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ULTRA-DEEPWATER DRY TREE SYSTEM FOR DRILLING AND PRODUCTION IN THE GULF OF MEXICO

Final Technical Report

RPSEA - Research Partnership to Secure Energy for America

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Applicable contract(s) governing the provision of this Report:

Objective:

This project is to perform proper validation and maturation of all safety/environmental critical aspects of two dry tree semi concepts so that they are 'project-ready' and the end users can select the concept with confidence for an on-time, on-budget delivery of a floating platform in the Gulf of Mexico that meets all functional requirements.

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1 EXECUTIVE SUMMARY

DNV GL was requested by RPSEA to manage a project, which develops dry tree semi concepts for the ultra-deepwater fields in Gulf of Mexico. DNVGL's role in this project has been two folds:

1. To manage on behalf of RPSEA for further development of two semi-submersible concepts suitable for drilling and production in Gulf of Mexico (GOM) ultra-deepwater using dry trees.

2. To act as an independent 3rd party verification agent for assessing the maturity of all safety and environmentally critical aspects of the concepts so that they are 'project-ready' in the Gulf of Mexico.

Under the aegis of this project, two previously developed dry tree semi-submersible concepts were further matured for operation at 8,000 ft. water depth in the GOM:

1. Paired Column (PC) semi-submersible developed by Houston Offshore Engineering (HOE)
2. Deepwater Dry Tree Semi-submersible (DWDTS) developed by Kvaerner Field Development (KFD)

Both concepts had previously gone through some development (i.e., previous RPSEA funded projects, DeepStar funded projects, etc.). The current RPSEA project has focused on critical design elements identified in the earlier work.

In evaluating the designs, DNV GL has endeavored to ensure that both concepts were developed in accordance with the same design basis. Of course, each design has had its own unique design challenges, which has been the focus of DNV GL's evaluation.

In previous projects, the following elements were identified as the most critical issues for each concept:

1. Vortex-Induced Motion (VIM) and quayside integration for HOE PC semi concept
2. Riser tensioner qualification for the Kvaerner DWDTS concept

Both concepts underwent VIM model tests and extensive engineering work. DNV GL conducted Approval-in-Principal (AiP) evaluations for both concepts and Technology Qualification (TQ) for each riser tensioning system.

DNV GL concludes that the above critical elements have been adequately addressed for the purposes of conceptual design. Therefore both concepts are considered feasible, and can be regarded as 'project ready' provided all comments and suggested actions in this report are properly addressed in the next project phase (e.g. FEED).

This project involved a large number of subject matter specialists from the industry and from DNV GL in key steps during design basis assessment, progress review, model tests, and final Conceptual HAZID workshops. Throughout the project, the objectives have been to ensure that the concepts (1) are in line with industry practice and (2) meet the requirements for safe operation in the GOM.

2 ABBREVIATIONS

AiP:	Approval in Principle
DD:	Deep Draft
DR:	Drilling Riser
DNV GL:	Legacy Det Norske Veritas and legacy Germanischer Lloyds have been merged as of September 12th, 2013, DNVGL is the new brand. Legal entity remains the same. This project contact was signed in October, 2012 between Det Norske Veritas USA (Inc.) and RPSEA.
DTS:	Dry Tree Semi
DWDTS:	Deepwater Dry Tree Semi
FEED:	Front End Engineering Design
FMECA:	Failure Mode Effect and Criticality Assessment
GOM:	Gulf of Mexico
HAZID:	Hazard Identification
HLD:	Heavy Lift Device
HOE:	Houston Offshore Engineering
KBPD:	Kilo-barrel Per Day
KFD:	Kvaerner Field Development
KOS:	Kiewit Offshore Services
LQ:	Living Quarter
MAWP:	Maximum Allowable Working Pressure
MBL:	Maximum Breaking Load
MMCFD:	Million Standard Cubic Feet per Day
PC:	Paired Column
RP:	Recommended Practice
RPSEA:	Research Partnership to Secure Energy for America
SCR:	Steel Catenary Riser
SIMOP:	Simultaneous Operation of Drilling and Production
ST:	Short tons
TLP:	Tension Leg Platform
TQ:	Technology Qualification
TRL:	Technology Readiness Level
TTR:	Top Tensioned Riser
Ur:	Reduced velocity
VIM:	Vortex Induced Motion
WPG:	Working Project Group, industry participants working as volunteers to provide comments/input to RPSEA project.

3 INTRODUCTION

3.1 Background

Operators in the Gulf of Mexico (GOM) are increasingly looking to ultra-deepwater (>6,000 ft. water depth) and more challenging reservoirs. These deep subsalt reservoirs frequently have complicated issues (i.e. additional required drilling, more complex completions, artificial lift, and workover/intervention complexity). These issues generally point towards the use of dry trees as the most economical solution. In many cases the depth of the reservoir requires a large drilling rig and drilling variable payload, resulting in very large topsides which challenge the limits of current spar technology.

