in with Mooring line Damaged case
SWL	Safe Working Load
TA&R	Technology Assessment & Research
T&C	Threaded & Coupled
THS	Tubing Head Spool
TLP	Tension Leg Platform
TSJ	Tapered Stress Joint
TTR	Top Tensioned Riser
U-value	Overall Heat Transfer Coefficient
VIM	Vortex Induced Motion
VIV	Vortex Induced Vibration
WF	Wave Frequency
W/O	Work Over
WL	Wire Line
WT	Wall Thickness
yr	Year

SELECTED UNITS

ft	Feet	ksi	Kips per square inch
F	Fahrenheit	lb	Pounds
HP	Horse Power	m	Meters
HZ, Hz	Hertz	N	Newton
Kg	kilograms	Pa	Pascal
Kips	Kilo Pounds	psf	Pounds per square ft
kN	Kilo-Newtons	pcf	Pounds per cubic ft
kPa	kilo Pascals		

1 INTRODUCTION

This report presents the work done by Granherne, Inc., Houston for a new Direct Vertical Access (DVA) riser concept, Compliant Vertical Access Riser (CVAR), under the Minerals Management Service (MMS) Technology Assessment & Research (TA&R) Project 536. The work focused on developing the conceptual level details and analysis of CVAR design, and assessing risks associated with its installation and in-service operations, and comparing with alternative riser designs.

This report summarizes the results of this study and is organized as follows:

- Description of the CVAR system including its key features, development scenarios using CVAR, and alternative solutions available for its components (Section 2);
- Basis of Design used in sizing, analysis, and design of CVAR for two cases selected (Section 3);
- Conceptual sizing and design of CVAR for two cases selected (Section 4);
- Conceptual analysis of Tubing CVAR case including strength, fatigue, Vortex Induced Vibration (VIV), and riser interference analysis (Section 5);
- CVAR system design review and categorization, MMS requirements for riser systems, and failure modes identification (Section 6);
- Risk assessment of CVAR using Failure Modes, Effects, and Criticality Analysis (FMECA) for the installation stage and in-service operations stage including production and well operations (Section 7);
- Comparison of the alternative DVA riser designs with the CVAR design, and assessment of risks associated with Top Tensioned Riser (TTR) tensioners (Section 8);
- Summary and conclusions of this study (Section 9); and
- References used in the study (Section 10).

2 CVAR System Description

2.1 General

The differences among the Compliant Vertical Access Riser (CVAR) concept and the conventional risers used for Direct Vertical Access (DVA) of wells are presented. The variations in riser system configurations, concepts, and behaviors are discussed. Two field development scenarios with the CVAR are identified for this study, with associated casing alternatives. The key components (structural, ancillary) required in a CVAR are identified and briefly discussed.

The CVAR design configuration presented is based on the work undertaken by Granherne and KBR (Kellog Brown & Root) during recent years through studies and development under the KBR Technology Programs that have shown its technical feasibility [Mungall et al, 2004; Bhat et al, 2006]. These studies have shown a significant value from use of CVAR design with semi-submersible Floating Production Unit (FPU) in 5,000 ft to 10,000 ft in the GOM and other regions, thus providing an alternative FPU solution for field development plans requiring a dry tree production and DVA of wells.

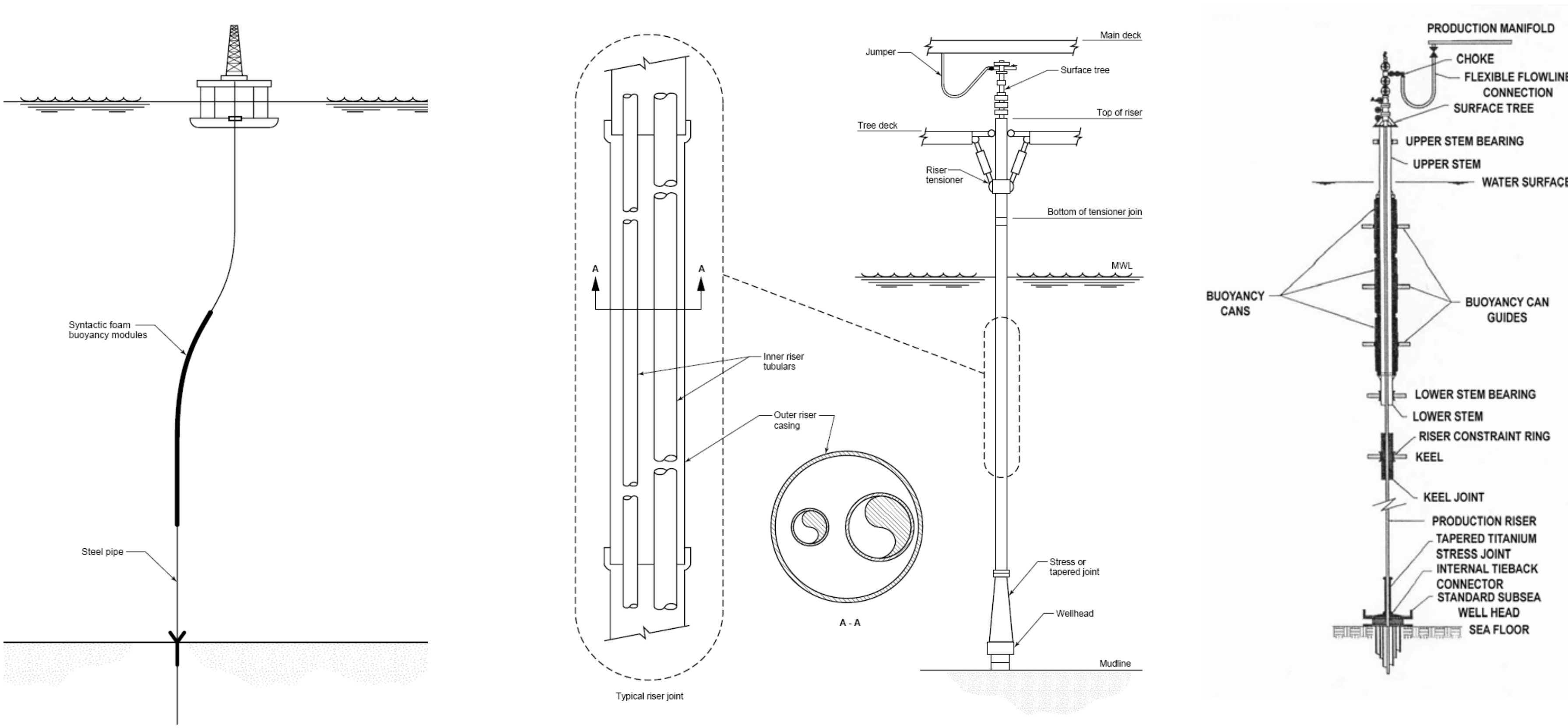
CVAR information was also provided to the DeepStar for their state-of-the-art review of ultra deepwater production technologies [Bell et al, 2005]. US Patents have been received on the recent development of CVAR solution by Granherne and KBR [US Patent, 2003 & 2009]. Previous evaluations of CVAR design were undertaken through an industry JIP that evaluated its use from a tanker based FPSO [Brinkmann et al, 2002; Ishida et al, 2001; Okamoto et al, 2002]. Analysis and large scale tests of CVAR concept were also undertaken in 800 ft water depth in a lake in the Highly Compliant Rigid (HCR) riser JIP to improve and verify the riser analysis methods [Grant et al, 1999 & 2000].

2.2 Features of the CVAR Concept

The CVAR concept illustrated in Figure 2-1(a), presents a new alternative production riser solution with DVA to wells from the deck of a FPU in deepwater and ultra-deepwater oil and gas fields. The key components of the CVAR concept are as follows:

- Direct connection of riser with the FPU hull by a flex joint or a stress joint;
- Steel riser pipe – tubing and casings;
- Insulation and corrosion protection coating over the riser pipe;
- Heavy weight coating over part length of the riser pipe;
- Buoyancy modules attached over part length of the riser pipe;
- Tapered Stress Joint (TSJ) at bottom of the riser; and
- Connection at the subsea wellhead offset from the platform.

The conventional top tensioned riser (TTR) designs for dry tree production and for DVA of wells are also shown in Figure 2-1. These designs have been used so far with Tension Leg Platform (TLP), SPAR, and Deep Draft Caisson Vessel (DDCV) hull designs operating in the Gulf of Mexico (GOM) and other regions. The top tension in these vertical risers is obtained generally in two ways, by use of tensioners or air cans (or buoyancy cans), as shown in Figures 2-1(b) and 2-1(c) respectively. In more recent designs of the SPAR concept, tensioners have been used in place of large diameter air cans.



a) Compliant Vertical Access Riser (CVAR) (Source: API RP 2RD, 2006)

b) TTR with Tensioners (Source: API RP 2RD, 2006)

c) TTR with Air Cans

Figure 2-1 Direct Vertical Access and Dry Tree Riser Design Alternatives

The key differentiating features of the CVAR design from two alternative TTR designs are presented below:

Direct Vertical Access (DVA):

The CVAR is directly connected at its top end to the FPU hull, and it does not require riser top tensioning system and production jumpers, which are used in TTR designs. The estimates of riser top tension and riser stroke increase significantly in case of FPUs in ultra-deepwater and for fields with high pressure high temperature (HPHT) production. Thus the CVAR design, without a need for top tensioners or large diameter air cans, brings potential for significant benefits in the development GOM fields in ultra-deepwater.

The elimination of the riser top tensioning system however leads to direct transfer of loads and motions from the CVAR to the floating hull, which has similarities to the connection used in case of the Steel Catenary Riser (SCR) design for tieback of subsea wells. The direct connection of the CVAR requires change in the design of riser from a conventional vertical riser (as for a TTR where tensioner system accommodated relative motions of riser and hull) to a compliant shaped riser as discussed further.

Compliant Riser:

The compliancy requirement, to enable direct connection of the CVAR to the platform hull or deck, is achieved by providing an excess length of pipe to give it the shape shown in Figure 2-1(a), and the fitting of buoyancy modules (syntactic foam) to ensure that the effective tension in the lower slick pipe section always remains sufficiently high to ensure avoidance of excessive bending stress at the riser base. Riser over-length is defined as the length of pipe over and above the straight line distance between the riser hang-off location and the subsea wellhead connection point at seabed. Over-length fraction is defined as the ratio of the over-length to the straight line distance between the hang-off position and the subsea connection point. The riser over-length fraction defines the degree of compliance in the CVAR system. A larger over-length fraction tends to make it easier to keep the extreme stresses within limits, for higher motion FPUs. Over-length fraction varies with FPU offsets, and often the "FAR" position of the FPU is the critical one for extreme response since the over-length fraction is the lowest for this position.

Sufficient compliance must exist in the CVAR system in order to satisfy the extreme response criteria when the FPU offsets to the NEAR and FAR positions. Increased compliance, however, must be balanced by the need to limit the potential for riser-to-riser contact.

Well Offset:

The compliant shape of the CVAR system permits the wellheads to be offset a considerable distance from the FPU – to a distance approaching one half of the water depth. Therefore, the proposed system enables DVA to wells located at relatively large offsets, as indicated in Figure 2-2. For comparison, a conventional dry tree platform system (with vertical TTRs) is shown on the left side of Figure 2-2. The proposed system has the potential to reduce the drilling and completion, and well intervention costs.

The recent Perdido Truss SPAR in 7,817 ft water depth is the first TTR with DVA for drilling and completion, where a single riser with DVA capability is used to access 22 subsea trees, and uses a surface Blow Out Preventor (BOP) for drilling, completion, and side-tracking operations.

Platform Type:

So far, dry tree production has been carried out from TLP and SPAR hull designs. Whereas, semi-submersible and FPSO hull shaped platforms, with lower hull costs, have been used to date as wet tree solutions with the tie-back of subsea wells using SCRs or riser towers. Due to the compliant shape of the CVAR design, dry tree operations could also be undertaken from semi-submersible and FPSO, and CVAR is connected directly to the platform hull/deck as done for a SCR design.

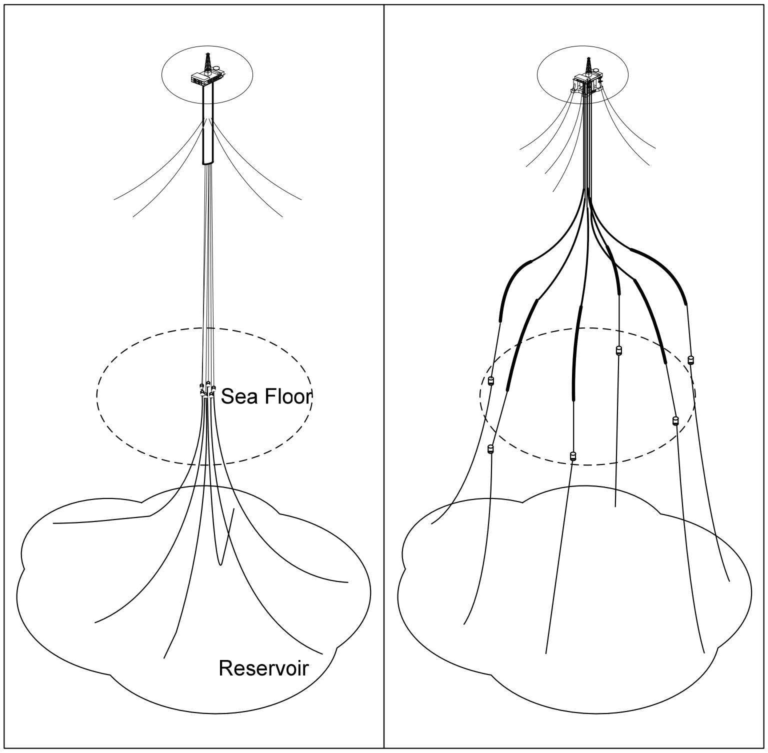


Figure 2-2 Vertical Access to Wells at Large Offsets

2.3 Field Development Scenarios

2.3.1 General

This riser solution provides varying levels of benefits to different FPU hull designs. For example, in case of a semi-submersible hull unit, with its advantages of lower cost hull and greater mobility, use of CVAR design in deepwater and ultra-deepwater applications would enable dry tree production and some well operations from the platform deck.

The objectives of CVAR system design are to design a riser system that will:

- Enable DVA to the wellbore for well intervention through the production riser, from the host facility;
- Maintain riser curvatures within acceptable limits to permit passage of downhole tools;
- Eliminate the requirement for a riser tensioning system;
- Eliminate the requirement for flexible jumpers to the production manifold;
- Reduces payload requirements; and
- Reduces riser response sensitivity to the motion characteristics of the FPU.

Thus, CVAR configurations for the following two field development scenarios are considered here:

- A marginal field development in ultra-deepwater in 8,000 ft water depth; and
- A medium sized field requiring dry trees in 10,000 ft water depth.

2.3.2 Marginal Field Development in Ultra-deepwater

A small field in ultra-deepwater with a FPU based development is considered in this study. The reservoir is assumed to have a high shut-in pressure initially, but low Gas-to-Oil Ratio (GOR) of the produced fluid is expected to result in severe declines in pressure as the field is produced, in which case electric submersible pumps (ESPs) could be used to improve the recovery. The following basis has been assumed for the sizing and analysis of the Case-1 CVAR:

- A GOM field in 8,000 ft water depth;
- Shut in pressure at the mudline of 12 ksi initially;
- Low GOR of 290;
- API 32, Bubble Point 1,100 psi; and
- Total depth of well 25,000 to 29,000 ft.

For 12 ksi shut-in pressure, CVARs may require High Strength Steel (HSS) up to Q-125. Since the field is small, a semisubmersible hull is considered to be appropriate, with no drilling rig as the drilling & completion of wells are to be undertaken from a MODU. The production CVAR is configured with a Tubing riser design, which reduces the riser payload on the FPU.

The installation of CVAR could be carried out in various ways. An approach is presented in detail in Section 7.2. Depending on location and connection of CVAR with FPU, its transfer from an installation vessel to the FPU would be undertaken.

The size of the Tubing CVAR assumed here is a 7.625" OD (nominal). The Tubing CVAR will require insulation for flow assurance purposes (primarily to provide sufficient "no-touch" time during unplanned shut-downs). Assumed insulation thickness in this case is 1.5".

Workover risers of this pipe size are in use in the deepwater GOM. Also, this size of pipe is likely to be adequate for the passage of relatively high powered Coiled Tubing Deployed ESP (CTDESP), which could be required to improve recovery. Thus, this concept of a low cost semi-submersible FPU, a Tubing CVAR, and ESPs to improve recovery may be cost-effective in development of marginal fields in deepwater.

2.3.3 Medium Sized Field Development in Ultra-deepwater

For comparison with an existing riser design alternative, a medium sized field in 10,000 ft water depth was chosen. The following basis has been assumed for the sizing and analysis of the Case-2 CVAR:

- A GOM field in 10,000 ft water depth;
- Shut in pressure of about 14 ksi at mudline;
- GOR of 1,000;
- API 30, maximum temperature 275 ^{O}F; and
- Total depth of well 25,000 ft.

A medium sized semi-submersible (or semi) hull is considered appropriate for this case. The production/workover semi-submersible is assumed to be equipped with a workover/completion rig. Dual casing CVAR design is considered for this case. The dual casing CVAR can be installed from the production/workover semi-submersible rig, with assistance from a work vessel and ROV for the horizontal positioning of the bottom end of CVAR to make the first connection with the subsea wellheads.

2.4 Production Riser Casing Alternatives

Alternative designs for production riser casing are evaluated to estimate variations in CVAR configurations with riser casing, and to identify associated issues. The following types of the alternative riser casing designs are identified:

- Tubing only with separate umbilical, and mudline tree package;
- Single casing; and
- Dual casing.

Typical schematic cross sections of the three alternatives, including umbilicals, are shown in Figure 2-3. In the case of a tubing riser, a tubing hanger at the mudline along with appropriate flow closure devices (mudline valves) and a second set of tubing hanger and flow-closure devices at the surface tree are required. Further discussions on these items are given in Sections 2.5 and 2.6.

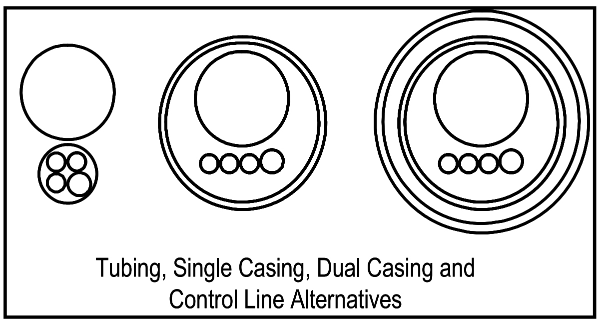


Figure 2-3 Production Riser Casing Alternatives

The production risers in worldwide operations from the dry tree platforms are in both designs: single or dual casing. In both of these designs, the tubing hanger is at the surface (platform) and a surface BOP is used for well workover. No application of the tubing riser for production has yet been done. In a single casing riser design, there is one pressure containing casing outside of the production tubing. A dual casing riser design has two such casings, with the inner casing designed for the shut-in pressure of the well. The outer casing of a dual casing production riser serves the following functions:

- Outer casing acts a structural barrier;
- Outer casing provides protection for the inner casing from damage and corrosion;
- The outer casing, inner casing and surface BOP are used for initial installation of the completion system and for any subsequent major workover operations that require that the completion string be retrieved; and
- In the event that the inner production casing or tubing leaks, the outer casing and kill weight fluid provide a secondary back-up for well control.

Tubing riser or a "one-pipe" riser is a third type of dry (or split) tree vertical access production riser, which would be applicable in certain situations. Industry studies have indicated that the tubing riser is likely to be a valuable alternative design in ultra-deepwater applications. It was evaluated in detail in the concept development and evaluation phases of the Magnolia TLP project in GOM, but it was not used [Gu et al, 2003]. This riser design alternative minimizes the riser payload or top tension that needs to be supported by the FPU, the tensioners or the air-cans.

The basic designs identified above for these alternative risers could also be varied for a specific application. For example, a single casing production riser can be designed with an "insert", which is an inner casing inserted prior to major workover. Another possible variation is the provision of a mudline tree in a single casing riser, similar to that presented for a tubing riser. Such variations have been studied in the past and implemented in projects. Such design variations of single casing riser system are not considered in this study.

The single and dual casing alternatives are functionally similar. Typically, production operations and all types of workover operations (including pulling the tubing and re-completion work) are carried out through the single casing and dual casing risers. Tubing riser is also feasible to provide most of these functions, including production operations and minor workover, wireline and coiled tubing operations. In case of the Tubing riser design alternative, a major workover involving pulling of the downhole tubing and re-completion would require the use of a separate workover or drilling riser.

Based on the above considerations, since the intended application of the CVAR system is ultra-deepwater, the following two cases are undertaken in this study:

- Case-1: Tubing CVAR design; and
- Case-2 - Dual Casing CVAR design.

2.5 CVAR Components

2.5.1 General

The CVAR design comprises of a selected production riser casing per Section 2.4, fitted with mechanical connections at ends, and several ancillary components on riser sections over its length to obtain the desired configuration and performance. The illustrations and brief discussion of these components or fittings are presented. Additional description and discussion of various components is given in Sections 6 and 7.

Conceptually CVAR configuration comprises of 3 regions: upper (top), transition (buoyancy), and lower (upright) as shown in Figure 2-4 (and also in Figure 2-1). The production riser casing design alternative selected per Section 2.4 defines the riser sections with threaded riser, which are coated with corrosion and insulation coatings throughout its length.

The upper region riser length is fitted with strakes or fairings to suppress riser Vortex Induced Vibration (VIV) and with heavy weight coating (or alternative clump weight) on part of the length. In the transition region, the buoyancy modules are fitted. The riser sections in the lower region are also fitted with large diameter buoyancy modules near its top.

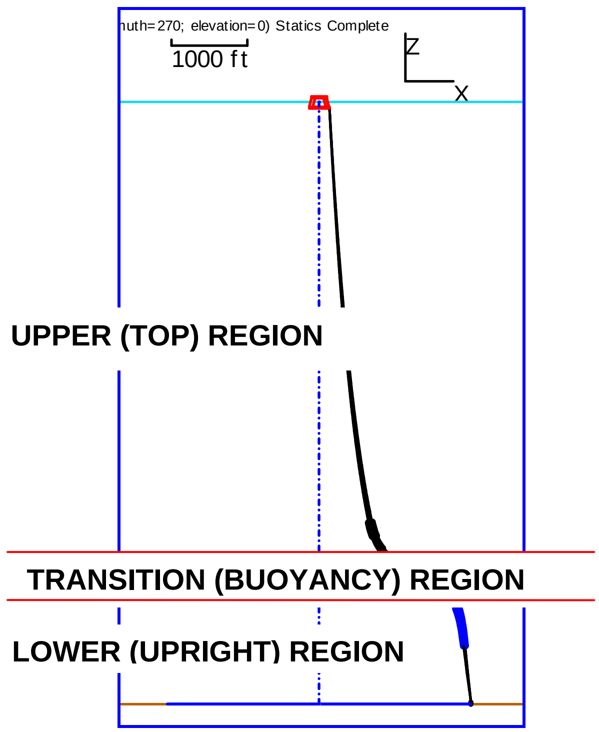


Figure 2-4 Generic CVAR Configuration

2.5.2 Riser Sections

The steel riser sections with threaded ends for connections are available in various steel grades. In TTRs various designs of threaded connections have been used: threaded & coupled (T&C); weld-on threaded connections; and integral threaded connections. Alternatively, flanged connections with bolts have also been used. The T&C connectors are used in low to moderate fatigue applications, and thick weld on threaded forging used in high fatigue applications. The use of thick weld-on forging (with threaded end) is used in steel grades up to 80 ksi and the weld with riser section is done at an onshore plant.

In one case, integral threaded connection with PIN and BOX ends (no onshore weld, no coupling) was used, and it is under qualification testing for HSS grades 110 ksi and 125 ksi. This design is developed for use in more demanding situations, and one such application evaluated in a JIP is its use as a fatigue design solution at SCR touch down zone (TDZ) subjected to high fatigue loading [Aggarwal et al, 2007].

In case of CVAR design, estimates have shown that HSS grade riser sections are required, thus the connections will be T&C or an integral threaded connection. There are several manufacturers who can supply the riser sections with T&C connectors. New designs of T&C connectors in HSS grades are also being qualified and have been used in a few TTRs installed in the GOM. [Sches et al, 2008]

In Figure 2-5 a design of T&C connection is shown.

Figure 2-5 Threaded & Coupled Connection
(Source: Vallourec & Mannesmann)

2.5.3 Flexible Joint

The flexible joint design has been used in direct connection of a SCR with FPU hull to obtain decoupling of motions of SCR and FPU to reduce high rotations in a riser. Figure 2-6 presents a design of FlexJoint® from Oil States Industries, which has been used in SCRs. Newer designs of FlexJoint and for HPHT applications are also available [Hogan et al, 2005].

The flexible joint shown sits within a purpose built receptacle designed for hang-off angle and azimuth departure angle orientation requirements. During the transportation and installation stages additional protection of a FlexJoint® from damage can be obtained by use of shrouds.

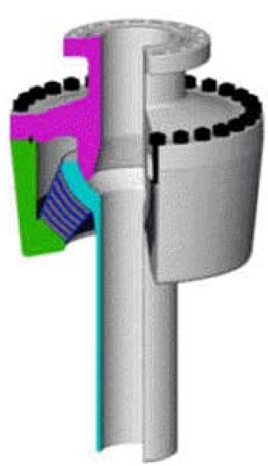
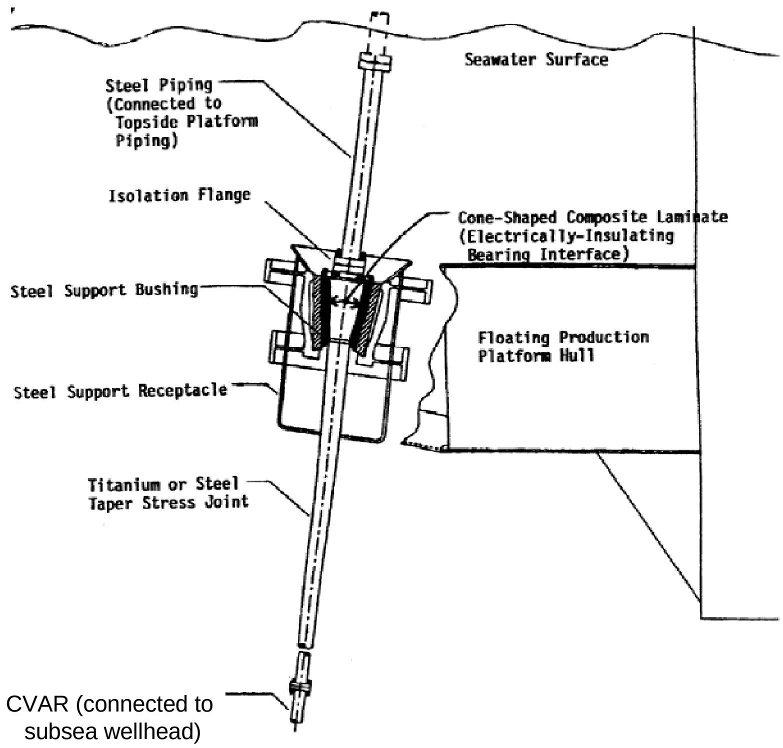


Figure 2-6 Flex Joint
(Source: Oil States Industries)

2.5.4 Titanium Stress Joint

An alternative to FlexJoint for direct connection of riser and hull is to use a Tapered Stress Joint (TSJ), which is rigidly connected and is designed to resist significant bending moment and axial loads. This is opposite of the basis for flexible joint design and the weight of steel TSJ is significant. Thus at the riser to FPU connection, light-weight TSJ in titanium design have been used for SCRs [Schutz, 2001; Baxter et al, 2007]. These stress joints have a flange connection with the steel riser sections, and special design measures are adopted for safety against effects of titanium and steel connection. A design for electric isolation of platform hull and CVAR section from titanium stress joint is shown in Figure 2-7(a) and of the compact flange (light-weight) design [Vector International AS, 2003] is shown in Figure 2-7(b). These are qualified components and have been used in a large number of deepwater floating platforms.



a) Electric Isolation System – FPU Hull and CVAR at Hangoff (Source: Schutz, 2001)

b) Compact Flange Connection (Source – Vector International AS, Drammen, Norway)

Figure 2-7 Titanium Stress Joint

2.5.5 Insulation and FBE Coating

Figure 2-8 shows the design of a 5-layer insulation coating for risers and pipelines. The first 3 layers of this coating (epoxy layer; polypropylene adhesive layer; and solid PP layer) provide the corrosion protection coating function. Then multiple layers of thin syntactic polypropylene are applied by a special mechanism to obtain desired bonding between layers and required insulation coating is obtained. Then the outer layer of solid polypropylene (PP) is applied for protection against damage or dropped objects. [SocoRIL, 2004].

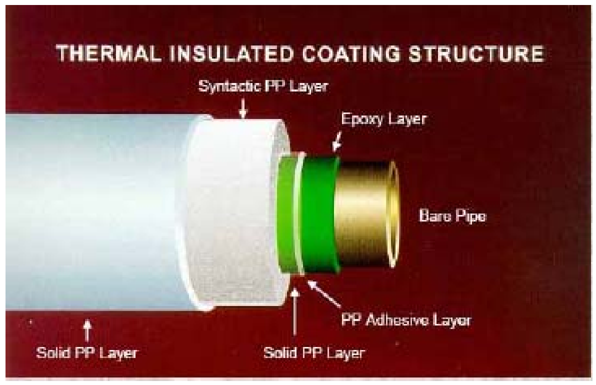


Figure 2-8 Insulation Coating Design
(Source: SocoRIL, Argentina)

2.5.6 Weight Coating

The Vikoweight rubber coating developed by Trelleborg Viking AS, Norway, considered in this study is available with a density of 3 T/m^3 [Trelleborg Engineered Systems, 2004]. The design of this coating consists of the following 3 parts as shown in Figure 2-9:

- Inner layer – to ensure bonding and corrosion protection of riser section;
- Middle layer – to provide the heavy weight coating; and
- Outer layer – to provide protection against wear and tear.

The inner and outer layers are of soft rubber with good flexibility and the middle layer is hard rubber for low thermal conductivity.

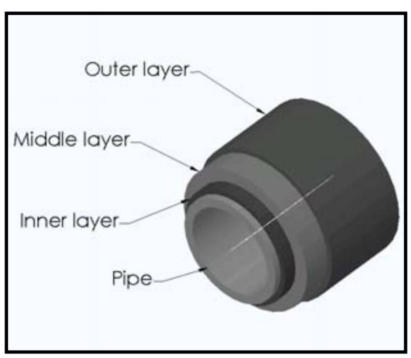


Figure 2-9 Weight Coating Design
(Source: Trelleborg Viking AS, Norway)

The performance of a coating in general varies with the water depth and the fluid temperature. The inner layer bonding is designed up to 140°C temperature and the middle layer up to 70°C. The manufacturing process and qualification testing have been undertaken by Trelleborg under DEMO 2000 program [Trelleborg Engineered Systems, 2004], and tests showed good results.

2.5.7 Buoyancy System

The CVAR design requires large diameter buoyancy modules fitted to the transition region and the lower region of the riser length. Thus use of discrete buoyancy modules design as shown in Figure 2-10 is considered. This design of buoyancy system constitutes of 4 key components: Buoyancy modules; Clamps; Thrust collars; and Straps. The buoyancy modules are fitted as follows to the Tubing CVAR with insulation coating (1.5" thick) or Dual Casing CVARs with no insulation coating:

- A clamp is fitted between the riser insulation and the buoyancy modules – individual clamps are required for each module. The clamp is tensioned by straps;
- Buoyancy modules in a set of half shells that fit over the clamp. The buoyancy modules are available in 2 halves of desired diameter and variable length (about 42" for the case shown) with Glass Reinforced Epoxy (GRE) skin shell, and filled with epoxy syntactic. Gap is kept between the ID of the buoyancy module and the OD of the insulated riser pipe on which clamps are fitted;
- Circumferential straps and bolts to secure the two halves of buoyancy modules, which are tightened by 3 straps tensioned; and
- Thrust collars are welded to the riser pipe at ends to eliminate longitudinal movement of modules.

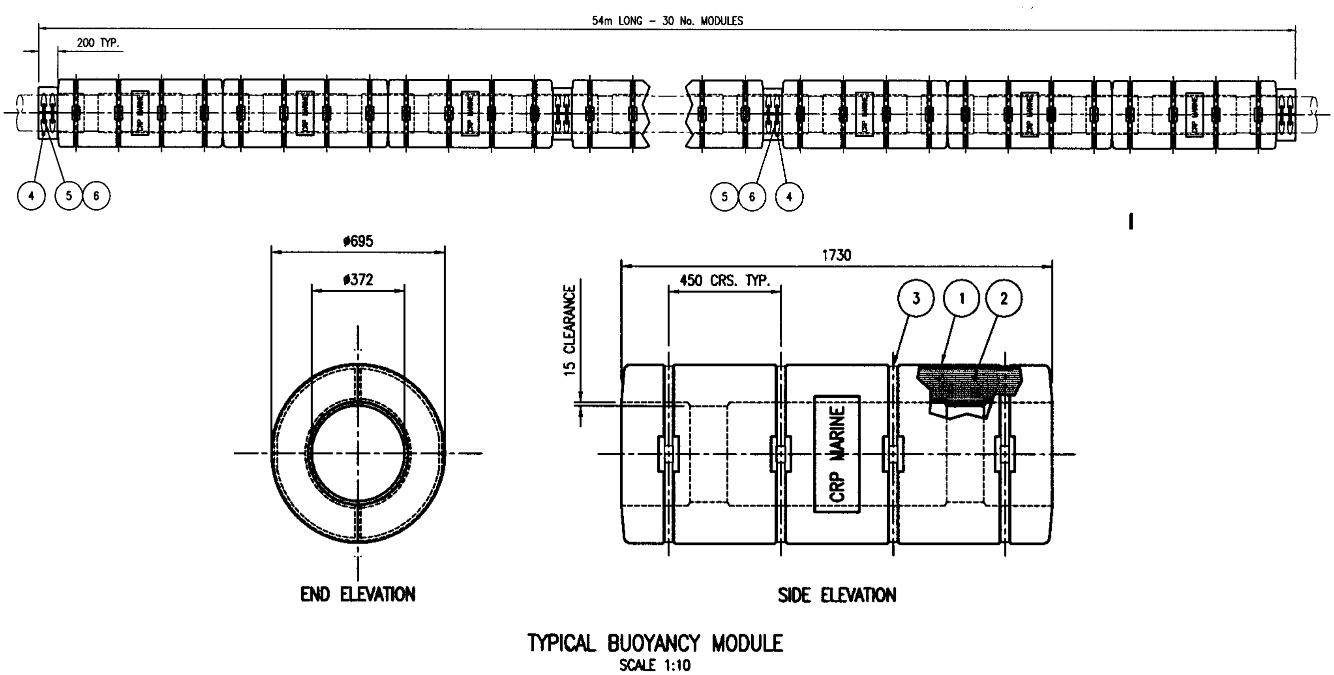


Figure 2-10 Buoyancy Module
(Source: CRP, unit of Trelleborg Viking AS, Norway)

The clamps are designed for the differential variations at the ends of riser section and the buoyancy modules.

The buoyancy modules of the type considered for the CVAR were used in SCRs connected to the Alleghany TLP for the tieback of wells from the King Kong/Yosemite field. The function of the buoyancy modules was to reduce the payload on the existing TLP. A total of 271 buoyancy modules (each 35.7" long, 26.7" OD) were fitted over a continuous length of 800 ft to provide a net buoyancy of 50 kips. [Korth et al, 2002]

Typical dimensions for a design supplied by CRP Marine for a buoyed SCR design [Korth et al, 2002] with conventional welded riser sections for a GOM installation are shown in Figure 2-10. The actual dimensions for the JIP case would vary. However, the overall design considerations will be similar.

2.5.8 VIV Suppression Devices

Two alternative designs shown in Figures 2-11 and 2-12 are available for suppression of VIV in the upper region of CVAR. The molded strakes have been mostly used so far for suppression of VIV in majority of TTR and SCR applications. A design of strakes from the Advanced Industrial & Marine Services, Inc. (AIMS) is shown in Figure 2-12.

In some cases, use of both strakes and fairings has been reported, such as in recent Independence Hub SCRs [Mekha, 2007]. Recent publications indicate that much more research is needed to quantify the effects of surface roughness and interference [Allen and Henning, 2008].

Strakes have been assumed in this study.

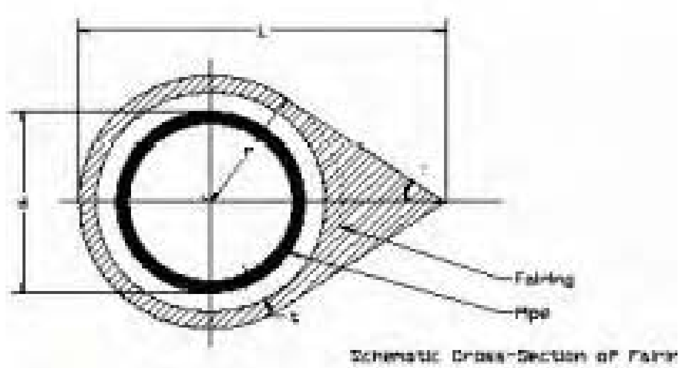


Figure 2-11 Short Fairings
(Source: Shell Global Solutions)

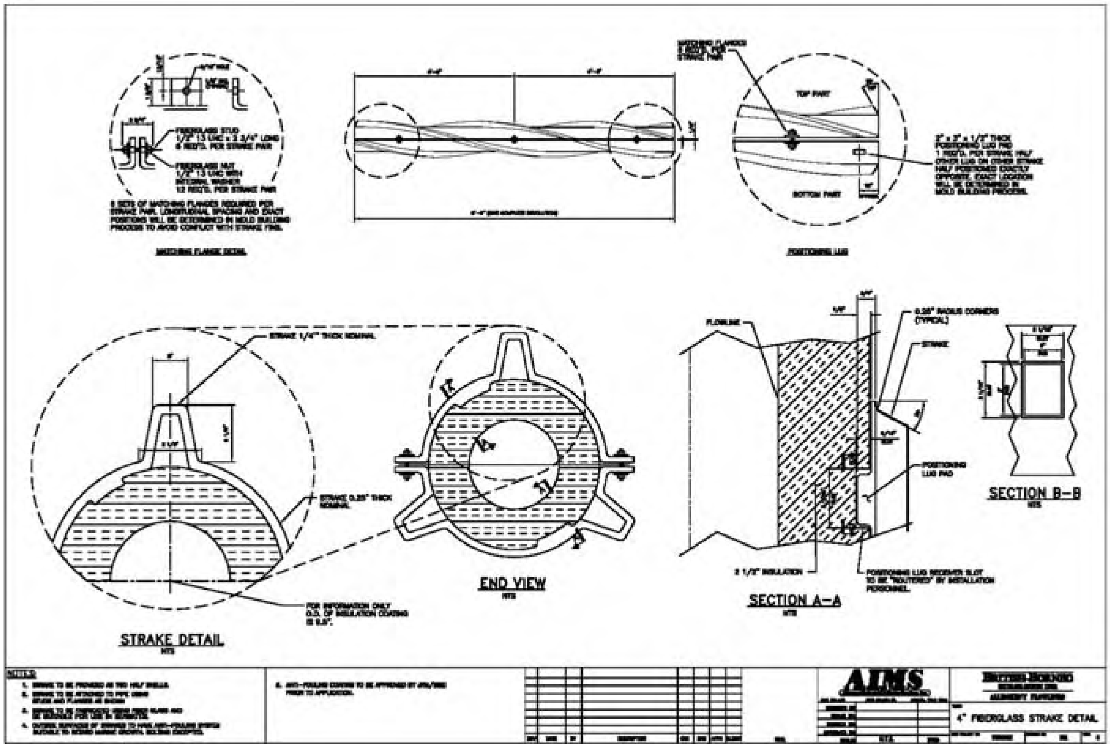


Figure 2-12 Strakes
(Source: AIMS)

2.5.9 Mudline Tree Package

In the Tubing CVAR case with a single pipe, it performs dual functions as a production riser and as a casing. Thus the safety level for this design would be reduced in comparison with a Dual Casing CVAR design. To compensate for this, additional safety for Tubing CVAR is obtained by provision of a "Mudline Tree Package (MTP)" as shown in Figure 2-13, which is positioned between the TSJ at the bottom of the CVAR and the Tubing Head Spool (THS). Detailed guidelines are given in API RP 17G for completion/workover risers [API, 2006]. The functional requirements for MTP and Shear Seal Disconnect are given below.

<u>Mudline Tree Package - Functional Requirements</u>

- Interface with conventional 18.75" wellheads;
- Hang production tubing off at mud-line;
- Allow drilling and completion with conventional rigs, completion and installation / workover systems;
- Provide redundant production bore isolation at the mudline to provide CVAR with a second barrier;
- Monitor and bleed of well annulus per 30 CFR 250;
- Provide for downhole penetrations for SCSSV and downhole hydraulic and electrical requirements per completion design; and
- Accommodate loads encountered from drilling BOP and CVAR.

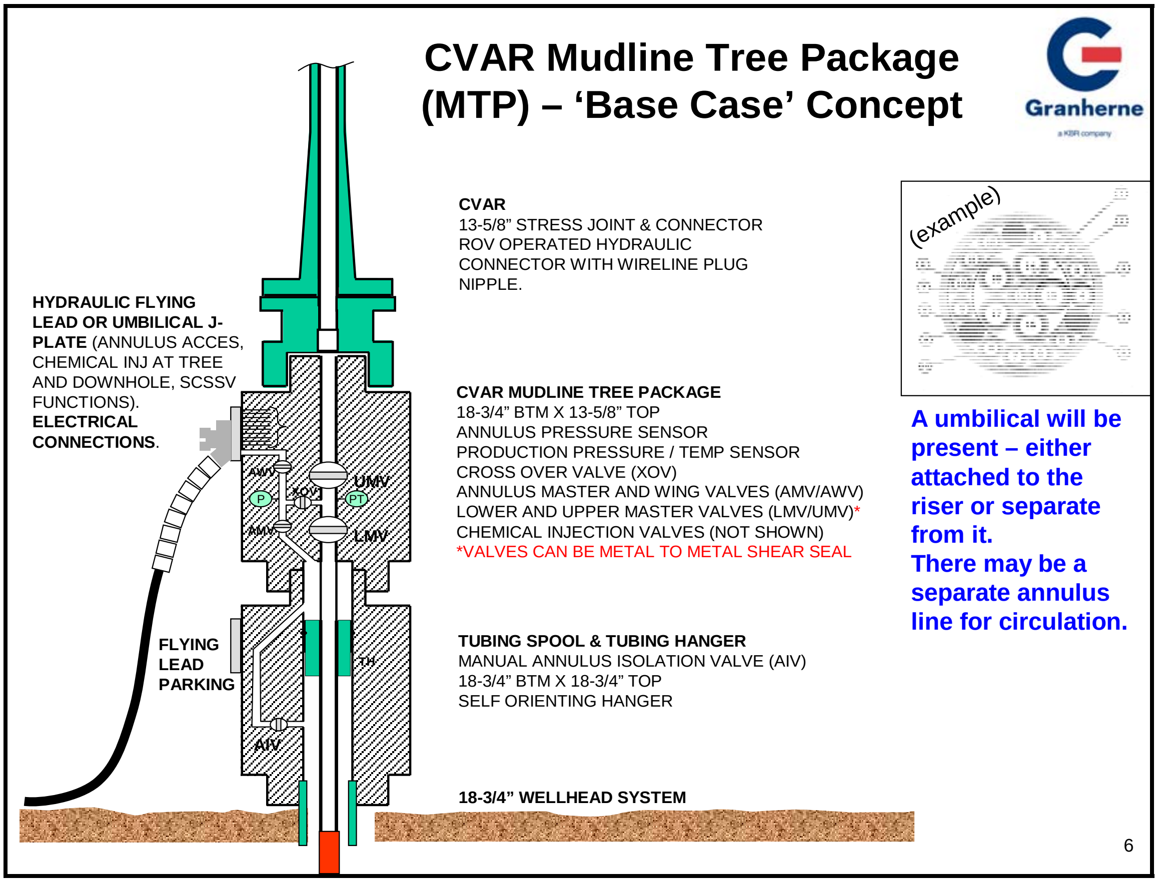


Figure 2-13 Mudline Tree Package “Base Case” Concept

The CVAR production flow path itself is vertical and for well operations, a vertical tree is preferred.

An additional function of MTP is to have facilities/tools to ensure a disconnect capability, especially when there is a tubing inside the riser. In some case, two shear RAMs are required and located at two different elevations.

Shear Seal Disconnect - Functional Requirements

- Automatic emergency disconnect of the CVAR is not required since the riser is permanently installed;
- The requirements for shearing and subsequent sealing off well at the mudline will be driven by operational likelihood and risk assessment, specifically if a coil tubing is in the hole and the CVAR starts to leak and the coil tubing cannot be recovered above the mudline then a shear seal device may benefit; and
- The MMS may dictate the requirement for shear valves. In that event operators will need to perform a detailed risk assessment.

The proposed base case design for CVAR MTP to accommodate shear valves, if they are required.

2.6 Umbilical

The control umbilical for the CVAR is shown in Figure 2-14. The figure shows the control lines required in the umbilical to operate the valves. The annulus line in the umbilical may limit its functionality to annulus bleeds only. The annulus could be run with larger tubes or in its own separate external umbilical, in which case the circulation capacity would be greatly speeded up. However, the need for large capacity annulus circulation requires further evaluation and is not likely to be necessary.

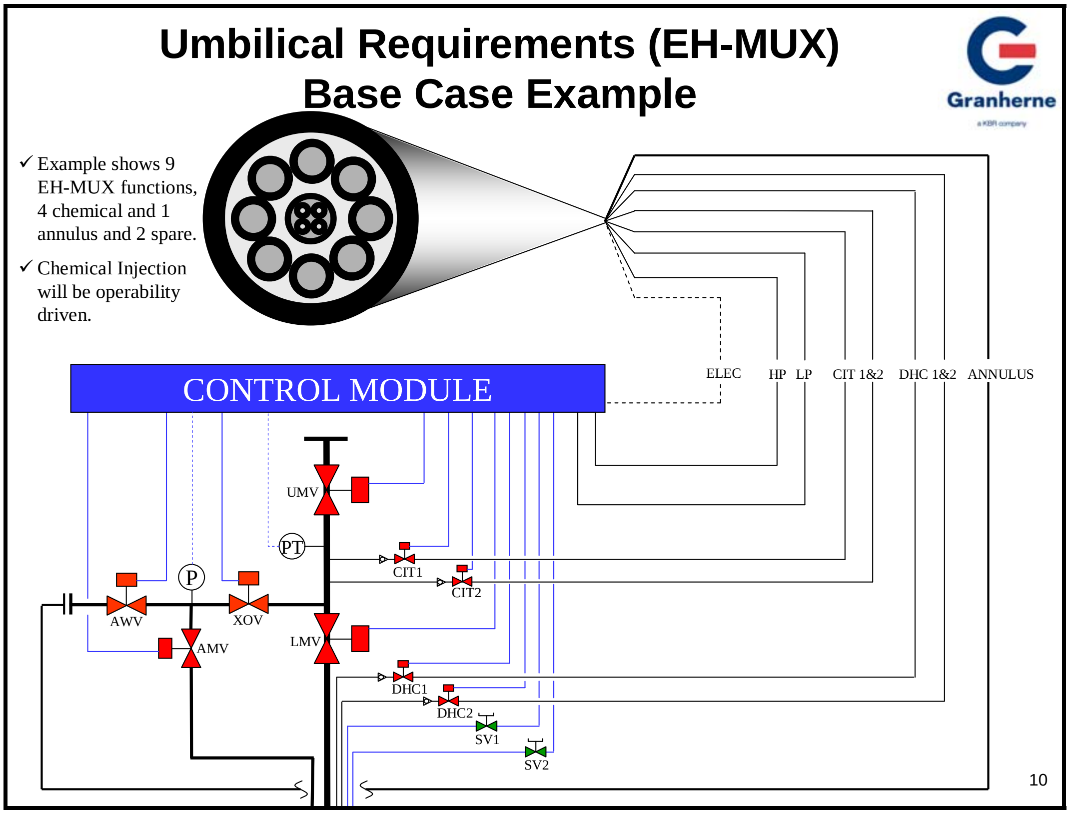


Figure 2-14 Umbilical Requirements "Base Case" Example

2.7 Summary

All components in a CVAR design have been used previously by the oil & gas industry in alternative designs of riser systems for production from the deepwater and ultra-deepwater wells in the GOM. The key components presented in this section utilize qualified and proven-in-service products. Thus, in general no new development of a key component is required for implementation of CVAR riser system solution in deepwater and ultra-deepwater fields. However, for some specific components development of qualification data from available industry experience and specific additional tests may be considered by an operating company to meet their own requirements or for regulatory submittals.

In Sections 6, 7, 8 additional aspects of the CVAR system and its components are presented, and risk associated issues are discussed.

3 Study Basis

3.1 General

This section summarizes the basis of design for CVAR sizing, analysis, and design for two case studies undertaken in this study.

3.2 Design Service Life

The design service life of 20 years has been considered for this study.

3.3 Field Data

Water Depth: The water depth assumed for the Case-1 is 8,000 ft (2,438.4 m) and for the Case-2 is 10,000 ft (3,048 m) in the Gulf of Mexico (GOM).

Seawater Density: It is assumed to be 1,025 kg/m^3 (64 pcf) and seawater kinematic viscosity is assumed to be 1.188x10^{-6} m^2/sec.

Marine Growth: It is neglected in the analysis done in this study.

Seafloor Soil Data:

The following soil design properties are assumed:

- Undrained shear strength (S_u) of 30 psf (1.4 kPa) at the seafloor and increasing linearly at 6 psf/ft (0.94 kPa/m) to 210 psf (10 kPa) at 30 ft (9 m) below the seafloor. S_u = 60 psf (2.9 kPa) has been assumed for this study.
- Submerged unit weight (γ_{sub}) of 20 pcf (3.1 kN/m^3) at the seafloor and varying linearly to 30 pcf (4.7 kN/m^3) at 20 ft (6 m) penetration below the seafloor.

3.4 Metocean Criteria

3.4.1 General

The metocean data for extreme response and fatigue analyses are based on recent industry studies undertaken for ultra-deepwater GOM. A severe metocean design basis is chosen in this study to demonstrate the concept feasibility.

3.4.2 Design Metocean Data

The design metocean criteria used is given in Table 3-1. The 100 year loop current is 8.8 ft/sec at the surface, which is higher than that used in most projects.

For the submerged current profile, depth variability is defined and the mid-point of the profile can be located at any depth between 150 to 350 m (approx. 500 ft to 1,150 ft) from the surface.

Regular wave analysis with variation of period over a certain range is used for the extreme response studies. Maximum wave height and associated maximum wave period are used for different load cases, and the wave period is varied by +/- 1.5 seconds on either side of T_{Hmax} to estimate variations in load.

The specific metocean load cases used in the conceptual sizing task are identified in Section 3.6.

Table 3-1 Metocean and Vessel Offset Data

Item		100-yr Loop Current	100-yr Hurricane	1,000-yr Hurricane
Vessel Offset		400 ft	400 ft	500 ft
Regular Wave Analysis	H_{max}	8.8 ft	77.4 ft	82.6 ft
	T_{Hmax}	5.2 sec	13.4 sec	14.3 sec
Irregular Wave Analysis	H_s	4.9 ft	44.0 ft	
	T_p	6.0 sec	14.9 sec	
	γ	1.0	2.6	
Surface Current Velocity		8.86 ft/sec	5.77 ft/sec	6.42 ft/sec

NOTES:
1. Full current profiles (through the entire water column) are considered in analysis.
2. Current and wave directions are assumed to be collinear for the vessel offset cases, NEAR, FAR.

3.4.3 Fatigue Metocean Data

The fatigue data for the first order response to wind, wave and current loadings, and associated directional probabilities (wave scatter data) available for GOM is used in the analysis.

The fatigue wave data considered in this analysis included data for 33 bins and 8 directions. Fatigue data was combined into a single set of 33 fatigue bins. This data was extracted from several occurrence tables (scatter diagrams), including H_s vs. T_p, H_s vs. direction, wind speed vs. direction, wind speed vs. wave height, loop current profiles, and background current profiles.

3.4.4 Current Profiles for VIV Analysis

Strong currents in the GOM area are considered to be caused by loop current and its eddies, and hurricane induced currents. The hurricane induced current occurs less than 1 day per year in the area based on hurricane hindcast model output, and the hurricane current profiles are not as severe as Eddy/Loop Current profiles. Therefore the hurricane current will be ignored in this analysis. The strong current events caused by Eddy/Loop Current happen only approximately once a year and lasts for up to several weeks. During the rest of the year, the current is generally weaker than the loop events.

Thus, for this study, the currents have been considered to have two regimes:

- Eddy/Loop Currents
- Background currents

Eddy/Loop Current Data:

A total of three (3) loop current eddy (LCE) profiles were used with the linear variation from the surface to 1,300 ft below reducing linearly to 12%, 22%, and 43% of the surface current. In two cases, the loop current at lower depths (below 1,300 ft) remaining same and in one case (case with 43% of surface current at 1,300 ft below the surface) reduding to 12% at 5,000 ft below the surface. The currents with speeds less than 20 cm/sec are not counted for the currents caused by the eddy/Loop Current.

Background Current Data:

For the background current, it is assumed that whenever the Loop Current or eddies are absent, the flows at the site are the background currents. A total of eight (8) background current profiles were used in the analysis. Their occurrence in days per year of background flows given the current speed and direction ranges associated with the eight types of profile (1 to 8) at the representative locations was used. The sum of the days of eddy currents and the background currents is 365.25 days.

3.5 Field Development Scenarios

3.5.1 Key Data for Cases

The two field development scenarios identified for this study were discussed in Section 2.3. The key data for two field development scenarios for the GOM (Case-1 and Case-2) for sizing, analysis, and design of CVAR is summarized in Table 3-2. The use of ESP is identified as an option to increase well productivity. However, in this study the effect of ESP operations on sizing of CVAR tubing has been included, but all of the risks associated with ESP operations are not addressed in Sections 6 and 7 as it in not in the scope of this study.

Table 3-2 Cases for Conceptual Sizing of CVAR

Item	Case-1	Case-2
Field Type	Marginal field	Medium size
Water Depth	8,000 ft	10,000 ft
Floating Production Unit (FPU) – Vessel type	Small sized semi-submersible	Medium sized semi-submersible – Production/ Workover semi-submersible
Vessel used for Drilling, completion, and workover	MODU (also useful for installation)	Workover/completion rig on platform
Shut-in Pressure	12 ksi at mudline	– 14 ksi at mudline – 10 ksi at surface – For KILL situation, match the pressure at the reservoir depth
Low GOR	290	1,000
Fluid Type	API 32 with Bubble Point 1,100 psi	API 30 with maximum temperature of 275 ^{o}F
Total depth of well	25,000 ft to 29,000 ft	25,000 ft
ESP requirements (optional)	600 to 1,000 HP as low as possible	NO
CVAR design type	Tubing only riser design	Dual casing riser design
CVAR riser size	7.625” nominal OD – Tubing only (higher diameter due to ESP passage)	– Production tubing: 5.5” OD – Inner casing: 10.75” OD – Outer casing: 14” OD
Insulation Thickness	1.5 inch thick	-

3.5.2 Fluid Properties

The estimate of kill fluid density for a well with total vertical depth (TVD) of 27,000 ft and shut in pressure at mudline of 12,000 psi is given in Table 3-3. The production tubing fluid contents and internal pressure at the platform for Case-1 (8,000 ft water depth) and Case-2 (10,000 ft water depth) are given in Table 3-4 and Table 3-5 respectively.

The kill fluid densities for startup and workover stages are different in Table 3-4 because the well is being killed from a MODU and not from the semi-submersible FPU. In Table 3-5 the kill fluid density values for workover and startup stages are same because a MODU is not present in either scenario.

Table 3-3 Kill Fluid Density Calculations

Given		
8,000	ft	Water depth
19,000	ft	well depth
27,000	ft	Total Vertical Depth of well
12,000	psi	Sut-in pressure at mud line
50	lb/ft^3	produced fluid density
Calculation		
0.347	psi/ft	equivalent pressure gradiant of produced fluids
18,597	psi	Formation pressure
0.689	psi/ft	Pressure gradient require to kill well from platform
99.2	lb/ft^3	Equivalent kill mud weight (to kill from platform)
13.3	lb/gal	Equivalent kill mud weight (to kill from platform)
0.446	psi/ft	Sea water gradient
3567	psi	Equivalent sea water pressure at sea floor
15031	psi	Differential required to kill well at sea floor
0.791	psi/ft	Pressure gradient require to kill well from sea floor
113.9	lb/ft^3	Equivalent kill mud weight (to kill from sea floor)
15.2	lb/gal	Equivalent kill mud weight (to kill from sea floor)
Constants		
144	in^2/ft^2	
7.481	gal/ft^3	
64.2	lb/ft^3	Seawater density

Table 3-4 Production Riser Fluid Contents: Case-1

Fluid Type	Weight in ppg	Internal Pressure at Platform (psi)
Sea water (Installation)	8.56	0
Sea water (Pressure test)	8.56	9,250
32 API Oil (Light)	5.0025	9,250
32 API Oil (Mean)	6.67	9,250
32 API Oil (Heavy)	8.3375	9,250
Kill fluid (Workover - well killed)	13.26	0
Kill fluid (Start up - well killed)	15.2	0

Table 3-5 Production Riser Fluid Contents: Case-2

Fluid Type	Weight in ppg	Internal Pressure at Platform (psi)
Sea water (Installation)	8.56	0
Sea water (Pressure test)	8.56	10,000
30 API Oil (Light)	5.325	10,000
30 API Oil (Mean)	7.1	10,000
30 API Oil (Heavy)	8.56	10,000
Kill fluid (Workover - well killed)	15.5	0
Kill fluid (Start up - well killed)	15.5	0

3.6 Design Load Cases

3.6.1 Design Case-1

The fluid densities for various design conditions (installation, pressure test, production, workover, and start up) for Case-1 (8,000 ft water depth) for Tubing CVAR are given in Table 3-4. In this case with a Tubing CVAR, a separate umbilical is considered (see Section 2.6.).

In general, API RP 2RD has been followed to define the requirements for different design load cases. A complete list of design load cases for a combination of design conditions (or operational modes), fluid parameters, and API load cases is given in Table 3-6. The design load cases for various riser conditions and associated metocean seastates are identified in Table 3-7, and the allowable stress factors and assumed mooring offsets (in %ge of water depth) are given for each design load case.

The damaged cases given in these tables for CVAR design are as follows, for which the allowable stress factors under extreme metocean loading are increased by 25% over those for operational loading case:

- Mooring line (one line) damaged during 100-yr hurricane and loop current seastates;
- Riser leakage during 100-yr hurricane and loop current seastates; and
- Well killed during 100-yr hurricane and loop current seastates.

Table 3-6 Design Conditions, Case-1

Design Case	Design Condition	Internal Pressure at Platform (psi)	Internal Contents		API 2RD Load Type
			Fluid Type	Weight in ppg	
1	Installation	0	Sea water	8.56	Installation
2	Internal pressure test	9,250	Sea water	8.56	Test
3	Operating, mean	9,250	32 API Oil	6.67	Operating
4	Operating, light	9,250	32 API Oil	5.00	Operating
5	Operating, heavy	9,250	32 API Oil	8.34	Operating
6	Shut-in, mean	9,250	32 API Oil	6.67	Opeating/Extreme
7	Shut-in, light	9,250	32 API Oil	5.00	Opeating/Extreme
8	Shut-in, heavy	9,250	32 API Oil	8.34	Opeating/Extreme
9	Shut-in, riser leak, mean	6,000	32 API Oil	6.67	Extreme
10	Shut-in, riser leak, light	6,000	32 API Oil	5.00	Extreme
11	Shut-in, riser leak, heavy	6,000	32 API Oil	8.34	Extreme
12	Workover, live wells	Same as 3, 4 and 5			Operating
13	Workover, well killed	0	Kill fluid	13.26	Extreme
14	Start-up after major workover	0	Kill fluid	15.2	Installation
15	Live well workover, riser leak	Same as 3, 4 and 5			Survival
16	Killed well workover, riser leak	0	Kill fluid	13.26	Survival
Notes					
1	Shut-in heavy case corresponds to oil+water in a well with some water production cold, and some weight tolerances.				
2	Shut-in light case corresponds to an undefined -25% density variation that is intended to account for a variety of factors including fabrication tolerances of the riser.				

Table 3-7 Design Load Cases, Case-1

Case ref	Riser Condition	Design Case #, Refer to Riser Operations Mode	Design Environment	Allowable Stress Factor	Mooring offset (%)
Installation	flooded riser	1	None	1.35	0
PT	Internal pressure test	2	None	1.35	0
Start-up	Start-up after major workover	14	None	1.35	0
PN-1	Producing, oil in riser	3,4,5	10 yr winterstorm	1	1
PN-2			10 yr loop	1	1
PN-3			100 yr loop	1.2	5
PN-4			100 yr hurricane	1.2	5
S-1	Shut-in	6,7,8	100 yr hurricane	1.2	5
S-2			100 yr loop	1.2	5
SMD-1	Shut-in, Mooring line damaged	6,7,8	100 yr hurricane	1.5	6.25
SMD-2			100 yr loop	1.5	6.25
SL-1	Shut-in with riser leak	9,10,11	100 yr loop	1.5	5
SL-2			100 yr hurricane	1.5	5
K-1	Well killed	13	10 yr winterstorm	1.2	1
K-2			10 yr loop	1.2	1
K-3			100 yr loop	1.5	5
K-4			100 yr hurricane	1.5	5
Notes:	1. Target maximum slope is 60 degrees from the vertical in a workover mode (no environment) with a vessel offset not exceeding 2.5% of water depth.				
	2. When three content densities are specified, only the the light and heavy cases will be checked.				

3.6.2 Design Case-2

The fluid densities for various design conditions for Case-2 (10,000 ft water depth) for the Dual Casing riser are given in Table 3-5. The basic considerations for this case have similarity to those for Case-1 and are given in Tables 3-8 and 3-9 for Case-2. The number of design conditions and fluid types vary for the outer riser, inner riser, and production tubing. The conceptual sizing of riser is done for the design cases 6, 7, 8 and 15 of Table 3-9.

Table 3-8 Design Conditions, Case-2

Design Case	Design Condition	Outer Riser			Inner Riser (I.R.)			Production Tubing			API 2RD Load Type
		Internal Pressure at Platform (psi)	Internal Contents		Internal Pressure at Platform (psi)	Internal Contents		Internal Pressure at Platform (psi)	Internal Contents		
			Fluid Type	Weight in ppg		Fluid Type	Weight in ppg		Fluid Type	Weight in ppg	
1	Installation	0	Sea water	8.56	0	Sea water	8.56	0	Sea water	8.56	Installation
2	Internal pressure test for O.R.	3,300	Sea water	8.56		Not present			Not present		Test
3	Internal pressure test for I.R.	200	Insugel	9.00	10,000	Insugel	9.00		Not present		Test
4	Inner riser leaking during normal operation -- mean (1)	200	Insugel	9.00	500	Insugel	9.00	10,000	30 API Oil	7.10	Operating
5	External pressure check for I.R.	0	Sea water	8.56	0	Nitrogen	0.20	10,000	30 API Oil	7.10	Test
6	Operating (oil wells) - mean	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	7.10	Operating
7	Operating (oil wells) - light	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	5.33	Operating
8	Operating (oil wells) - heavy	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	8.56	Operating
9	Shut in (oil wells) - mean	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	7.10	Operating
10	Shut in (oil wells) - light	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	5.33	Operating
11	Shut in (oil wells) - heavy	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	8.56	Operating
12	Shut in (oil wells) tubing leak - mean (2)	200	Insugel	9.00	7,500	30 API Oil	7.10	10,000	30 API Oil	7.10	Extreme
13	Shut in (oil wells) tubing leak - light (2)	200	Insugel	9.00	7,500	30 API Oil	5.33	10,000	30 API Oil	5.33	Extreme
14	Shut in (oil wells) tubing leak - heavy (2)	200	Insugel	9.00	7,500	30 API Oil	8.56	10,000	30 API Oil	8.56	Extreme
15	Workover, well killed	200	Insugel	9.00	0	Kill fluid	15.5	0	Kill fluid	15.5	Extreme
16	Start-up after major workover	200	Insugel	9.00	0	Kill fluid	15.5		Kill fluid	15.5	Extreme
17	Workover I.R. leak	3,300	Insugel	9.00	0	Kill fluid	15.5	0	Kill fluid	15.5	Survival
18	Shut in (oil wells) 100 yr hurricane with SCSSV - mean	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	7.10	Extreme
19	Shut in (oil wells) 100 yr hurricane with SCSSV - light	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	5.33	Extreme
20	Shut in (oil wells) 100 yr hurricane with SCSSV - heavy	200	Insugel	9.00	500	Nitrogen	0.20	10,000	30 API Oil	8.56	Extreme
Notes											
1	Outer riser could be evacuated up to upper 5000' WD due to inner riser leak.										
2	Pressure in inner riser may go up to 10,000 psi in survival case.										

Table 3-9 Design Load Cases, Case-2

Dual Casing Riser: Load Case Table					
Case ref	Riser Condition	Design Case #, Refer to Riser Operations Mode	Design Environment	Allowable Stress Factor	Mooring offset (%)
Installation	flooded riser	1	None	1.35	0
PT-1	Internal pressure test	2	None	1.35	0
PT-2	Internal pressure test	3	None	1.35	0
PT-3	Internal pressure test	4	None	1.35	0
PT-4	External pressure test	5	None	1.35	0
Start-up	Start-up after major workover	16	None	1.35	0
PN-1	Operating, oil in tubing	6,7,8	10 yr winterstorm	1	1
PN-2			10 yr loop	1	1
PN-3			100 yr loop	1.2	5
PN-4			100 yr hurricane	1.2	5
S-1	Shut-in	9,10,11	100 yr hurricane	1.2	5
S-2			100 yr loop	1.2	5
SMD-1	Shut-in, mooring line damaged	9,10,11	100 yr hurricane	1.5	6.25
SMD-2			100 yr loop	1.5	6.25
SL-1	Shut-in with internal leak	12,13,14	100 yr loop	1.5	5
SL-2			100 yr hurricane	1.5	5
K-1	Well killed	15	10 yr winterstorm	1.2	1
K-2			10 yr loop	1.2	1
K-3			100 yr loop	1.5	5
K-4			100 yr hurricane	1.5	5
SV-1	Shut-in with SCSSV	18,19,20	100 yr hurricane	1.2	5
SV-2			100 yr loop	1.2	5
Notes:	1. Target maximum slope is 60 degrees from the vertical in a workover mode (no environment) with a vessel offset not exceeding 2.5% of water depth.				
	2. When three content densities are specified, only the the light and heavy cases will be checked.				

3.7 Floating Production Unit Data

In this study, a semi-submersible floating production unit (FPU) has been considered for sizing, design, and analysis of a CVAR riser system. The CVAR is considered to be tied to the semi-submersible hull in the same way as done for a SCR. The main particulars of the semi-submersible unit and its mooring system for the Design Case 1 are given in Tables 3-10 and 3-11 respectively.

The risers are designed to handle the FPU offsets given in Tables 3-7 and 3-9. The FPU motions are taken into account in the analysis of CVAR for extreme loading, vessel induced fatigue, and VIV fatigue. The effects of the hull on local currents are not accounted in this study.

Table 3-11 presents the diameters and lengths of 12 line mooring system considered for the semi-submersible FPU in 8,000 ft water depth in GOM.

Table 3-10 Main Particulars of Semi-submersible FPU

Parameters/Item	Base Case Values	Variations over Base Case
Displacement	40,000 MT	
Draft	98 ft	
Pontoons (BxH)	35 ft x 30 ft	
Columns (LxB)	37 ft x 37 ft	
Deck size	240 ft x 180 ft	
Height to bottom box girder	149 ft	
Width to outside of pontoons	250 ft	
CVAR hang-off points horizontal separation	20 ft	30 ft
CVAR minimum azimuth at separation	5°	
CVAR hang-off location	82 ft below MWL 80 ft from Semi c/l	

Table 3-11 Mooring System for Semi-submersible FPU

Segment Property	Mooring Lines 1 Through 12			
	Units	Platform Chain	Polyester	Anchor Chain
Description		K4 Studless	Marlow Superline	K4 Studless
Nominal diameter	in	5	9	5
Catenary length	ft	500	10,500	600

3.8 Riser Sizing and Design

3.8.1 Basis for Riser Components

The product information available from the following vendors supplying various riser system components is used in this study, where necessary:

- Buoyancy and Weight Modules: Trelleborg Engineered Systems (earlier CRP-Balmorals) and Cuming Corporation
- T&C and Integral Connectors: V&M Tubes, Houston
- Flex joints: Oil State Industries
- Stress Joints in Titanium: RTI Energy Systems
- Umbilicals: DUCO

3.8.2 Design Codes and Standards

In general, API RP 2RD [API, 2006] has been used in sizing and design of the CVAR, which is assembled similar to a TTR, using threaded riser sections. Additional codes and standards are used, for sizing and design of components and attachments. The riser pipe design is based on the following:

- Internal Pressure (Burst) Design; and
- External Pressure (Collapse) Design.

In this study, a riser pipe of uniform thickness throughout the entire riser length has been assumed. Design checks are performed at the surface (burst) and at the base of the riser (collapse). Collapse checks at the base of the riser assume that the annulus is empty.

The allowable stress factors for different design conditions per API RP 2RD are given in Table 3-7 and Table 3-9 for Case-1 and Case-2 respectively.

3.8.3 Riser Design Type

The construction of the CVAR pipe would be an assembly of threaded riser pipe sections, similar to a TTR, which would enable installation and retrieval of riser sections from the FPU deck.

The applications evaluated in Case-1 and Case-2 are for ultra-deepwater, and these design cases are for 12 ksi and 14 ksi shut-in pressures respectively, which would require riser sections in HSS of 95 ksi or higher grades. Thus for these HSS riser sections "weld on threaded connector" design is not feasible, which has been used in several TTR designs. The HSS designs of riser sections with T&C connectors are available from multiple manufacturers, and a design supplied by V&M Tubes is shown in Figure 2-5. Additional discussion on alternative designs available is given in Section 2.5.2.

The material properties obtained from V&M Tubes for HSS qualified riser pipes meeting the API 5CT standard guidelines [API, 2006] are given in Table 3-12. The status of application of the pipe designations provided by V&M Tubes is as follows:

- C-110 tubing riser is currently being fabricated using the VAM Top FE connector;
- C-110 well casing pipes are being used in Thunder Horse project in the GOM;
- P-110 riser casing pipes have been used for inner and outer casings of risers in the GOM;

- C-95 is a non-sour service version of T-95, and higher ultimate strength is possible with C-95; and
- Q-125 inner riser pipe is being produced by V&M for installation in 2005.

Table 3-12 Riser Pipe Properties
(Source: V&M Tubes, Houston)

Pipe Designation	Yield Stress (ksi)	Ultimate Strength (kips)	Sour Service	Maximum Thickness (inch)
T-95	95-110	105	Yes	2
P-110	110-140	125	No	0.05
C-110	110-120	120	Yes	1.5
Q-125	125	135	Yes	0.05

Note: The above pipes meet requirements for API 5CT standard

3.8.4 Riser Strakes

The strakes are required to reduce VIV of the upper region length of CVAR, which has no buoyancy modules. The length requiring fitting of strakes could be in the order of 5,000 ft. Typical design of strakes considered in this study is based on previous work and is given in Table 3-13.

Table 3-13 Strake Data

Item	Pipe OD	
	14 inch	7.625 inch
Strake ID	14 inch	10.625 inch
Strake Type	16D Pitch x 0.25D Outstand	16D Pitch x 0.25D Outstand
Straked Length of CVAR	Entire Top Slick Section	Entire Top Slick Section
Strake Dry Weight	24.2 lb/ft (36 kg/m)	22.5 lb/ft (33.5 kg/m)
Strake Wet Weight	2.7 lb/ft (4 kg/m)	2.4 lb/ft (3.6 kg/m)

Note: The tubing riser has an insulation coating 1.5in thick, which is not required for the dual casing riser.

In the equivalent model of riser used in conceptual analysis, the wet and dry weights of strakes are converted to an equivalent thickness and equivalent mass per unit length. The riser pipe diameter for drag load estimates is assumed as the OD at the base of the strakes.

3.8.5 Hydrodynamic Parameters

The hydrodynamic parameters used in strength analysis and fatigue analysis (vessel induced motion fatigue analysis) are given in Table 3-14.

Table 3-14 Hydrodynamic Parameters for Strength Analysis

Hydrodynamic Coefficients	Strength Analysis		Fatigue Analysis (vessel induced motion)	
	Bare Pipe	Straked Section	Bare Pipe	Straked Section
Normal Drag Coefficient	1.2	2	0.7	2
Tangential Drag Coefficient	0	0.05	0	0.05
Normal Added Mass Coefficient	1	1.5	1	1.5
Tangential Added Mass Coefficient	0	0.05	0	0.05
Note 1: The hydrodynamic coefficients for the straked sections are based on the outer diameter of the pipe including coatings and base strake material, but not including the height of the strake.				

The design service life of 20 years has been assumed for CVAR design in this study. The design fatigue life for steel riser sections and connections is to be a minimum of 200 years (with a safety factor of 10 over service life). The fatigue life estimates account for fatigue damage from the first and second order vessel motions.

Table 3-15 presents the hydrodynamic parameters and assumed stress concentration factor (SCF) and fatigue S-N curves used for the VIV analysis.

Table 3-15 Parameters for VIV Analysis

Parameters	Value
Added Mass Coefficient, C_a	1.5 (Straked Sections) 1.0 (Bare Sections)
Drag Coefficient, C_d	2.0 (Straked Sections) 1.0 (Bare Sections)
Strouhal Number	200 (For Rough Cylinder)
Multi-mode Bandwidth	0.5 [SM] & 0.2 [MM]
Mode Cut-off	0.0 (Multi-mode Response)
SCF	1.8
Fatigue Curve	DnV B1curve

4 Conceptual Sizing

4.1 General

The conceptual sizing task includes the following:

- To develop feasible CVAR configurations for the two field development scenarios identified in Section 2.3, and estimate the amount and location of buoyancy and/or weight modules to meet the conditions and basis given in Section 3 and in API and DNV recommended practices or specs;
- To establish the basis and requirements for other components attached to the CVAR riser;
- To establish the general impact on the CVAR configuration and buoyancy/weight requirements from variations in vessel motions, water depth and subsea well offset; and
- To identify the critical issues in the sizing and design of CVAR that should be focused during the conceptual analysis and risk assessment tasks.

4.2 Key Design Considerations

The characteristic shape of the CVAR as illustrated in Figures 2-1(a) and 2-4 (upper, transition, lower regions) is formed by a combined effect of longer riser length (than for a vertical TTR), identified as riser over-length, and specific zones of riser length fitted with external syntactic foam buoyancy modules, and weighted modules. Figure 4-1 shows a group of CVARs supported by a floating unit, and fitted with buoyancy and weight modules, which are distributed over a small length of riser below mid-depth, to obtain the desired configuration. The CVAR features are discussed in Section 2.2 and its components are defined in Sections 2.4 to 2.6.

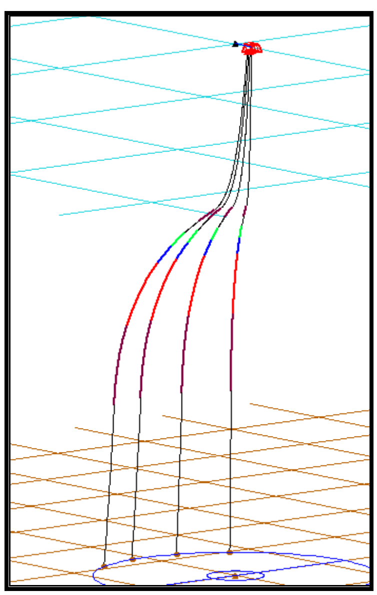


Figure 4-1 Generic Configuration for a Group of CVARs

Examples of various operational and design requirements that would influence (or define limitations to design parameters) the CVAR design are given below:

- Movement of tools for pigging and workover operations through the CVAR pipe requires limitations to riser curvature in the transition zone;
- Degree of compliance required in a CVAR would vary with the type of FPU and its mooring system;
- Variations in the fluid density over the life of riser introduces additional load cases that may need fitting of increased number of buoyancy elements;
- Riser-riser interferences shall be within acceptable limits and it introduces limits to the acceptable riser motions over its complete length under all combinations of operational and metocean load cases; and
- Metocean loading on the CVAR system and its various components could lead to VIV response, which adds to the fatigue damage estimates.

The CVAR configuration development requires consideration of the operational and design conditions identified above and to ensure that the following three loading and stress conditions are met:

1. Curvatures should be kept low (say no greater than 3 degrees per 100 ft) and maximum angles from the vertical should not become excessive (say no greater than 60 degrees), which would permit the passage of tools through the riser under their own weight.
2. Maximum stresses must conform to code requirements (e.g., API RP 2RD).
3. Compression should be minimized or eliminated.

A balance in design is required in order to ensure that the above three loading and stress conditions are met. The Condition-1 above requires that the riser be as taut as possible, whereas Condition-2 requires that the riser should not be too taut, and special measures are adapted to remain within recommended riser curvature for moving of tools by gravity. In addition, the curvature requirements could be relaxed by considering alternative measures for moving tools through the riser, or else the FPU could be repositioned to meet the curvature requirements.

Curvature Limits:

The maximum curvature of the riser and the maximum angle from the vertical are controlled in the following ways:

- The target minimum slope (angle from horizontal) is set as 30 degrees during the workover operations. This is based on the work performed in the Brown and Root JIP (1986) on "Downhole maintenance of subsea completions" and the key findings are identified as follows:
  - Wireline tool lowering by gravity, which would require a minimum angle of 30 degrees for the riser from the horizontal (applies in the transition zone);
  - Wireline/riser friction and tension increase considerations lead to about 20 degree minimum angle;
  - Vessel heave motion helps. A larger angle from the vertical is acceptable when the FPU vessel dynamics is included; and
  - Internal pressure has no effect on slope.

- In addition, in case wirelines are designed for tractors, both limits: 30 degree and 20 degree would be applicable.

In case of risers, the following curvature limits were identified:

- The Minimum Bend Radius (MBR) depends on the riser ID; and
- For a 6" ID riser, lowest acceptable MBR was about 60 ft for wireline operations and 100 ft for coiled tubing operations.

Riser Length, Degree of Compliance, and Riser-Riser Contact:

The length of the CVAR must be sufficient to avoid overstressing the bottom stress joint when the semisubmersible FPU is in the FAR position, and yet be short enough so that problems do not arise when the vessel is in the NEAR position (Figure 4-2). The FAR position refers to vessel displacements from the CENTER (when the vessel is at the center of its watch circle) vessel position in a direction away from the riser base. The NEAR position refers to vessel displacements towards the riser base from the CENTER vessel position.

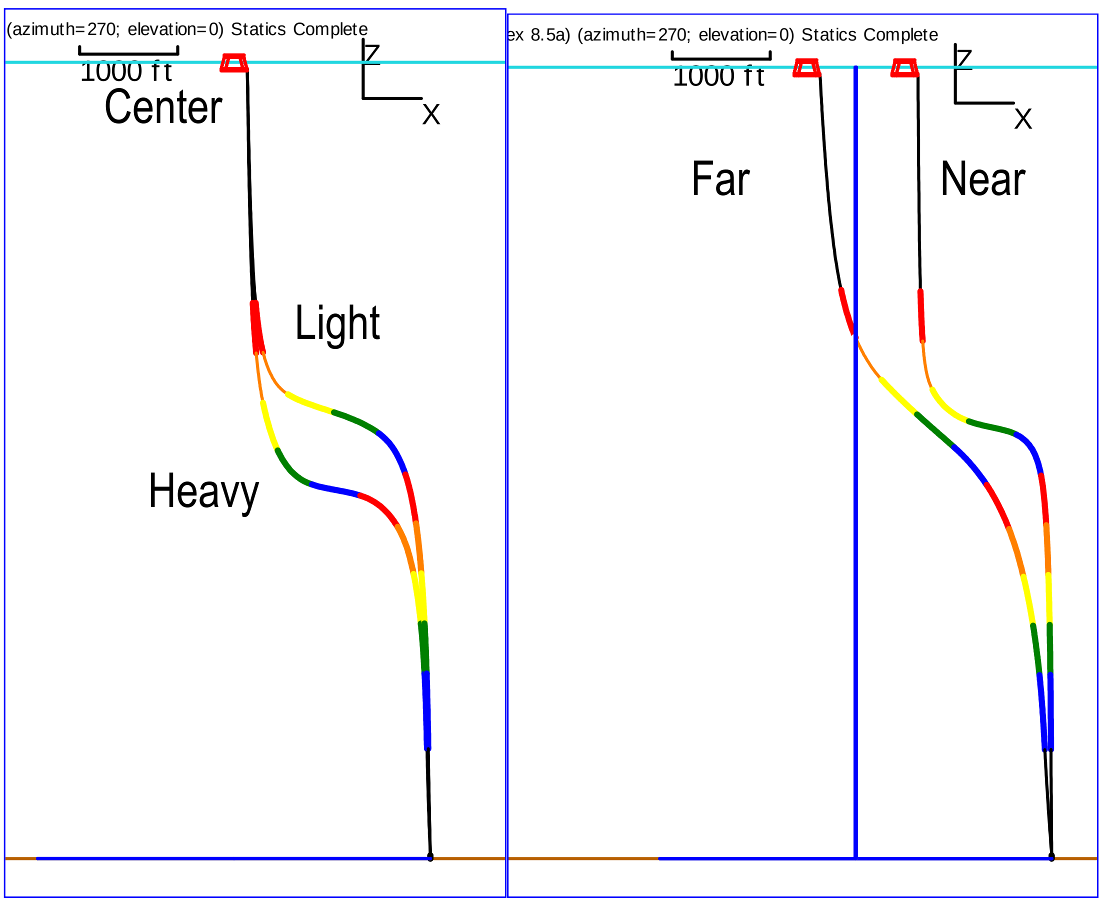


Figure 4-2 Variations in CVAR Configurations - Fluid Density Effects and Vessel Locations

The required degree of compliance is also dependent on the mooring watch circle and on the vessel motion characteristics. Sufficient compliance must exist in the CVAR system in order to satisfy extreme response criteria when the vessel offsets to the NEAR and FAR positions. Increased compliance, however, must be balanced by the need to limit the potential for riser-to-riser contact.

Variation in Fluid Density:

A significant challenge in design of the CVAR is to develop its configuration and size the riser sections, buoyancy modules and their distribution to obtain "acceptable vertical movement" for the complete range of fluid densities and other conditions that will be present during the life of the riser. While this problem can be alleviated somewhat by making the riser casing(s) heavy (so that changes in fluid density have less impact on the weight in water per unit length of the pipe), but it would increase the riser system cost. Therefore for the CVAR case, it is important to identify the operational scenario in detail (see Section 3). The variations in fluid densities during various operations over the riser design life for the Case-1 are given in Table 3-4. Figure 4-2 illustrates potential CVAR configurations due to variations in the fluid density.

Buoyancy Requirement:

The buoyancy must be sufficient to support and protect the riser regardless of changes in the internal fluid density. The behavior of the transition region in the CVAR changes with variations in the internal fluid density. The vertical movements of this region of the riser would vary with the fluid density, and it requires detailed considerations to include effects of all design conditions and load cases identified in Section 3.6.

The configuration of syntactic foam buoyancy modules is as shown in Figure 2-10. The buoyancy distribution would vary for each CVAR design. The following considerations are made in the sizing of buoyancy modules and the length of transition region:

- The transition region buoyancy modules are sized to minimize both static curvatures and dynamic stresses in CVAR; and
- The large diameter buoyancy modules near top of the lower region are sized to provide positive effective tension of the order of 100 Kips minimum at the bottom end TSJ.

Within each of the above distinct regions, the option exists to 'fair' or vary the external diameter of the foam modules. In addition, by providing weight coating or weight modules over a few riser sections at bottom of the upper region CVAR length, the extreme stresses are reduced.

4.3 Sizing and Design Approach

The sizing is accomplished using a spreadsheet based sizing tool developed by Granherne. The design basis data for water depth and FPU offset (design, accidental) is used and the casing sizes are based on the flow assurance and other considerations.

The following quantities for CVAR are established using the sizing spreadsheet tool:

- Depth range for buoyancy modules in CVAR;
- Specific buoyancy requirement for riser segments in the depth range with buoyancy modules;
- Riser tension estimates for different design conditions (installation, in-place operation); and
- Input data for global riser analysis.

The various design load cases for Case-1 (Tubing CVAR in 8,000 ft water depth) and Case-2 (Dual Casing CVAR in 10,000 ft water depth) are given in Table 3-7 and Table 3-9 respectively. Table 3-6 identifies the

Design Conditions for different design load cases (installation, testing, operating, extreme, and survival) for Case-1. Table 3-7 provides description of CVAR condition, metocean state, mooring offset, and allowable stress factors for each design load case for Case-1. Similarly, Tables 3-8 and 3-9 identify design load cases and associated data for Case-2. During conceptual sizing, the riser is sized for the design load cases 3, 4, 5 and 13 in Table 3-7 for Tubing CVAR design Case-1, and for the design load cases 6, 7, 8, and 15 in Table 3-9 for Dual Casing CVAR design Case-2.