GOM dry tree solutions have been dominated by spars and Tension Leg Platforms (TLPs). For water depths beyond about 6,000 feet, the TLP becomes cost prohibitive. For large payload systems, especially those requiring large drilling payload, the spar size, transportation options, and offshore installation become a challenge. The semi-submersible vessel offers several advantages over the spar option, including larger deck space and the possibility of quayside topsides installation and integration. It is expected that the dry tree semi will be cost competitive with the spar in most cases and will overcome the size limitations of the spar option.

The industry has shown significant interest in developing a dry tree semi solution over the last few years to increase contracting options (e.g., Lee, et al, 2014). However, there remains an uncertainty about the total system maturity, constructability, performance, and cost efficiency.So far no dry tree semi has been selected as a host platform for large payload systems in ultra-deepwater.

3.2 Objective

Building on recent development of dry tree systems, including that done by RPSEA 1402 (HOE, 2011), this project is aimed at delivering project-ready and cost competitive dry tree semi solutions for the GOM in a minimum of 8,000-foot water depth with drilling and production capabilities for moderate to large payloads. The objective of this study has been to consider two promising hull forms with the associated riser tensioning systems that make use of conventional technologies to the extent possible. Key technical challenges and/or new technologies, which require qualification before being field ready, are to be addressed with associated technology qualification plans developed.

The study also is to identify deployment opportunities associated with each solution with respect to field applications and considerations for overall safety, equipment limitations, fabrication, transportation, installation, and geographical locations.

3.3 Scope of Work

RPSEA selected two awardees (KFD and HOE) for this study, each with its own unique hull form. Each awardee was tasked with providing a hull form and associated riser tensioning systems, while making use of conventional technologies to the extent possible. The work requires performing pre-front end engineering design (pre-FEED) equivalent engineering and cost estimates.

RPSEA also selected DNV GL to manage the project and to act as an independent 3rd party verifier for assessing the maturity of all safety and environmentally critical aspects of the concepts.

Under the aegis of this project, two previously developed dry tree semi-submersible concepts were further matured for operating at 8,000 ft. water depth in GOM:

1) Paired Column semi-submersible developed by Houston Offshore Engineering (HOE)
2) Deepwater Dry Tree Semi-submersible (DWDTS) developed by Kvaerner Field Development (KFD)

Both concepts had gone through some development previously (i.e. previous RPSEA funded projects, Deepstar funded projects etc). The current RPSEA project has focused on critical design elements identified by earlier work.

For the HOE concept, the following key issues shall be addressed:

1. Vortex induced motion (platform behavior when subjected to high currents) – Model test

2. Qualification of riser tensioner equipment (confirmation by equipment suppliers that the forces, moments and strokes are within the capacity of existing off-the-shelf tensioner equipment and further design of the tensioner system including keel guide)

3. Feasibility of quayside integration and transportation

4. Evaluate the design basis for safe operation in GOM, update the design configurations if needed and perform engineering analysis accordingly

5. Further engineering work and pursue an Approval in Principle evaluation (AiP) by DNVGL

For the Kvaerner concept, the following key issues shall be addressed:

1. Further engineering with appropriate documentation of the conceptual design, incl. hull global design, air-gap, stability, mooring, and riser configuration

2. Evaluate the design basis for safe operation in GOM, update the design configurations if needed and perform engineering analysis accordingly

3. Further enhancement of structural design of riser interfaces with topside and hull structures

4. Qualification of the tensioning system:

a. Analyze structural integrity and stability of riser tensioning system

b. Perform a scaled model test of riser tensioner

c. Conduct a technical qualification of the riser tensioner system

5. Perform a scaled model test of hull vortex-induced-motion (VIM)

6. Pursue an Approval-in-Principle (AiP) evaluation by DNVGL

4 METHODOLOGY

The designers HOE and KFD have further developed their dry tree semi concepts based on the scope defined in the proposal.

The Working Project Group (WPG) was established at the very beginning of the project. The WPG consists of subject matter specialists from the industry and DNV GL as well as the RPSEA project manager. Periodic WPG meetings have been arranged by DNV GL to review progress and seek input from subject matter specialists.

DNV GL used Approval-in-Principal (AiP) as an approach to evaluate the overall concept feasibility. AiP is a typical process used for a class project to assess early conceptual feasibility. For this project, some design aspects that are beyond typical class scope but considered to be critical for dry tree semi concept (e.g. quayside integration) were also included in the evaluation. DNV GL also used our Technology Qualification (TQ) process for the riser tensioner qualification. Details of AiP and TQ process are described below.

4.1 Approval-in-Principal

Approval in Principle (AiP) is a structured process used by DNVGL to carry out an independent assessment of a concept within an agreed requirement framework. The aim of the AiP assessment is to confirm that the design is feasible and that there are no insurmountable obstacles ("showstoppers") that would prevent the concept being realized.

AiP is particularly useful to assess novel designs which will not be adequately addressed by existing recognized codes and standards. The AiP approach is a risk-based approach, which is considered to be the most effective means of identifying and addressing hazards associated with a novel concept. Such hazards may arise from use of novel technology (or operation), from a novel application of existing technology and from an interface between novel and existing technology. Identifying these areas is a key part of the AiP process, which will be initially intuitive and then subsequently part of a structured iterative process. Having identified hazards (or critical elements) to be further addressed, the AiP process will assess how the designer has addressed these concerns. Typically the designer will carry out risk and engineering studies to document the probability and consequence associated with the hazards and the effects of mitigation measures proposed.

The AiP process will review documentation produced in the risk assessment, will confirm that all considered risks have been adequately addressed, and that mitigation measures are considered appropriate. Compliance with relevant prescriptive requirements will also be considered. Depending on the design concept and its intended application, it may also be appropriate to consider any regulatory barriers which might impact the design. In addition, actions to be taken towards full classification will be listed.

As part of AiP process, Conceptual HAZID workshop(s) should be held with subject specialists and the designers. Unlike a typical design HAZID, this conceptual HAZID is similar to a peer review workshop, which will identify potential challenges and risks of a concept. This would typically involve qualified personnel from DNV GL who would facilitate the workshop, together with a team of designer's specialists, industry subject matter specialists, and DNV GL specialists with experience in the design and intended operations. This workshop will focus on critical design elements and systematically discuss the potential risks of the design concept. The intention is to identify potential show-stoppers, identify design novelties (new technology or new application of existing technology), systematically assess 'what if' scenarios of the identified elements to

evaluate potential failure mechanism and consequences of failure, discuss mitigations/improvements, and thereafter determine the feasibility of the concept.

4.2 Technology Qualification

The Technology Qualification (TQ) process is defined as a "Qualification Procedure for New Technology." It is a procedure developed as part of the DEMO 2000 project funded by the Research Council of Norway (Steensen, 2014). The Recommended Practice (RP) was developed to cover the need for a systematic approach to qualify new technology and ensure that the technology functions reliably within specified limits. The main steps in the qualification procedure are shown in Figure 4-1. The scope of the DNV-RP-A203 is applicable for components, equipment and assemblies used in hydrocarbon exploration and exploitation at any development stage.