The results of sizing are verified by static analysis and by regular wave dynamic analysis using ORCAFLEX® software and the basis provided in Tables 3-6 to 3-9. The results are given as follows:

Static design checks

The purpose of the static design checks is to ensure satisfactory riser performance prior to conducting dynamic design checks. After the initial design of the CVAR from the sizing spreadsheet, the minimum slope from the horizontal and the curvature are checked for the scenarios mentioned above (250 ft offset towards the FAR location of FPU) for an appropriate internal fluid density:

- The length of the Upper Region is adjusted until 30 degree slope criteria is achieved; and
- Stresses and curvatures are checked throughout the CVAR length for the NEAR, CENTER and FAR positions of FPU for the 100-yr RP hurricane and 100-yr RP loop current shut-in scenarios. Particular attention is paid to the behavior of the bottom TSJ.

Dynamic design checks (Case 1-only)

A preliminary series of design checks for CVAR dynamic analysis for regular waves are carried out using ORCAFLEX® software. The goal of dynamic analysis is to confirm adequacy of the CVAR configuration developed through the static design check stage and that a satisfactory preliminary design is feasible to meet the design requirements for extreme stresses and minimum tensions in the primary structural components of CVAR. The following conditions are analyzed (Table 3-7):

- Stresses and curvatures checked throughout the riser for the NEAR and FAR positions of FPU for the SMD-1 case (Shut-in Mooring line Damage for 100-yr RP hurricane).
- One of the well-killed cases is selected for analysis. The metocean data appropriate to this operational case is used.

The CVAR configuration is then further analyzed for irregular wave extreme stresses and conventional vessel/wave induced motion fatigue analyses and are given in Section 5. The analysis approaches used are per the standard industry practice. Based on the results of the basic analysis performed during the conceptual sizing, a decision is made on the selection of a few load cases for detailed non-linear dynamic analysis. The possible load cases for detailed analysis may include one or more design load cases from the following (shown by shaded boxes in Table 3-7 and Table 3-9):

- Start-up, Start-up after major workover case;
- PN-4, Producing oil in riser for 100-yr RP hurricane;
- S-1, Shut-in case for 100-yr RP hurricane;
- SMD-1, Shut-in with mooring line damaged case, for 100-yr RP hurricane; and
- K-4, Well killed case with 100-yr RP hurricane.

4.4 CVAR Sizing Estimates

The CVAR sizing estimates are done for the following two design cases:

- Case 1: Tubing CVAR in 8,000 ft water depth, with 1,500 ft well offset from vessel centre.
- Case 2: Dual Casing CVAR in 10,000 ft water depth, with 2,000 ft well offset from vessel center.

The fluid properties used in the design of these cases are given in Table 4-1 and the schematics of the riser pipe casings used are shown in Figure 4-3. The design metocean and vessel offset data used in analysis are given in Table 3-1. The CVAR steel pipe sizes (obtained using a spreadsheet tool) and material specifications are identified in Table 4-2.

The regular wave analysis of CVAR is performed for the NEAR and FAR offset positions of FPU. These positions are assumed to be in-line with the vertical plane of the CVAR and the flexible joint (Figure 4-4).

Table 4-1 Design Basis – Fluid Properties

Parameter	Light Weight Oil	Mean Weight Oil	Kill Fluid
Case-1: Tubing CVAR			
Fluid Type in Tubing	Production		Kill
Fluid density in tubing annulus (ppg)	5.00	6.67	13.26
Pressure in tubing annulus at waterline (psi)	9,250	9,250	0
Case-2: Dual Casing CVAR			
Fluid Type in Tubing	Production		Kill
Fluid density in tubing annulus (ppg)	5.33	7.10	15.50
Pressure in tubing annulus at waterline (psi)	10,000	10,000	0
Fluid Type in Inner Annulus	Nitrogen		
Fluid density in inner annulus (ppg)	0.20		
Pressure in inner annulus at waterline (psi)	500		
Fluid Type in Outer Annulus	Insugel		
Fluid density in outer annulus (ppg)	9.00		
Pressure in outer annulus at waterline (psi)	200		

NOTES:

1. 1 ppg = 7.4805 lb/ft^3
2. For the Dual Casing CVAR, for the Outer Casing Internal Test Pressure case, the internal test pressure on the outer casing is 3,300 psi with seawater (64 pcf). The fluid outside the outer casing is seawater.
3. For the Dual Casing CVAR, for the Inner Casing Internal Test Pressure case, the internal test pressure on the inner casing is 7,500 psi with seawater (64 pcf). The outer annulus is assumed with 9.0 ppg Insugel at 200 psi. The inner riser casing pass the API 5CT test for 10,000 psi.

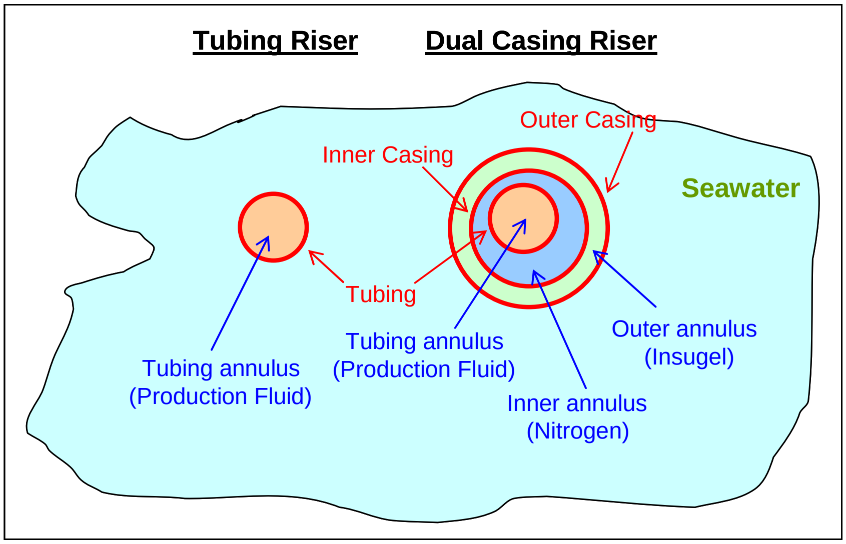


Figure 4-3 Schematics of Alternative CVAR Configurations

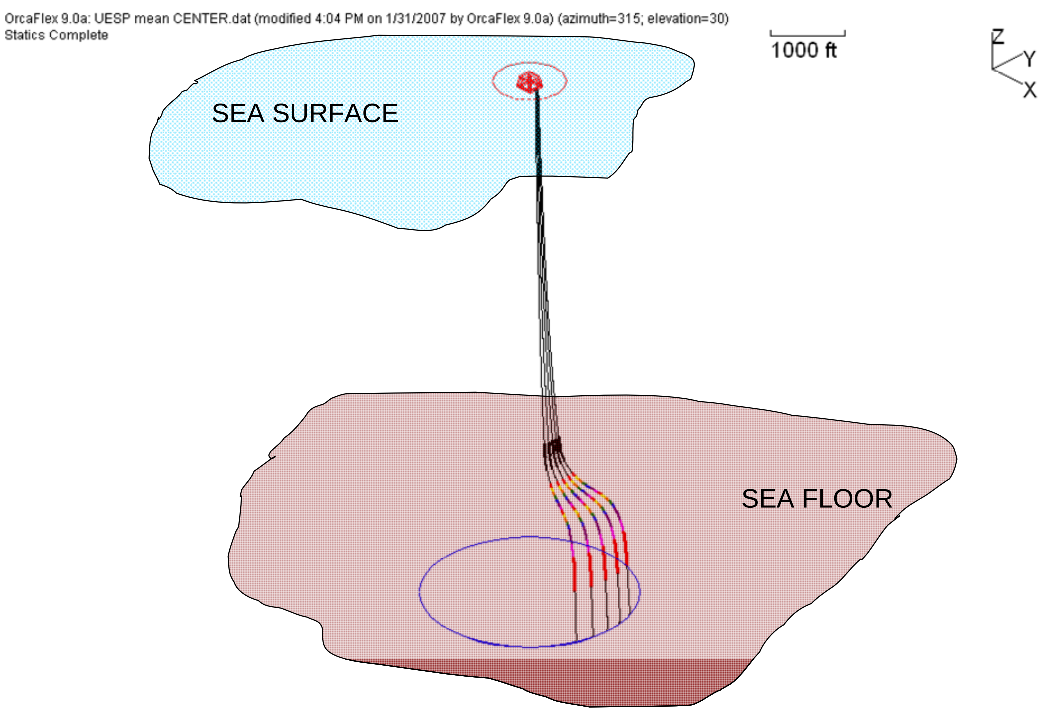


Figure 4-4 General View of a Typical Large Offset CVAR

4.4.1 Riser Size

The riser pipe is designed using the recommendations given in API RP 1111 [API, 1999]. The basic sizes of the riser pipe and material grade used to start the conceptual sizing and analysis tasks for the two cases are given in Table 4-2. The tubing diameter in Case-1 is larger compared to that for the Case-2 dual casing case due to provision of an option for passage of an ESP through the Tubing riser.

Table 4-2 Pipe Size and Material Grades

Item	Material	OD	Wall Thickness
Case-1: Tubing CVAR			
Tubing	API 5CT P-110	7.625 inch	0.750 inch
Case-2: Dual Casing CVAR			
Tubing	API 5CT P-110	5.500 inch	0.594 inch
Inner Casing	API 5CT Q-125	10.750 inch	0.626 inch
Outer Casing	API 5CT Q-125	14.000 inch	0.594 inch

NOTES:

1. Wall thicknesses are derived from spreadsheet calculations based on API RP1111 recommendations.
2. Thermal insulation of 1.5 inch thickness is assumed along the entire length of the Case-1, Tubing CVAR.

4.5 Case 1 - Tubing CVAR

4.5.1 Riser Configuration

The general shape of a typical large offset CVAR is shown in Figure 4-4. The shape of the same in elevation is shown in Figure 4-5. The 7.625 inch tubing (which also serves as the casing) consists of API-5CT P-110 pipe. The design conditions for the design case 3 (see in Table 3-7) are applied. The design wall thickness is calculated as 0.75 inch.

The riser is divided into three regions: Upper (or Top) region, Transition (or Buoyancy) region, and Lower (or Upright) region, each with a particular function. The Upper region consists of about 69% of total length and the Transition region is about 16% of total length. Thus the total length is 8,535.2 ft, which generates an over-length of 535 ft or 6.7% of water depth.

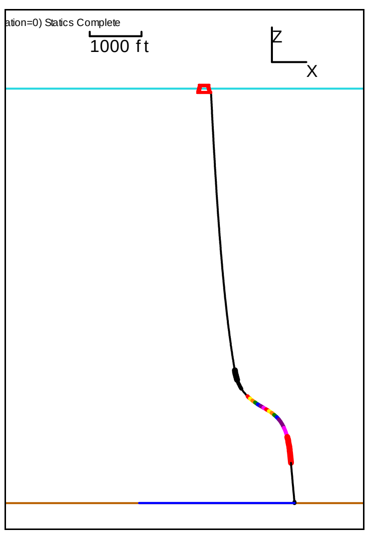
The upper region length is kept as long as feasible to improve the dynamic response of CVAR. The performance of the riser upper region is further improved by use of a weighted riser section near the bottom of the upper region.

The transition (buoyancy) region contains multiple segments with different net buoyancies as shown by different colors in Figure 4-5. Some of the segments are only one riser joint long (63 ft assumed in this example). The buoyancies are faired and the fractional mass change between segments is minimized in order to reduce the generation of vibration amplitudes.

The lower region consists of three segments, namely a buoyed section, a bare pipe section and a TSJ, which require specific considerations as discussed further. There is a need to provide sufficient tension at the base of the riser to prevent bottom angles from exceeding about 15 degrees (for the case of a titanium TSJ). The desired minimum tension is 150 kips, which is determined using a stress joint design spreadsheet. The buoyancy required to obtain this tension at top of about 1,000 ft long riser pipe in the lower region becomes very large. In case of installation of the CVAR from a MODU, the OD of the buoyancy is kept less than 60 inches to enable it pass through the rotary table, which could result in longer buoyancy (or provision of several buoyancy modules). It is impractical to maintain a constant fractional mass change in this part of the riser; however this does not seem to cause static or dynamic problems.

In order to deploy tools during workover using the effects of gravity, maximum angles from the vertical must be limited to 60 degree. To further facilitate the deployment, the semi-submersible is displaced 250 ft away from the watch circle center (in the –X direction, Figure 4-5). The upper region riser length with straked pipe (without buoyancy elements) is adjusted until the maximum angle from the vertical is equal to 60 degree. No current loads are considered, and the tubing riser is assumed to contain the operating fluid with mean fluid density.

The analysis model is developed using ORCAFLEX® software and static design checks are made to confirm the basic configuration identified from the sizing spreadsheet tool.



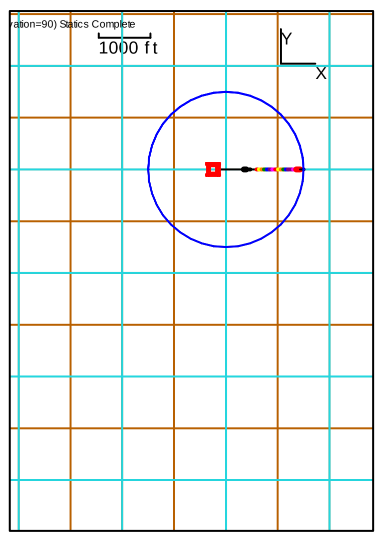


Figure 4-5 Case-1 Tubing CVAR - Elevation and Plan Views

4.5.2 In-place Wave Analysis

The regular wave analysis is done using ORCAFLEX® software for two metocean load cases: 100-yr RP hurricane and 100-yr RP loop current as given in Table 3-1. The design cases 3 to 5 in Table 3-6 for the CVAR tubing with mean, light, and heavy fluid density are evaluated for two positions (NEAR and FAR) of FPU for each metocean loading. Thus a total of 6 analysis scenarios for each metocean load case are evaluated. An overpressure is maintained at the top when oil is used as the internal fluid.

The surface current, wave (towards), and vessel offset directions are assumed to be collinear. For the FPU FAR scenario, this coincides with the "-X" direction as shown in Figure 4-5. For the FPU NEAR scenario, this coincides with the positive "+ X" direction.

Load Case 1: 100 Year Return Period Hurricane

The riser tension and von Mises stress results from the static and the dynamic analyses for 100-yr RP hurricane (H_{max} = 77.4 ft, T_{max}=13.4 sec, surface current = 5.77 ft/sec, vessel offset = 400 ft) are tabulated in Table 4-3. The envelopes of the effective tension range and the von Mises stress range are shown in Figure 4-6.

Table 4-3 Tubing CVAR – Inplace Analysis for 100-yr RP Hurricane

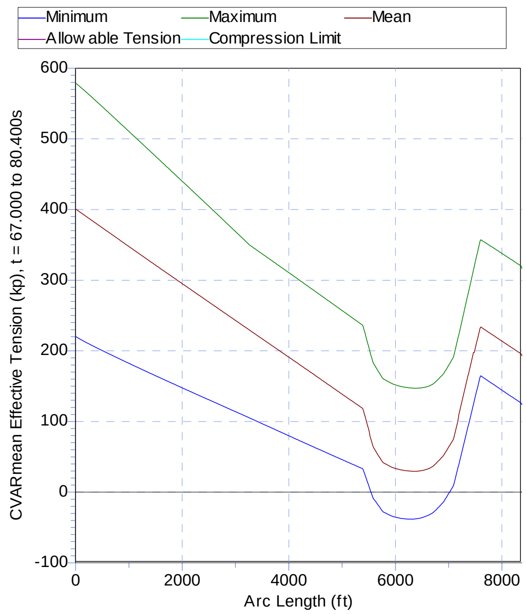
Parameter / Item	Units	FAR (-X)			NEAR (+X)		
		Light Weight Oil	Mean Weight Oil	Light Weight Kill Fluid	Light Weight Oil	Mean Weight Oil	Light Weight Kill Fluid
Fluid density	ppg	5.00	6.67	13.26	5.00	6.67	13.26
Pressure at riser top	psi	9,250	9,250	0	9,250	9,250	0
Static Analysis Results							
Top Region							
Max. tension	kips	367	381	439	385	399	458
Max. von Mises stress	ksi	51	51	28	51	52	30
Buoyancy Region							
Min. tension	kips	4	4	5	29	30	32
Max. angle from vertical	deg	87	87	88	55	55	55*
Max. von Mises stress	ksi	51	53	42	43	45	17
Dynamic Analysis Results (for the last wave of regular wave run)							
Top Region							
Max. tension	kips	464	481	549	555	579	661
Max. von Mises stress	ksi	56	56	38	59	60	45
Buoyancy Region							
Min tension	kips	-8	-8	4	-37	-38	-45
Max. angle from vertical	deg	91	91	92	60	60	59
Max. von Mises stress	ksi	53	55	47	65	67	64

* The maximum declination (angle) is measured from the vertical and occurs over the entire length, thus 55 degrees from vertical occurs near the transition.

The results presented in Table 4-3 confirm that the riser sections meet the API RP1111 code check, and the maximum tension is higher for the NEAR position case. The ranges of effective tensions and von Mises stresses along the CVAR length are plotted in Figure 4-6 for the analysis case with mean fluid density and the FPU at the FAR position. In the Figure 4-6 plots, the left end of the abscissa denotes the top of the CVAR at the hang-off point and the right end denotes the CVAR end at the wellhead.

Three distinct regions can be seen in the tension and stress responses. In the upper (top) region fitted with strakes, the tension and stress distributions are monotonic. In the transition (buoyancy) region, the tension distribution is non-monotonic. Similarly, the stress distribution shows rapidly changing stresses with few large spikes. In the lower region, the tension and stress distributions are again monotonic. The largest values of the tension distribution occur at the hang-off points. The important observations are as follows:

- Effective tension is seen to change sign and produce compression over part of the transition (buoyancy) region of the Tubing CVAR. The magnitude of this compression is higher for the NEAR position case; and
- The maximum stress occurs near the beginning of the transition (buoyancy) region.



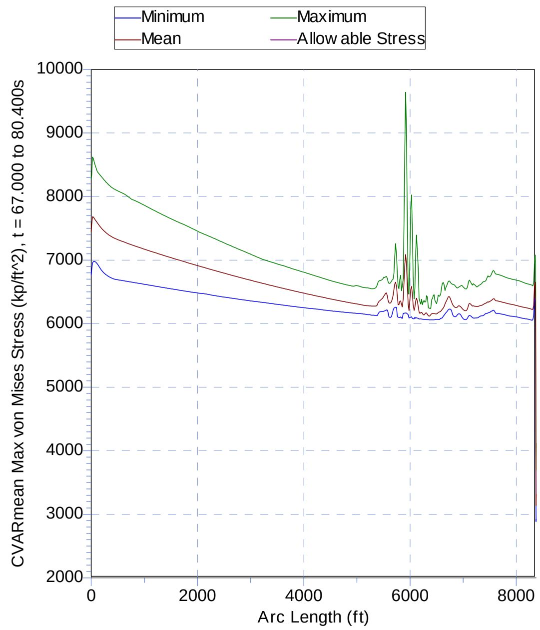


Figure 4-6 Tubing CVAR Inplace Analysis – 100-yr RP Hurricane
(Mean Fluid Density Case)

Load Case 2: 100 Year Return Period Loop Current

The CVAR configuration and loading scenarios analyzed under the 100-yr RP loop current case (H_{max} = 8.8 ft, T_{max} = 5.2 sec, surface current = 8.86 ft/sec, vessel offset = 400 ft) are the same as for the 100-yr RP hurricane conditions. The tension and von Mises stress results from the static and the dynamic analyses are tabulated in Table 4-4.

Table 4-4 Tubing CVAR – Inplace Analysis for 100-yr RP Loop Current

Parameter / Item	Units	FAR (-X)			NEAR (+X)		
		Light Weight Oil	Mean Weight Oil	Light Weight Kill Fluid	Light Weight Oil	Mean Weight Oil	Light Weight Kill Fluid
Fluid density	ppg	5.00	6.67	13.26	5.00	6.67	13.26
Pressure at riser top	psi	9,250	9,250	0	9,250	9,250	0
Static Analysis Results							
Top Region							
Max. tension	kips	366	380	438	390	405	464
Max. von Mises stress	ksi	52	52	30	53	53	32
Buoyancy Region							
Min. tension	kips	3	3	4	35	36	38
Max. angle from vertical	deg	92.5	92.4	92.5	52.4	52.5	52.2
Max. von Mises stress	ksi	55	57	48	43	45	17
Dynamic Analysis Results (for the last wave of regular wave run)							
Top Region							
Max. tension	kips	369	383	441	400	415	475
Max. von Mises stress	ksi	52	52	30	53	53	32
Buoyancy Region							
Min. tension	kips	2.9	3.0	3.5	32	33	35
Max. angle from vertical	deg	92.5	92.7	92.6	52.4	52.5	53.0
Max. von Mises stress	ksi	55	57	48	43	45	18

The most important observation from the analysis results for the 100-yr RP loop current case is that the dynamic stresses and tensions are very close to the static stresses and tensions. In addition, the CVAR does not experience any compression for this metocean loading case. The angle of the transition (buoyancy) region with the vertical shows similar behavior for all analysis cases. The von Mises stresses remain within limits for the CVAR under this metocean loading case.

Load Case 3: 1-Line Broken, 100 Year & 1,000 Year Return Period Hurricane

A "damage" condition with one mooring line broken and the FPU/CVAR system subjected to 100-yr RP and 1,000-yr RP hurricane conditions was analyzed. The metocean conditions associated with those of a 1,000-yr RP hurricane are estimated from conditions reported at the Matterhorn TLP and URSA TLP sites, and given in Table 3-1. This analysis was done for only mean fluid density case and for two positions of FPU (NEAR, FAR) resulting in a total of four different cases. In the 1,000-yr RP hurricane cases, the pressure at the top of the riser is assumed to be half of the pressure under the 100-yr RP hurricane cases. The inplace analysis results for the damage case scenario with one mooring line broken and the FPU and riser systems subjected to 100-yr RP and 1,000-yr RP hurricane events are given in Table 4-5 for the NEAR and FAR positions of FPU, and riser pipes containing mean density fluid. In the FAR position, the vessel offset of 500 ft has been considered.

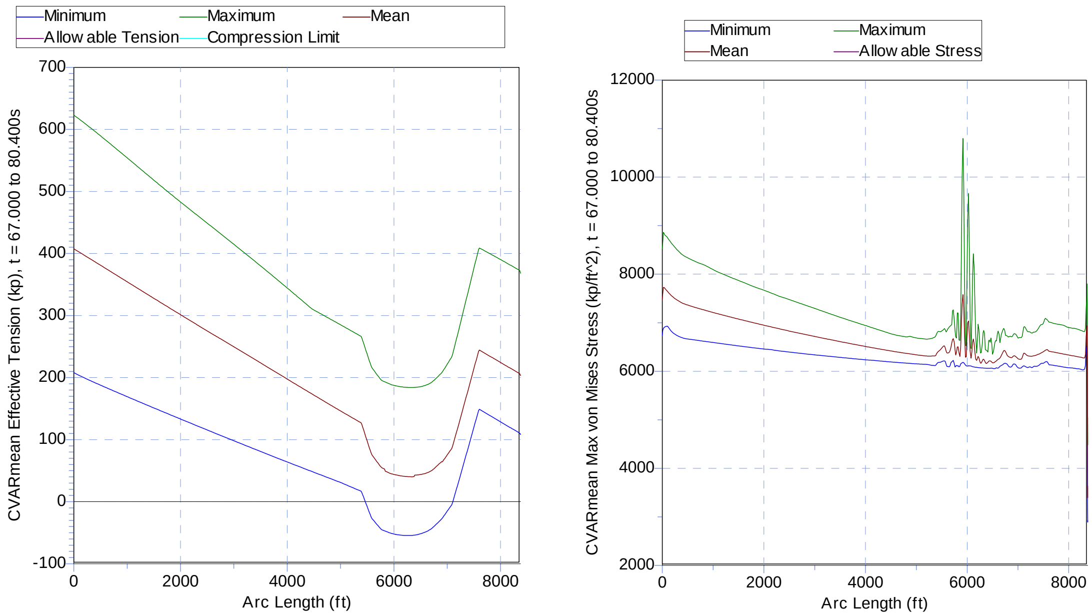
Table 4-5 Tubing CVAR – Inplace Analysis for Damage Case w/ Hurricane Events

Parameter / Item	Units	100 –yr Return Period		1,000-yr Return Period	
		FAR	NEAR	FAR	NEAR
Mean weight fluid density	ppg	6.67	6.67	6.67	6.67
Pressure at riser top	psi	9,250	9,250	4,625	4,625
Hmax	ft	77.4	77.4	82.6	82.6
Tmax	sec	13.4	13.4	14.3	14.3
Surface current	ft/sec	5.77	5.77	6.42	6.42
Static Results					
Top Region					
Max. tension	kips	381	405	381	405
Max. von Mises stress	ksi	51	52	34	35
Buoyancy Region					
Min. tension	kips	3	36	3	36
Max. angle from vertical	deg	93	53	93	52
Max. von Mises stress	ksi	57	45	50	25
Dynamic Results (for the last wave of regular wave run)					
Top Region					
Max. top region tension	kips	481	623	477	635
Max. von Mises stress	ksi	56	62	41	48
Buoyancy Region					
Min. tension	kips	-6	-54	-7	-54
Max. angle from vertical	deg	98	62	98	64
Max. von Mises stress	ksi	60	75	55	78

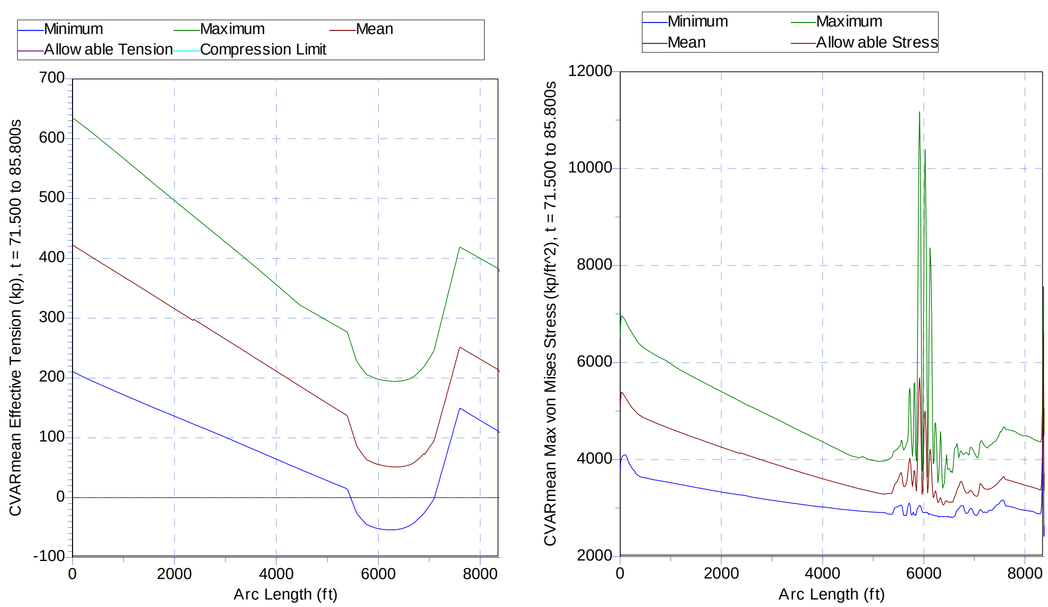
The observations from the results given in Table 4-5 are as follows:

- Compression is seen to develop in the buoyancy region for all cases; and
- The maximum stress of 78 ksi is obtained in the buoyancy region for the vessel NEAR position in 1,000-yr RP hurricane conditions. This is within the code requirements for a survival condition.

Plots of the effective tension ranges and the von Mises stress ranges, for the 100-yr RP and 1,000-yr RP hurricane events for the 1 mooring line broken case are shown in Figure 4-7.



a) 100-Yr RP Hurricane, Mean Fluid Density



b) 1,000-Yr RP Hurricane, Mean Fluid Density

Figure 4-7 Tubing CVAR Inplace Analysis – Mooring Line Damage Case

4.6 Case-2: Dual Casing CVAR

4.6.1 Riser Configuration

In Case-2, the CVAR is designed as a dual casing riser, where the production tubing is located inside two casings (inner, outer) as shown in Figure 4-3. Using a spreadsheet sizing tool, the following dimensions were obtained for two casings and tubing. For each pipe, the operating condition is given by the design load case 6 (Table 3-8) and the pressure test case is given by the design load case 2 (for the outer casing) and design load case 3 (for the inner casing):

- Outer casing: 14" OD x 0.594" WT, Q-125
- Inner casing: 10.75" OD x 0.626" WT, Q-125
- Production tubing: 5.5" OD x 0.563" WT, P-110

The additional weight of riser in case of the Dual Casing CVAR design (Case-2) in comparison to that for the Tubing CVAR design (Case-1) results in considerable differences in their behavior. Although the geometry (shape) of the Dual Casing CVAR has similarities to that of the Tubing CVAR, there are following differences in case of the dual casing design:

- The bottom tension during installation can become quite large as can the top tension after installation; and
- No insulation coating is required for the dual casing CVAR.

During installation, the unit weight in water of the straked outer casing and contained seawater is 76.7 lb/ft. This is the un-buoyed straked upper region length of the CVAR. The unit weight for the same part of the riser increases to 140.6 lb/ft when the CVAR is installed, i.e., the inner casing and the production tubing are installed and the tubing contains the operational fluid. The difference between the installation and the operational unit weight (63.9 lb/ft) is nearly ten times that of the corresponding difference in the case of the tubing riser (7.3 lb/ft). This difference has considerable consequences – mainly, when buoyed, the Case-2 riser will be substantially lighter during installation than when it is operational. The precise amount depends on how much buoyancy is needed to maintain the characteristic shape of the CVAR, to provide an adequate tension in the lower region of the riser (to prevent bottom angles to the vertical from exceeding about 15 degrees) and to minimize the stresses (to the degree necessary) due to tension in the upper region of the riser.

The total length is estimated as 10,485 ft with an over-length of 5% of the water depth. Inner casing and the production tubes are also of the same length.

4.6.2 In-place Wave Analyses

Similar to the Case-1, upon completion of static configuration checks, the dual casing CVAR design developed using the sizing spreadsheet tool was subjected to regular wave analyses for the 100-yr RP hurricane and 100-yr RP loop current metocean loading cases given in Table 3-1.

Six scenarios similar to the ones analyzed for the Case-1 were also analyzed for the Case-2. An overpressure is maintained at the top end when oil is used as the internal fluid. The following sub-sections present the main results from these analyses.

Load Case 1: 100 Year Return Period Hurricane

The analysis results obtained for the maximum tension, von Mises stress and the angle of the transition (buoyancy) region with the vertical for this load case are given in Table 4-6. The analysis was done for the 100-yr RP metocean loading estimated for the design data given in Table 3-1 (H_{max} = 77.4 ft, T_{max} = 13.4 sec, surface current = 5.77 ft/sec, vessel offset = 500 ft).

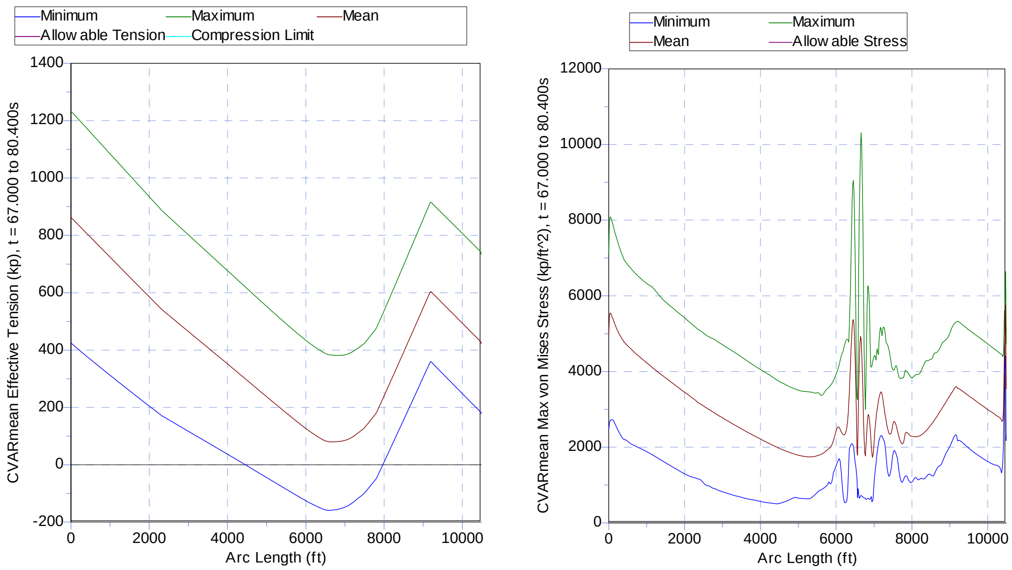
The plots of the effective tension and the von Mises stress distributions along the length of the CVAR are shown in Figure 4-8. The analysis results are shown for light, mean, and kill fluid density cases, i.e., a total of six analysis scenarios.

Table 4-6 Dual Casing CVAR – Inplace Analysis for 100-yr RP Hurricane

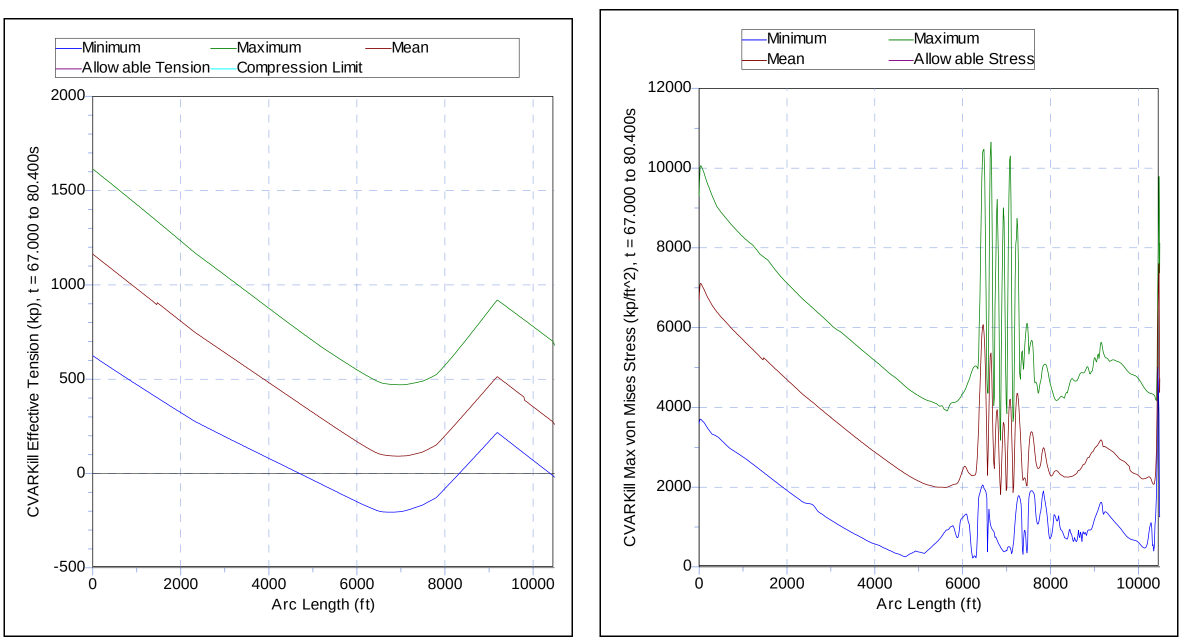
Parameter/Item	Units	FAR (-X)			NEAR (+X)		
		Light Weight Oil	Mean Weight Oil	Kill Fluid	Light Weight Oil	Mean Weight Oil	Kill Fluid
Fluid density in tubing	ppg	5.33	7.10	15.50	5.33	7.10	15.50
Pressure in tubing at riser top	psi	10,000	10,000	0	10,000	10,000	0
Static Analysis Results							
Top Region							
Max. tension	kips	806	815	1,116	845	854	1,162
Max. von Mises stress	ksi	34	34	46	35	36	48
Buoyancy Region							
Min. tension	kips	12	13	13	63	64	73
Max. angle from vertical	deg	86	86	83	54	54	53
Max. von Mises stress	ksi	65	65	52	21	21	21
Dynamic Analysis Results (for the last wave of regular wave run)							
Top Region							
Max. tension	kips	1,019	1,030	1,384	1,222	1,234	1,615
Max. von Mises stress	ksi	46	46	58	56	56	70
Buoyancy Region							
Min. tension	kips	-19	-19	-31	-158	-159	-205
Max. angle from vertical	deg	89	89	86	69	69	62
Max. von Mises stress	ksi	72	72	58	72	72	74

Load Case 2: 100 Year Return Period Loop Current

The analysis results obtained for the maximum tension, von Mises stress and the angle made by the transition (buoyancy) region with the vertical for the 100-yr RP loop current event (H_{max} = 8.8 ft, T_{max} = 5.2 sec, surface current = 8.86 ft/sec, vessel offset = 500 ft from Table 3-1) are given in Table 4-7.



a) Mean Fluid Density Case



b) Kill Fluid Density Case

Figure 4-8 Dual Casing CVAR Inplace Analysis – 100-yr RP Hurricane

Table 4-7 Dual Casing CVAR – Inplace Analysis for 100-yr RP Loop Current

Parameter/Item	Units	FAR(-X)			NEAR(+X)		
		Light Weight Oil	Mean Weight Oil	Kill Fluid	Light Weight Oil	Mean Weight Oil	Kill Fluid
Fluid density in tubing	ppg	5.33	7.10	15.50	5.33	7.10	15.50
Pressure in tubing at riser top	psi	10,000	10,000	0	10,000	10,000	0
Static Analysis Results							
Top Region							
Max. tension	kips	805	814	1,115	850	860	1,167
Max. von Mises stress	ksi	36	36	47	38	38	49
Buoyancy Region							
Min. tension	kips	11	11	12	69	70	78
Max. angle from vertical	deg	88	87	85	53	53	52
Max. von Mises stress	ksi	69	68	55	25	25	21
Dynamic Analysis Results (for the last wave of regular wave run)							
Top Region							
Max. tension	kips	814	823	1,130	877	887	1,211
Max. von Mises stress	ksi	36	36	48	39	39	51
Buoyancy Region							
Min tension	kips	11	11	11	59	59	57
Max. angle from vertical	deg	88	87	85	53	53	52
Max. von Mises stress	ksi	69	68	55	25	25	21

5 CONCEPTUAL ANALYSIS

5.1 General

The following analyses are presented in this section for the Case-1 Tubing CVAR design in 8,000 ft water depth in the GOM, which is assumed to be connected to a semi-submersible FPU:

- Strength analysis;
- Fatigue analysis – wave loading;
- VIV analysis; and
- CVAR clearance and interference analysis.

The Case-1 Tubing CVAR design shown in Figure 5-1 is analyzed by irregular wave analysis using the Marintek/DNV Riflex software. The fatigue analysis is done to estimate the fatigue damage from wave frequency (WF) and low frequency (LF) FPU motions, and from VIV.

5.2 Strength Analysis

5.2.1 Analysis Basis

The irregular wave analysis is done for the two metocean loading cases: 100-yr RP hurricane; and the 100-yr RP loop current. The relevant metocean, vessel offsets and other data are given in Table 3-1. The analysis is done for the mean fluid density (production) and for the heavy fluid density (well kill) cases (see Table 3-4).

5.2.2 Model Description

The Tubing CVAR configuration with component sizes in three regions (upper, transition, and lower) is shown in Figure 5-1. The details of Tubing CVAR sizing configuration and design are given in Section 4. The illustrations of mechanical fittings and ancillary components are given in Section 2.5.

5.2.3 Results

The effective tension and von Mises Stress results from the irregular wave analysis are summarized in Table 5-1 and Table 5-2 for the 100-yr RP hurricane case and 100-yr RP loop current case respectively.

From these results the following conclusions can be drawn:

- The largest compression of (-)36 kips occurs in the transition (buoyancy) region in the FAR vessel position for the heavy density liquid case;
- The maximum von Mises stress is 60% of the yield stress of the P-110 steel considered in the design of Tubing CVAR, and meets the strength design requirements under the survival cases; and
- The governing case for strength design of Tubing CVAR is the heavy fluid density case with the FPU in FAR position and subjected to the 100-yr RP hurricane metocean loading.