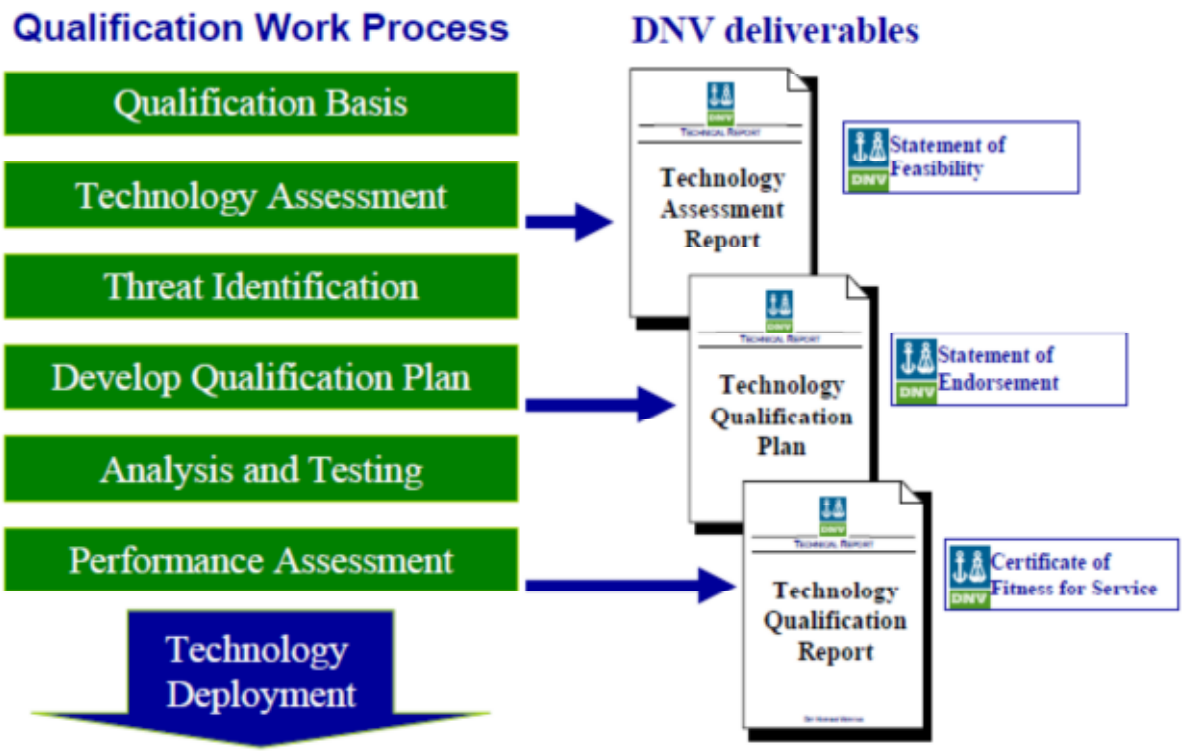

Figure 4-1 DNV GL Technology Qualification Process

5 DESIGN BASIS

DNVGL, in close collaboration with the WPG group performed a comparison of the original design basis used by each designer (KFD and HOE). Some discrepancies and ambiguities were found, e.g. metocean data, acceptance criteria etc. There were also some comments raised on living quarter (LQ) capacity, SCR configurations etc. As an example, the definition in the original Design Basis doesn't seem to be practical for a safe operation in GOM. Based on the above findings and comments received from the Working Project Group (WPG) members and subject matter specialists, some updates were made to the Design Basis in order to develop the concepts for safer operations in GOM. These updates resulted in additional design iterations and some extra engineering work. The finalized Design Basis is summarized in Table 5-1 and used for the design development of both concepts in this project. Metocean criteria are listed in Tables 5-2 and 5-3.

Table 5-1 Design Basis

Item		RPSEA Design Basis
General		
Production TTRs		Up to 12
Drilling Risers		1
Oil Production rate		100 kbpd
Gas Production rate		50 mmcfd
Max. total fluids processing rate		120 kbpd
Water produced rate		40 kbpd
Water injection rate		80 kbpd
Tie back		3 satellite wells (6 SCRs)
Required min deck area		95,741 ft2
Personnel quarters capacity		Total 200 man 1. Drilling: 100 2. Normal Operations: 60 3. Completions/ others: 40
Drilling rig (type/weight)		Dry-tree wells 10,000 st for drilling
Topsides Payload Budget		
Topside facility (dry) incl LQ/lifeboats/cranes		6,000 st (due to increased LQ)
Drilling rig	Dry	4,000 st
	Operating	7,000 st
Other drilling variable		3,000 st
Riser – General		
Water depth		8,000 ft
Wellbay layout		15 slots total - One dedicated 20'x20' slot for drilling - Production slots to be 16' x 16'
Seabed wellhead arrangement		35 ft spacing
Initial installed risers		1 Drilling TTR

	4 Production TTRs 1 Oil Export SCR 1 Gas export SCR
Max installed risers	12 Production TTRs 6 Production SCRs 3 Export SCRs 2 Water Injection SCRs 6 Umbilicals
Hydrodynamic coefficients	Cd = 1.6 (based on nominal diameter of riser casing) Ca = 2.0
Fatigue Design Life	20 yrs
SCR Location	Outside of pontoon
Drilling Riser	
Top tension	1,000 st
Min. top tension factor	To be designed based on no compression in TTRs
Production Riser	
Design pressure	Test = 9,000 psi Shut-in = 9,000 psi Gas kick = 9,000 psi Operating = 2,500 psi
Casing OD and material	13.813” outer casing 10.750” inner casing Yield = 125 ksi
Internal Tubing	OD x WT: 5.5” x 0.689” Yield = 110 ksi Weight = 35.4 lb/ft
Wall thickness	-12.5% / +0%
Corrosion allowance	0.125 in
VIV suppression	Add strakes for 50% of riser length
Min. Top tension factor	1.3 (at nominal position)
Service Life	20 yr
Fatigue SF	10 SCF = 1.3
Export SCR	
Oil export size	OD x WT = 18” x 1.1”
Oil export design pressure	2,500 psi
Oil export fluid data	7.16 ppg
Oil export top angle	14 deg
Oil export vertical payload	910 st
Oil export hang-off system	Stress or flex joint on porch
Gas export size	OD x WT = 18” x 1.1”
Gas export design pressure	2,500 psi
Gas export fluid data	2.31 ppg
Gas export top angle	14 deg
Gas export vertical payload	530 st
Gas export hang-off	Stress or flex joint on porch