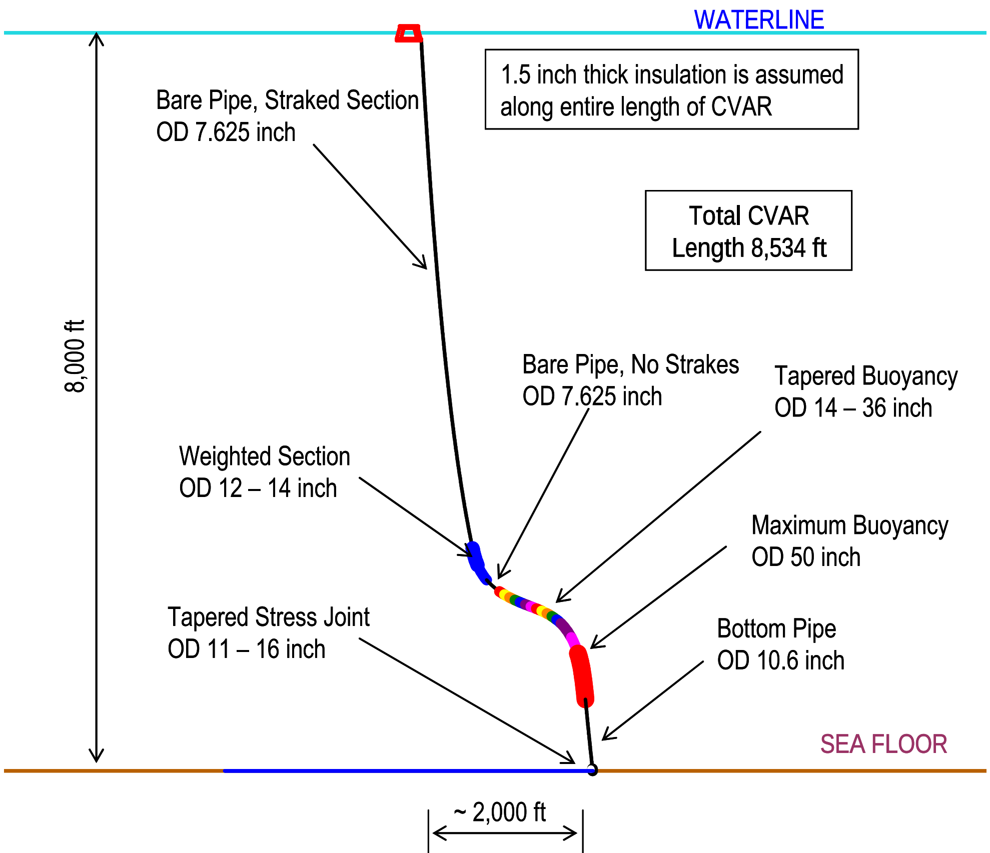


Figure 5-1 Tubing CVAR Configuration

Table 5-1 Tubing CVAR Strength Analysis – 100-yr RP Hurricane

Location	Maximum von Mises Stress		Maximum Effective Tension	
	Hang-off	Transition Region	Hang-off	Transition Region
	Pa (ksi)	Pa (ksi)	N (kips)	N (kips)
Mean Density – Near	3.86E8 (56)	3.45E8 (50)	2.30E6 (517)	-1.47E4 (-3)
Mean Density – Far	4.33E8 (63)	3.30E8 (48)	2.74E6 (616)	-1.56E4 (-4)
Heavy Density – Near	3.91E8 (57)	3.63E8 (53)	2.39E6 (537)	-1.59E4 (-4)
Heavy Density – Far	4.39E8 (64)	3.46E8 (50)	2.84E6 (638)	-1.59E5 (-36)

Table 5-2 Tubing CVAR Strength Analysis – 100-yr RP Loop Current

Location	Maximum von Mises Stress		Maximum Effective Tension	
	Hang-off	Transition Region	Hang-off	Transition Region
	Pa (ksi)	Pa (ksi)	N (kips)	N (kips)
Mean Density – Near	3.71E8 (54)	3.52E8 (51)	1.88E6 (423)	2.63E4 (6)
Mean Density – Far	4.00E8 (58)	3.16E8 (46)	2.03E6 (456)	1.36E5 (31)
Heavy Density – Near	3.75E8 (55)	3.70E8 (54)	1.96E6 (441)	2.70E4 (6)
Heavy Density – Far	4.31E8 (63)	3.30E8 (48)	2.16E6 (486)	1.17E5 (26)

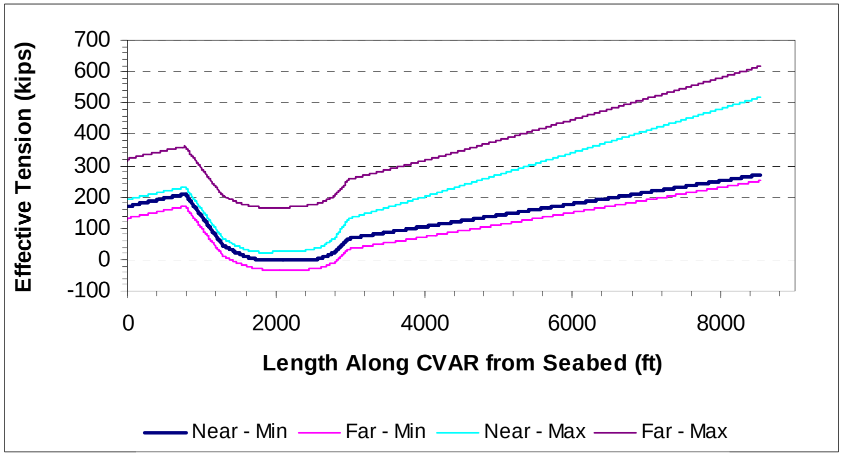
The effective tension and von Mises stress envelopes are plotted in Figures 5-2 and 5-3 for the analysis cases for 100-yr RP hurricane (Table 5-1) and 100-yr RP loop current (Table 5-2) respectively. These plots show the distributions of the minimum and maximum values along the length of the Tubing CVAR.

The following nomenclature has been used in Figures 5-2 and 5-3:

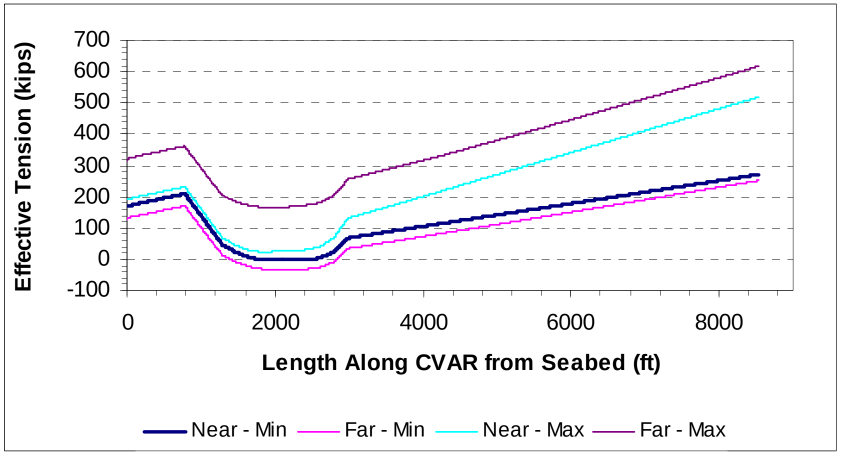
- Near – Min: NEAR position of FPU and Minimum values of tension or stress;
- Far – Min: NEAR position of FPU and Minimum values of tension or stress;
- Near – Max: FAR position of FPU and Maximum values of tension or stress; and
- Far – Max: FAR position of FPU and Maximum values of tension or stress.

These results show that the maximum riser tension and maximum von Mises stresses occur at the hang-off at FPU. The minimum riser tension (or small compression) occurs in the Transition (buoyancy) region.

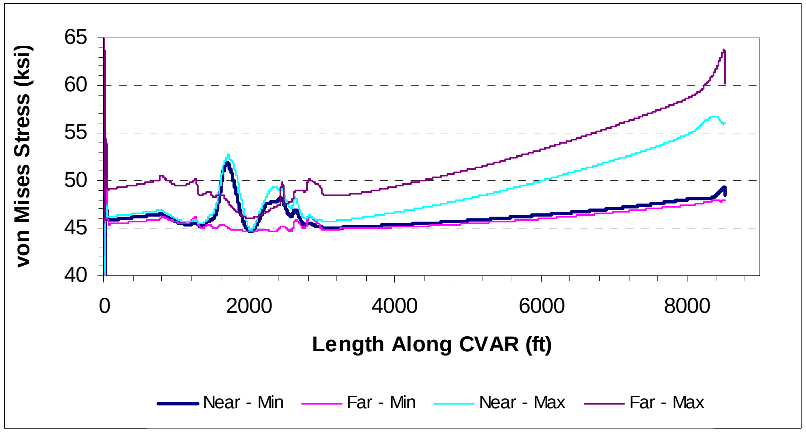
The compression in the Transition Region is estimated to occur for the 100-yr RP hurricane case only, and it is less than 5% of the maximum tension estimated at hang-off, which is acceptable. The T&C connectors are in general designed for a compression loading of about 40% of maximum load capacity.



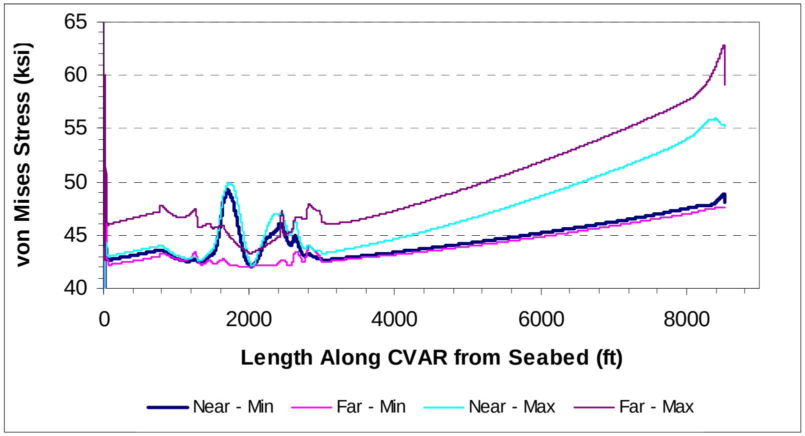
a) Effective Tension Envelopes – Mean Fluid Density



b) Effective Tension Envelopes – Heavy Fluid Density

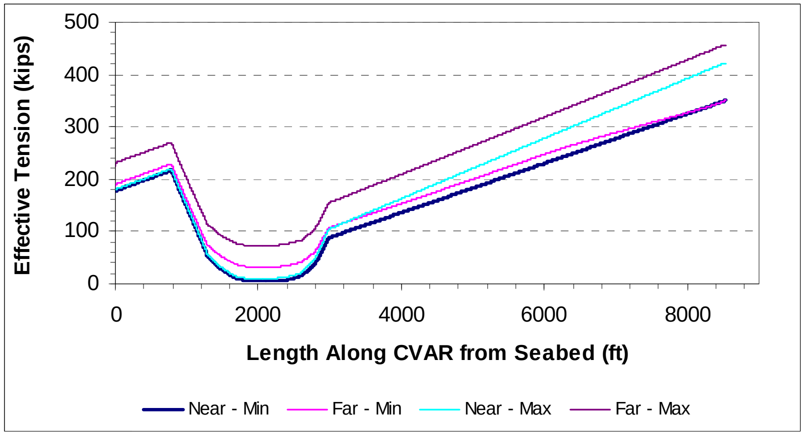


c) Von Mises Stress Envelopes – Mean Fluid Density

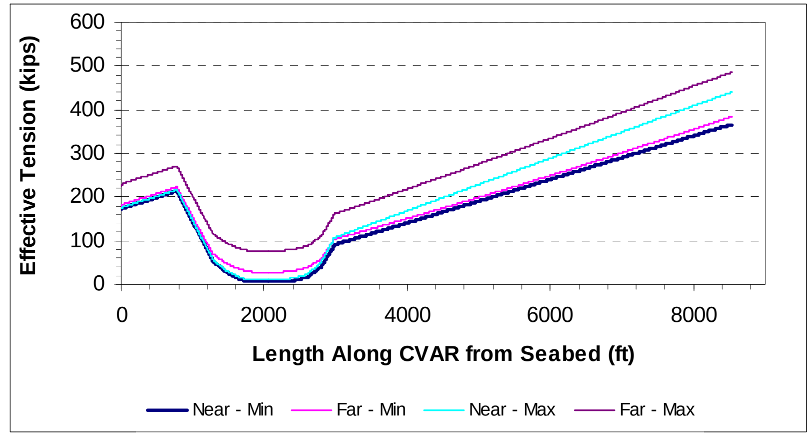


d) Von Mises Stress Envelopes – Heavy Fluid Density

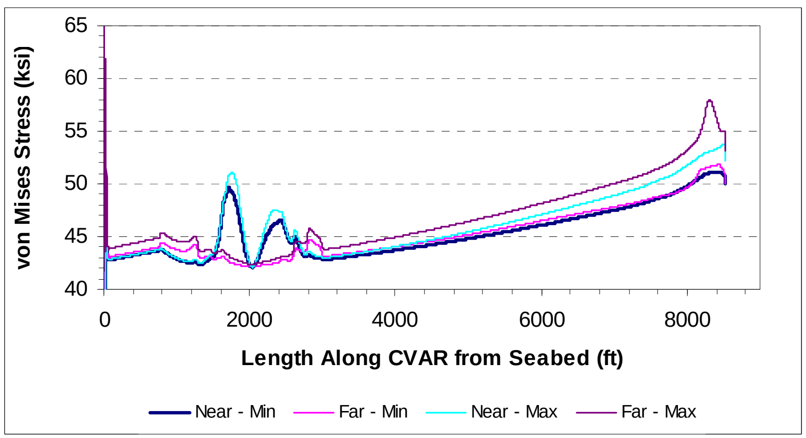
Figure 5-2 Tubing CVAR Strength Analysis – 100-yr RP Hurricane



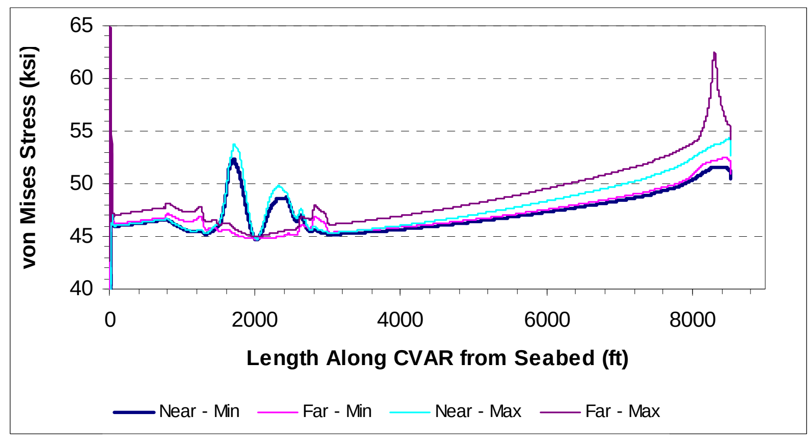
a) Effective Tension Envelopes – Mean Fluid Density



b) Effective Tension Envelopes – Heavy Fluid Density



c) Von Mises Stress Envelopes – Mean Fluid Density



d) Von Mises Stress Envelopes – Heavy Fluid Density

Figure 5-3 Tubing CVAR Strength Analysis – 100-yr RP Loop Current

5.3 Fatigue Analysis – WF and LF Vessel Motions

Fatigue analysis is conducted using the metocean data basis identified in Section 3.4. The GOM wave scatter data is plotted in Figure 5-4. The hydrodynamic coefficients and other parameters are given in Tables 3-14 and 3-15. The fatigue analysis is conducted with vessel mean offsets corresponding to each environment, and includes the damage due to first and second order wave frequency (WF) and low frequency (LF) vessel motions, but does not include the effects of vessel motion induced VIV of the CVAR. Irregular wave, time domain methodology is used for the fatigue analysis, which is conducted using the Marintek Riflex software package.

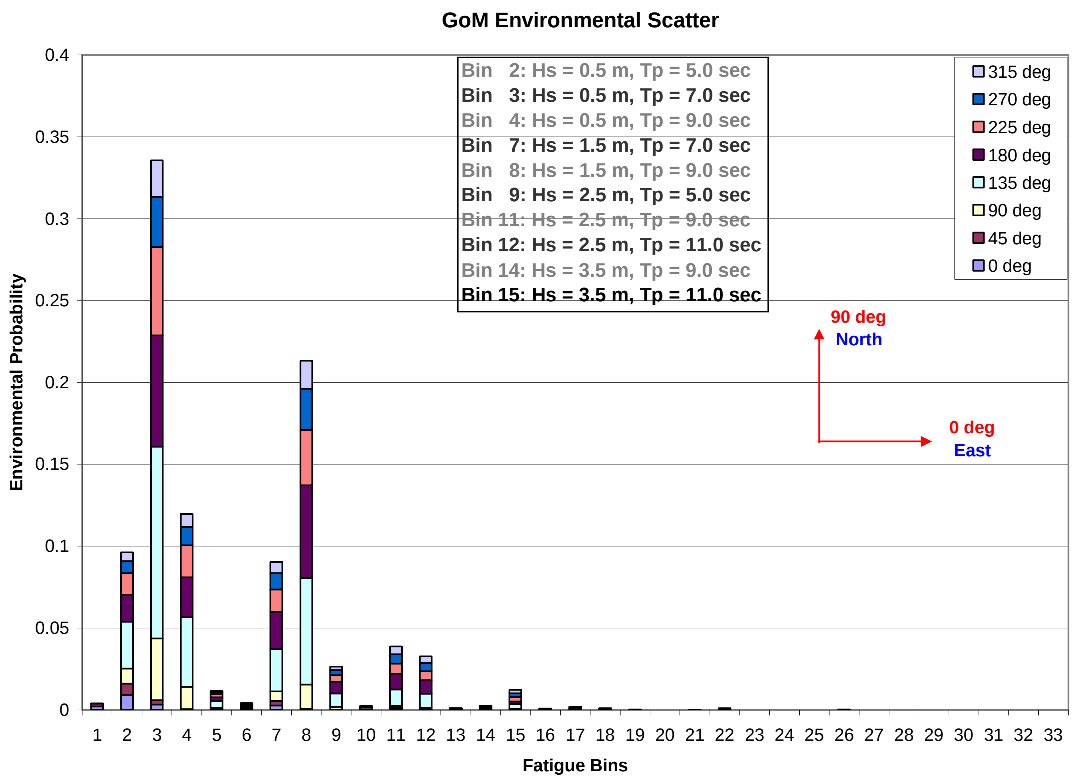


Figure 5-4 Wave Scatter Data for Fatigue Analysis

Figure 5-5 shows a plan view of the Semi-submersible FPU with CVAR and identifies the metocean loading directions used in the fatigue analysis.

The vessel is oriented with the surge axis pointing East, and the CVAR azimuth pointing West. For the analysis purposes it is assumed that the CVAR is suspended on the outside of the pontoon on the transverse centerline at a depth of 64.6 ft (19.7 m), and at a distance of 135.8 ft (41.4 m) from the longitudinal centerline. The CVAR bottom (at the mudline) is at a horizontal distance of 2,000 ft (610 m) from the center of the platform. A flex-joint with rotational stiffness of 15.52 kip-ft/deg (21,040 N-m/deg) is assumed at the hang-off, and a Titanium TSJ of length 23.2 ft (7.072 m) is assumed at the mudline.

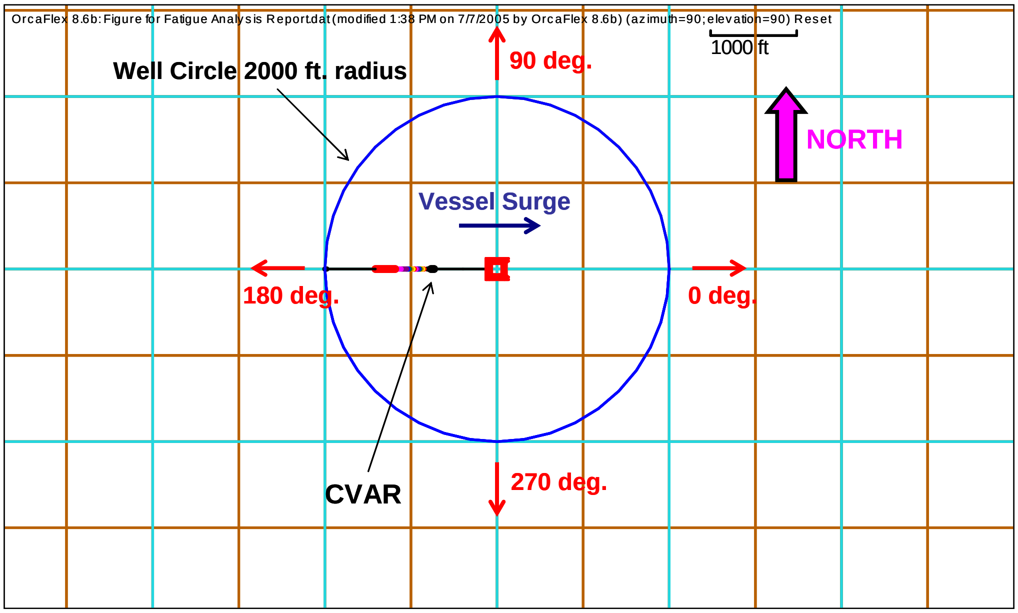


Figure 5-5 Fatigue Analysis Basis – FPU and Wave Directions

The mean (static) and low frequency (sinusoidal) vessel offsets are calculated using the specified metocean data for an 8,000 ft (2,438 m) water depth case. As mentioned in Section 3.4, a total of 33 fatigue bins were run for 8 directions each, and the damage from 16 points around the CVAR cross-section at each fatigue hot-spot are polled to arrive at the maximum damage at that particular hot spot.

The fatigue properties used for the welds and connections are given in Table 5-3 and a comparison of the fatigue curves is shown in Figure 5-6. The "B" S-N curve for the main steel is used for estimation of fatigue lives at the threaded connections over the CVAR length. The "D" S-N curve applies to the weld-on connectors at the weld between the thick forged end weld to the riser section. The "Titanium" S-N curve is used for the welds between the titanium TSJ and the riser section.

The fatigue damage estimated along the CVAR (from the Hang-off point to the Mudline) is shown in Figure 5-7. These results indicate that in most sections of the CVAR, the estimates of fatigue life are very high.

Table 5-3 Fatigue Design – S-N Curves

Connection Type	S-N Curve	C (ksi Units)	m	SCF
Titanium Weld	Asgard/Marintek Curve	6.16E12	5.0	1.2
T&C Connector	Steel DnV (1984) B Curve in Air	4.47E11	4.0	2.0
Weld-on Connector	Steel DnV (2001) D Curve in Seawater	1.77E9 (up to 1.0E6 cycles) 2.59E11 (over 1.0E6 cycles	3.0 5.0	1.2

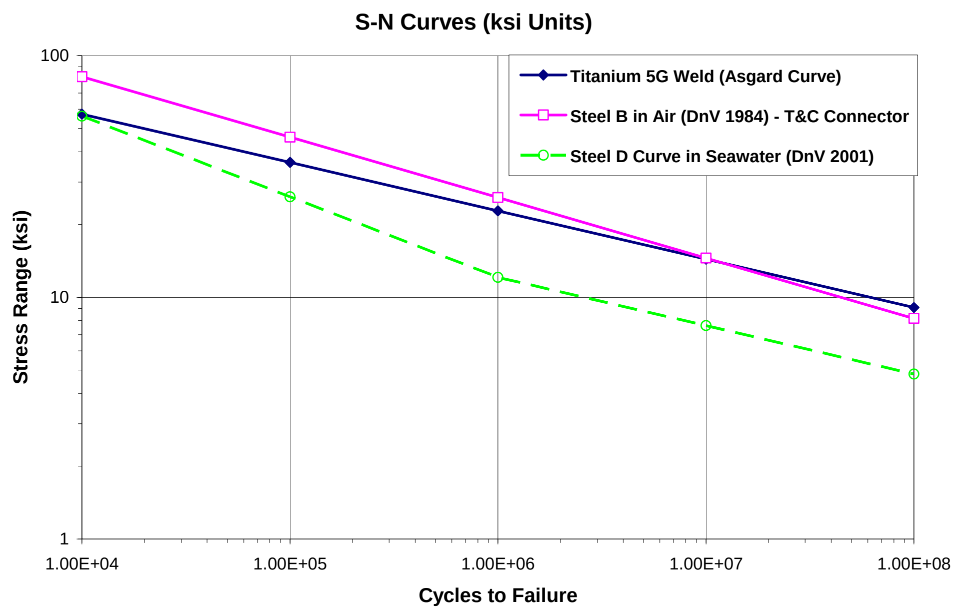


Figure 5-6 Fatigue Design Basis – S-N Curves

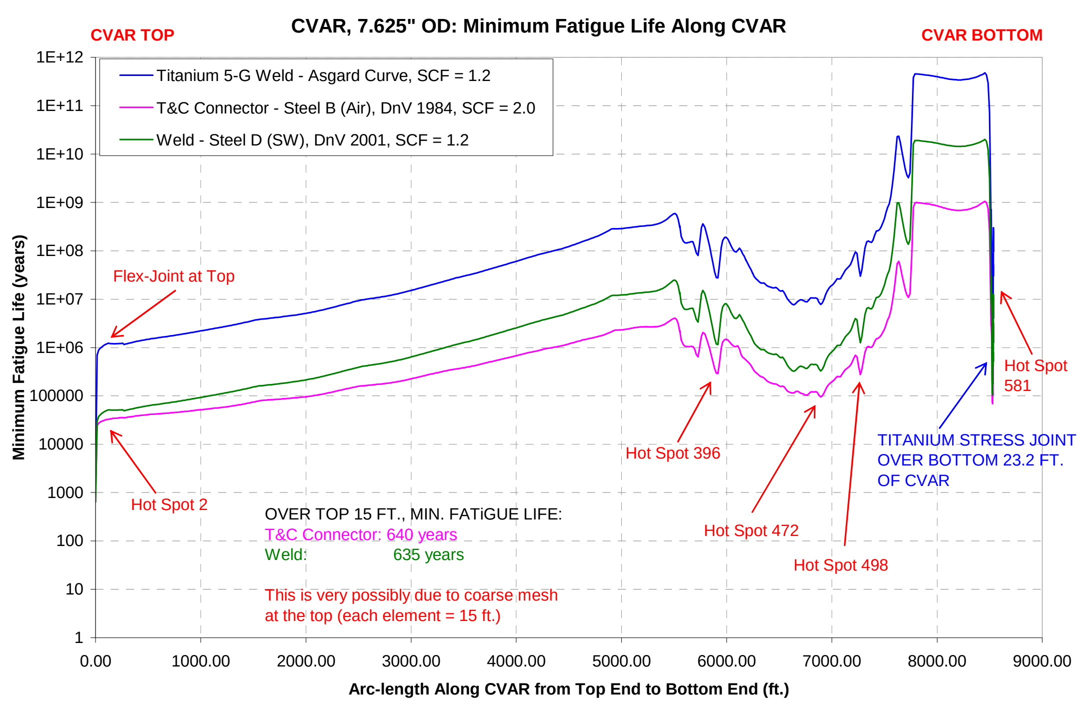


Figure 5-7 Fatigue Damage Estimates Along Tubing CVAR

The following are noted from this analysis results:

- In the CVAR riser sections, the minimum fatigue life of 95,244 years occurs at a distance of 6,893 ft (2,101 m) along the CVAR from the hang-off location.
- Within 14.8 ft (4.5 m) of the flex-joint at the hang-off, the fatigue life drops precipitously to 635 to 640 years. This is due to a relatively coarse mesh in this region in the analysis model. The fatigue life at this connection can be increased by change in the design. At this connection, a titanium TSJ could be used as done for SCRs, which would have the welded connection farther below the TSJ connection with FPU.
- At the bottom end of the CVAR, within the titanium TSJ, the minimum fatigue life is estimated as 2.48 million years. A steel TSJ of the same dimensions (length, OD, etc) as the titanium TSJ would have a minimum fatigue life estimated as 104,000 years. At the bottom end, steel TSJ is used and a titanium TSJ has not been used so far. However, in the present study, a steel TSJ design to meet all criteria (strength as well as fatigue) was not examined, and a steel TSJ would be considerably longer compared to the titanium TSJ to meet all design conditions. This need to be further evaluated.

Figure 5-8 shows the approximate location of the selected hotspots, and Table 5-4 gives the description of the same along the length of the CVAR.

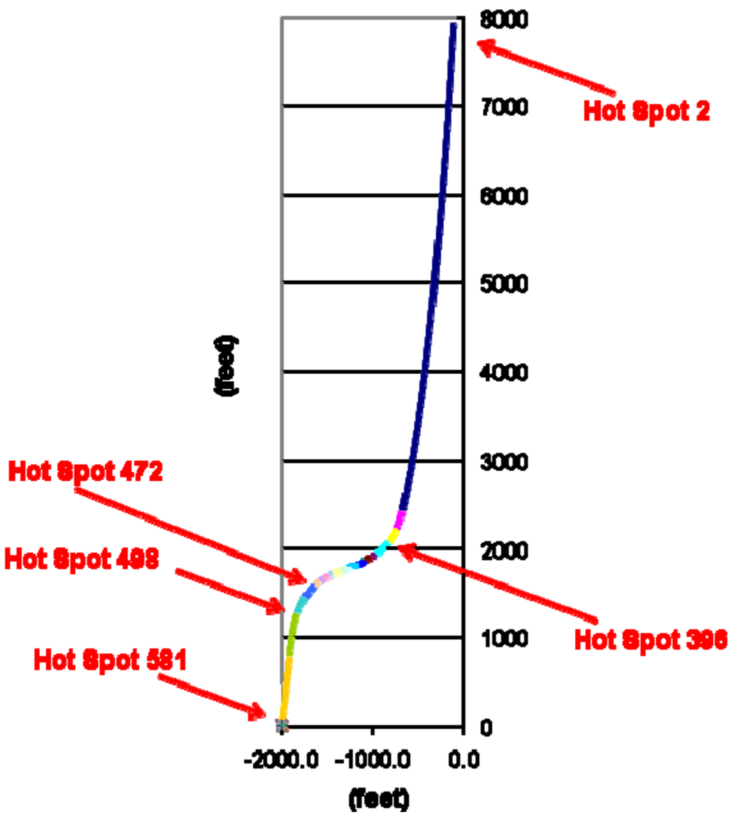


Figure 5-8 Location of Selected Hot Spots

Table 5-4 Definition of Selected Hot Spots

Hot Spot	Segment	Element	End	Distance (Along CVAR) from Hang-off Point	Description
2	1	1	2	15 ft	Close to the flex-joint at the hang-off location
396	3	11	2	5,913 ft	
472	17	1	2	6,889 ft	At maximum damage (minimum fatigue life) location in the body of the CVAR (away from ends of CVAR)
498	19	1	2	7,267 ft	
581	20	50	2	8,512 ft	At interface of the CVAR to the Titanium TSJ

The fatigue damage histograms for the hot spots given in Table 5-4 are shown in Figures 5-9 to 5-13.

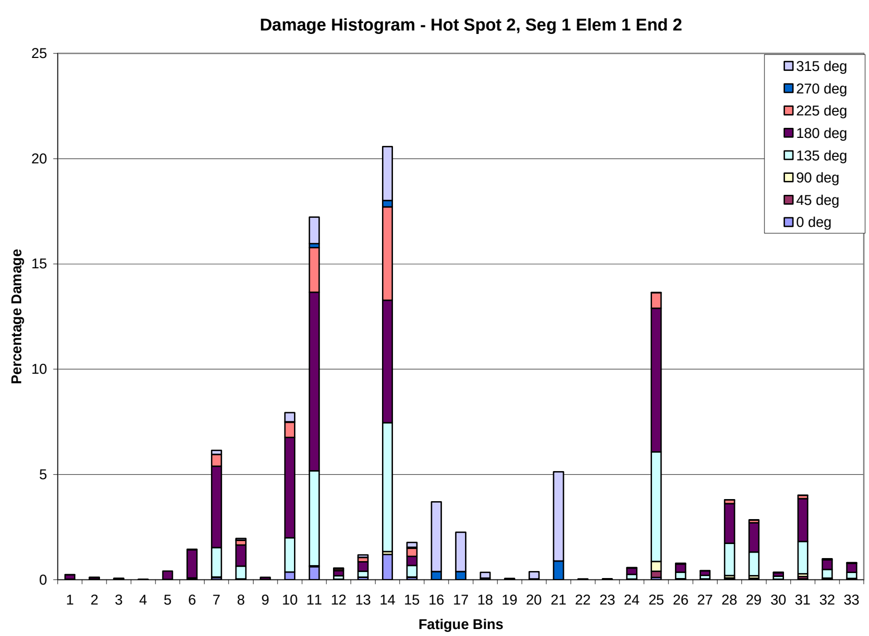


Figure 5-9 Fatigue Damage Histogram for Hot Spot Number 2

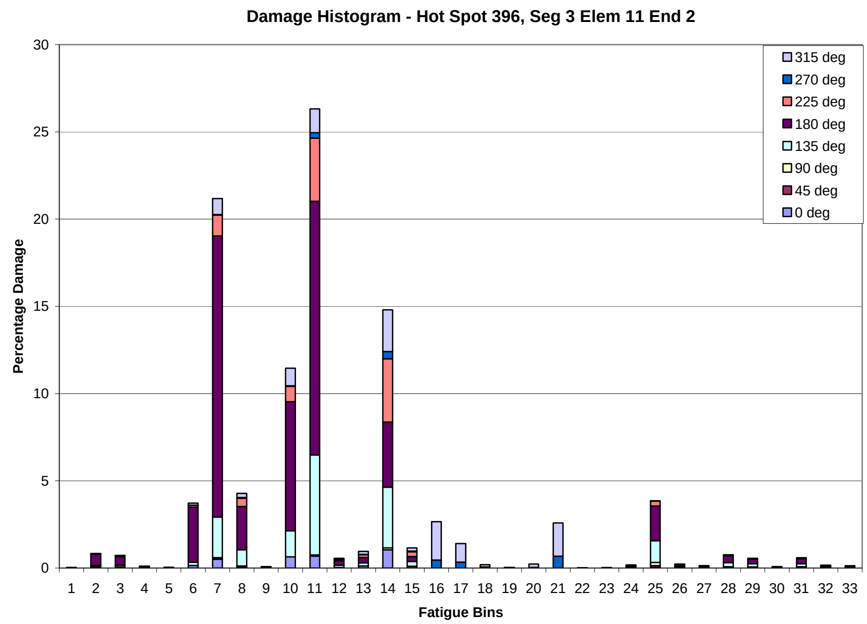


Figure 5-10 Fatigue Damage Histogram for Hot Spot Number 396

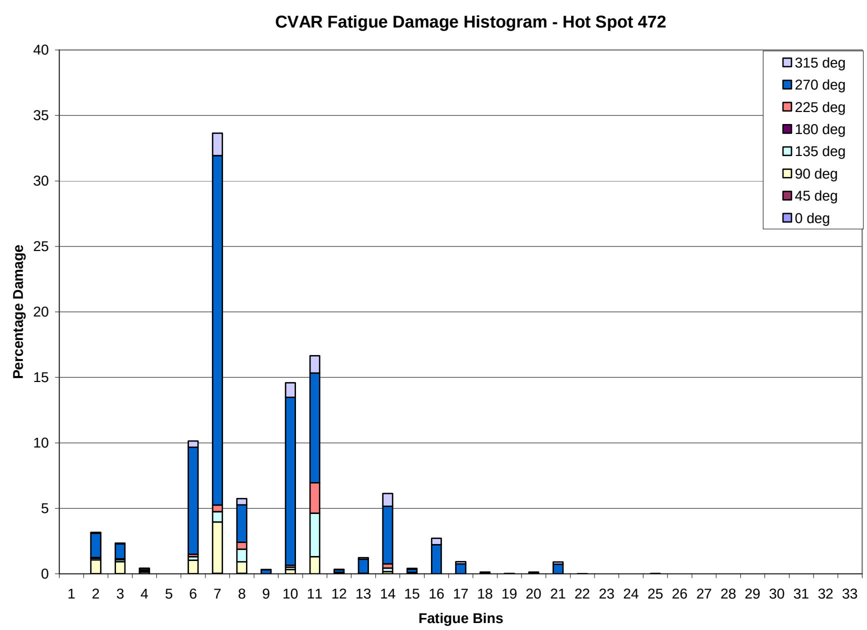


Figure 5-11 Fatigue Damage Histogram for Hot Spot Number 472

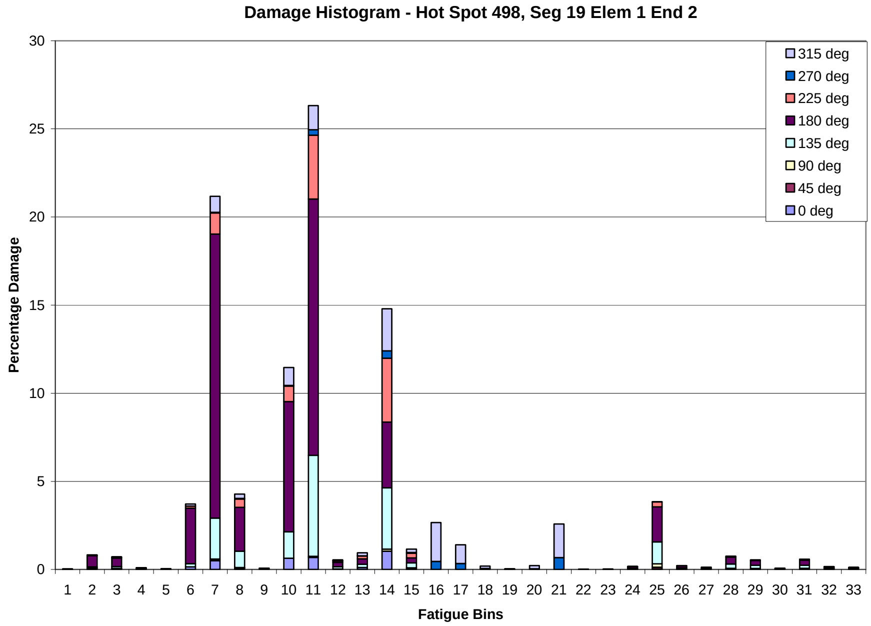


Figure 5-12 Fatigue Damage Histogram for Hot Spot Number 498

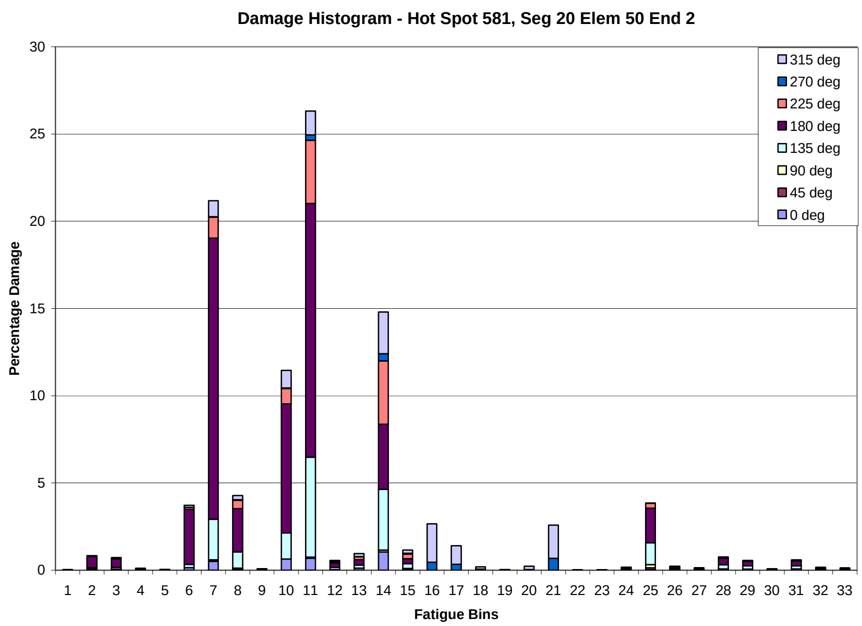


Figure 5-13 Fatigue Damage Histogram for Hot Spot Number 581

It is observed that, in general, Bin 7 (Hs = 4.9 ft. or 1.5 m, Tp = 7 sec) and Bin 11 (Hs = 8.2 ft. or 2.5 m, Tp = 9 sec) are the most critical, except for hot spot number 2 (just below the flex-joint) where Bin 14 contributes significantly. In general, the maximum damage contribution is from the metocean loading direction 180 deg, (from East), but in some instances, the most critical direction is 270 deg (from North).

Tables 5-5 and 5-6 present the relative contributions of mean offsets, and WF and LF motions at these hot spots for the critical fatigue damage bins 7 and 11. The results are presented as the amount of damage which is the inverse of the fatigue life in years. Thus the lowest predicted fatigue life is 172,000 years at the hot spot 472 in bin 7 (Mean +WF, WF). For bin 11, the hot spot 2 produces the lowest fatigue life of 139,000 years (WF+LF).

Table 5-5 Relative Fatigue Damage, Threaded Connectors, Bin 7

Hot Spot	Mean + WF + LF	Mean + WF	WF + LF	WF
2	2.5E-6 (1.00)	2.3E-6 (0.92)	2.7E-6 (1.06)	2.4E-6 (0.94)
396	7.3E-7 (1.00)	1.1E-6 (1.51)	7.1E-7 (0.97)	1.0E-6 (1.44)
472	2.7E-6 (1.00)	5.8E-6 (2.14)	2.7E-6 (1.00)	5.8E-6 (2.15)
498	1.0E-6 (1.00)	2.3E-6 (2.23)	1.0E-6 (1.00)	2.3E-6 (2.24)
581	8.3E-8 (1.00)	3.0E-6 (36.7)	8.5E-8 (1.03)	3.2E-8 (0.39)
Note: Numbers in parentheses (xxx) are relative values with respect to corresponding (Mean + WF + LF) values.				

Table 5-6 Relative Fatigue Damage, Threaded Connectors, Bin 11

Hot Spot	Mean + WF + LF	Mean + WF	WF + LF	WF
2	7.0E-6 (1.00)	6.9E-6 (0.97)	7.2E-6 (1.03)	7.0E-6 (1.00)
396	9.0E-7 (1.00)	9.5E-7 (1.05)	7.5E-7 (0.83)	7.8E-7 (0.85)
472	1.5E-6 (1.00)	1.8E-6 (1.20)	1.4E-6 (0.94)	1.8E-6 (1.16)
498	8.6E-7 (1.00)	9.1E-7 (1.05)	8.3E-7 (0.97)	8.7E-7 (1.00)
581	1.5E-8 (1.00)	1.0E-8 (0.67)	2.2E-8 (1.49)	1.5E-8 (0.99)
Note: Numbers in parentheses (xxx) are relative values with respect to corresponding (Mean + WF + LF) values.				

The fatigue damage at all hotspots is estimated to be less than 1.0E-05, which is negligible.

QA of the fatigue analysis results, fatigue analysis with Mean+WF+LF motions was conducted using the MCS Flexcom-3D software for one critical fatigue bin (bin number 7). Table 5-7 provides a comparison of fatigue analysis results, obtained using alternative Riflex and Flexcom-3D software, at a few selected hot spots along the length of the CVAR for critical fatigue bin number 7 (Hs = 4.9 ft or 1.5 m; Tp = 7 sec) and including damages from all 8 metocean loading directions.

Table 5-7 Fatigue Damage Estimates in CVAR with Threaded Connections - Bin 7
(Riflex versus Flexcom 3-D Software)

Hot Spot	Distance Along CVAR from Hang-off	Distance Along CVAR from Mudline (Note 1)	Max. Fatigue Damage (Riflex)	Max. Fatigue Damage (Flexcom 3-D)
2	15.1 ft (4.6 m)	8519.6 ft (2596.8 m)	2.5E-6	< 1.0E-5
472	6889.3 ft (2099.9 m)	1674.8 ft (501.5 m)	2.7E-6	< 1.0E-5
581	8511.7 ft (2594.4 m)	23.0 ft (7.0 m)	8.3E-8	< 1.0E-5
Note 1. The total length of the CVAR from Hang-off to Mudline is 8534.7 ft (2601.4 m)				

From Table 5-7, the results using the Flexcom-3D software confirm that the fatigue damage estimates are negligible along CVAR, as obtained using the Riflex software.

In conclusion, the CVAR configuration is not sensitive to the wave fatigue damage due to the first and second order vessel motions. The fatigue effects on the CVAR from VIV motions are addressed in Section 5.4, and the fatigue damage from wave fatigue and VIV fatigue to be combined in design.

5.4 VIV Analysis

5.4.1 Analysis Basis

Vortex Induced Vibration (VIV) analysis was performed using the metocean data basis identified in Section 3. Hydrodynamic coefficients and other parameters for VIV analysis are specified in Table 3-15. The analysis was performed using the SHEAR7 version 4.4 software in conjunction with the MCS Flexcom-3D software.

The VIV response of the CVAR has been estimated for three metocean loading conditions – the long term current case, the 100-yr RP loop current case, and the 100-yr RP submerged current case. The 100-yr RP loop and submerged current cases are for survival durations, i.e., how long the riser will survive, if either of the two current scenarios were to occur continuously.

For VIV analysis using the SHEAR7 software, the modal curvatures are required as input. This was done through the common.mds file that is produced by Modes-3D software. The finite element structural model of the CVAR using the Flexcom-3D software is the same as that used in the strength checks.

The following approach is used in the VIV analysis for the Case-1 Tubing CVAR:

- Only transverse (to the current direction) VIV was analyzed and the in-line (to the current direction) VIV damage was not accounted for. This is considered acceptable due to lack of facility within SHEAR7 or any other commercially available software to analyze the in-line VIV, and consideration that the conservatism built into the fatigue damage computation makes up for the in-line damage component;
- The modal analysis was performed with the CVAR in the FPU MEAN position, i.e., with no vessel offset;
- Multi-modal VIV response was studied; and
- The CVAR was modeled with a hinge at the hang-off location.

5.4.2 Model Description

The analysis model used is the same as used for the extreme event analysis in previous sub-section (Figure 5-14 show values of x/L ratio at mudline and at top of riser). The distributions of the modal frequency and modal period with the Eigen pair numbers are shown in Figure 5-15 for the FPU mean position.

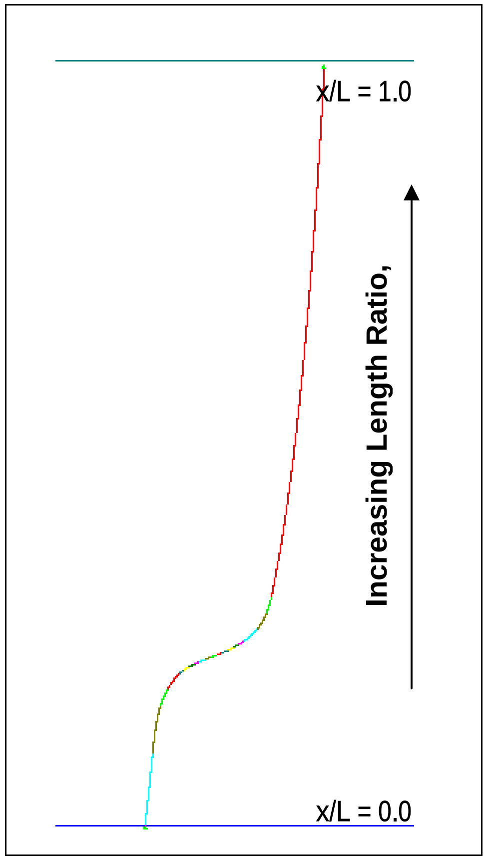


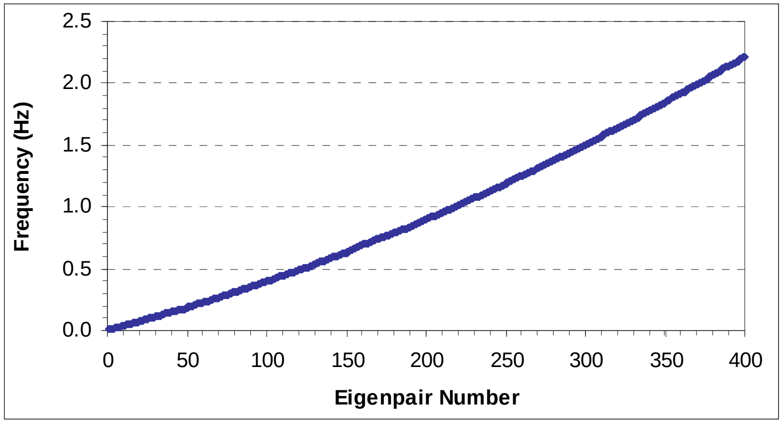
Figure 5-14 CVAR - VIV Analysis Basis

5.4.3 Analysis Results

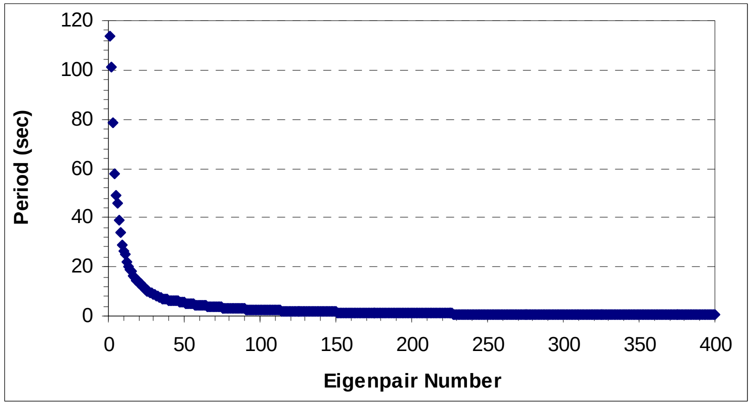
Figure 5-16(a) shows the variation of maximum normalized modal curvature with Eigen pairs for the CVAR. It is seen that the maximum modal curvature does not occur at the same location for all modes. In fact, as can be seen from Figure 5-16(b), the location can vary significantly between different Eigen pairs. The length ratio, x/L, is defined as the ratio between the length along the riser from the seabed and the total length of the CVAR. Thus, the bottom end of the CVAR will have a length ratio of x/L = 0.0 while the top has a length ratio of x/L = 1.0 as shown in Figure 5-14.

As can be seen from Figure 5-16(b), the maximum curvature location for most of the modes is between x/L of 0.14 and 0.22, corresponding to the Maximum Buoyancy and Tapered Buoyancy zones. A few modes also have their maximum modal curvature occurring around a length ratio of 0.33, which corresponds to the weighted pipe segment.

Modal shapes and curvatures for the first 10 in-plane and cross-plane modes are given in Figure 5-17, which show that the in-plane modal curvatures are generally higher than the cross-plane modal curvatures. This provides an indicator that the VIV fatigue damage due to in-plane modes may be higher than that due to the cross-plane modes. Since this analysis is for transverse VIV only (and does not include in-line VIV), the in-plane modes are excited by cross currents, i.e., currents that are in a direction perpendicular to the plane of the CVAR. Indeed, analysis shows that the damage due to in-plane modes excited by cross-plane currents is more than the damage due to cross-plane modes.

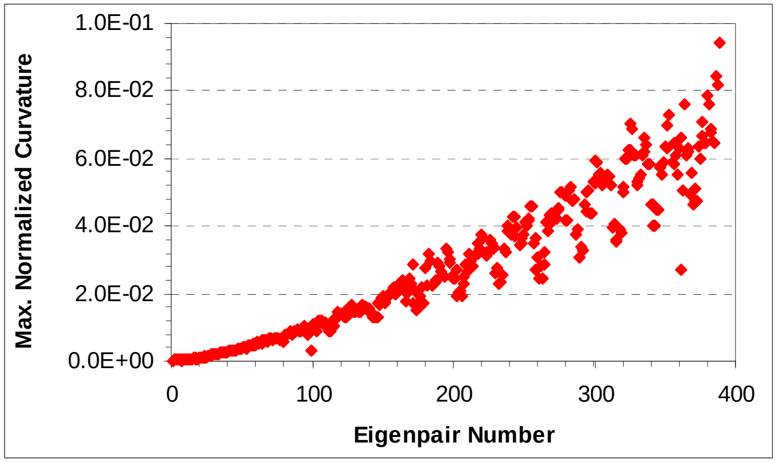


a) CVAR Modal Frequencies

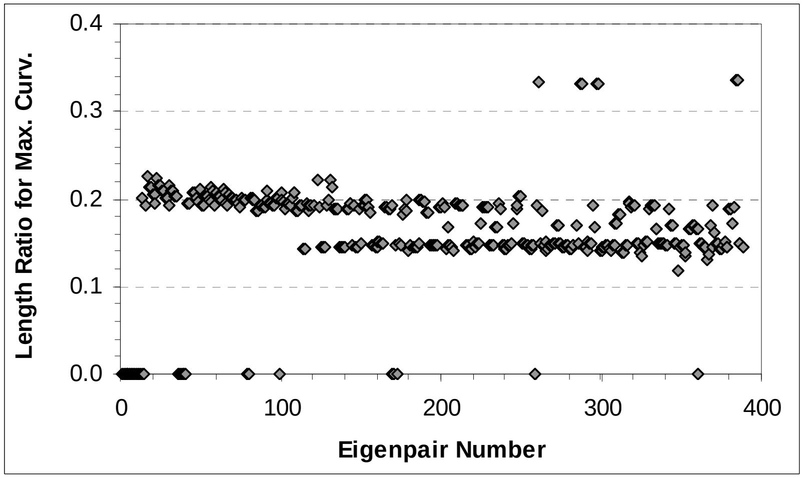


b) CVAR Modal Periods

Figure 5-15 Modal Analysis Input

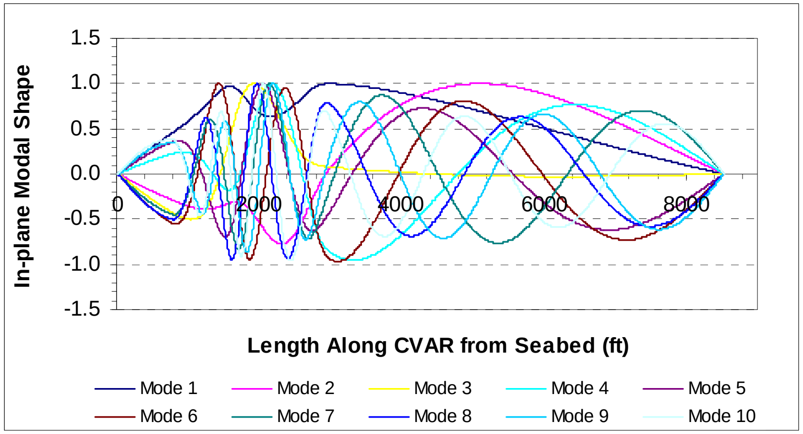


a) CVAR Maximum Normalized Modal Curvature

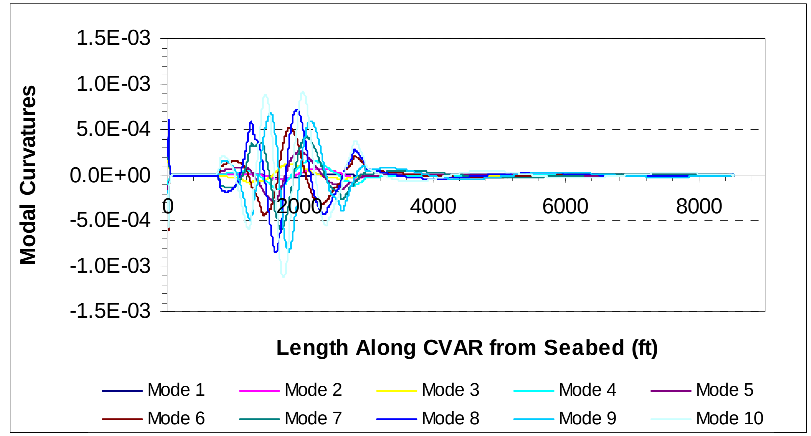


b) Length Ratio of Maximum Normalized Modal Curvature

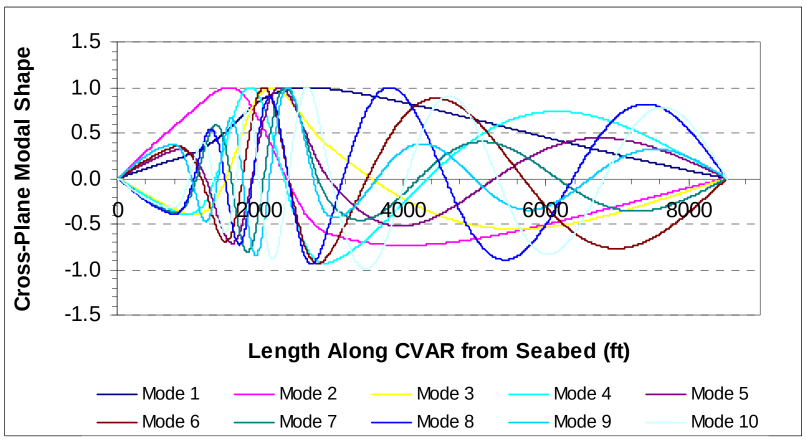
Figure 5-16 Modal Analysis Results



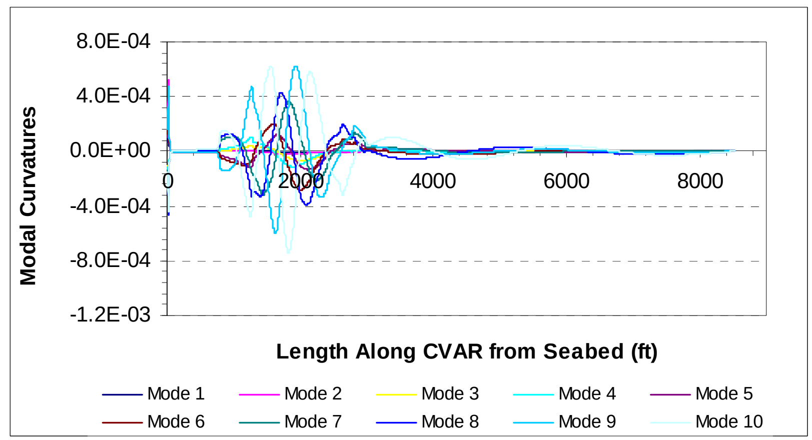
a) Mode Shapes – In-Plane Modes



b) Modal Curvature – In Plane Modes



c) Mode Shapes – Cross Plane Modes



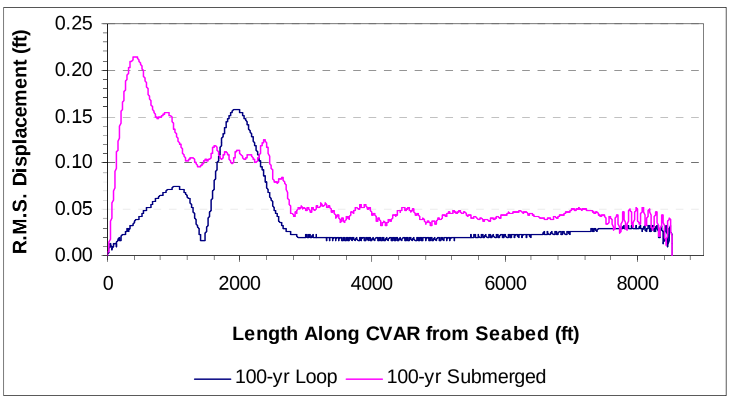
d) Modal Curvature – Cross Plane Modes

Figure 5-17 Mode Shapes and Curvatures – Modes 1 to 10

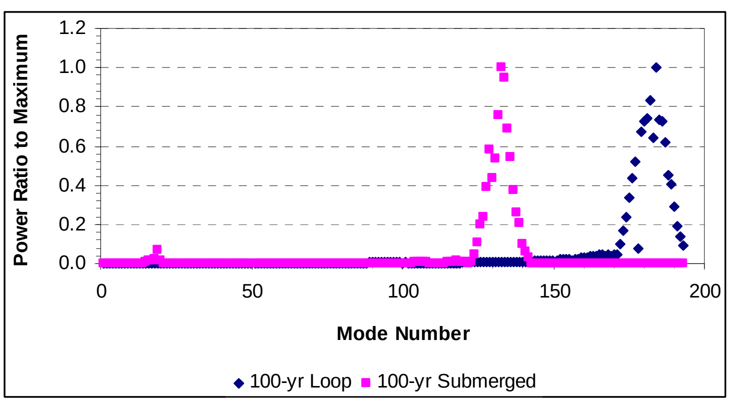
The estimates of unfactored fatigue damage and fatigue life due to VIV are given in Table 5-8. Figure 5-18 shows the distribution of RMS displacement along the CVAR for two 100-yr RP current profiles and the maximum power-in ratio distribution along the modes for the 100-yr RP loop current and 100-yr RP submerged current cases. As can be seen, the mode with the highest power-in for the 100-yr RP loop current is Mode 184 and for the 100-yr RP submerged current profile is Mode 133.

Table 5-8 Unfactored Fatigue Damage and Fatigue Life Due to VIV

Current Type	x/L Ratio	VIV Damage	Fatigue Life	Damage Type
100 Year Loop	0.191	1.44E-01	6.9 yrs	Survival Damage
100 Year Submerged	0.239	3.84E-01	2.6 yrs	Survival Damage
Long Term	0.143	1.75E-05	57,260 yrs	Long Term Damage



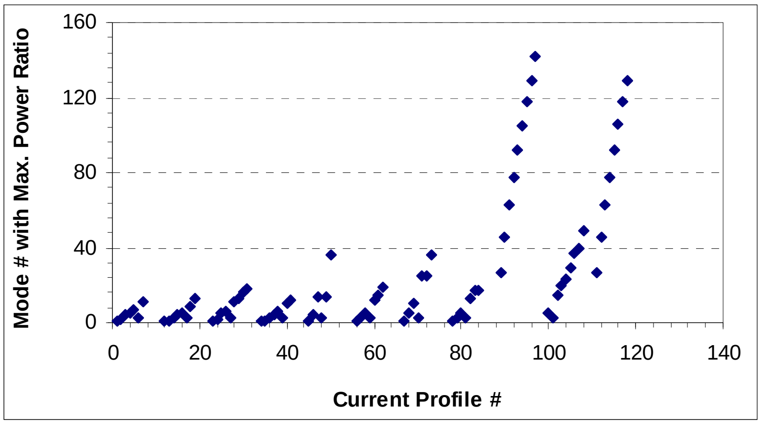
a) RMS Displacement Along CVAR



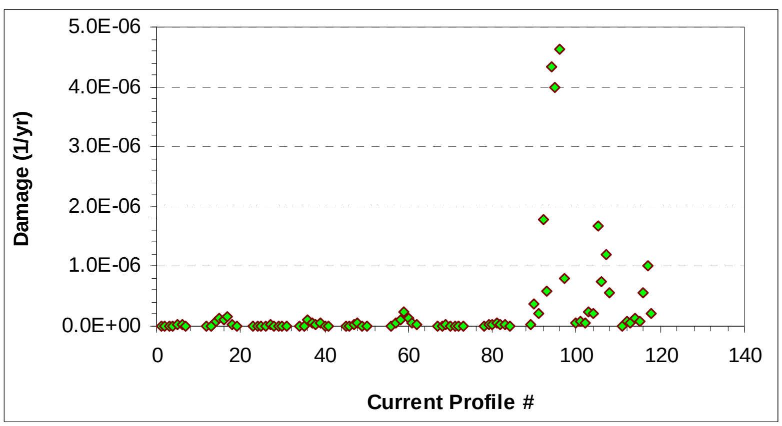
b) Modal Power Ratios

Figure 5-18 Modal Analysis Results – Loop and Submerged Currents

Figure 5-19(a) shows the mode numbers with the highest power-in ratios for the different long-term current profiles. A total of 121 current profiles are considered in the long-term VIV assessment. Of these 121 profiles, the first 88 are combinations of background current profiles, while the next 33 are combinations of loop current eddies. The analysis results show that the loop current combinations excite the mode numbers higher than those excited by the background current profiles. Figure 5-19(b) shows the contributions of damage from the different long term current profiles. Figure 5-18(b) shows that the loop current and submerged current profiles excite the higher modes thereby causing higher damage in comparison to the long term current case.



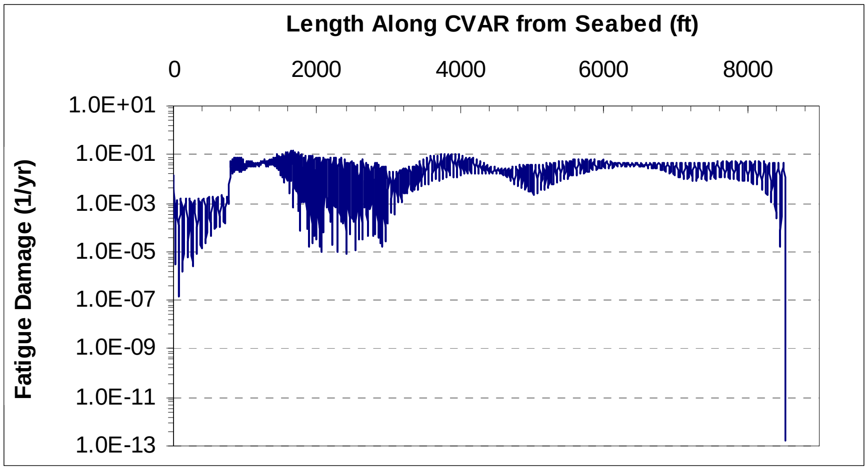
a) Mode Numbers with Maximum Power-in Ratios



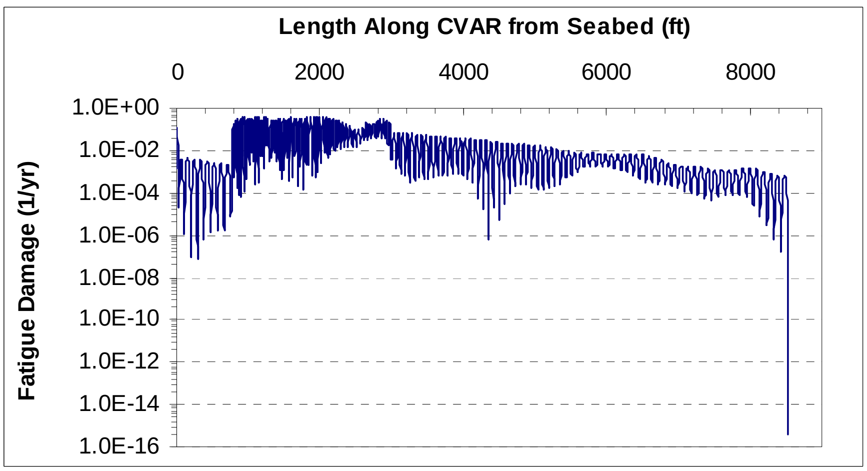
b) Distribution of Damage Among Current Profiles

Figure 5-19 Modal Analysis Results – Long Term Currents

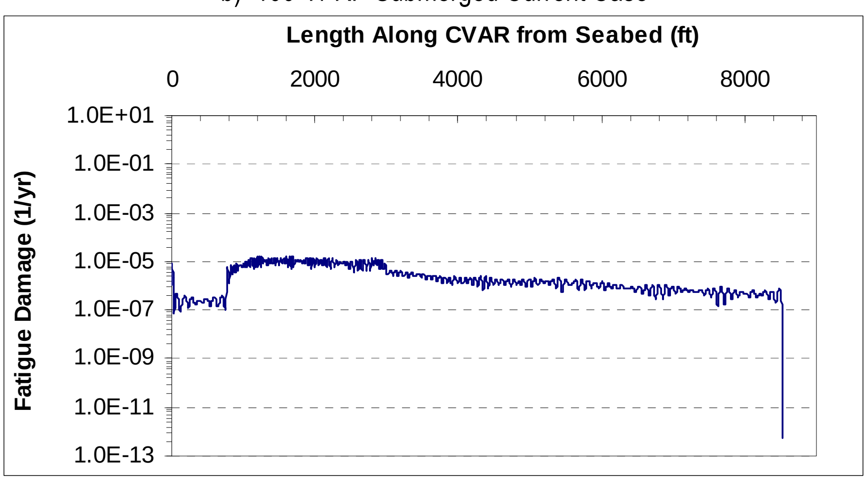
Figure 5-20 shows the fatigue damage distribution along the length of the CVAR for the three current cases analyzed. Figure 5-21 shows the plot of modal curvature of the mode (Mode 184) causing maximum damage for the 100-yr RP loop current case.



a) 100-Yr RP Loop Current Case



b) 100-Yr RP Submerged Current Case



c) Long Term Currents Case

Figure 5-20 VIV Fatigue Damage Distribution Along CVAR

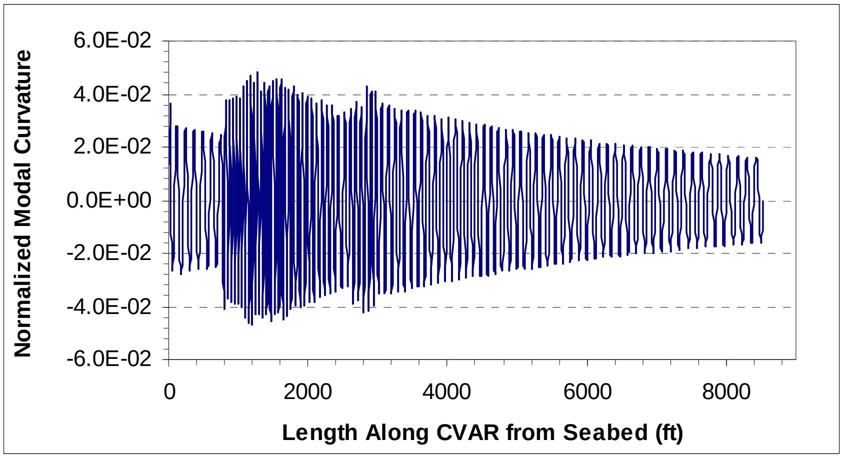


Figure 5-21 Modal Curvature for Mode Causing Maximum Damage – 100-yr RP Loop Current

5.4.4 Sensitivity Studies

The following two cases were considered for VIV sensitivity analysis of the CVAR when subjected to 100-yr RP loop current:

- Effect of mean vessel offset on the VIV response and VIV damage; and
- Comparison of damage between fully straked and partially straked CVAR configurations.

Sensitivity Case 1 – Effect of Vessel Mean Offset

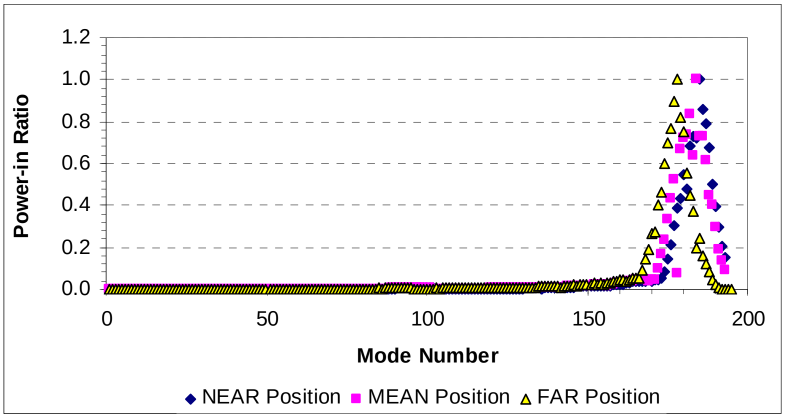
For the first case, the 100-yr RP loop current profile is applied with a mean vessel offset of 6.25% of the water depth in the NEAR and FAR directions. The MEAN position is the one that has no associated vessel offset. Also, in the NEAR and FAR positions, only the hang-off location has been moved to the appropriate position but the 100-yr RP loop current has not been applied before the modal analysis was performed – thus, the current induced static deflections are not included in the analysis. The analysis results for unfactored fatigue damage and fatigue life for 100-yr RP loop current case are given in Table 5-9. The VIV response analysis results are summarized in Table 5-10 and the plots of results are shown in Figure 5-22.

Table 5-9 Unfactored Fatigue Damage and Fatigue Life – 100-yr RP Loop Current

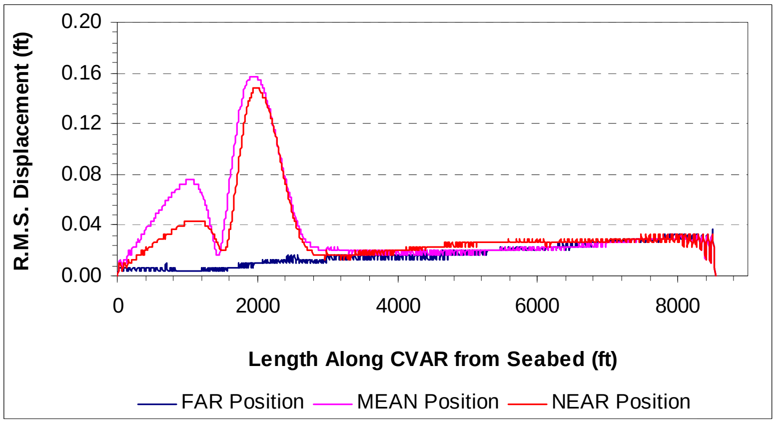
Position	x/L Ratio	VIV Damage	Fatigue Life	Damage Type
NEAR	0.215	5.80E-01	1.7 Years	Survival Damage
MEAN	0.191	1.44E-01	6.9 Years	Survival Damage
FAR	0.148	6.87E-02	14.5 Years	Survival Damage

Table 5-10 VIV Response for 100-yr RP Loop Current

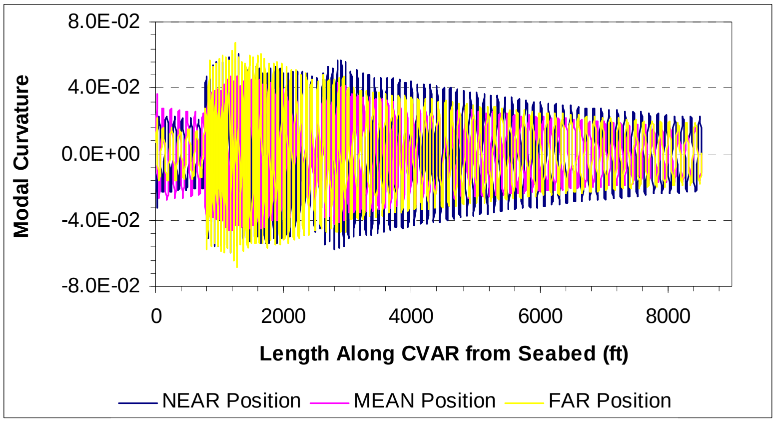
Vessel Position	Most Damaging Mode	Frequency (Hz)	Max. Curvature Along CVAR	Curvature @ Max. Damage Location	RMS Displacement (ft)
NEAR	185	1.9983	6.08E-02 @ x/L = 0.139	5.08E-02 @ x/L = 0.215	0.039 m or 0.128ft @ x/L = 0.215
MEAN	184	2.0056	4.73E-02 @ x/L = 0.149	4.51E-02 @ x/L = 0.191	0.026 m or 0.085ft @ x/L = 0.191
FAR	178	2.0015	6.83E-02 @ x/L = 0.149	3.45E-02 @ x/L = 0.148	0.004 m or 0.013ft @ x/L = 0.148



a) Power-in Ratio Distributions



b) RMS Displacements



c) Most Damaging Curvatures

Figure 5-22 VIV Sensitivity Analysis Case 1 – 100-yr RP Loop Current

From Figure 5-22 it is seen that the maximum normalized curvature values at the location of maximum damage decrease from the NEAR to FAR positions and the RMS displacements at the location of maximum damage also follow the same pattern. Since the damage is a combination of both of these, it also follows the same pattern, with the maximum damage estimated at the NEAR position.

The most damaging modes presented in Table 5-10 are 185 and 184 for the NEAR and MEAN position cases respectively. The distribution of power-in ratio among the various participating modes can be seen in Figure 5-22-a. This figure shows that the 100-yr RP loop current excites very high mode numbers in the region of 1.8Hz to 2.1Hz.

Comparing the RMS displacement values along the CVAR for the three vessel offset positions, it can be seen that the MEAN and NEAR positions have significantly larger displacements than that for the FAR position in the transition (or buoyant) region sections of the CVAR. In the tension dominated regions of the CVAR, the displacements are comparable (see Figure 5-22-b). Figure 5-22-c shows the modal curvature plots for the modes causing maximum damage with the 100-yr RP loop current with the prescribed vessel offsets.

<u>Sensitivity Case 2 – Effect of Straking the Entire Length of the CVAR</u>

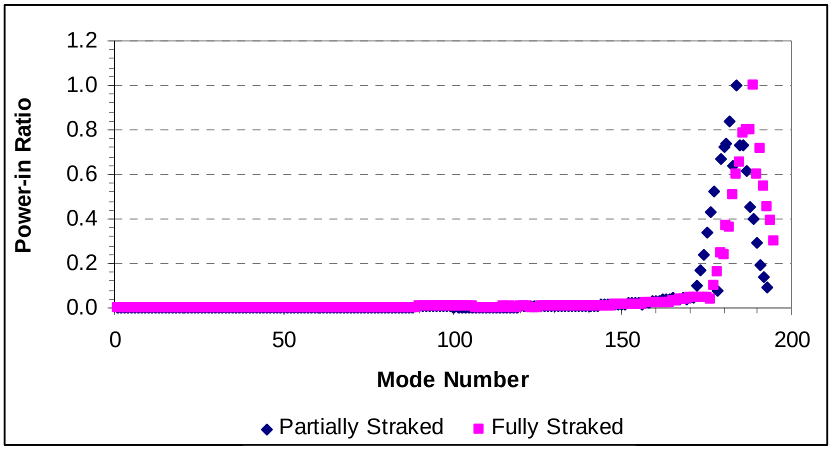
The results for the second sensitivity case to evaluate the effects of fully straking the CVAR are given in Tables 5-11 and 5-12. The results given are for the FPU in its MEAN position. The VIV response results given in Table 5-12 and the plots in Figure 5-23 show that having strakes run all the way down to the TSJ does produce a significant reduction in the fatigue damage. Also, the location of the maximum fatigue damage shifts upwards along the CVAR.

Table 5-11 Unfactored Fatigue Damage and Life – 100-yr RP Loop Current

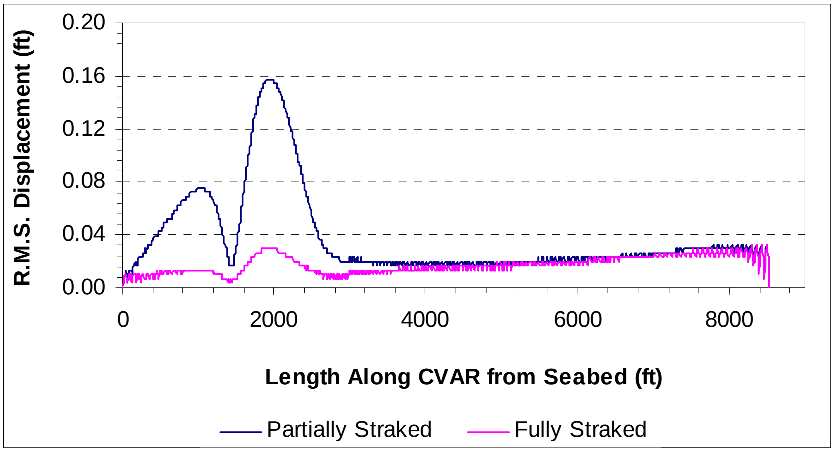
Condition	x/L Ratio	VIV Damage	Fatigue Life	Damage Type
Partly Straked	0.191	1.44E-01	6.9 yrs	Survival Damage
Fully Straked	0.335	4.95E-02	20.2 yrs	Survival Damage

Table 5-12 VIV Results for Partially and Fully Straked Configurations

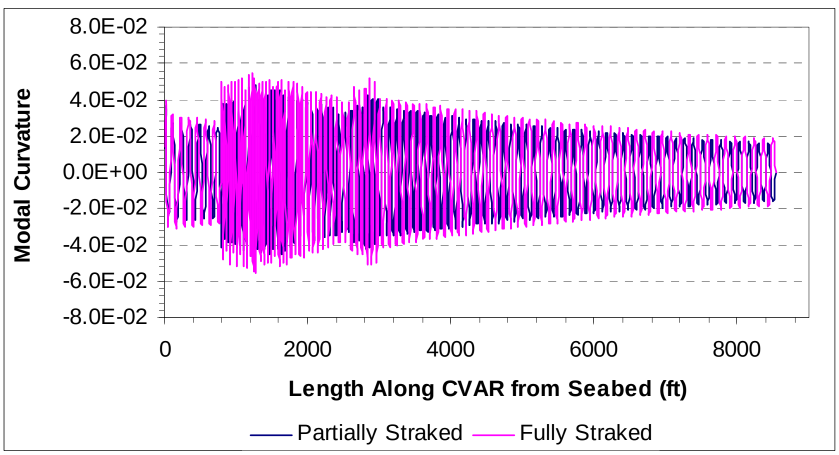
Vessel Position	Most Damaging Mode	Frequency (Hz)	Max. Curvature Along CVAR	Curvature at Max. Damage Location	RMS Displacement
MEAN Position	184	2.0056	4.73E-02 @ x/L = 0.149	4.51E-02 @ x/L = 0.191	0.026 m or 0.085ft @ x/L = 0.191
MEAN Position – Fully Straked	189	2.0075	5.52E-02 @ x/L = 0.150	5.14E-02 @ x/L = 0.335	0.003m or 0.010ft @ x/L = 0.335



a) Power-in Ratio Distribution



b) RMS Displacement



c) Most Damaging Modal Curvatures

Figure 5-23 VIV Sensitivity Analysis Case 2 – Partially and Fully Straked Configurations

5.5 Clearance and Interference Analysis

The analysis is performed for the current loading only, and no wave dynamic effects were included. The loadings investigated are from the maximum loop current and the maximum submerged current given in Section 3.4. In general the riser interference guidelines given in DNV RP F203 [DNV, 2009] are followed.

The interference analysis is conducted with the FPU at the MEAN position and the current loading at right angles (cross-current) to the upstream CVAR. The upstream CVAR is assumed to be hung-off with the longitudinal centerline of the FPU (which has its surge axis pointing towards East) and to have an azimuth going towards East. The downstream riser has a hang-off point 15 ft North of the upstream riser's hang-off location, and it is oriented at 5 deg away from the upstream riser. The current direction (both for loop and submerged current cases) is from the South to the North. The ORCAFLEX® software package is used for this analysis. The orientations of CVARs for the interference checks are as shown in Figure 5-24. The contact clearance implies the riser pipe outer-to-outer clearance, including outstands of strakes, as shown in Figure 5-25.

Strake outstand is a function of the strake design, and it can vary from 0.15D to 0.25D for a strake pitch of 5D to 16D, respectively. Diameter (D) is the pipe OD plus two times the insulation thickness and other coatings on the pipe. D does not include the thickness of the HDPE (high density poly-ethylene) jacket which forms the base of the strake.

Table 5-13 presents summary of the results obtained from the CVAR interference analysis. The contact clearance variations along the CVAR length for the various cases given in Table 5-13 are shown in the plots in Figures 5-26 and 5-27.

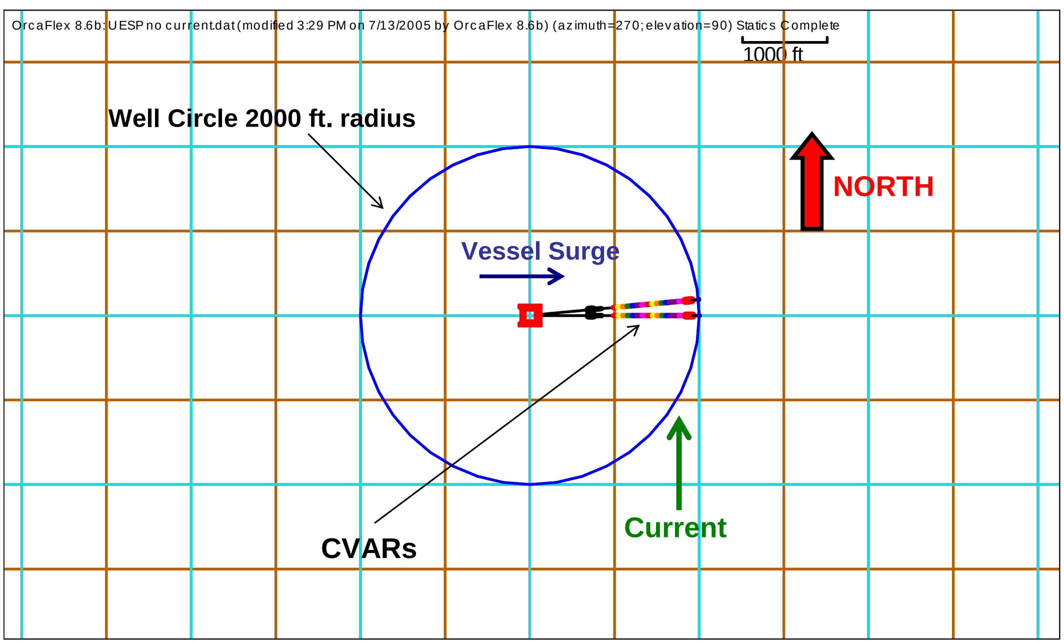


Figure 5-24 Orientations of CVARs for Interference Checks

Table 5-13 Riser Interference Analysis Results

Analysis Case	Maximum Loop Current				Maximum Submerged Current			
	Upstream CVAR	Downstream CVAR	Minimum Contact Clearance	Minimum Centerline Clearance	Upstream CVAR	Downstream CVAR	Minimum Contact Clearance	Minimum Centerline Clearance
1	Light	Heavy	9.7 ft	11.3 ft	Light	Heavy	11.1 ft	12.7 ft
2	Light	Light	13.0 ft	14.5 ft	Light	Light	13.3 ft	14.9 ft
3	Light	Heavy	CLASH (-0.85 ft)	0.7 ft				

NOTES

1. For Light CVAR, content density is 5.0025 ppg, and pressure at platform is 9,250 psi.
2. For Heavy CVAR, contents density is 8.3375 ppg, and pressure at platform is 9,250 psi.
3. For Cases 1 and 2, for both upstream and downstream CVARs, the drag coefficients are assumed to be 2.0 and 1.2 for straked and unstraked regions, respectively.
4. For Case 3, for the upstream CVAR, the drag coefficients are assumed to be 2.0 and 1.2 for straked and unstraked regions, respectively. For the downstream CVAR, they are assumed to be 1.4 and 1.0 for straked and unstraked regions, respectively. This reduction in drag for the downstream CVAR is to approximately account for quasi-static shielding and wake instability effects from the upstream CVAR on the downstream CVAR.
5. Contact clearance implies pipe outer-to-outer distance, including 0.25D (D=pipe OD + insulation) outstand for strakes over the upper 5,550 ft length of the CVAR.