system	
Production SCR	
Size	OD x WT = 8.625” x 0.812”
Max allowable operating pressure at surface	5000 psi
Vertical Payload	310 st
Umbilical	
Size and weight	6” (nominal) 120 st vertical load
Top angle	8 deg
Water Injection	
Size and weight	10.75” OD, 1” wall thickness 490st vertical load
Top angle	12deg
Hull and Mooring	
Freeboard	According to air gap reqs.
Max column height	Quayside integration
Max offset with mooring intact (100yr hurricane)	5% of water depth
Max offset with one mooring missing (100yr hurricane)	7% of water depth
Max combined pitch and roll with mooring intact and TTRs/SCRs installed	4 deg (operating/intact) 10 deg (100yr hurricane)
Min. air gap	+5ft for 100yr hurricane measured to bottom of deck structure; Positive for 1000yr hurricane measured to bottom of deck structure or design for wave slamming for localized area
Max horizontal acceleration (upper limit)	0.15g for operating/intact 0.35g for 100yr hurricane
Design Life for hull and mooring system	20yr
Mooring system	Chain-polyester-chain system Polyester rope stiffness: Static = 12 x MBL Dynamic = 28 x MBL (follow DNVGL Offshore Standards for VIM stiffness)
Mooring chain corrosion allowance	0.4mm/yr
Soil Data	
Submerged unit weight	25 lb/ft^3 at surface 40 lb/ft^3 at a depth of 50 ft 40 lb/ft^3 constant for remainder of profile
Undrained shear strength	30 lb/ft^2 at seafloor Linearly increasing with depth at a rate of 8 $lb/ft^2/ft$
Strain at 50% of max shear stress	0.020 for the top 40 ft 0.015 below40 ft

Metocean Criteria – API RP 2INT MET (Central Gulf of Mexico)	
1yr	API RP 2INT MET
100yr	API RP 2INT MET
1000yr	API RP 2INT MET
Fatigue	
Spectrum	JONSWAP
Gamma	1.0
Seastates / Distribution	*Reference Tables 3.2*
Standards and Codes	
Stability	• DNV-OS-C301 Coefficients based on USCG CFR, no wind tunnel test results
Mooring	• API RP 2SK • API RP 2SM
Risers	• API RP 2RD • OS-F201 (no compression allowed in TTRs)
Structure	• DNV-OS-C201
Systems	• DNV-OS-D101 • DNV-OS-D201 • DNV-OS-A101

Table 5-2 Environmental Data – Based on API 2INT-MET

Independent Extreme Values for Hurricane Winds, Waves Currents and Surge, Central Gulf of Mexico (89.5^0 W to 86.5^{0}W)

Return Period (Years)	10	25	50	100	200	1000	2000	10000
Wind (32.8 ft. Elevation)								
1-hour Mean Wind Speed (ft/s)	108.3	131.6	145.7	157.5	167.3	196.9	204.7	220.5
10-min Mean Wind Speed (ft/s)	119.8	147.3	164.4	178.8	191.0	228.0	237.9	258.2
1-min Mean Wind Speed (ft/s)	134.5	167.7	188.3	206.0	221.1	267.7	280.9	306.8
3-sec Gust (ft/s)	153.9	194.2	219.5	241.8	260.5	319.9	336.3	370.1
Waves, WD > = 3280 ft								
Significant Wave Height (ft)	32.8	43.6	48.6	51.8	54.1	65.0	67.3	72.5
Maximum Wave Height (ft)	58.1	77.1	85.6	91.5	95.5	114.5	119.1	128.3
Maximum Crest Elevation (ft)	38.7	51.5	57.1	61.0	63.7	75.5	78.1	84.0
Peak Spectral Period(s)	13.0	14.4	15.0	15.4	15.7	17.2	17.5	18.2
Period of Maximum Wave(s)	11.7	13.0	13.5	13.9	14.1	15.5	15.8	16.4
Currents, WD > = 492 ft								
Surface Speed (ft/s)	5.4	6.6	7.3	7.9	8.4	9.8	10.2	11.0
Speed at Mid-Profile (ft/s)	4.1	4.9	5.5	5.9	6.3	7.4	7.7	8.3
0-Speed Depth (ft)	227	273	306	331	351	413	430	463
Currents, WD 33 ft – 230 ft								
Uniform Speed at 33 ft Depth (ft/s)	3.6	5.3	6.5	7.5	8.5	10.6	11.5	13.3
Uniform Speed at 230 ft Depth (ft/s)	3.2	4.8	5.8	6.8	7.7	9.5	10.3	12.0
Water Level, WD > = 1640 ft	1.0	1.7	2.2	2.6	3.1	3.7	4.0	4.6
Storm Surge (ft)	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4
Tidal Amplitude (ft)								

Notes:

Wind speeds for a given return period are applicable to all water depths throughout the region.

Crest elevation includes associated surge and tide.

See Figures 4.5.3-1B, 4.5.3-2B, and 4.5.3B in API 2INT-MET for wave and crest elevation values for water depths between 33ft. and 3280 ft.

The peak spectral period and period of maximum wave apply to waves in all water depths.

Currents in water depths between 230 ft and 492 ft should be estimated as described in 4.3.3 in API 2INT-MET.

See Figure 4.5.3-4B for surge and tide in water depths less than 1640 ft.