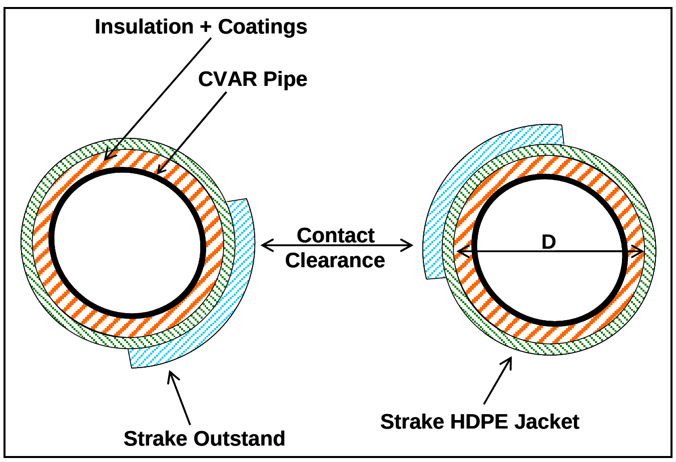
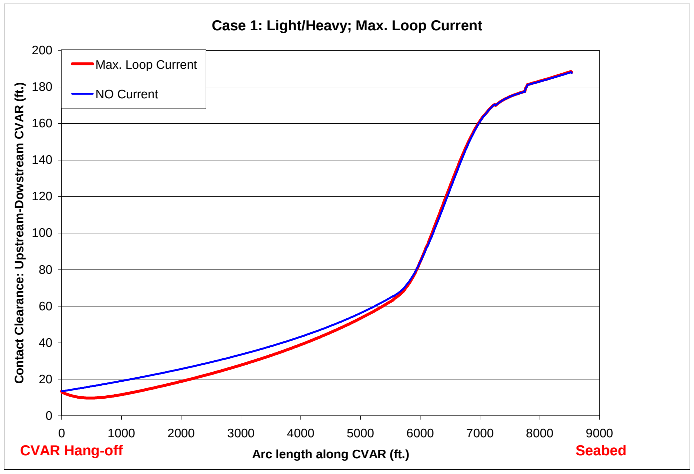


Figure 5-25 Description of CVAR-to-CVAR Contact Clearance

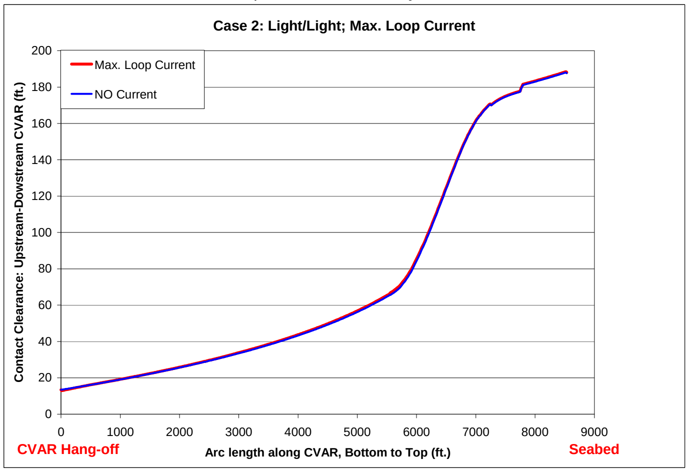
The following are observed from the riser interference analysis:

1. The critical region for riser-to-riser interference is in the upper 500 to 1,000 ft of the CVAR. In this region, the CVAR pipe OD is 7.625 inch, with 1.5 inch thick insulation. Including the strake HDPE jacket, the diameter is approximately 13.06 inch (1.088 ft). The minimum contact clearance (including strake outstands) is estimated as 9.7 ft (Case 1, Maximum Loop Current), which gives an OD/clearance ratio of 8.9 – this is much greater than the two times outer diameter (2 OD) required per DNV-RP-F203 on Riser Interference [DNV, 2009].
2. It is possible that quasi-static shielding effects and wake instability effects, as discussed in DNV-RP-F203 (Sections 4.2 and 4.4 of RP-F203), would reduce the for riser-to-riser clearance. The procedures given in the DNV RP would require a considerable effort and is not done at this stage. Thus a simplified assessment was made in this study by decreasing the drag coefficients of the downstream riser to approximately mimic the effects of shielding and wake instability. The drag coefficients were reduced from 2.0 (straked section) and 1.2 (unstraked section) for the upstream CVAR to 1.4 (straked section) and 1.0 (unstraked section), respectively. The results in Table 5-13 indicate that this change in drag coefficients the maximum loop current case could possibly lead to a "light" riser-to-riser contact.
3. In addition, the following approaches could be considered to obtain an increase in the riser clearance:
    - Increase the hang-off CVAR-to-CVAR clearance greater than 15 ft;
    - Change (marginal) the azimuth of adjacent CVARs; and
    - Add more weight in the bottom of the upper region sections of CVAR to increase resistance to the lateral motions from current.
4. Lastly, the CVAR system can be designed such as to allow a minimal amount of light contact in infrequent maximum loop current conditions.

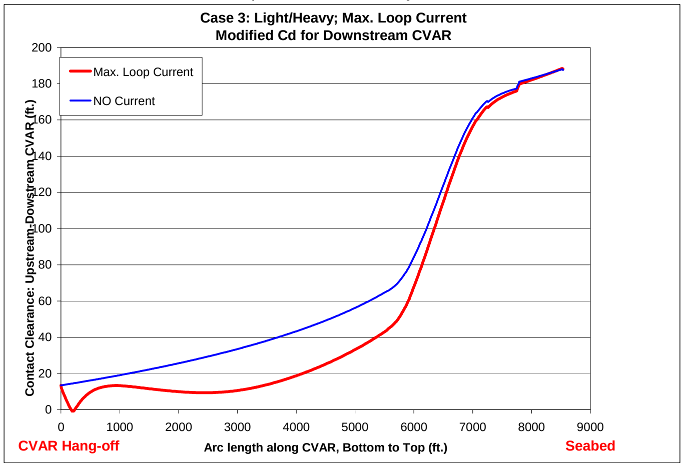
Staggering of CVARs is not a viable option to control the riser-to-riser contact since it is the upper sections of the CVARs that are most susceptible to contact under current loading, and these upper sections would remain substantially vertical even if the CVARs were to be staggered.



a) Case-1 Analysis

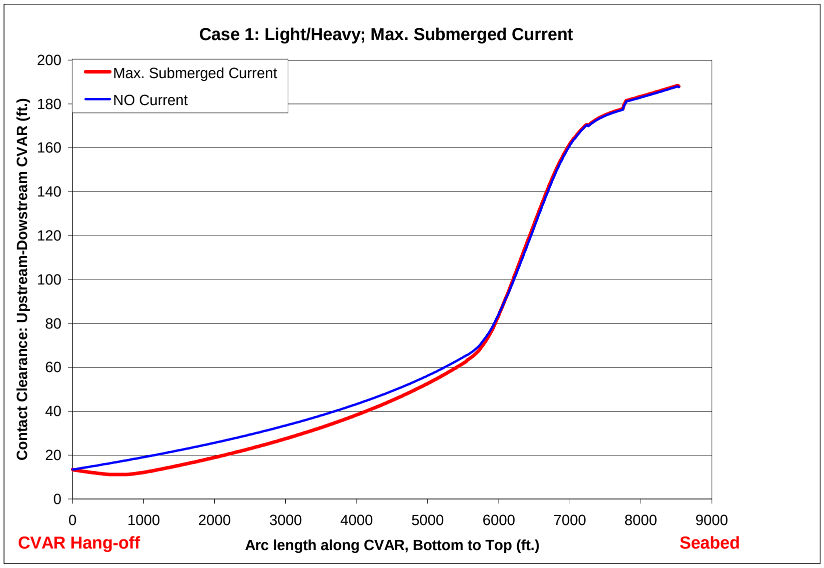


b) Case-2 Analysis

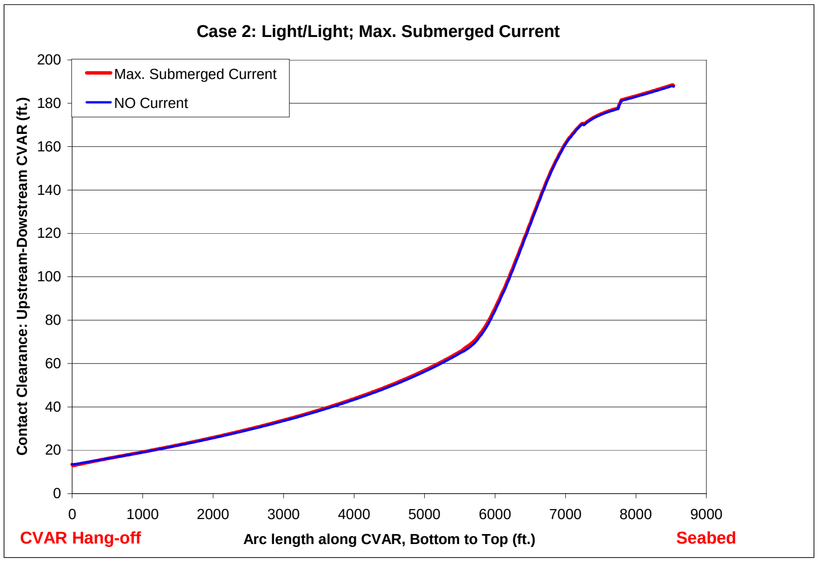


c) Case-3 Analysis

Figure 5-26 Contact Clearance Analysis – Maximum Loop Current



a) Case-1 Analysis



b) Case-2 Analysis

Figure 5-27 Contact Clearance Analysis – Maximum Submerged Current

5.6 Summary of CVAR Analysis

The analysis of the Case-1 design with Tubing CVAR has been performed using the irregular wave analyses. A set of analyses including strength, fatigue, VIV, and riser-to-riser interference were performed and the results are reported. The following are observed from the analysis performed:

- The governing case for the strength design, is the "Heavy density fluid (kill fluid) with the FPU at the FAR position" and subjected to the 100-yr RP hurricane metocean loading:
  - The maximum stresses generated under the above governing strength condition are less than 0.6 of the yield stress in the riser pipe under the 100-yr RP hurricane condition, hence the design satisfies the code requirements under survival conditions.
- The CVAR fatigue characteristics are exceptionally well, based on the following estimates:
  - The main body of the CVAR shows wave-induced fatigue life of almost 100,000 years thus satisfactorily fulfilling the design requirement of 250/500 years; and
  - The flex joint/stress joints (CVAR connections to the hang-off point or above the mudline) are estimated to have fatigue lives of more than 500 years.
- The CVAR design shows excellent VIV response against three current cases.
- For the configuration evaluated in above analysis, the Tubing CVAR design exceeds the interference criteria as established by DNV codes.

6 CVAR SYSTEM REVIEW

6.1 CVAR Configuration and Components

The configuration and design developed in Sections 4 and 5 for the Case-1 Tubing CVAR is shown in Figure 6-1.

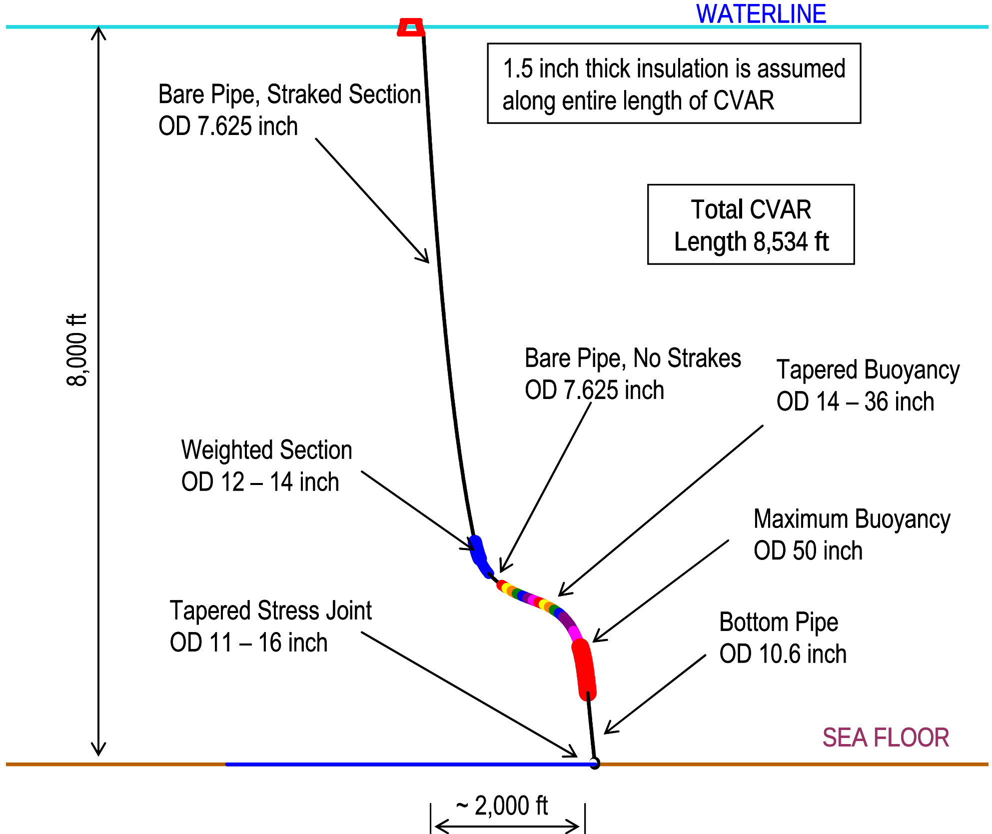


Figure 6-1 CVAR Configuration

The following key components are required in the design of a CVAR:

- Surface tree;
- Flexible joint or titanium TSJ at top;
- Riser joints with threaded ends – similar to the T&C riser joints used in TTR;
- Insulation coating on steel riser sections, and field joints at T&C connections on barge – required for the tubing riser;
- FBE coating for corrosion protection on all steel riser sections;
- Cathodic protection anodes on complete length of the riser;
- Strakes in the upper region riser length;

- Heavy weight coating or weighted sections over lower part of the upper region riser length;
- Buoyancy modules in the transition region riser length;
- Large buoyancy modules at top of lower (upright) region riser length;
- Steel TSJ at the bottom end of CVAR;
- Mudline tree package – in case of tubing and single casing CVARs; and
- Umbilical – designed as separate from CVAR.

The illustrations or vendor designs for most of the above components or sub-systems are given in Section 2. In case of the Tubing CVAR design shown in Figure 6-1, the estimates of required sizes of buoyancy modules, weight coating, and stress joints are as follows:

- Insulation coating – 1.5" thick in case of tubing riser;
- Weight coating over part of upper riser length at its lower end, of which over half length may be tapered or stepped;
- Buoyancy modules (11" to 13" thick) and tapered or stepped buoyancy at ends with thickness reducing to 2";
- Buoyancy modules (20" thick) or buoyancy tanks;
- Titanium TSJ for connection of the upper end of CVAR with the FPU hull; and
- Steel TSJ for connection of the lower end of CVAR with the mudline tree package – length 23 ft.

6.2 MMS Requirements for Riser Systems

Discussions were held with the Minerals Management Service (MMS) to identify and review key regulatory issues applicable to maintaining integrity of the oil and gas production risers in deepwater and ultra-deepwater installations in the GOM. A teleconference and two project meetings were held with the MMS at the Granherne, Houston office and at the MMS, New Orleans offices to review the CVAR riser design, installation plan, analysis results, and discuss potential hazards and risks associated.

The provisions given in MMS 30 CFR Part 250 states that CVA (Certifying Verification Agent) review of riser system design is required. Besides meeting the requirements of industry design standards, the MMS requires inspectability and maintainability assurance. The MMS mentioned that new designs of riser systems may need a thorough review by the MMS, and based on that they would identify if it is necessary to introduce some test sections, in initial applications, with capability for removal and testing at a later date to check their performance.

6.3 CVAR System Design Review

The CVAR design presents a riser system with significant variations along its length in the cross section of the riser pipe, its coating, and the attachments. Thus the possible sources of failures and their consequences would vary along the riser length, and the risk will be a function of the location along the riser length. The weight coatings and buoyancy modules have the primary function to enable the CVAR maintain its compliant configuration and meet the design requirements for effects from various combinations of internal fluid, external pressure, platform loading (local and global), but they also provide protection to the riser pipe. Thus to identify potential hazards and risks, the CVAR design components are grouped under the following three categories giving consideration to their functional requirements and interface in the overall CVAR assembly:

- Steel riser sections: An assembly of HSS riser sections, with T&C connectors at both ends, for tubing or single casing or double casing CVAR designs in the following three groups (see Figure 2-4):
  - Upper (Top) Region riser length with insulation, strakes, and weight coating at lower part of this length. The upper end is fitted with a flex joint or a TSJ (Titanium with compact flange connection between titanium and steel riser sections), which is connected to the FPU hull.
  - Transition (Buoyancy) Region riser length with insulation and buoyancy modules between the lower region riser and upper region riser.
  - Lower (Upright) Region riser length with insulation and large diameter buoyancy modules at its upper end and a steel TSJ welded at its bottom end.
- Mechanical fittings/components:
  - Surface tree;
  - Flex joint or titanium TSJ at top;
  - Steel TSJ at bottom; and
  - Mudline tree package with shear ram.
- Ancillary Components or Attachments:
  - Buoyancy modules with varying diameter in the transition region riser length;
  - Large diameter buoyancy module – at top of the lower region riser length;
  - Insulation coating;
  - Heavy weight coating or weight modules;
  - Strakes (molded attachments) or fairings; and
  - Anodes.

The hazards would vary for each of the above groups or three parts of the riser length, and effects of an event occurring in a part of the riser length and associated components could in some cases have consequences on other part of riser or the whole system. However, the probability of such an occurrence will be lower.

The integrity of steel riser sections assembly and the mechanical components is the most important for safe production from the CVAR and to minimize the impact from failure of a riser component or system on the overall FPU. These components are subjected to the effects of the following loading sources and operations:

- Environmental and accidental loading on the FPU and the riser system;
- Effects of production fluid or gas and variations in properties; and
- Effects of other operations (such as workover, inspection, etc.) undertaken from the riser.

In addition, variations of the as-installed state of the CVAR and its components from the design drawings have an effect on the riser pipe loads and stresses.

The design processes for these components consider sources for loading and deterioration, and various uncertainties associated with their manufacturing processes, inherent capacities, and anomalies during installation and commissioning. In addition, damage scenarios are considered in the design of riser to account for loss of some attachments or local damage in some components, to ensure that allowable stresses per the design codes and standards are met, as given in Tables 3.6 to 3.9.

The ancillary components or attachments are not the load carrying elements and their function, when effects of all of them is considered together, is to maintain the CVAR offset position and its configuration to perform the desired operations, including well intervention, maintain flow, and keep stresses and deflections in the steel riser sections and mechanical components/fittings within design limits. The functions of each individual ancillary component in the design of riser pipe and its mechanical fittings/components are as follows:

- Buoyancy modules enable the CVAR maintain its configuration under static and dynamic loadings, from global performance of FPU and from the local loads on the CVAR and its components, in the design range with acceptable stresses and riser curvatures;
- Large diameter buoyancy modules in the lower (upright) region riser length enable maintain the rotation angle at the TSJ at bottom, and the riser curvature within the design limits;
- Insulation coating to maintain the temperature of fluid in the riser pipe and avoid hydrate formation and maintain production rate;
- Weight coating enable reduce the potential for compression loads in the riser and improve its stability against VIV loading;
- Strakes in the upper region riser length help in VIV suppression and to increase the analytical estimates of fatigue life of the riser pipe and its connections; and
- Anodes provide protection to the riser pipe and its mechanical fittings against degradation from corrosion and its effects on their capacity and fatigue performance.

These attachments however increase the metocean loads and load effects on the steel riser sections and mechanical fittings. Failures of these attachments from external sources and metocean loads are possible and are important to consider for their impact on the integrity of the CVAR steel sections and mechanical fittings. The consequences from their failures and the remedial measures required could be as follows:

- Increase in stresses (tensile, bending) or compression loading in the CVAR pipe sections and mechanical fittings/components;
- Changes in riser curvature from failure of some attachments could lead to difficulty in well operations before repair and maintenance work for the failed components is completed;
- Blockage of riser pipes from formation of hydrates, leading to stoppage of production from that riser and need for pigging operations;
- Faster rate of fatigue damage from VIV due to damaged/lost strakes; and
- Need for replacement of damaged/lost strakes or buoyancy modules or anodes.

Thus, failure or loss of some of these attachments in most cases would have marginal to low consequence on the CVAR riser pipe sections and mechanical fitting/components, when they are replaced within a short period of time. The scenarios of increased level of damage to an individual category or group of these ancillary components would have higher consequences due to potential for significant overload of steel riser sections and mechanical fittings and impairment of their functions. For such scenarios control and risk reducing measures are identified from risk assessment. The need for periodic inspection to record deterioration of the riser pipe and its mechanical fittings is also established.

Historical data from damage and failure of these attachments is not generally available. A few cases of damage incidents reported in publications are given in the following sub-sections. However, it is believed that due to a significant increase in the use of these components and fittings in the development of deepwater fields, their design, manufacturing and fitting procedures, and inspection and monitoring systems have been improved in comparison with previous applications. Thus in future applications, the failure probabilities are likely to reduce and by implementation of risk reducing measures the risk level would likely reduce below the acceptable level based on current operations.

6.4 Failure Modes Identification

6.4.1 General

The CVAR riser components grouped under three categories above are further reviewed to identify the failure modes. The potential failure modes and defects for each component in three categories are identified in Tables 6-1 to 6-4, and the critical failure modes leading to the failure of complete riser are then further addressed in Section 7 with use of FMECA work.

6.4.2 Failure Modes - Steel Riser Sections with T&C Connection

Riser sections with threaded ends have been used in TTR designs for production and drilling from TLP and SPAR platforms. A large number of such applications in deepwater installations with increased fatigue required use of weld on threaded connectors (thick forged end machined with threads at one end and welded to a riser section at other end) in steel grades up to X80 grade, with weld to the riser pipe done at an onshore plant or yard. The manufacturers of threaded connectors have recently undertaken significant development of fatigue enhanced designs in higher steel grades (110 ksi, 125 ksi) and eliminated need to weld thick forged ends [Sches et al, 2008].

The riser sections with T&C connectors in the three zones of CVAR will be subjected to global loads from the platform and its operations, and local loads on a section from various sources including metocean, fluid, and impact of detachment of ancillary items. The riser pipe and its threaded end connections in HSS (with no welds) could have the following failure modes:

- Buckling of riser pipe due to high compression loading;
- Burst of riser pipe from internal overpressure combined with axial tension and bending loads;
- Yielding of riser pipe or threaded connector;
- Leakage at threaded connector from sealability impairment or cracks in the pipe;
- Wear and tear at ID of pipe and at threaded ends from well operations; and
- Fatigue damage of threaded ends or of the main pipe.

In addition, corrosion at riser pipe ID and OD could occur and lead to some of the above failure scenarios. The failure of riser sections with T&C connections in the above ways could lead to impairment of the Tubing CVAR, and may also have a negative impact on the adjacent risers, mooring lines and FPU. The failure modes in the three zones of riser sections are listed in Table 6-1.

Table 6-1 Failure Modes Identification – Riser Sections with T&C Connections

Failure Mode	Stage		
	Installation	Production	Well Operations
Fatigue of riser section		√	
Overstressing of riser section or significant bend		√	
Higher compression loading		√	
Higher fluid pressure		√	
Metal-to-metal seal failure of T&C connectors		√	
External corrosion, local pitting		√	
Wear of ID of riser joint			√
Wear of seal surface	√		
Inappropriate make-up curve	√		
Corrosion, metal loss on riser pipe ID		√	

Most of the failure modes given in Table 6.1 will be applicable to the three riser zones identified in Section 6.3. But the initiating events and propagation to a terminal event (or a hazardous event) and the associated consequences would vary in its three riser zones. For example, a riser-to-riser clash is more likely in the upper region riser length in comparison to riser sections in other regions, and impact from a dropped object may be higher on the riser sections in the transition region than in other two regions. These are addressed in FMECA evaluation presented in Section 7.

The detailed work done on the design development and qualification of riser sections with integral threaded connectors at ends for use at the SCR touch down zone (TDZ) indicated that the performance of a riser section with threaded ends depends on the following [Aggarwal et al, 2007]:

- Appropriate make-up curve;
- Adequate contact pressure at threaded end shoulders and seals;
- Acceptable von Mises stresses in connection sections;
- Low stress concentration factors (SCFs) in threads;
- Reduced number of sources for fatigue crack initiation, such as tong marks; and
- Adequate amount of thread compound.

The above indicates that for the integrity and performance of riser sections with threaded connectors, the make-up of connection at the installation stage is critical. This has also been seen from a recent installation of TTR with riser sections with threaded ends in the Magnolia TLP in GOM where damage occurred in riser sections during the riser running/installation phase [Sokoll et al, 2005]. During installation of the first TTR in the Magnolia TLP platform, the riser connections (T&C) and tieback connector stab sub seal were damaged and required the riser to be retrieved and repaired. See discussion under "connection of TSJ with mudline tree" in Section 6.4.3. These were identified to be result of not undertaking interface testing of the tieback connector and subsea guidance equipment. These connections are reported to have been made by inexperienced tong and torque turn operators. Thus, all threaded connections of the production risers were noted to have galled upon retrieval in the metal-to-metal seal area, due to placement of tong dies in wrong positions on the PIN and BOX connectors. [Sokoll et al, 2005]:

Thus, the risks from T&C connectors will be associated with impairment of the following conditions or functions:

- Make-up of the connector;
- Load carrying capacity and performance under compression;
- Sealability of connector;
- Fatigue performance;
- Corrosion protection; and
- Back-out potential.

6.4.3 Mechanical Fittings/Components

Flex Joint:

Damage in flex joints was reported in GOM deepwater platforms (semi-submersible, TLP) and specifically in larger diameter export risers. The following damage cases were noted from an event in 2004 and subsequent inspection of 58 other flex joints in TLPs and SCRs [Hogan et al, 2005]:

- Four export risers due to fatigue of elastomer layers subjected to combined loads from pressure, tension, rotation;
- No damage reported in flex joints of import risers or TLP tendons; and
- Leakage from 1 flex joint (out of 2 on the same platform) that had been in-service for 8 years.

From the Oil States Industries (OSI) experience datasheets the following are noted:

- Operating pressure range: up to 10,000 psi
- Angular Cocking range: up to +/- 20 deg.
- Axial Tension range: 100 kips to 2,600 kips

In 2002 OSI undertook qualification tests to develop flex joints for HPHT SCR, for 10,000 psi and 235^{O}F design applications, and with a maximum rotation angle of +/- 17 degree.

The new design of flex joints developed by OSI comprises of increased number and thinner elastomer layers, increased shear modulus, higher stiffness, which results in increased fatigue life estimates in elastomer. The fatigue life estimates in elastomers for new designs are between 10 to 20 times of the estimates for previous designs, and the fatigue life of elastomers new design is lower than the estimates at the first weld in previous designs.

In sour service case, the Inconel bellows are used to improve performance and shield the flex-joint from the high temperature of the fluid. Explosive decompression has been identified as a potential failure mode for gas export flexible risers, due to gas permeating in the layers.

The failure modes are identified in Table 6-2.

Titanium TSJ at Top:

This provides an alternative design to the flex joint for connection of the CVAR to a FPU hull. The TSJ in Titanium has been used for the top connection of SCR with the FPU hull, and the same could be used for the top connection of CVAR with the FPU hull. In comparison to a flex joint, the TSJ alternative will provide a simpler system. However, by use of a TSJ at the upper end, there will be a significantly high bending moment compared to the case with a flex joint, which would vary the design of supporting structure at hull. Use of a Titanium TSJ provides several advantages over a larger diameter and heavier Steel TSJ at top.

In this case, total electric isolation is required for the titanium TSJ and titanium riser section from adjoining cathodic steel riser sections and other steel components (receptacle etc.). This is achieved by incorporation of isolation connections at both ends of Titanium sections, to break electrical contact between titanium and steel components/sections.

Table 6-2 Failure Modes Identification – Mechanical Fittings and Connections

Component or Sub-system	Failure Mode	Stage		
		Installation	Production	Well Operations
Flex Joint at Upper End of CVAR	Cracks at welded connection		√	
	Damage of elastomer layer		√	
	Rotation exceeding design maximum	√	√	
	Failure of receptacle seating the flex joint	√	√	
	Disbonding of elastomer layers		√	
	Deterioration of elastomer layer		√	
	Corrosion		√	
	Damage to flex joint during transportation, installation	√		
	Unable to pass tools in wire bushing			√
Titanium TSJ at Upper End of CVAR (an alternative to flex joint)	Cracks at welded connection		√	
	Wear at ID			√
	Compact Flange - bolt connection corrosion		√	
	Titanium flange weld cracks		√	
	Hydrogen charging/damage of titanium joint		√	
	Leak	√		
	Damage during transport/tow/installation phases	√		
Steel TSJ at the Lower End of CVAR	Cracks at weld between TSJ and riser section		√	
	Wear at ID of TSJ			√
	Deterioration at ID of TSJ & weld		√	
	External damage to TSJ	√	√	
Mudline Tree Package with Shear Rams	External damage to mudline tree package	√	√	√
	Loss of barriers			√
	Damage valve seat			√
	Failure of controls			√
	Unable to shear			√

The connection at top of the CVAR will be subjected to high cyclic loading and the proven connection used for the SCR connection with FPU hull will be used. An example of the connection used for an SCR is given in Figure 2-7(a) [Baxter et al, 2007]. The connection shown includes a non-conductive breaking interface between titanium and steel, and isolation flange connection above the titanium TSJ for riser-to-platform isolation. The long term performance of both of these connections is required when subjected to seawater exposure and fluid service temperature.

The lightweight SPO Compact Flange design shown in Figure 2-7(b) consists of the following sub-components:

- Titanium flange welded to titanium riser section;
- Steel flange welded to a steel riser section;
- Sealing system include metal-to-metal seals at both inner and outer ends of flange;
- Primary seal by flexible metal ring located in seal ring groove as shown; and
- Test port for pressure testing after flange assembly to ensure integrity of seals.

Qualified procedures are available for welding of titanium TSJ with titanium compact flange.

A recent study sponsored by MMS (MMS TA&R 572) based on industry survey of deepwater riser design and incidents [JP Kenny, Inc., 2007] reports two failure incidents in titanium TSJs: during the hydrotest in one case; and after 6 months of service in another case. Both of these failures are reported to have occurred in the upper titanium flange, with crack initiation just below the top flange. The initiation of crack is identified due to underestimation of installation bending loads in flanges in the design stage for S-lay installation of the SCR.

As a risk mitigation measure, use of protective shrouds (similar to those designed for flex joints) is considered to safeguard the titanium TSJ during installation. The shroud consists of two steel half shells bolted together.

The failure modes are identified in Table 6-2.

Steel Taper Stress Joint (TSJ):

The TSJ in steel is fitted at the bottom of the lower region riser length, which is then connected to the mudline tree package unit. It is typically 20 ft long, with its ID same as for the riser pipe section. The OD at the lower end of TSJ is approximately 2 to 3 times the OD at the weld at its upper end with the last riser section.

In case of TTRs, TSJ is required at the bottom end of riser for connection with the wellhead. Steel TSJs have been used and no Titanium TSJ at the bottom end of TTR has been used. TSJs are manufactured in a single piece by forging and machining.

The failure modes are identified in Table 6-2.

Connection of Steel TSJ with the Mudline Tree Package:

The connection at the lower end of Tubing CVAR will have similarities to those for a TTR with tieback riser. The integrity of this connection and interface is very important.

One failure event during the installation stage of a TTR for the Magnolia TLP Platform is reported, which damaged the riser connections and tieback connector stab sub seal. The riser was retrieved and repaired during the installation stage. The following reasons are identified as a result of undertaking no interface testing of the tieback connector and the subsea guidance equipment [Sokoll et al, 2005]:

- Mismatch between stab sub seal and installed lock down sleeve;
- Guide base, guideposts, and guideline tension resulting in guide post angle relative to wellhead exceeding stab stub seal installation angle; and
- Inexperienced tong and torque turn operators.

Thus, by undertaking extended stack up integration testing of all riser system components and interface components or systems, the potential for such events and consequences could be reduced to a negligible level.

The failure modes are identified in Table 6-2.

Mudline Tree Package (MTP) with Shear RAMs:

The MTP details are shown in Figure 2-13 in Section 2.5.9 and details of well operations are given in Section 7.4. The functional requirements for MTP and shear seal disconnect are given in Section 2.5.9. The MTP unit and associated components/systems provide a very important function of maintaining the production operations in a controlled and safe manner, and it includes the equipment necessary to perform safe well servicing by CT and WL methods. Thus a damage of MTP from external dropped objects may need stoppage of operations and implementation of remedial measures.

The CVAR design evaluated in this report is for a production riser and is connected to a FPU, and does not require disconnection as done for a drilling riser.

The shear rams provided for shearing of CT may not function properly and not able to shear. Thus, integrity of controls provided through a separate umbilical and implementation of remedial measures are important to maintain their performance, such as replacement of shear ram blades after each operation.

The failure modes are identified in Table 6.2.

6.4.4 Ancillary Components or Attachments

Insulation Coating:

The primary function of insulation coating is to maintain the fluid temperature in the riser pipe to avoid hydrate formation and maintain production rate. The coating is subjected to loads and load effects from hydrostatic pressure, temperature, and during the installation stages. The coating is also subjected to impact loads from dropped objects and loads from clashing of adjacent risers. In addition, the insulation increases the metocean loads on the riser depending on the insulation thickness.

The capacity of coating is related to the long term performance of the material and its deterioration with time and age, manufacturing defects, installation defects, and anomalies between its current and as designed states.

The field joint for the insulation coating is done on-board the installation vessel after make up of the T&C connection between two riser sections. Thus it forms a weaker zone for the coating and its interface connection with the pre-coated insulation is important.

The failure modes are identified in Table 6-3.

Table 6-3 Failure Modes Identification – Ancillary Components-1

Component or Sub-system	Failure Mode	Stage		
		Installation	Production	Well Operations
Insulation Coating	Loss of adhesion between adjacent insulation layers		√	
	Disbondment of FBE coating from steel riser section		√	
	Failure of field joint insulation contact with insulation applied at plant		√	
	Cracking of insulation (outer layer)	√	√	
	Reduction in U value		√	
	Abrasion of outer surface of coating	√	√	
	Water absorption		√	
	Creep and ageing of insulation		√	
Weight Coating	Disbondment of rubber coating from riser pipe		√	
	Damage to outer layer	√	√	
	Water absorption		√	
	Wear of exterior layer	√	√	
Strakes	Detachment of 1 or 2 sets of strakes from clamps	√	√	
	Failure of strake operability		√	
	Water absorption		√	
	Damage of strake	√	√	√
Fairings	Getting stuck and not weathervaning.		√	

Weight Coating:

The weight coating design shown in Figure 2-9, comprises of 3 layers with varying functions as given in Section 2.5.6. The performance of a coating in general varies with water depth and fluid temperature. The inner layer binding is designed for up to 140 degC temperature and the middle layer for up to 70 degC.

The qualification of the manufacturing process and the qualification testing have been undertaken by Trelleborg under DEMO 2000 program [Trelleborg, 2004], and tests showed good results. These tests showed that the coating is flexible with an elongation of more than 500% at breaking.

The rubber based heavy weight coating provides the following characteristics:

- Rubber is chemically resistant to most corrosive liquids, gases, and salt water;
- Qualification tests have shown less than 2% swelling of samples after 32 weeks;
- Rubber wears well because of its elasticity and strength; and
- Rubber provides excellent protection against sharp and abrasive particles and objects.

To improve the wear characteristics, use of the outer layer with a higher abrasive resistance is required than the resistance provided by standard rubber. The failure modes for its application as thick weight coating are identified in Table 6-3. No historical performance data for this product is available.

Rubber coating has been used previously in the GOM over Titanium TSJ at top to protect the titanium OD surfaces from hydrogen uptake, while maintaining electrical continuity, and thereby, CP system protection between the adjoining steel riser components. The rubber coating provides increased level of protection, with its low permeation rate and absorption characteristics.

Strakes:

An incident of damage to strakes during installation phase has been reported over one-third of length requiring VIV suppression [Mekha, 2007]. This was estimated to reduce the VIV fatigue life by 20%.

A recent study (MMS TA&R 572) sponsored by MMS based on industry survey of deepwater riser design and incidents reports that only a small number of strakes damage reports during SCR installation were received [J.P. Kenny Inc., 2007].

The failure modes of strakes during the installation and production stages are identified in Table 6-3. Upon detection of a damaged or lost strake by ROV inspection of the upper region riser length of the CVAR, an evaluation is normally done to estimate the effects on VIV suppression by remaining strakes and to identify a need for their replacement. Thus a few spare strakes could be kept on the platform or at onshore storage to enable reduce the time from detection of a damaged or lost strake to its replacement.

Buoyancy System:

The buoyancy system considered in this study for CVAR design is shown in Figure 2-10, which consists of 4 key components: Buoyancy modules; Clamps; Thrust collars; and Straps.

The clamps design is crucial as it accounts for the differential variations at the ends of riser sections and the buoyancy modules, and variations in riser sections from temperature and pressure effects. The clamp assembly by itself includes the following:

- Clamp body of syntactic composite;
- Securing strap, tensioning screw, and locking/tensioning nut of titanium;
- Rubber element of natural rubber; and
- Retaining bar of nylon.

Each buoyancy module is fitted to one clamp and requires the following:

- Buoyancy element halves (2 no.) in epoxy syntactic composite, and GRE skin;
- Internal clamp (1 no.); and
- Securing straps (3 no.) in Alloy 625.

The failure modes of the buoyancy assembly (modules, clamps) are identified in Table 6-4.

The buoyancy modules of the type considered for CVAR were used in SCRs connected to the Alleghany TLP for the tieback of wells from King Kong/Yosemite field [Korth et al, 2002]. The function of the buoyancy modules was to reduce payload on the existing TLP. Thus a total of 271 buoyancy modules were fitted over a continuous length of 800 ft to provide 50 kips of net buoyancy.

Table 6-4 Failure Modes Identification – Ancillary Components-2

Component or Sub-system	Failure Mode	Stage		
		Installation	Production	Well Operations
Buoyancy Modules - Transition Region and Lower Region Riser Lengths	Detachment of buoyancy halves or complete module (1 or 2 adjacent modules)	√	√	√
	Loss of all buoyancy modules		√	
	Damage of buoyancy material - outer sheath	√	√	
	Abrasion of surface	√	√	
	Reduced buoyancy		√	
	Creep		√	
	Ageing		√	
	Failure of a clamp		√	√
	Galvanic corrosion		√	

7 RISK ASSESSMENT - CVAR

7.1 Approach

The approach used in this study to address assessment of risks associated with CVAR is based on qualitative assessment of risks associated with operations or activities during the following three stages:

- Installation
- Production
- Well Operations – completion, workover

The failure modes associated with various CVAR components, which were grouped in 3 categories (riser pipe/section; mechanical/end fittings; and ancillary attachments), are identified in Tables 6-1 to 6-4 in Section 6. The failure modes that are applicable for each of the above three operations or stages were also identified in Tables 6-1 to 6-4. In this section, Failure Modes, Effects, and Criticality Analysis (FMECA) is given for each of the above three operations/stages for associated failure modes. The inter-dependency and inter-relationship is very important in the risk assessment using FMECA. The failure modes included in FMECA work are reduced to the important failure modes. However, there are additional failure modes associated with other units and vessels required during the above stages. The potential events initiating from these additional units and vessels could have an impact on the CVAR riser system, and such scenarios are addressed for each of the above operations/stages.

The general approach followed in this study is similar to that used in a FPSO Risk JIP for a comprehensive risk assessment of FPSO in the GOM, which included flexible risers [Nesje, Aggarwal et al, 1999]. In this JIP, the riser risk analysis was done for riser system divided in four zones, and estimation were made of the likelihood of occurrence of leaks from different zones of the riser and their consequences on the overall FPSO system. The failure modes, causes, and end effects for flexible riser were identified and detailed quantitative risk assessment (QRA) was performed.

The work in this CVAR study is done by qualitative assessment only, and includes evaluation of the failure modes for an operation or stage of CVAR by FMECA by identifying the initiating events, local effects on CVAR components or operations, and system effects on the CVAR. Then the likelihood of occurrence and consequences to production loss/delay and pollution are identified, and a qualitative criticality level is identified. The options available to detect the failure modes and the remedial measures to reduce the risk from specific failure modes are also identified. The general approach for FMECA given in recent API RP 17N [API, 2009] for subsea production system reliability and technical risk management has been followed. Expert judgment has been primarily used in identifying local and system effects of failure modes, and severity levels.

A criticality ranking assigned for frequency and consequences for each failure mode can be presented in a criticality categorization and risk levels plot as given in Figure 7-1. The frequency of occurrence (or likelihood) rankings for various failure modes are based on 5 categories as defined in Table 7-1. These are based on the DNV RP F206 on riser integrity management [DNV, 2008] and in ISO 17776. Based upon discussions held with the MMS, the consequences for production loss/delay and pollution were selected for this study as given in Tables 7-2 and 7-3. The severity categories for these consequences for each failure mode are decided based on these tables. In this way, the potential risk levels associated with the failure of a component for an operation are estimated. They can be compared with corresponding components or operations for other riser systems, such as Top Tensioned Riser for a TLP and a Spar. This is addressed in Section 8 on comparative risk assessment.

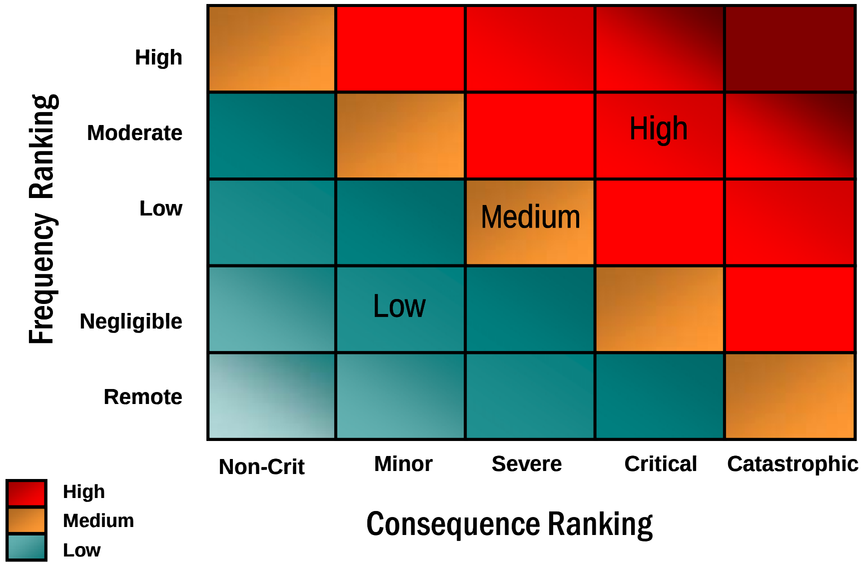


Figure 7-1 Criticality Category

Table 7-1 Frequency of Occurrence Categories

No.	Severity	Abbreviation	Characteristics
1	Remote	R	Failure is not expected.
2	Negligible	N	Never heard of in subject components or system; Rarely expected to occur.
3	Low	L	Has occurred in the subject component.
4	Moderate	M	Has been experienced by several operators.
5	High	H	Happens several times per year per operator.

Table 7-2 Production Loss/Delay Categories

No.	Severity	Abbreviation	Characteristics
1	Non-critical	NC	Events that cause less than 1 week loss of total production.
2	Minor	MI	Hazards that have the potential to cause between 1 week and 2 months loss of production, e.g., replacement of damaged/lost attachments.
3	Severe	SE	Hazards that have the potential to cause between 2 and 6 months loss of production.
4	Critical	CR	Hazards that have the potential to cause between 6 months and 1 year loss of production, e.g., riser broken and need replacement.
5	Catastrophic	CA	Hazards that have the potential to cause more than 1 year loss of production.

Table 7-3 Pollution Categories

No.	Severity	Abbreviation	Characteristics
1	Non-critical	NC	Events that cause insignificant oil spill.
2	Minor	MI	Hazards that have the potential to cause up to 100 bbls of oil pollution, e.g., from a single connection (or riser joint) failure and everything shuts-in.
3	Severe	SE	Hazards that have the potential to cause up to 100 to 1,000 bbls of oil pollution, e.g., from failure of multiple connections/joints of a riser and riser shut-in.
4	Critical	CR	Hazards that have the potential to cause up to 1,000 to 100,000 bbl of oil pollution, e.g., by loss of containment from a producing riser.
5	Catastrophic	CA	Hazards that have the potential to cause more than 100,000 bbls of oil pollution, e.g., by loss of containment from a producing riser that can't be stopped.