Table 5-3 Fatigue Sea-states and Directional Probability:

Fatigue Bin	H_2 (ft)	T_P (s)	V_W (ft/s)	V_C (ft/s)	Probability of Occurrence
1	0.75	4.5	16	0.5	0.18038
2	2.5	5.5	20	0.65	0.39250
3	4.5	5.5	24	0.75	0.11887
4	4.5	7.5	24	0.75	0.12406
5	6.5	6.5	28	0.9	0.05908
6	6.5	8.5	28	0.9	0.05082
7	8.5	8.5	34	1.1	0.04211
8	11.0	9.5	38	1.3	0.02162
9	13.75	9.5	46	1.5	0.00518
10	17.5	11.5	56	1.8	0.00473
11	22.5	12.5	72	3.1	0.00068
12	27.5	12.5	88	3.8	0.00014
13	32.5	14.5	104	4.4	0.00003
14	37.5	14.5	116	5.2	0.00003

Wave Direction (deg.)	Probability of Occurrence
0	0.076
30	0.081
60	0.113
90	0.160
120	0.160
150	0.135
180	0.068
210	0.027
240	0.025
270	0.037
300	0.050
330	0.068

6 HOE PAIRED COLUMN DRY TREE SEMI (PC SEMI) CONCEPT

6.1 General

The HOE PC SEMI has two columns in each corner, which are connected by pontoons (Figure 6-1). The PC SEMI configuration is different from a conventional Deep Draft Semi (DD Semi) in three aspects:

1) 8 columns vs. 4 columns;
2) Rectangular column vs. Square column
3) Larger column slenderness ratio

Key dimensions of this concept are presented in Table 6-1. General configurations of the concept can be seen from Figures 6-2 and 6-3. Further details of the design concept can be found in HOE's "Conceptual Design Report", H12122-G-RPT-GN-15001 in *Appendix A-1*.

Table 6-1 Key Design Data for HOE PC Semi

Design Cases		**Maximum Riser Config. (1DR+11TTRs + 17 SCRs)**	**Minimum Riser Config. (1 DR+1 TTR +3 SCRs)**
Draft	(ft)	175.0	
Displacement	(kips)	220,056	
Water Depth	(ft)	8,000	
Number of Inner Columns		4	
Inner Column Height	(ft)	244.0	
Inner Column freeboard height	(ft)	69.0	
Inner Column Side Length	(ft)	34 x 46	
Inner Column c/c Span	(ft)	165	
Numbers of main pontoon		4	
Main Pontoon Width	(ft)	42.0	
Main Pontoon Height	(ft)	27.0	
Number of outer Columns		4	
Outer Column Height	(ft)	250.0	
Outer Column Side Length	(ft)	44 x 46	
Numbers of connecting pontoon		4	
Connecting pontoon Width	(ft)	46.0	
Connecting Pontoon Height	(ft)	27.0	
Distance between inner/outer columns (length of connecting pontoon)	(ft)	67.0	
Main deck dimension	(ft)	245' (EW)x217.5'(NS)	
Production deck dimension	(ft)	245' (EW)x217.5'(NS)	
Deck height (BOS to TOS)	(ft)	50.0	
Deck Post above Column	(ft)	6.0	
Deck Clearence (distance between TOS and MWL)	(ft)	75.0	

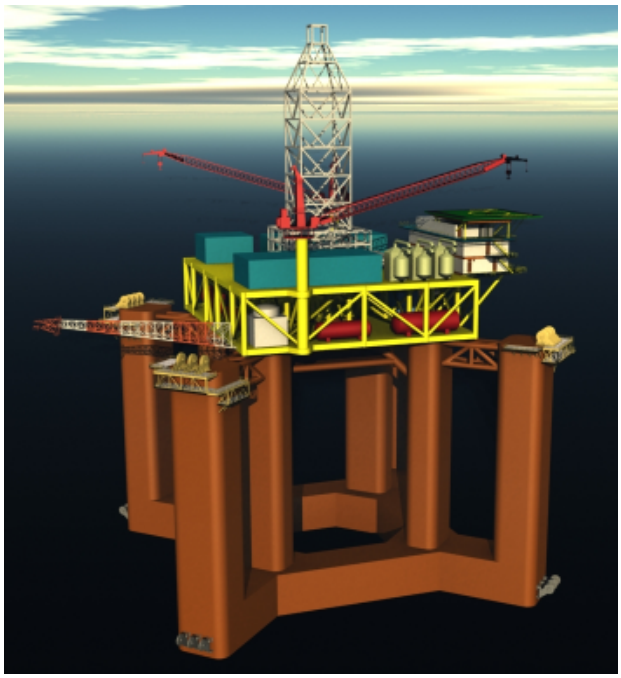

Figure 6-1 HOE PC Semi

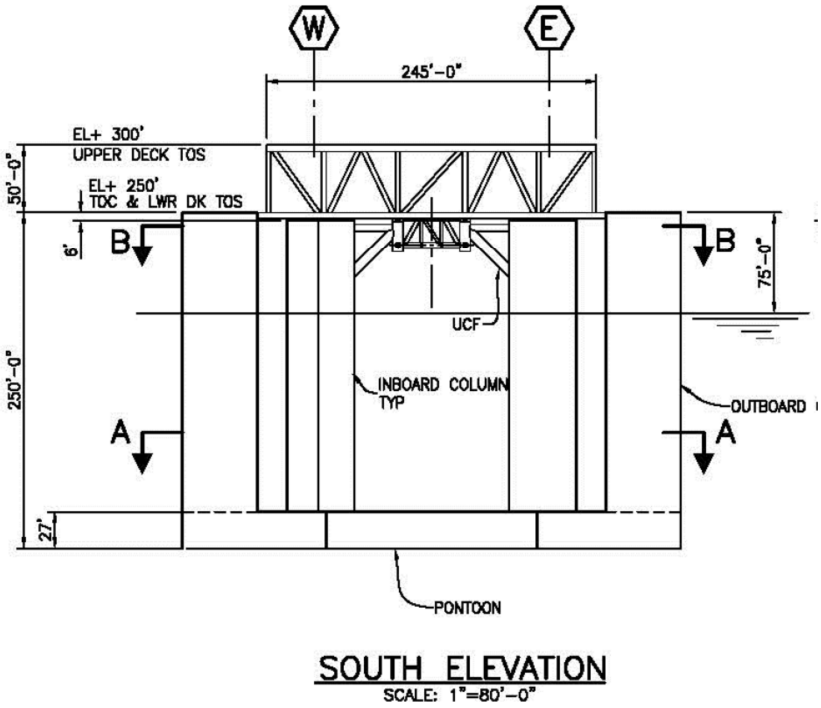

Figure 6-2 HOE PC Semi, Profile View

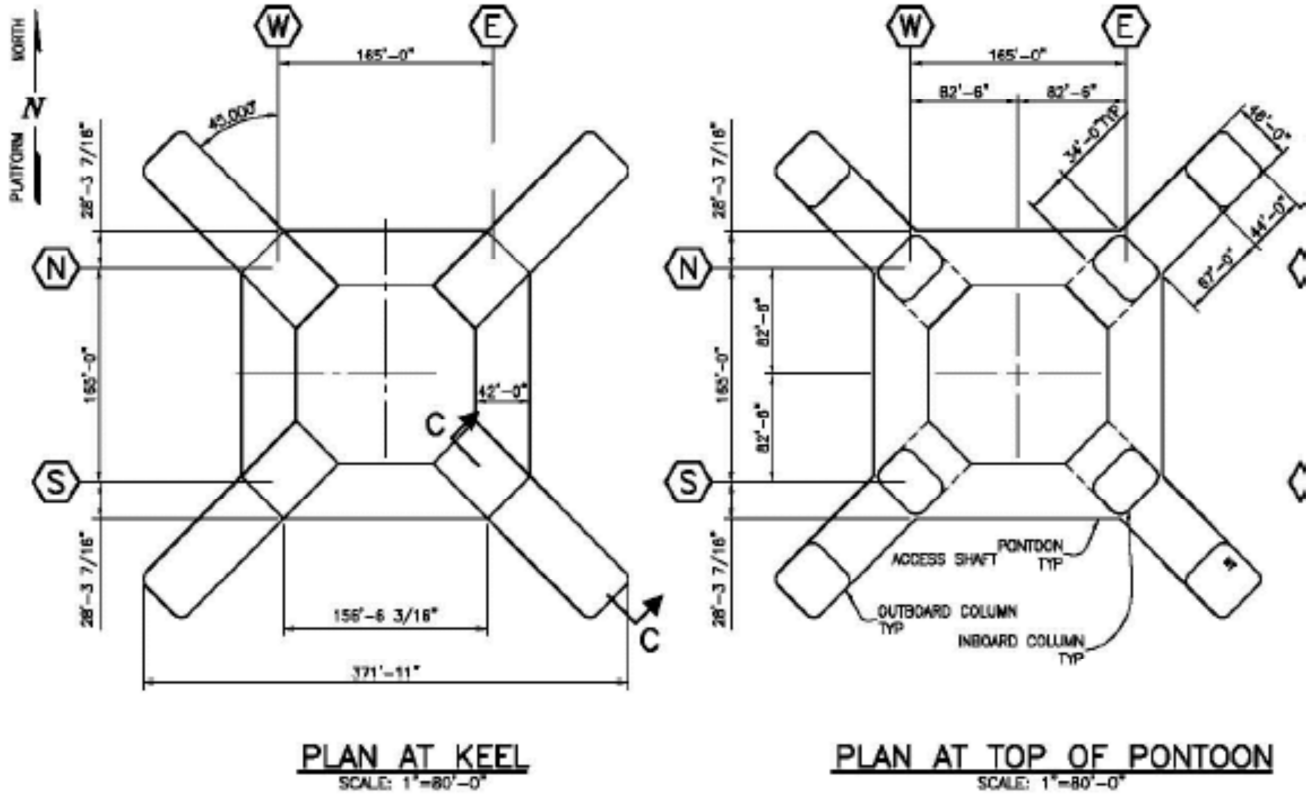

Figure 6-3 HOE PC Semi, Top View

The HOE concept has undergone some development under previous projects (e.g., RPSEA, 2011; DeepStar, 2011). The following have been defined as critical issues and are addressed in this project:

1. Vortex-Induced Motion: Vortex-induced motion (VIM) is motion of the floating platform that can occur when the floater is subjected to high currents such as the Loop Current. This concept has 8 columns (2 in each corner), as opposed to 4 columns in a conventional semi design. There is a concern that there could be significant VIM for this concept, which could affect riser and mooring design, etc. This should be checked by model test.