7.2 Installation Stage

7.2.1 General

The CVAR configuration presented in Figure 6-1 indicates that in the running of CVAR riser system or its installation at a platform site, it would require consideration of effects of the following key design features:

- Offset of CVAR connection at FPU from wellhead, leading to increased overall length; and
- Connection of CVAR top with FPU by a flex-joint similar to that for a SCR or by a TSJ (steel or titanium), and option to connect CVAR on the perimeter of floating hull.

In the past decade, with a significant increase in the number of installations of subsea systems for deepwater and ultra-deepwater GOM, the level of reliability of vessels, equipment, and tools used has been increased. Thus, the riser running and installation process presented will utilize the proven methods, equipment and tools to obtain the equivalent reliability acceptable to the industry. As the CVAR concept is taken up for further evaluation and development with operating companies, the running and installation procedure and options discussed above will be further refined with engagement of an installation contractor and the potential risks associated with the installation procedure will be further reduced by implementing risk reduction and QA/QC measures. The procedure related risks may vary with an installation contractor using specific vessel, installation approach, and tools.

7.2.2 Approach

The challenge in the installation of CVAR is that it is positively buoyant due to the buoyancy of its S-shaped Transition Region riser length. In order to lower the bottom end of the CVAR and to connect it to the well, it is necessary to ballast the bottom section of the CVAR, as shown in Figure 7-2. This is accomplished by the following measures:

- Placement of deadweight of approximately 15 tons at the bottom of the CVAR. The 15 ton deadweight is temporary and is removed upon completion of the installation operations; and
- Attachment of a 4-1/2" dia, 650 ft long, heavy ballast chain to a padeye located at about 400 ft from the bottom end of CVAR. The other end of the ballast chain is connected to a polyester rope hanging from the installation AHV.

During the CVAR installation process, the chain is held in a U-shape, with approximately half of its weight being held by the CVAR and the other half being held by the AHV. In addition to applying a downward force to the CVAR, the ballast chain also applies a lateral force to the CVAR that can be used to position it horizontally. The downward and horizontal force provided by the ballast chain can be adjusted by increasing or decreasing the tension in the line that holds the chain and by increasing or decreasing the distance of the AHV from the CVAR.

After the initial CVAR installation the chain is disconnected by ROV from the polyester rope, which is recovered to the surface using the work winch of the AHV.

In heavy seas or large swell environments, a low tension (~100 kips or less) synthetic line from the AHT can be used to further stabilize the elevation of the CVAR bottom by using a constant tension winch.

In this procedure it is assumed that the mudline tree package (in case of tubing and single casing CVAR) has already been run by the MODU when the well was drilled and completed.

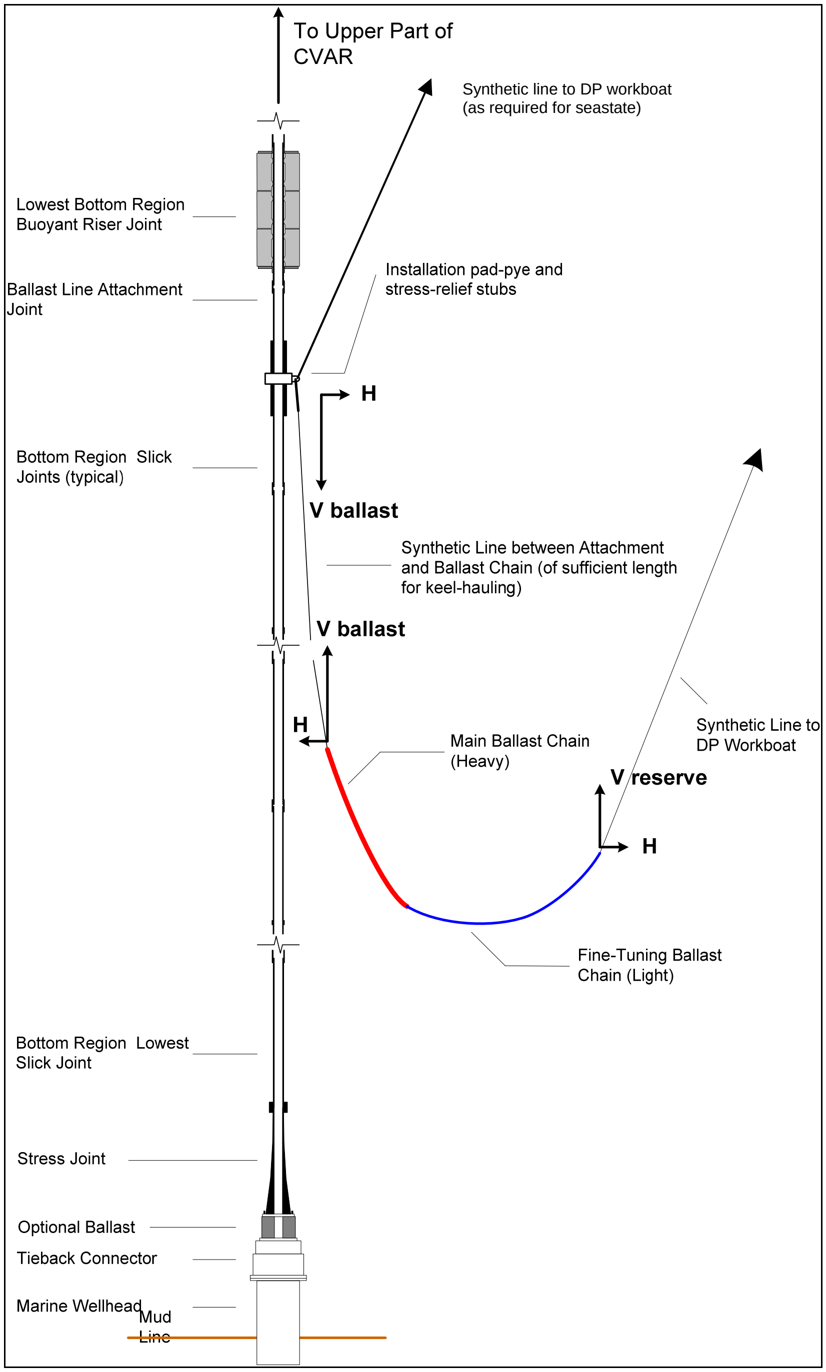


Figure 7-2 General CVAR Installation Scenario Using Two Ballast Chains

7.2.3 Installation Plan

The installation plan is shown in Figures 7-3 and 7-4. There are various methods to install CVARs using existing equipment and standard procedures currently used in the deepwater offshore industry. The CVAR can be installed from the production platform after it is in-place or from a drilling rig while pre-drilling activities are undertaken or assembled at a distance from the location of production platform and towed to the platform site for connection with the FPU and the subsea mudline package.

This method is based on running the CVAR from a semi-submersible production platform using a small workover derrick that can handle T&C riser sections. Regardless of the CVAR design or type of support vessel used, installation of a CVAR would require the following basic steps:

1. Deploy the CVAR with T&C riser sections like running threaded pipe using a derrick, draw works, and hang-off tools. A seafloor mudline tree (split tree) may be either run with the CVAR, or first run using a running string and the CVAR run afterwards.
2. External items to the CVAR are strapped on during the running process. These may include buoyancy modules, weight modules (if weight coating is not integral to the CVAR pipe joints), strakes. These items can be attached above or below the derrick floor depending on the size of floor opening. Typically, external items will have a diameter smaller than the standard rotary table opening (59 inches).
3. Offset the bottom of the CVAR away from the installation vessel (the production vessel in this case) towards the well using an anchor handling or other vessel to control azimuth and elevation of the bottom end. More vessels (up to 3) might be required depending upon the installation vessel and equipment used, and limiting metocean conditions for installation operations.
4. Run final joints of CVAR pipe and obtain required offset per CVAR design.
5. Land the bottom assembly onto the well using a means of compensating for the relative motions between the vessel and the seafloor. In this assessment, use of a ballast chain is proposed. Other methods may use either a compensating winch (loads can be engineered to be quite low, ~ 100-140 kips or less); or an inline compensator.
6. Perform pressure test of the fully assembled CVAR either before or after connection to the wellhead.

In this case it is estimated that a 175 kips counter-weight would be required to reduce the buoyancy loads during deployment. Some weight is fixed on the bottom of the CVAR assembly, and the remainder is provided by a ballast chain. Figure 7-3 shows details for handling the bottom of the CVAR with the counter-weight ballast chain attached. Chain ballasting is a method to compensate for vessel motions while controlling the vertical elevation. It has been previously used for the installation of submerged buoys and subsea equipment.

For this study, the alternative of assembly/running of CVAR at a distance is considered for risk assessment work, as it involves additional operations.

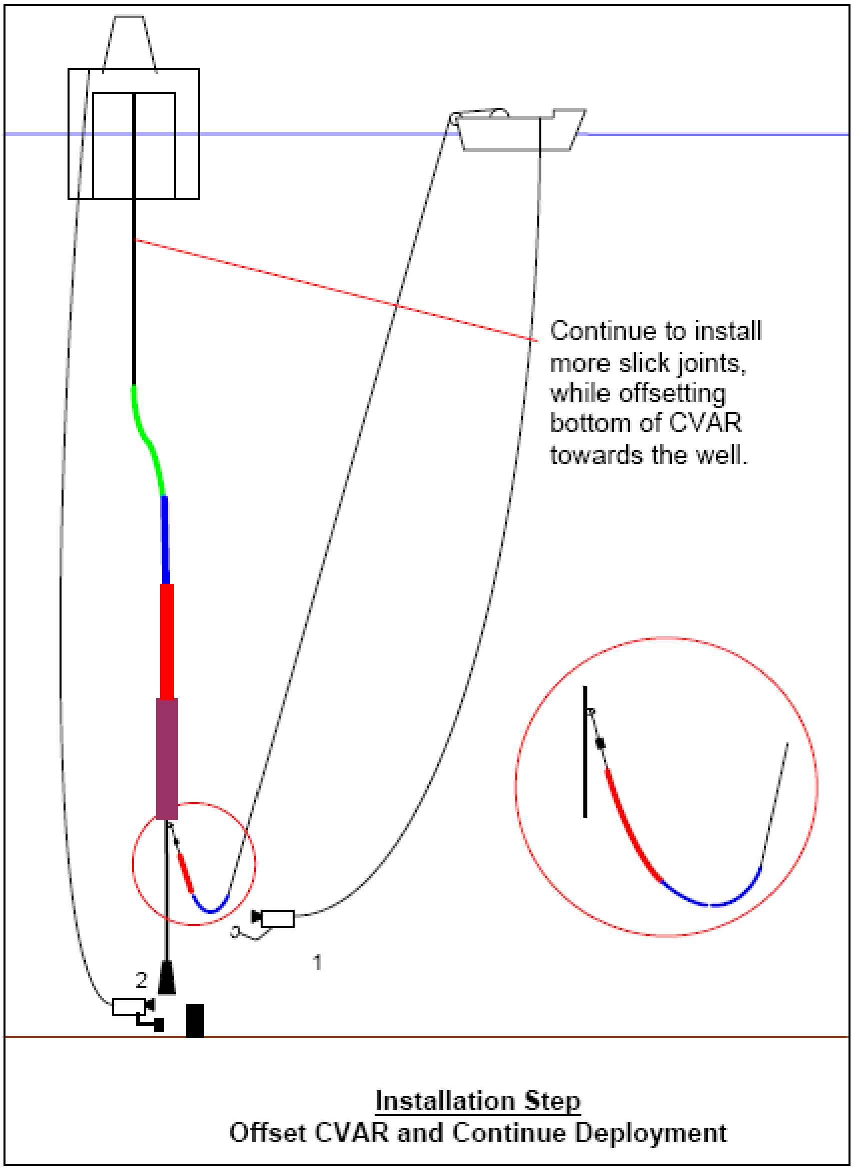


Figure 7-3 Installation Step Before Connection to Well

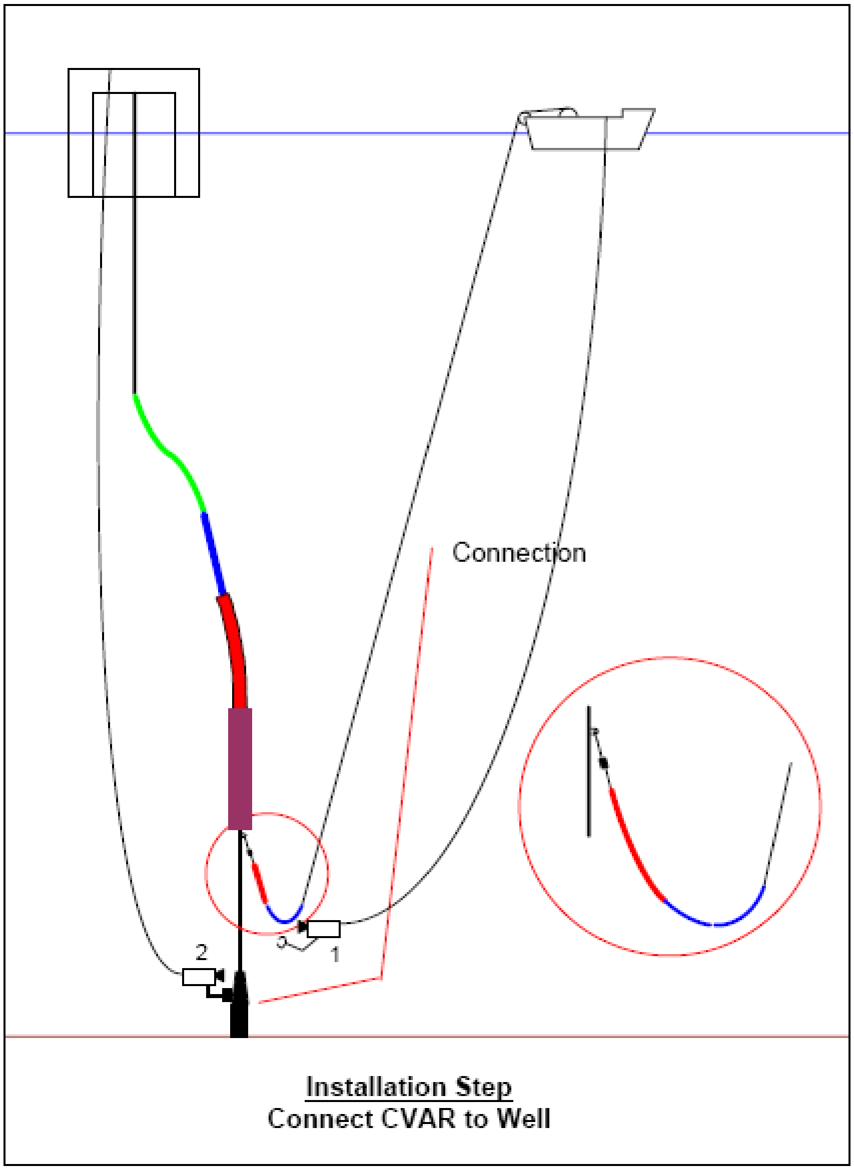


Figure 7-4 Installation Step After Connection to Well

The installation plan above was presented to MMS at meetings held at Houston and New Orleans and their input were obtained. The important considerations identified are as follows:

- A lot of installation work (or riser run-up) can be done away from the wellhead, e.g., at 5 miles away. This option applies to tubing CVAR design;
- There may be a concern of riser contacting mooring lines, because of current; and
- There may be potential for VIV during initial installation phase when ballast weight is not present, especially in loop current situation. Use of VIV suppression devices may be required or else the riser may need to drift with the current. This is based on a common practice used by drilling rigs to avoid high current induced motions to caissons during installation.

Analysis results for the case studied confirm the ability to install the CVAR. The following conclusions are made from evaluation of installation steps:

- The natural configuration of the CVAR initially places the base at an offset of ~300 ft;
- In order to assure that the CVAR never goes into compression, a minimum 135 kips downward force must be applied to the CVAR via the ballast chain;
- The maximum top tension required during the installation sequence ranges from 55 to 70 kips. This tension range correlates to the installation vessel layback range of 700 to 1,000ft; and
- The vessel layback range will make connection monitoring by a ROV deployed from the AHV difficult, and an additional ROV vessel may be needed.

The synthetic rope used in the analysis demonstrated a maximum stretch of 1%. The stretch of the rope most likely eliminates the need for any heave compensation.

7.2.4 Installation Spread

From the above it is clear that the installation plan requires several vessels and operations that would take several weeks from the running of the CVAR sections to its final connection with the mudline tree or wellhead. In case of tubing risers, the running of the CVAR could be accomplished at some distance from the wellhead and can be done in a region not impacted by high currents. Whereas, the installation of the dual casing CVAR may require running of riser sections from the platform. This need to be further determined.

The CVAR installation spread will consist of the following:

- Derrick and pipe handling equipment on the production vessel or intervention vessel.
- 10,000 HP Dynamically Positioned AHVs (2 no.) outfitted with the following equipment:
  - 150 HP Work Class ROV spread;
  - DGPS/Short Baseline Acoustic Positioning System;
  - Standard anchor handling equipment such as work wire winch (minimum two drums), sharks jaw stopper, tow pins, etc.; and
  - Miscellaneous equipment (chain connecting links, shackles, chasers, etc.).
- Chain lockers and chain wildcat sized to store a 650 ft length of 4-1/2” dia. Chain.

- 500 kips SWL 10 ft stroke in-line Passive Motion Compensator.
- Optional, a ~100 kips constant tension winch to aid in elevation control.

The key issues in the installation plan above are as follows:

- Installation weather window:
  - Lesser impact for the Tubing CVAR compared to the Dual Casing CVAR or a conventional TTR with single/dual casing.
- Most of the installation activity can be done away from the wellhead.
- Less tension during installation results in higher impact of current on the riser during installation:
  - VIV potential when no weight attached; and
  - Analysis for disconnect in high currents is required.
- Controllability – use of additional installation vessels/ tug boats.
- Installation of sequential CVARs:
  - Impact of change in the current direction.

7.2.5 Failure Modes Identification

The failures modes for various components of a CVAR during its installation are given in Tables 6-1 to 6-4 in Section 6. The risks to the CVAR (and its components) or the FPU will be primarily from the external sources, such as other vessels and other units (e.g., ROV, ballast chain) and their failure during installation operations. Such scenarios and specific events for the overall system and installation operations are listed below for assessment:

- Blackout of DP2 installation vessel.
- Blackout of DP2 AHV.
- Metocean loading effects:
  - Change in tension; and
  - High current (mid-depth slab current) making it difficult to move.
- Limited weather window available:
  - Delay in operations.
- Collision of vessel with the platform.
- Dropped object from vessel operations or from platform deck/operations impacting riser system components:
  - Buoyancy modules in intermediate zone or in the lower zone;
  - Weight coating;
  - Strakes in upper zone;
  - Riser section (T&C) with insulation;

- Stress joint at bottom; and
- Lower safety package/module.

- ROV operations – required for a short duration when CVAR is near seafloor or the well:
  - Losing connection/visibility;
  - Applying too much torque; and
  - Difficulty in fit-up to the pre-installed mudline package unit.
- Breakage of installation wire-rope due to severe weather:
  - Reduction in tension; and
  - Leading to loss of the TSJ above mudline.
- Difficulty in connecting the CVAR bottom with the wellhead or pre-installed mudline tree package (in case of a tubing CVAR or a single casing CVAR).
- Loss of containment during pressure testing – this requires testing at several stages of riser running to mitigate effect.
- Keel haul operation:
  - Complete riser dropping – The well would be offset at 2,000 ft away, thus riser will not hit the well.
- Riser-to-riser interference:
  - The probability of a CVAR being installed hitting the previously installed CVARs will be remote due to the distance between CVARs kept about 400 ft.

The above failure modes are known to the industry through a significant number of installations of subsea units, riser towers and other systems. Thus the procedures used and approaches have been tested and probability of occurrence of initiating events leading to these failure modes will be generally low. In case of the CVAR with offset well, and proposed installation plan with running of riser sections away from the FPU and wellhead locations, the risk of damaging the wellhead from dropped objects during riser running is eliminated or it is significantly reduced. The towing of riser from a distance will require an increased number of AHVs (2 or more) and longer weather downtime, which will require the riser installation schedule to fit within the MODU schedule for drilling and completion operations. During the towing operations, the weather window could be longer due to avoidance of the loop current or high metocean seastate, which would have an impact on the overall installation schedule and cost. However, the ability of running a Tubing CVAR at a distance provides a potential to significantly reduced risk to the overall system.

7.2.6 FMECA

Table 7-4 presents FMECA work done for each system in the overall installation plan or spread including the vessel, wire rope, AHV or tug boats, ROVs, mudline tree/stress joint, riser sections with threaded connectors, and pressure test of CVAR upon installation. The important failure modes and the likely initiating events are identified and the potential effects on CVAR installation operation, CVAR system, or FPU with connected CVAR are presented.

Table 7-4 FMECA – CVAR Installation Stage

Item	Component or Sub-system or Operation	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
1-1	Installation Vessel	Blackout of DP2.	Computer system or software failure.	Thrusters stop functioning.	Vessel starts drifting and controlled by AHV.	Automatic	N	MI	NC	L	Periodic testing of functionality of DP2 and control systems.
1-2	Installation Wire Rope (connecting bottom/mid of CVAR with vessel)	Breakage of wire rope.	Bad weather.	Reduced maximum top tension in CVAR.	Uncontrolled CVAR motion subjected to current.	Automatic	L	NC	NC	L	Maintain spare wire rope; inspection planned before start; job safety analysis (JSA).
1-3	Anchor Handling Vessels (AHV) or Tug Boats	Blackout of DP2.	Computer system or software failure.	Thrusters stop functioning.	AHV starts drifting and could collide with FPU.	Visual inspection	L	MI	NC	L	Redundant system in AHV or tug boats.
1-4	ROVs	Loss of visibility.	Power failure.	Loss of control from surface/vessel.	ROV non-operational; could hit the riser or mudline tree package.	On-board system	L	NC	NC	L	Installation contractor operational plan to consider this case.
1-5	Riser Sections with T&C Connectors: Running/Make-up	Inappropriate make-up of T&C connection.	Improper connection by inexperienced tong and torque turn operators.	Inadequate connection capacity.	Reduced load carrying capacity of CVAR; Re-do the connection to ensure design capacity.	Test port	L	NC	NC	L	Operators training and selection; QA/QC procedures; tests at yard/shop.
1-6		Wear of seal surface.	Mishandling during connection make-up.	Source for fatigue damage in-service.	Remove affected connection and re-do.	Visual inspection	N	NC	NC	L	Operators training and selection; QA/QC procedures; JSA.
1-7		Riser falling.	Mishandling during connection make-up.	Loss of riser.	No effects when run-up done away from FPU location; schedule delay & cost effects.	Visual & ROV inspections	L	MI	NC	L	Operators training and selection; QA/QC procedures; JSA.

Table 7-4 FMECA – CVAR Installation Stage (Contd.)

Item	Component or Sub-system or Operation	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
1-8	CVAR - Riser with TSJ fitted at the bottom (Riser tow condition)	Difficulty in towing riser.	High current, esp. loop current.	Current moves the lower part of riser with large diameter buoyancy modules.	Change in installation wire-line tension.	Current monitoring devices.	M	NC	NC	L	Undertake operations in adequate weather window with no likelihood of loop current
1-9		Loss of 1 or 2 riser ancillary attachments (strakes, buoyancy modules).	Dropped objects (tools; riser section).	Hit by dropped object loosens 1-2 strakes (upper region) or 1-2 buoyancy modules (transition or lower region riser sections).	Marginal change in riser tension; decide on options to replace lost attachments by ROV or pulling of riser.	ROV inspection.	L	MI	NC	L	Develop qualified procedures for replacement of strakes or buoyancy modules in installed state.
1-10		Riser hitting mooring line(s).	High current when riser is near platform.	Riser attachments abrasion (buoyancy modules or strakes or fairings) in local area becoming loose.	Mooring line gets disconnected at the top and damage other components or riser.	Visual inspection.	R	SE	NC	L	Monitor weather for appropriate weather window.
1-11		Towed riser hitting an installed CVAR.	High currents or installation vessel/AHV loosing control.	Riser attachments (buoyancy modules or strakes or fairings) in local area get loose.	Snapping of installation wire rope.	Visual inspection.	L	MI	NC	L	Spare attachments to replace lost parts kept in storage or on-board FPU.
1-12		Riser falling.	Mishandling during keel-haul operation (if required).	Loss of riser.	Potential damage to subsea units, mooring lines; schedule & cost effects.	Visual & ROV inspections.	L	SE	NC	M	Operators training and selection; QA/QC procedures; JSA.
1-13		Unable to connect (fit-up) the riser base/TSJ with the mudline tree.	Higher current or ROVs not functioning properly or a mix-up in riser connector.	Difficulty in making connection.	Increase in schedule and operations of vessels and delay in first oil.	ROV inspection	L	SE	NC	M	Undertake SIT for all connections at yard.

Table 7-4 FMECA – CVAR Installation Stage (Contd.)

Item	Component or Sub-system or Operation	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
1-14	Flex Joint at upper end of riser	External damage during transportation or installation.	Impact from other objects or vessels, mishandling.	Damage to flex joint or its connection.	Impairment or require replacement, with impact on schedule.	Visual inspection	L	SE	NC	L	Protective shroud is available to safeguard during installation stage.
1-15	Mudline tree or stress joint	External damage during installation.	Dropped objects (tools; riser section).	Potential to damage assembly or TSJ.	Schedule and cost effects.	ROV inspection	L	SE	NC	L	
1-16	Pressure test	Loss of containment during pressure testing from T&C joints.	Due to over-pressuring during test.	Riser stresses increase and a riser section bursts at a joint of in riser section.	Riser need to be pulled and replaced.	Pressure monitoring	L	MI	NC	L	Spare riser sections and attachments.

Frequency Ranking	Non-Critical	Minor	Severe	Critical	Catastrophic
High					
Moderate	Difficulty in towing riser;	MEDIUM			HIGH
Low	Breakage of installation wire rope; ROV Loss of visibility; Inappropriate makeup of T&C connection;	AHV - blackout of DP2; Riser falling during T&C make-up; Loss of 1 or 2 ancillary attachments; Towed riser hitting an installed CVAR; Loss of containment during pressure testing from T&C joint.	Riser falling during keel-haul operation; Unable to connect riser base/TCJ with MTP; External damage to MTP or TSJ;		
Negligible	Wear of T&C seal surface;	Installation vessel - blackout of DP2			
Remote		LOW	Riser hitting mooring lines;		

Consequence Ranking

Figure 7-5 Risk Matrix for Production Loss/Delay Consequence – Installation Stage

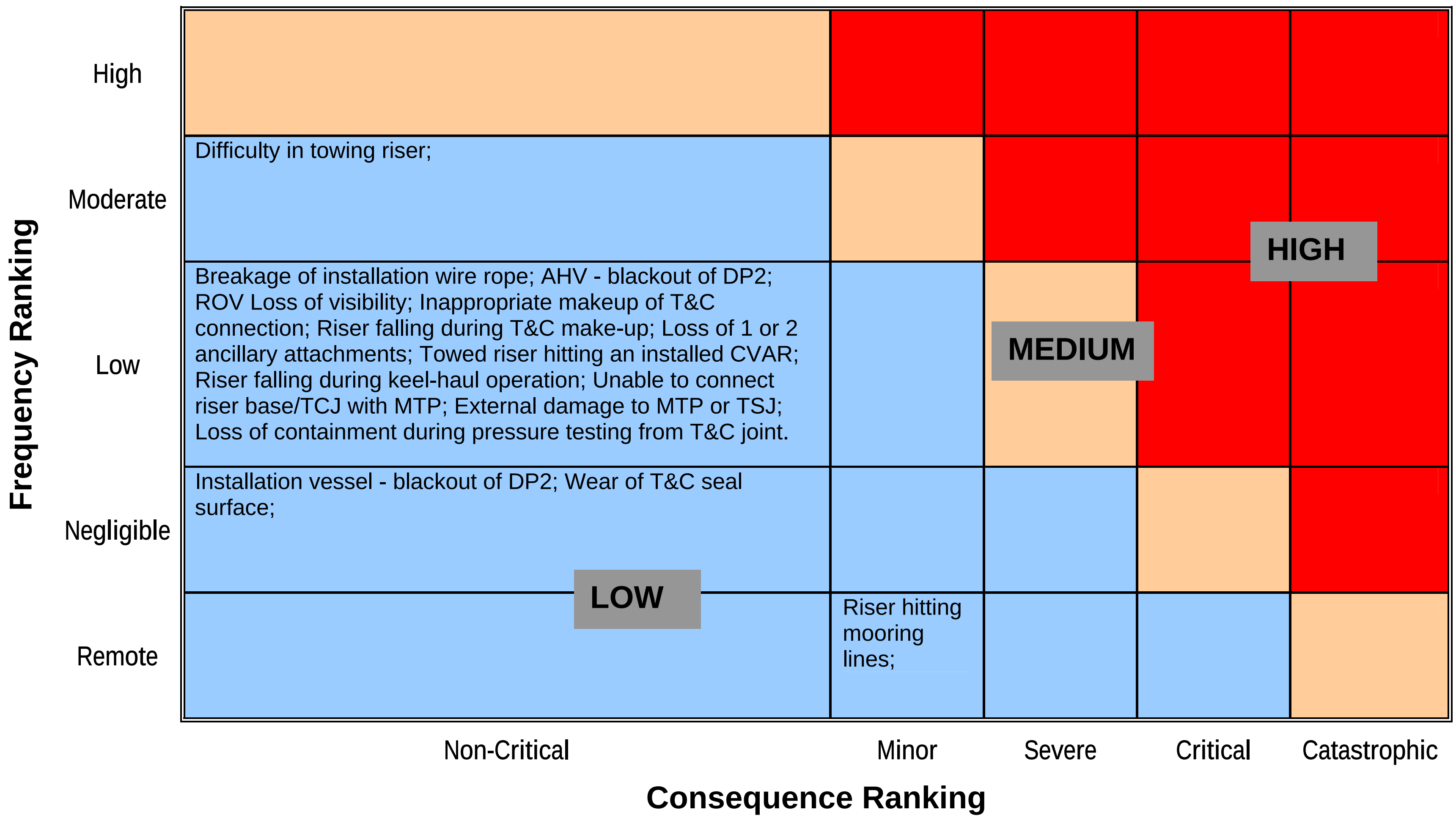


Figure 7-6 Risk Matrix for Pollution Consequence – Installation Stage

From FMECA presented in Table 7-4, most of the failure modes associated with various systems are estimated to have "Low" criticality (or risk) levels during installation operations. The following two failure modes are estimated to have potential for "Moderate" criticality (or risk) level:

- Riser falling at the platform site, due to mishandling during keel-haul operation (operation applicable when the riser is located at the mid of platform). Such an event would lead to a complete loss of the riser requiring installation of a replacement riser at a later date, and the potential of damaging subsea systems or mudline tree and the FPU mooring system or other installed CVARs.
- Failure to connect the CVAR (with a TSJ welded at its base) to the MTP unit, due to problems associated with the ROV operations, higher current, or mix-up in riser connectors. The initiating events of higher current and the ROV operational problems would essentially delay in connection and reduce the weather window, but the mix-up in riser to MTP connector would have higher consequences and may require implementation of significant measures to correct the problem. Thus pre-installation tests, such as system integration test (SIT) shall be included in the overall plan to reduce the likelihood of mix-up in connection.

The above failure modes with estimated "Moderate" and "Low" Criticality (or Risk) Levels could be avoided or significantly reduced to acceptable levels by implementation of risk reducing measures in the installation plan. Some such measures are given in the last column of Table 7-4 and as listed below:

- Undertake run-up of CVAR sections away from the platform (FPU) location and subsea wellheads; An alternative may be to lay the CVAR at the seabed as has been done for some SCRs;
- Undertake SIT at the yard or at manufacturing units to ensure that all metal-to-metal connections are functioning properly;
- Include one more line for displacement control to avoid hitting the ocean floor or a flowline;
- Include operators training and selection as an important item in the plan;
- Implement QA/QC and Job Safety Analysis (JSA) procedures in the overall project management system;
- Weather monitoring to decide on appropriate windows; and
- Maintain critical spares identified on board the FPU.

7.3 Production Stage

7.3.1 Approach

The potential risks associated with CVAR during normal production operations, excluding well operations (included in Section 7.4), are addressed in this section. The CVAR design utilizes the proven components and systems as shown in Section 2, which have been used in the design of other riser systems operating in deepwater. In Section 6 the potential failure modes during the production stage were identified for the CVAR systems and components grouped in three categories. The figures and descriptions of each of these components are given in Section 2. The failure modes for each component or sub-system were identified and presented in Tables 6-1 to 6-4. The risks associated with these individual components are well known to the industry, from their use in other riser designs.

During the normal production, in addition to manning and operations from the platform additional vessels and helicopters approach the platform for supplies and transfer of people. Thus the additional events originating from such operations and their impact on the FPU have been considered, where they are likely to initiate a failure mode in the CVAR or its components.

7.3.2 Failure Modes

The operational, accidental, fatigue initiating events could have effect on the key components and sub-systems of CVAR that need cause and effect evaluation to address the potential risks associated. The scenarios that are important to consider are listed below:

- Blowout;
- Loss of containment – due to leakage from T&C connection or from failure of riser main body;
- Excessive deformation of CVAR at its top connection with FPU – due to loss in position from FPU mooring failure or from collision from other vessels;
- Failure of riser pipe or T&C connection – due to overpressure, corrosion, fatigue cracks (missed in inspection), increased fatigue from unknown behavior/events;
- Damage of FBE coating – from dropped objects or from clashing/interference of adjacent risers;
- Damage of insulation outer layer – from clash/interference of adjacent risers;
- Loss of buoyancy module – from impact of dropped objects and damage may be limited to 2 modules;
- Reduction in buoyancy – from increased water absorption;
- Damage of weight coating in upper length of riser – from impact of dropped objects;
- Riser disconnection at top – this is unlikely to occur in production mode;
- Riser disconnection at bottom (at top of mudline valve) – from ROV plugging into wrong hole; and
- Loss of tension in riser.

The failure modes associated with each sub-system are listed in Tables 6-1 to 6-4 and identified as failure modes associated with each major component.

7.3.3 FMECA

Table 7-5 presents FMECA work done for each major sub-system in the CVAR connected to a FPU. The failure modes listed in Tables 6-1 to 6-4 with each major component/sub-system of CVAR and additional failure modes related to FPU, and their impact on the CVAR are addressed in Table 7-5. The qualitative rankings for production loss/delay and pollution consequences and for likelihood of occurrence of each failure mode, and the criticality levels or the resulting potential risk levels are identified based on the criticality (and risk) matrix given in Figure 7-1.

The blowout occurrence and risks will be similar to the industry experience with riser systems in operation. The consequences of a blowout event will be lesser in case of CVAR due to the well being offset from the platform.

From review of the CVAR concept with MMS, an additional consequence related to the impact on Worm Beds in the deepwater GOM was identified as an important factor to consider in the development. The potential impact on Worm Beds in deepwater GOM is discussed as below.

Impact on Worm Beds:

In the deepwater GOM, worm beds exist at shallow depth (below seabed) flow areas, which are about 3 inch in diameter and 6 ft long, and are the oldest living things. CVAR design with offset wells could enable avoid damage to worm beds, by keeping distance between wellheads at the seabed more than 200 ft. A check of CVAR configuration presented in Section 5 indicates that by changing the hang-off angle from 10 degrees to 12.5 degrees on a 1,500 ft radius, the distance between the wellheads is increased from 181.5 ft to 326.5 ft. Thus the worm beds can be avoided by changing the azimuth of CVAR.

From FMECA presented, it is seen that the criticality levels for most of the failure modes is "low." A few failure modes associated with primary components (steel risers sections, mechanical fittings/connections) are estimated to have potential for "Medium" criticality (or risk) level. The criticality (or risk) is "low" from failure of individual or group of components of ancillary components. The critical and selected cases for selected components or systems or scenarios are briefly discussed below.

Floating Production Unit:

Dropped Objects: The consequences could be "Severe" from a dropped object, falling from the FPU in the production stage, when a large size object drops and hits riser section(s) and results in a significant damage of riser section(s) or a significant reduction in its capacity or into a hydrocarbon release. However, the probability of occurrence of a dropped object hitting the riser sections in the transition and lower regions is likely to be "Low" due to the offset shape of CVAR, and with possible undertaking of the lifting operations from the supply boats on the opposite side of the FPU side with CVAR.

Excessive FPU Motions: The excessive motions of the FPU when subjected to metocean loads larger than the design loads could lead to failure of the CVAR or leakage of its sections/joints. The pollution consequence category will be less than "Severe" due to evacuation of personnel and production shut-in in accordance with the GOM operational philosophy.

The above two scenarios also apply to the other riser designs and the effects of such events are acceptable to the industry.

Table 7-5 FMECA – CVAR Production Stage

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-1	Floating Production Unit (FPU)	Excessive displacement.	Collision of a large vessel with FPU.	Overload of riser sections - higher tensile loading.	Loss of structural integrity of CVAR and operations; leakage potential; riser disconnection.	Visual inspection.	N	SE	SE	L	Production shut-in at mudline upon occurrence of such events.
2-2		Overstressing of riser section or significant bend; or in components/ systems at seabed.	Dropped object from FPU.	Reduced capacity of riser section; or of components/systems at seabed (TSJ, mudline tree).	Leakage potential; CVAR capacity reduction requiring replacement.	ROV inspection.	N	SE	SE	L	CVAR offset reduces probability of dropped object hitting the lower region riser sections, TSJ or mudline tree.
2-3		Excessive FPU motions.	Metocean loading beyond design parameters.	Excessive riser loads leading to its failure.	Loss of structural integrity of CVAR and operations; leakage potential; riser disconnection.	ROV inspection.	L	SE	SE	M	Production shut-in ahead of storm and evacuation.
2-4	Upper Region Riser Sections with T&C connectors	Increased fatigue of riser sections.	VIV or excessive pressure or tong marks during riser section make-up.	Fatigue cracks initiation and propagation.	Loss of pressure retaining capability of a riser section.	Inspection by Pig; VIV monitoring.	L	MI	MI	L	Implementation of QA/QC procedures to reduce probability of tong marks.
2-5		Higher compression loading at its lower end.	Variation in conditions (fluid, metocean loading); loss of buoyancy modules in transition or lower region riser sections.	Buckling of riser sections.	Loss of structural integrity of CVAR and operations.	ROV inspection; Stress/load monitoring of critical section.	L	SE	SE	M	Monitoring of fluid conditions and implementation of remedial measures.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-6	Upper Region Riser Sections with T&C connectors (contd.)	Overload of riser section.	Higher operating pressure or higher axial tension from loss of buoyancy modules.	Burst of riser section.	Loss of structural integrity of CVAR; leakage.	Temperature/ Pressure sensors.	L	SE	SE	M	Relief valve could be considered.
2-7		Metal-to-metal seal - galling or other imperfections.	Higher operating pressure or higher axial tension from loss of buoyancy modules; corrosion.	Sealability impairment at T&C connector.	Leakage potential.	Sensors to detect loss of pressure.	N	MI	NC	L	Implementation of QA/QC procedures to reduce probability of undetected galling during installation
2-8		External corrosion, local pitting.	Failure of CP system; Damage to FBE coating.	Reduced capacity of riser section.	Leakage potential; damaged sections requiring replacement.	Visual or ROV inspection.	L	MI	NC	L	Replace CP anodes based on inspection
2-9		Corrosion or metal loss at ID.	Sour crude beyond design; galvanic acceleration due to inadequate electric isolation from titanium TSJ.	Corrosion exceeding the allowance considered in design.	Reduced capacity of riser section leading to its failure, and requiring replacement of 1 or more riser sections.	Inspection by Pig.	L	MI	MI	L	Use of corrosion inhibitor.
2-10	Transition & Lower Regions Riser Sections	Overstressing of riser section or significant bend.	Dropped object effect; variation in connector makeup; variation in riser dynamics.	The buoyancy modules detachment; reduced capacity of riser section.	Leakage potential; CVAR capacity reduction.	ROV inspection.	L	MI	SE	L, M	Operational plan to reduce probability of dropped objects
2-11		Higher compression loading in riser sections.	Loss of buoyancy modules; variation in conditions (fluid, metocean loading).	Potential for bucking of riser sections.	Loss of structural integrity of CVAR and operability.	ROV inspection.	L	MI	SE	L	Monitoring and shut-off of operations.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-12	Transition & Lower Regions Riser Sections (contd.)	Corrosion or metal loss at ID.	Sour crude beyond design basis.	Corrosion exceeding the allowance considered in design.	Reduced capacity of riser section leading to its failure; potential for leakage	Inspection by Pig.	L	MI	MI	L	Use of corrosion inhibitor.
2-13	Flex Joint	Cracks at weld connection.	Fatigue loading effects.	Crack propagation leading to leakage.	Weld failure could lead to riser loss	Visual inspection.	L	MI	MI	L	Implement QA/QC procedures during welding.
2-14		Damage or disbonding or deterioration of elastomer layer.	Fluid properties beyond design basis; sour crude, HPHT.	Damage of elastomer layers.	Flex joint damage, fatigue, leakage, requiring replacement of flex-joint	Visual inspection.	L	MI	MI	L	Use of bellow system to reduce effects of abnormal conditions.
2-15		Failure of receptacle seating the flex joint.	Vessel impact leading to significant movement of FPU and CVAR.	CVAR moving beyond angular cocking range of flex-joint.	Disconnection of CVAR at top	Visual inspection.	L	MI	SE	M	Undertake SIT at yard to ensure proper seating.
2-16	Tapered Stress Joint (TSJ) in Steel at Lower End of Riser	Cracks at weld between TSJ and riser section.	Fatigue loading effects at weld.	Propagation of crack to through thickness crack.	Potential leakage; impairment of structural integrity	Inspection by pig.	L	MI	NC	L	Implement QA/QC procedures during welding and installation.
2-17		Deterioration at ID of TSJ & weld.	Corrosion from sour crude.	Potential for corrosion induced fatigue leading to cracks at weld.	Potential leakage; and Impairment of structural integrity	Inspection by pig.	L	MI	NC	L	Use of corrosion inhibitor to reduce likelihood.
2-18		External damage to TSJ.	Dropped object impact.	Reduction in effectiveness of TSJ.	Impairment of structural integrity	ROV inspection.	L	MI	NC	L	Low probability due to offset; Undertake lifting operations on opposite side.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-19	Mudline Tree with Shear Rams	External damage to mudline tree.	From impact of dropped objects.	Damage or bending of some items in mudline tree.	Impairment of operability of tree.	ROV inspection.	L	MI	NC	L	Low probability due to offset; undertake lifting operations on opposite side.
2-20	Insulation Coating	Loss of adhesion between layers.	Excessive riser motions; high temperature of fluid beyond specs.	Reduction in U value; increase in water absorption.	Marginal reduction in riser tension	ROV inspection.	N	NC	NC	L	QA/QC procedure implementation; project specific qualification testing.
2-21		Disbondment of FBE coating from riser pipe.	Excessive riser motions; high temperature of fluid beyond specs.	Reduction in U value; increase in water absorption.	Potential for steel pipe corrosion; build-up of wax or hydrates	ROV inspection; inspection by pigging.	L	NC	NC	L	QA/QC procedure implementation; project specific qualification testing.
2-22		Failure of field joint contact with insulation applied at plant.	Excessive riser motions; high temperature of fluid beyond specs.	Reduction in U value; increase in water absorption.	Potential for steel pipe corrosion; build-up of wax or hydrates	ROV inspection; inspection by pigging.	L	NC	NC	L	QA/QC procedure implementation; project specific qualification testing.
2-23		Cracking of insulation (outer layer).	Damage of external layer/protection.	Potential for increased water absorption in local area.	Build-up of wax or hydrates	ROV inspection.	N	NC	NC	L	Use thicker outer layer.
2-24		Water absorption impact on thermal conductivity degradation.	Due to external hydrostatic pressure.	Reduction in U value. Increase in water absorption.	Potential for wax and hydrate deposits; blockage of production; requires cleanup by pigging	Inspection by pigging.	L	NC	NC	L	Thicker outer layer to reduce the probability of occurrence.
2-25		Abrasion of outer surface of coating.	Riser-to-riser clashing.	Potential for damage of a protective outer layer in local area.	No measurable impact on the riser system.	ROV inspection.	L	NC	NC	L	Thicker outer layer or use of high abrasion coating.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-26	Insulation Coating	Creep and ageing of insulation.	Excessive hydrostatic pressure; temperature.	Reduced thermal conductivity; degraded properties of coating.	Potential for wax and hydrate deposits leading to production blockage.	Inspection by pigging.	L	NC	NC	L	QA/QC procedure implementation; project specific qualification testing.
2-27	Weight Coating	Disbondment of rubber coating from riser pipe.	Ageing from temperature effects.	Reduction in insulation properties.	Marginal impact on riser performance.	ROV inspection.	N	NC	NC	L	QA/QC procedure implementation; project specific qualification testing.
2-28		Damage to outer layer.	Dropped objects.	Increased water absorption.	Marginal impact on riser performance.	ROV inspection.	N	NC	NC	L	Thicker outer layer to reduce likelihood.
2-29		Wear of exterior layer.	Riser-Riser clash/abrasion.	Potential for increased water absorption in local area.	Marginal impact on riser performance.	ROV inspection.	N	NC	NC	L	Thicker outer layer or use high abrasion coating.
2-30	Strakes	Detachment of 1 or 2 sets of strakes from clamps.	Riser-to-riser collision.	Change in VIV behavior.	Potential increase in VIV fatigue damage and failure of some riser sections.	Diver or ROV inspection; VIV monitoring.	L	NC	NC	L	Maintain spare strake halves on board FPU or in an onshore storage.
2-31		Failure of strake operability.	Higher marine growth.	VIV induced fatigue effects.	Leakage, fracture of a riser section.	Diver or ROV inspection.	L	NC	NC	L	Use anti-fouling coating on strakes.
2-32		Water absorption.	Excessive hydrostatic pressure.	Localized to strakes at depth; reduction in riser tension.	Marginal impact on riser performance.	Riser tension monitoring.	L	NC	NC	L	
2-33		Damage of strake.	Improper procedures.	VIV induced fatigue effects.	Leakage, fracture of a riser section.	Diver or ROV inspection.	L	NC	NC	L	Maintain spare strake halves on board FPU or in an onshore storage.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-34	Buoyancy Modules Transition Region Riser Length	Failure of a clamp or module attachment.	Impact from dropped object or clashing of risers; excessive riser motion (esp. bending).	Detachment of buoyancy halves or a module.	Potential for higher compression leading to buckling of riser section.	ROV inspection.	N	NC	NC	L	Limited to 1 or 2 modules; undertake SIT at yard to ensure proper fitting.
2-35		Loss of all buoyancy modules.	Manufacturing defects or improper connection of modules with riser section.	Significant reduction in riser tension & potential buckling of riser sections.	Impairment of riser integrity and operations.	ROV inspection.	N	SE	SE	L	Undertake SIT at yard to ensure proper fitting.
2-36		Damage of buoyancy material - outer sheath.	Impact from dropped object; clashing of risers.	Increased water absorption.	Reduction in riser tension in specific modules.	ROV inspection.	L	NC	NC	L	Limited to 1 or 2 modules.
2-37		Abrasion of surface.	Clashing of risers.	Damage of protective layer.	Water absorption - local area.	ROV inspection.	L	NC	NC	L	Use anti-abrasive coating on modules.
2-38		Reduced buoyancy.	Water absorption; compression; creep.	Reduction in riser tension.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Design basis provision.
2-39		Creep.	Hydrostatic pressure and temperature.	Reduction in buoyancy leading to reduced tension in riser section.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Qualification testing of material performance.
2-40		Ageing.	Temperature, chemicals.	Degradation in material properties.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Qualification testing of material performance.

Table 7-5 FMECA – CVAR Production Stage (Contd.)

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
2-41	Buoyancy Modules - Lower Region Riser Length	Failure of a clamp or module attachment.	Impact from dropped object.	Detachment of buoyancy halves or a module.	Potential for higher compression leading to buckling of riser section.	ROV inspection.	N	NC	NC	L	Limited to upper modules; SIT at yard to ensure fitting.
2-42		Loss of all buoyancy modules.	Manufacturing defects or improper connection with riser section.	Significant reduction in riser tension & potential buckling of riser sections.	Impairment of riser integrity and operations.	ROV inspection.	N	SE	SE	L	Undertake SIT at yard to ensure proper fitting.
2-43		Reduced buoyancy.	Water absorption; compression; creep.	Reduction in riser tension.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Design basis provision.
2-44		Creep.	Hydrostatic pressure and temperature.	Reduction in buoyancy leading to reduced tension in riser section.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Qualification testing of material performance.
2-45		Ageing.	Temperature, chemicals.	Degradation in material properties.	Marginal impact on riser performance.	Riser load monitoring.	L	NC	NC	L	Qualification testing of material performance.

Riser Sections in High Strength Steel and with T&C Connectors:

The HSS riser sections with threaded ends are required in this case to meet the strength or fatigue estimates of CVAR. The make-up of such riser connections is important and strict adherence to the procedures is necessary to reduce the probability of occurrence of failure modes listed.

By following the QA/QC procedures for the make-up of threaded connections, the probability of damage of CVAR steel sections by the handling equipment (such as power tongs, etc.), and from galling at the metal-to-metal seals can be reduced.

It is important to maintain configuration of the CVAR and its various attachments to reduce the potential for riser overload scenarios, which could buckle or burst the pipe. Thus the integrity of buoyancy modules is very important.

The leak frequency of risers in deepwater application is not available as very limited experience exists and a comprehensive data of failures and evaluations is required. The PARLOC data [AME Ltd., 1998] available is based on riser applications primarily in shallower water depths with the steel jacket platforms. The leak frequencies available from the UK operations need to be adjusted for the GOM case with varying loop current conditions and reduced fatigue damage. In addition, adjustments may be required for the effect of VIV response.

The MMS database for GOM pipelines and risers [Kominsky, 2002] identifies the four top reasons for failures of risers and pipelines as corrosion (internal, external), natural hazards, impact, and structural. The riser damage in this database seems to be primarily related to shallow water platforms. The failures are very less in deeper water depths. The impact cases reported are mostly from anchor drag, jackup rig, ship on riser, trawl/fishing net and the impact incidents below 250 ft water depth are only 5%. Thus only a few cases would apply to the deepwater riser case. The internal corrosion damage is reported in 30% cases of risers and pipelines combined and 70% failed due to external corrosion. The external corrosion failures reported are mostly in case of risers. In 124 risers, internal corrosion damage is reported. The corrosion cases are reported to have resulted in minor spills (1 bbl to 1,000 bbl), and impact cases are reported to cause spills greater than 1,000 bbl. The failures reported in the MMS document need further evaluation to identify the cases related to deepwater risers, where the initiating events and consequences would vary.

Flex joint:

The flex joint design has been modified by a manufacturer after the failure of several flex joints [Hogan et al, 2005]. See discussion in Section 6.4.3. The potential of failure of the receptacle seating the flex joint, and the potential for disconnection of the CVAR at this connection, when the FPU has large displacement upon a hit by a vessel, are identified to fall under “Critical” category. This criticality level can be reduced to “Low” level by undertaking for each riser SITs for seating of the flex joint in receptacle at a yard.

Insulation Coating:

The multi-layer insulation coating comprises of 5 layers: the first 3 layers providing corrosion protection; the outer syntactic polyurethane layer providing protection; and the intermediate layer of syntactic polypropylene providing primarily insulation to the pipe. The weak link in an insulation coating is normally at the field joints done on the installation vessel upon make-up of two riser sections (or two assemblies of riser sections).

The performance of insulation coating has been well proven and qualified products and application techniques from multiple vendors are available. In case of a Tubing CVAR design the insulation coating required for flow assurance of fluid will also provide additional protection to steel riser sections from some incidents.

Heavy Weight Rubber Coating:

The heavy weight rubber coating has been qualified by Trelleborg through extensive testing [Trelleborg Engineered Systems, 2004] and the product for insulation coating has been used in subsea in a few cases. Additional evaluation of test documents of heavy weight coating and discussions for its application on the CVAR may be undertaken with Trelleborg to further identify issues and establish the procedures for its application.

Strakes:

From ROV inspections in the GOM, riser motions in "figure of eight" have been reported to the MMS, and such motions could be 4 to 5 times the riser diameter. Such motions were considered in estimation of the clearance between risers and/or potential damage from impact. Riser clash events have been recorded by MMS from post-hurricane inspections, and the damage was noted to be minimal and non-consequential with only some coating damage.

The interference analysis presented in Section 5.5 estimated that the critical region for interference is likely to be the upper 500 ft to 1,000 ft of the CVAR. In the Upper Region, the CVAR pipe is coated with 1.5" thick insulation and then fitted with strakes (or fairings). The minimum clearance between adjacent CVAR's was estimated as 9.7 ft and the case with varying drag coefficient for "Heavy" conditions showed that the riser-to-riser clash would occur (see in Table 5-13). The impact loads will be low and interference should not occur when strakes are fitted and adequate angle is provided between adjacent risers.

The strakes are fitted in the upper region riser sections of the CVAR, which could have potential for damage from contact/clashing of adjacent risers. The potential of contact of adjacent risers will be reduced significantly by change in their azimuth or the hang-off angles. In the design of a SCR, variations in the hang-off angles are considered for the same reason. This was also identified to benefit by reducing the likelihood of affecting worm beds (below seabed) in deepwater GOM.

In general the design process includes a provision for additional strakes to account for the damage or loss of a few strakes. In case of strakes, the consequences from clashing shall not be worse than when strakes pass over a stinger. In this case, the installation of CVAR riser sections and fitting of strakes is proposed to be done from a MODU or a J-lay vessel.

Buoyancy Modules:

Multiple buoyancy modules with varying diameters or with tapered sections are required over the transition region riser sections of CVAR. The attachment clamps (for the buoyancy modules) fitted over the insulated riser sections are designed for the life of field, and the clamps and buoyancy modules are designed for easy disconnection of modules if their retrieval is required.

However, this product has been used over a SCR in the GOM to reduce the riser payload [Korth et al, 2002], where a significant number of buoyancy modules were fitted (see Section 2.5.7 and Figure 2-10). Thus their performance subjected to the current loading in the GOM has been tested over a riser.

The buoyancy modules and their clamps may need further detailed evaluation to identify loads at the connection, from dynamic motions of a CVAR.

It is very important to maintain buoyancy modules as detachment and loss of several modules could lead to significant overload of the CVAR sections. In order to avoid clash events upon failure of a few buoyancy modules or halves, the hang-off angle and elevation of transition region (with large diameter buoyancy tanks) in adjacent risers may differ.

7.3.4 Risk Reducing Measures

In order to reduce the likelihood of initiating events, various measures are included in the operational plans of platforms. Some of these measures are identified below:

- Implementing QA/QC procedures and undertake JSA for various operations, or undertake SIT for some components or systems;
- Undertaking SIT to ensure proper make-up of threaded connectors of riser sections, and the connections of riser section with the mechanical components;
- Monitoring the fluid properties, the performance of selected components and systems by sensors and by other means such as inspection by pigging, ROV, or divers (in shallow water);
- Cleaning of the marine growth periodically to reduce the drag load on the riser and to reduce the VIV behavior;
- Periodically inject corrosion inhibitor in the riser pipe to control the effect of damaged or failed anodes (cathodic protection system).
- Undertaking lifting operations from supply vessels at the side of the FPU other than with the CVAR, where feasible;
- Maintaining spares available for some critical components to enable implement remedial action at the earliest; and
- Providing extra thickness of coating or using high abrasion coating to the outer protective layers of coatings or buoyancy modules, to reduce the consequences from abrasion due to riser-to-riser clash or from impact of dropped objects.

7.4 Well Operations

7.4.1 General

The well intervention operations undertaken from the CVAR will vary with the design type of steel riser section selected. Based on the preliminary work, it is shown that three alternative designs for riser sections are feasible for the CVAR as given in Figure 2-3 (see Section 2.4). The intervention operations feasible from these riser section design alternatives are as follows:

- Single Casing and Tubing Risers:
  - Light well intervention; and
  - Minor workover interventions.
- Dual Casing Risers:
  - Light well intervention;
  - Minor workover interventions; and
  - Heavy intervention operation.

The potential risks associated with the well operations are addressed for the tubing riser design case only.

7.4.2 Tubing CVAR – Mudline Tree Package

The MTP for a Tubing CVAR design case is presented in Figure 2-13 in Section 2.5.9. The MTP is positioned between the TSJ at the bottom of the CVAR and the Tubing Head Spool (THS). The MTP provides additional safety measures to the Tubing CVAR design that has only one riser pipe in comparison to the single casing or dual casing design options, which have been used in the past with the dry tree FPUs. Typical umbilical design is given in Figures 2-13 and 2-14.

The MTP is fitted with shear rams to disconnect casing or riser at the bottom by shear operation and seal production flow. Figure 7-7 shows the selection and location of the valves in the upper and lower parts of the MTP (the tree and the tubing head spool). The procedure shown is for the case of undertaking completion and workover operations from a MODU. The procedures and tools used are proven, and failure modes are known to the industry.

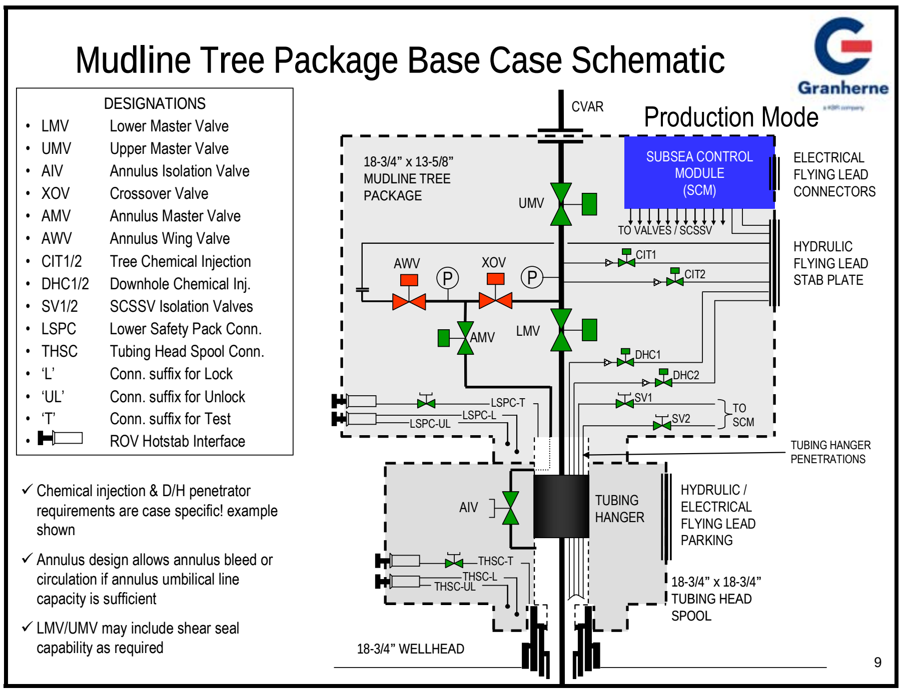


Figure 7-7 Mudline Tree Package "Base Case" Schematic

7.4.3 Tubing CVAR – Minor Workover Procedure

The minor workover and final completion (perforation etc.) after connection of the CVAR can be undertaken by direct vertical access (DVA) from the platform. This is also proven and performed by the industry. But in case of a CVAR due to its S-shape configuration at deeper depths (below 6,000 ft water depth for the case presented in this study) the wear potential at ID of the CVAR is important to consider and identify necessary measures to mitigate effects of wear. The mitigation measures may include lining of ID or provision of wear bushings at the bends and the flex joint.

Figure 7-8 shows how the base configuration changes for drilling, completion, installation and minor workover operations. Steps 1 and 2 are conducted from a MODU. In step 3 the CVAR is installed from a

MODU and 'handed' over to the Semi-submersible FPU. In step 4 minor workover is performed through the CVAR from the Semi-submersible FPU.

An assessment was done using Cerberus software package, with special algorithms designed and utilized by Halliburton to run any kind of coiled tubing (CT) or snubbed pipe operations, to evaluate CT intervention feasibility from CVAR. The preliminary analysis performed has shown the feasibility for the following:

- Selective representative well profiles in deep water GOM;
- Multi-slope well profiles;
- Horizontal sections less than 4,000 ft long;
- Well depths less than 25,000 ft; and
- Constant diameter and tapered coiled tubing string profiles.

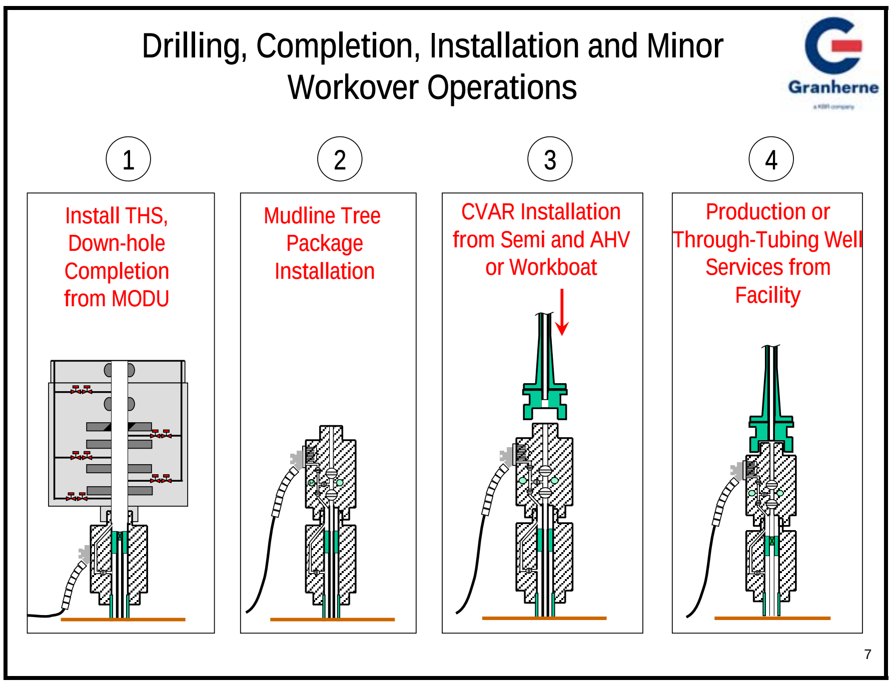


Figure 7-8 Drilling, Completion, Installation and Minor Workover Operations

7.4.4 Tubing CVAR – Major Workover Procedure

The major workover operations are considered to be conducted from a MODU as shown in Figure 7-9. The CVAR is moved to a parking stump using either MODU or an AHV. The tree (upper part of the MTP) is removed for maintenance by the MODU, and a BOP is run from the MODU. During the major workover, the removal of a downhole tubing can be performed from the MODU.

The procedure for a major workover from a tubing riser is identified as below:

- Start of operation with well shut-in:
  - Well is treated and shut-in; and

- CVAR connector can be plugged, if required for isolation and to hold riser contents.

- Relocate CVAR to "parking" stump:
  - CVAR is pulled and parked at about 200 ft; and
  - Close mudline tree valves to provide well isolation.
- Retrieve tree:
  - Close annulus valve on THS to provide annulus isolation;
  - Umbilical (or flying head) connection to the mudline tree is parked on THS;
  - Mudline tree can be pulled for services/checks, as required; and
  - Need a plug in tubing when retrieving.
- Run BOP and commence heavy W/O operations:
  - Run stack on THS and test connector/rams;
  - Open THS annulus valve with ROV;
  - Pull tubing hanger isolation plug and circulate well through choke/kill as required; and
  - Run tubing hanger running tool to unlock and hanger and recover completion.

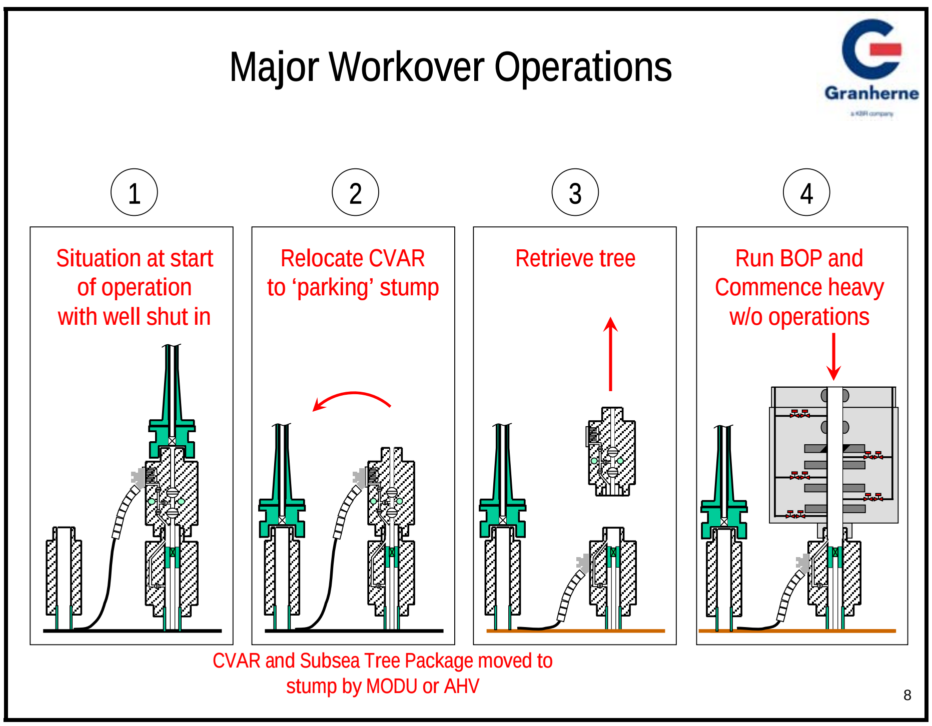


Figure 7-9 Major Workover Operations

7.4.5 Coiled Tubing

Figure 7-10 presents an illustration of the arrangement of CT with cables that are located inside the riser pipe. The control flatpack is also within the coiled tubing in one design.

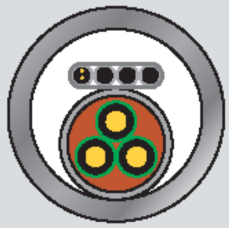


Figure 7-10 Coiled Tubing with Electrical Flatpack Inside Riser Pipe

7.4.6 FMECA

The failure modes associated with various components of a CVAR during well operations were identified in Tables 6-1 to 6-4. The FMECA is done for the failure modes possible during the well operations and is presented in Table 7-6, which indicated that during well operations the following failure modes could occur:

- Riser and mechanical fittings (TSJs, Flex Joint) – primary components:
  - Wear at ID from operations of CT and WL tools; and
  - Tools unable to pass through.
- Damage or loss of strakes from dropped objects during well operations;
- Detachment of buoyancy halves from dropped objects during well operations;
- Damage to buoyancy clamps from dropped objects during well operations; and
- Shear ram at the mudline tree package unable to shear.

To safeguard against excessive wear by CT or WL, wear bushings or wear liners are provided. These are useful at high bends (as in the transition region of the CVAR) and at the flex-joint.

Table 7-6 FMECA – CVAR Well Operations

Item	Component or Sub-system or Activity	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
3-1	Upper region riser sections	Excessive Wear at ID	Completion or Abrasion from CT or WL.	Loss of riser pipe WT.	Reduced design pressure capacity of pipe.	Internal pipe log	L	MI	MI	L	Design WT for wear. Use protector and centralizers.
3-2		Increase in curvature	Vessel collision/mooring failure/loss of buoyancy modules.	CT stuck and damage to ID of pipe or mechanical fittings.	Delay in production restart.	Visual	L	NC	NC	L	Limit operations to a weather window; undertake SIT or trials before and establish extreme operations criteria.
3-3	Transition region riser sections	Excessive Wear at ID	Completion or Abrasion from CT or WL.	Loss of riser pipe WT.	Reduced design pressure capacity of pipe.	Internal pipe log	L	SE	SE	M	Design WT for wear. Use protector and centralizers. Install wear liner or bushings.
3-4	Lower region riser sections	Excessive Wear at ID	Completion or Abrasion from CT or WL.	Loss of riser pipe WT.	Reduced design pressure capacity of pipe.	Internal pipe log	L	SE	SE	M	Design WT for wear. Use protector and centralizers. Install wear liner or bushings.
3-5	Tapered Stress Joint (TSJ)	Wear at ID	Abrasion from CT or WL.	Loss of riser pipe WT.	Marginal impact on TSJ capacity.	Internal pipe log	L	MI	MI	L	

Table 7-6 FMECA – CVAR Well Operations (Contd.)

Item	Component or Sub-system or Activity	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
3-6	Flex Joint	Wear or damage at flex joint	Abrasion from CT or WL.	Damage to flex-joint elements.	Potential for leakage or riser disconnection.	Visual or internal pipe log	L	MI	MI	L	Use wear bushing.
3-7		Unable to pass tools	Imporper seating of flex joint in receptacle.	Damage to flex-joint elements.	Delay in well operations.	Visual	L	NC	NC	L	Undertake SIT at onshore yard.
3-8	Umbilical	Detachment	Significant movement of CVAR due to high metocean loads.	Loss of control of MTP operations.	Delay in well operations.	ROV inspection	L	NC	MI	L	

8 COMPARATIVE RISK ASSESSMENT

8.1 Approach

The conventional top tensioned riser (TTR) designs for dry tree operations or for direct vertical access (DVA) of wells from a platform have been used in TLPs and Spars as shown in Figure 2-1. The risks associated with production from these TTR designs are known to the industry and are acceptable. In this section, a comparison of key components of the CVAR design is done with those of the TTR and steel catenary riser (SCR) designs to identify differences in component types among these alternative riser systems. Then an assessment of the potential risks associated with specific connections or components that differ for the TTR are presented.

8.2 Comparison of Riser Systems

A significant advantage of the CVAR design is from its potential for dry tree operations and DVA of wells from alternative FPU designs including semi-submersibles and FPSOs, thus its potential for enabling dry tree operations from platform types that were not feasible earlier. This is made possible by the offset design of the CVAR and using specific mechanical fittings and ancillary components, which differ from the conventional TTR designs used in TLPs and SPARs as shown in Figure 2-1. Some of the mechanical fittings or connections in the CVAR design are similar to those used in a SCR design.

In Table 8-1, a comparison of variations in components of alternative riser designs is made, which is then used to qualitatively address potential variations in risks associated with selected components.

The CVAR design variations from a TTR could be identified as follows:

- CVAR riser length is longer by about 5% to 7%;
- CVAR has a reduced number of different key load bearing (primary) components;
- CVAR would typically have smaller magnitude of loads (tension, BM) at top than those for a TTR in comparable water depth; and
- CVAR have an increased number of ancillary (secondary) components.

The ancillary components play a very important role by maintaining shape of the CVAR to meet the operational requirements and to keep the utilization of the steel riser sections and mechanical/end fittings within the design limits. Thus integrity and performance of the attachments are important in ensuring the reliable performance of CVAR designs. Some of these ancillary components could be designed for replacement (if needed) during the lifetime production from a riser, thus providing a remedial measure to reduce the effects of damage or failure of a few units of ancillary components on the CVAR behavior and operations.

The CVAR is connected to the FPU by a flex-joint or a TSJ in Titanium (similar to that done for a SCR) and at the seabed to the wellhead by a TSJ in steel (for double casing riser design) or to a mudline tree (in case of tubing or single casing riser design).

The comparison in Table 8-1 shows that all of these components have been used in TTRs and/or SCRs in service in the GOM and significant industry experience exists. The designs of these systems have been further advanced and more recently integrity management has gained significant importance and measures are being taken to further improve their reliability and performance. Thus it is believed that the risks associated with the failure modes of mechanical components would be similar. In case of a CVAR due to offset well the risk of failures of the mudline tree package (provided with shear rams) or the TSJ from dropped objects from the platform during operations are expected to be significantly lower.

Table 8-1 Comparison of Key Components in Alternative Riser Systems

<table>
<tr><th>Components/Type</th><th>Tubing CVAR</th><th>Dual casing CVAR</th><th>TTR w/ Buoyancy Cans</th><th>TTR w/Top Tension Riser</th><th>SCR</th></tr>
<tr><td>At Deck</td><td>-</td><td>-</td><td>Jumpers</td><td>Jumpers; Tensioner</td><td>-</td></tr>
<tr><td>Connection with hull or deck</td><td colspan="2">Direct connection; flex joint or stress joint (steel or titanium)</td><td>Air cans; Lateral guides for air cans in Spar Moonpool</td><td>Tensioners connected to deck</td><td>Direct connection; flex or stress joint (steel or titanium)</td></tr>
<tr><td>Joints at riser top</td><td>-</td><td>-</td><td>-</td><td>Tensioner joint and load ring</td><td>-</td></tr>
<tr><td>Connection at bottom of hull</td><td>-</td><td>-</td><td>Keel Joint - lateral support</td><td>Guide frames (used in one TLP)</td><td>-</td></tr>
<tr><td rowspan="5">Riser sections</td><td colspan="2">High Strength Steel (HSS) riser section with Threaded Connections (110 ksi or 125 ksi) – More number of riser sections than TTR</td><td colspan="2">Weld on Threaded Connections up to 80 ksi steel or HSS sections up to 110 ksi or 125 ksi</td><td>Welded X65 or X70 grade riser sections</td></tr>
<tr><td>Insulation coating</td><td colspan="3">FBE coating</td><td>Insulation coating</td></tr>
<tr><td colspan="2">Strakes or fairings</td><td colspan="2" rowspan="3">Strakes or fairings</td><td>Strakes or fairings</td></tr>
<tr><td colspan="2">Buoyancy modules</td><td>Buoyancy modules in lazy wave SCR</td></tr>
<tr><td colspan="2">Weight coating</td><td>Weight coating in some cases</td></tr>
<tr><td>Connection at bottom of riser</td><td colspan="2">Taper stress joint in steel</td><td colspan="2">Taper stress joint in steel</td><td>To PLEM/ pipeline</td></tr>
<tr><td>Mudline Tree Package</td><td>Mudline tree w/shear rams</td><td>-</td><td colspan="2">In case of tubing or single casing riser</td><td>-</td></tr>
</table>

The following observations are made from the comparison of components presented in Table 8-1:

- The CVAR riser sections in HSS with threaded ends and no welds are similar to those used in newer designs of TTR applications in deepwater and ultra-deepwater. The make-up procedures are proven.
- The mechanical fittings and connections required for a CVAR (flex joint or TSJ in titanium at the top end of a CVAR; TSJ in steel at the bottom end of a CVAR; mudline tree with shear rams) have been used in various TTR and SCR connections.

- TTRs have additional mechanical fittings and connections, which are primary components and very important to their operation and performance. These for a TTR with tensioner system include: Tubing jumpers; tensioners; tensioner joint; load ring; and associated connections. In case of a TTR with buoyancy cans the additional components include: air cans and guides, keel joint or guide frame.
- The CVAR design requires increased number of ancillary components (strakes, insulation coating, FBE coating, weight coating, buoyancy modules, cathodic protection anodes) and all of these have been used in TTR or SCR designs in-service in the GOM. Weight coating, a product known to have not been used so far on riser sections, has been qualified.
- The SCR design varies from the CVAR primarily due to use of welded riser sections, and it is a tieback riser for wet tree operations. No well completion, well workover and maintenance operations are undertaken from a SCR. Maintenance of the SCR pipe is done using pigs.

The important differences in the CVAR design are the provision of large diameter buoyancy modules in riser sections in the transition and lower regions, weight coating at the lower end of upper region riser sections. Such buoyancy modules have been used in drilling risers and were also used in a SCR in a GOM platform [Korth et al, 2002].

The orientation and layout arrangement for a CVAR and use of buoyancy elements have similarities to those for a lazy wave SCR [Torres et al, 2002 & 2003], flexible risers and umbilicals. The lazy wave SCR design (not used in-service so far) and flexible risers are both well tieback solutions. This feature of flexible risers and umbilicals, and the observed/recorded performance would provide additional basis to support the CVAR solution operations and its reliability. However, the historical databases and damage records need careful consideration of their design development and use in similar scenarios.

The mechanical components or fittings required in a TTR design with tensioners are listed in Table 8-1 and these will have various additional failure modes with associated criticality levels to production loss or pollution from TTR. Thus, in general it can be said that these additional components, which are required in multiple numbers for each riser (minimum 4 tensioners used per riser), are likely to increase the criticality level for production loss or delay consequence. These are assessed in the following sub-sections.

8.3 Review of Top Tension Riser Components

General illustration of riser tensioner system is given in Figure 2-1(b). In addition to provision of multiple tensioners in each riser, the top riser section used is a specially designed tension joint to support the production riser tensioner system, and a production jumper connects the dry tree wellhead with the platform piping system. These are important structural items for operations of a TTR fitted with tensioners and are not required in case of a CVAR, which is directly connected to the FPU hull similar to that done for a SCR.

<u>Tension Joint and Tension Ring:</u>

The tension joint provides an interface between the production riser and the platform deck. At the lower end it has the threaded end for connection with the riser section. At the upper end it has an integrally machined connection as a wellhead connector for interface with the surface tree.

The tension ring (or load ring) assembly consists of a split threading housing and connecting bolts. The tension ring is installed on the tension joint threaded area on OD (in middle zone) using steel bolts. The connection to the tensioner is through the tension ring, and the middle zone of tension joint is designed with higher thickness to withstand tension and bending loads from the tensioner system.

Production Riser Tensioner:

The production riser tensioner is designed with a tension spring to support the riser weight and accommodate the platform motions. It allows relative movement between an individual riser and the platform (TLP or Spar), while maintaining near constant tension at the top. The production riser tensioner consists of the following key components (see Figure 2-1(b)):

- Hydraulic cylinders with end attachments;
- Accumulator bottles filled with gas and fluid;
- Structural cassette frame at deck with padeyes for cylinders attachment;
- Centralizing roller on structural cassette to keep the riser centered; and
- Instrumentation of tensioner to monitor pressure, fluid levels, and other parameters.

The hydraulic cylinder and accumulator assembly acts as hydro-pneumatic spring and provides the most important function of compensating effects of relative motions of the platform and risers. The cylinder is connected to the structural cassette frame at one end and the tension joint at the other end.

Production Jumpers:

The production jumper (or flexible flowline connection) shown in Figure 2-1(b) is connected at top of each production riser to transfer the produced fluid from the Christmas tree to the processing system located on the deck. It is designed to absorb the effects of relative motions between riser and floating platform. The integrity of jumpers and their connections to the riser and to the process unit are important to avoid spills and pollution.

The most critical areas on tensioners are at the tension ring (load ring) area and the roller area, which are subjected to significant bending moment. Each tensioner unit (cylinder & accumulator) is an independent tensioning system, and can be replaced.

8.4 FMECA of TTR Tensioner System

The failure modes associated with the key components of a tensioner system are given in Table 8-2 and assessed to identify the initiating events, local and system effects, and categories of likelihood of occurrence and consequences on TTR. Then criticality level is identified to provide an assessment of potential risk level.

The assessment for the selected components of a TTR tensioner system summarized in Table 8-2 shows that the criticality to the CVAR from failure modes for most components would be Low (L). In case of Item 4-1 with potential failure of connection leading to a reduction in capacity and requiring replacement is estimated with Medium (M) consequence to production loss. But this can be controlled by periodic implementation of IMR programs.

Table 8-2 FMECA – TTR Tensioner System

Item	Component or Sub-system	Failure Mode	Initiating Event	Local Effects	System Effect	Detection Options	Likelihood	Consequence 1- Production	Consequence 2- Pollution	Criticality (Conseq-1 & 2)	Comments/ Recommendations
4-1	Tensioner - top connectors	Failure of connection	Corrosion; fatigue; or overloading from higher Metocean loads.	Loss of mounting; shut-in production from riser.	Reduction in tensioning required, but accommodated by provision of additional tensioner.	Visual inspection	M	MI	NC	M(1), L(2)	Periodic inspection and maintenances to maintain integrity of connections.
4-2	Tensioner cylinders	Failure of tensioner damper	Loss of pressure or seal or failure of tensioner rod.	Loss of response from one damper.	No loss of tensioning.	Visual inspection	L	MI	NC	L	Undertake tensioner system integration stack-up test of all equipment and any interfaced equipment.
4-3		Failure of all tensioners	Failure of tension ring or common mode failure.	Loss of tensioning & tensioner inoperable.	Failure of riser possibly requiring replacement.	Visual inspection	R	C	SE	L(1), L(2)	
4-4	Air supply to tensioner system	Loss of air supply	Compressor failure.	No resupply available.	Riser failure in case of depletion of all air in cylinders; damage to seal.	Pressure monitoring	L	MI	MI	L	Maintain spare accumulator bottles.
4-5	Flexible Jumper	Failure of jumper pipe	Fatigue or overstress.	Release of HC	Shutdown & loss of production.	Easily detectable	L	MI	MI	L	Maintain spare jumper pipes on the platform.
4-6		Connection failure	Overstress or fatigue.	Release of HC	Shutdown & loss of production.	Easily detectable	N	MI	MI	L	
4-7		Blockage of jumper	Variation in fluid properties.	Shut-in the riser and undertake pigging or CT.	Loss of production.	Pressure monitoring	L	NC	NC	L	

9 SUMMARY AND CONCLUSIONS

This study has shown that the Compliant Vertical Access Riser (CVAR) design concept is a feasible Direct Vertical Access (DVA) and dry tree solution for oil & gas production from the fields in deepwater and ultra-deepwater in the Gulf of Mexico (GOM) and other regions. Feasibility of designing a Tubing CVAR has been shown for such operations from a semi-submersible production vessel in 8,000 ft water depth in the GOM, which is of a significant value. In this study, the work has been presented for a Tubing CVAR design with a mudline split tree, and the wells are offset from the platform. Thus, the drilling and completion plan will differ for a field developed using Tubing CVAR from that for a single or dual casing TTR, because even for the case of pre-drilled wells, it will require a MODU to do completion.

The offset configuration of the CVAR design and its feasibility to vary the location of transition region riser sections and curvature provides significant flexibility in developing its configuration and its design to meet needs for a specific field application. This feature would enable accommodate effects of variations in fluid properties, water depth, and location effects. This would also help in developing variations in configurations of adjacent CVARs to reduce riser-to-riser clash potential, to accommodate random pattern of subsea wells, and to safeguard worm beds in the deepwater GOM.

The sizing and preliminary analysis results for a Dual Casing CVAR have also been shown. Additional work is required to develop it further.

The analysis case presented for a Tubing CVAR utilizes the HSS threaded and coupled (T&C) steel riser sections similar to those used in more recent TTRs and that they meet all performance requirements including strength, fatigue, VIV, and riser interference. In case of the CVAR design HSS T&C riser sections, which are without any weld, are required similar to those used in recent applications of TTRs in the GOM. The HSS threaded connector designs are being further qualified for sour service applications in a RPSEA funded project.

The CVAR riser system utilizes the ancillary components and mechanical connections that have been proven or qualified by the industry through riser applications in several deepwater platforms. The compliant shape of CVAR design require changes from the existing rigid (vertical) riser system installations, but to some extent there is a similarity to the configuration for flexible risers, thus riser layout using multiple CVARs would be similar to that for a group of flexible risers.

The important difference from other riser designs lie in the use of large diameter buoyancy modules that are fitted in the transition and lower region riser sections, which do not increase the metocean loads as the modules are fitted at depth of 6,000 ft or below in the case studies, and they provide increased protection to the steel riser section from the consequences of an accidental event like dropped object. The loss of a few buoyancy modules from such events would not compromise the integrity of the CVAR and is normally a damage design criteria in the design basis, but a plan to replace the damaged/lost buoyancy modules is required. If a large number of buoyancy modules are detached due to inconsistencies in material, fabrication, connections the consequences on CVAR design will be very high. Thus, implementation of a QA/QC process and system integration tests (SITs) are important to increase the reliability of their connection and in addition performance monitoring sensors may be considered to evaluate their in-service performance.

An installation plan is presented and the potential failure modes are identified and discussed. A potential risk reducing measure is to undertake the running of the CVAR away from the platform, which reduces the risks associated with riser installation from the platform itself. This is of a significant value as it would reduce the probability of occurrence of heavy dropped objects falling over the wellhead and mudline tree package. In addition, the well offset feature of the CVAR design is identified to provide increased possibility to avoid damage to worm beds that exist in the deepwater Gulf of Mexico.

During the production stage, the risk (or criticaility) levels for most of the failure modes were assessed to be "Low." There were only a few failure modes that were assessed to have "Medium" risk levels, and through implementation of standard QA/QC procedures during installation of CVAR and of an IMR program during production the risk levels can be reduced to "Low" category.

In general the risks associated with well operations (completion, workover) will be similar to the industry experience with existing installations, except for the increased wear potential in case of the CVAR design due to its S-shape configuration in the transition region, which would require development of a wear management program. Wear liners or wear bushings have been used to manage wear in the past in drilling risers. The offset of wells in case of the CVAR provides an alternative of doing such operations from a MODU as illustrated, which would reduce risks associated with the CVAR design.

Various components in the CVAR design were compared with other riser designs (TTR, SCR) and it was shown that the CVAR design utilize some elements and features of both these designs. It does not require a top tensioning system (tensioners and associated elements or air cans and supporting guides) and production jumpers as required for a TTR, and the top end of the CVAR is directly connected to the platform hull similar to that done for a SCR, which is a significant advantage from reliability and availability considerations.

The CVAR design requires a lesser number of different types of the primary load carrying members, thus reducing the total number of potential failure modes associated with the primary load carrying member designs. On the contrary the CVAR design requires an increased number of ancillary components, and some of them (buoyancy modules, strakes) safeguard the steel riser sections from a direct hit by dropped objects. In case of a TTR design with tensioners, several additional primary load bearing components are added with associated additional failure modes that could lead to increased production loss. Thus the overall risks associated with operations from a CVAR concept are likely to be similar or lesser than those experienced by the industry from deepwater and ultra-deepwater production risers.

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