2. Qualification of Riser Tensioner Assembly: The dry tree semi has relatively higher tensioner strokes than TLPs and spars. The application of a push-up type RAM style tensioner should be qualified.

3. Feasibility of Quayside Integration and Transportation: One of the major advantages of a dry tree semi compared to a spar is its possibility to have quayside integration as opposed to offshore integration, which involves higher risks due to unprotected environment. Due to the deep draft of the HOE concept, the possibility of quayside integration and transportation has been a question mark. This should be further studied and verified in this project.

4. Approval in Principle: Complete further engineering work required to obtain an Approval in Principle (AiP) from DNV GL. This ensures that the concept is feasible and that there will be no major show-stoppers to materialize the project in GOM.

6.2 VIM Model Test

VIM Model test for the HOE PC Semi concept was conducted by MARIN as requested by HOE in June 2013 to study the following parameters:

- To measure the drag coefficients with and without VIM motions
- To measure A/D as a function of reduced velocities (Ur) and headings
- To measure yaw as a function of reduced velocities (Ur) and headings
- To investigate VIM response characteristics at different drafts
- To investigate separation distances between the inner and outer columns on VIM responses

The model test was witnessed by DNVGL as well as industry subject matter specialists.

Extensive analysis of the data was carried out and the conclusion in terms of the VIM design envelopes was extracted from the HOE report and presented in Figure 6-4 and Figure **6**-**5**, where D = 6.37 ft., which is the diagonal of the outer column. All test data including outliers were used to encompass the design curves. Further details can be found in the HOE report attached in *Appendix A-1*.

The VIM impact on the mooring lines was investigated in the analysis based on the curves derived in the model tests and mooring fatigue is found acceptable.

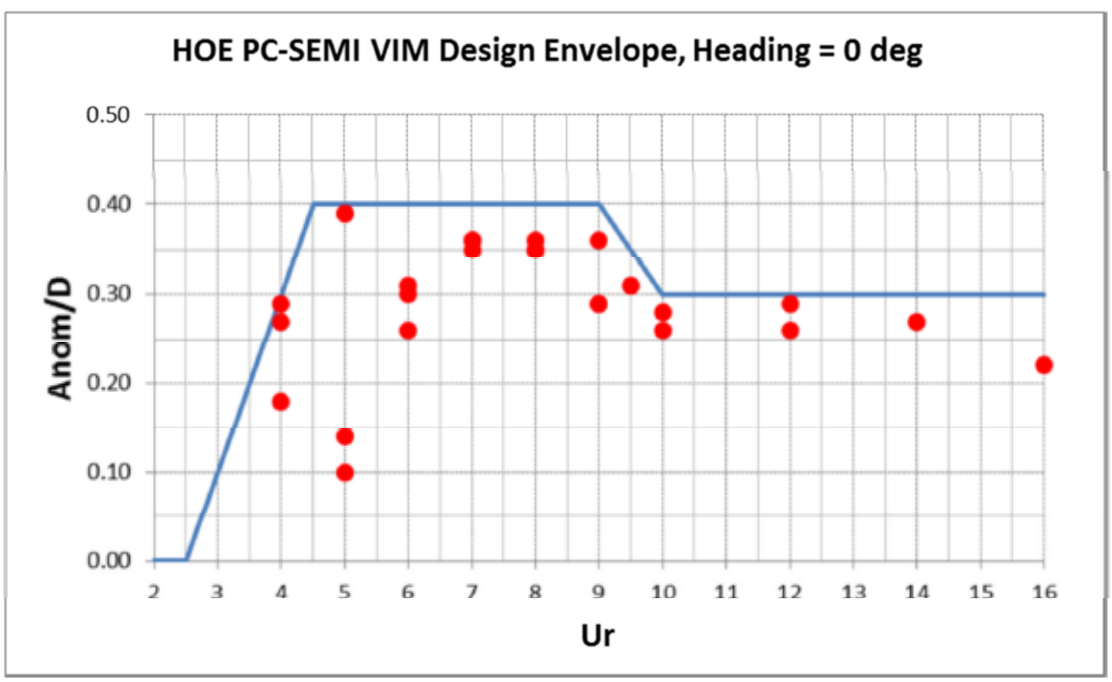

Figure 6-4 VIM Design Envelope for 0 degree Heading

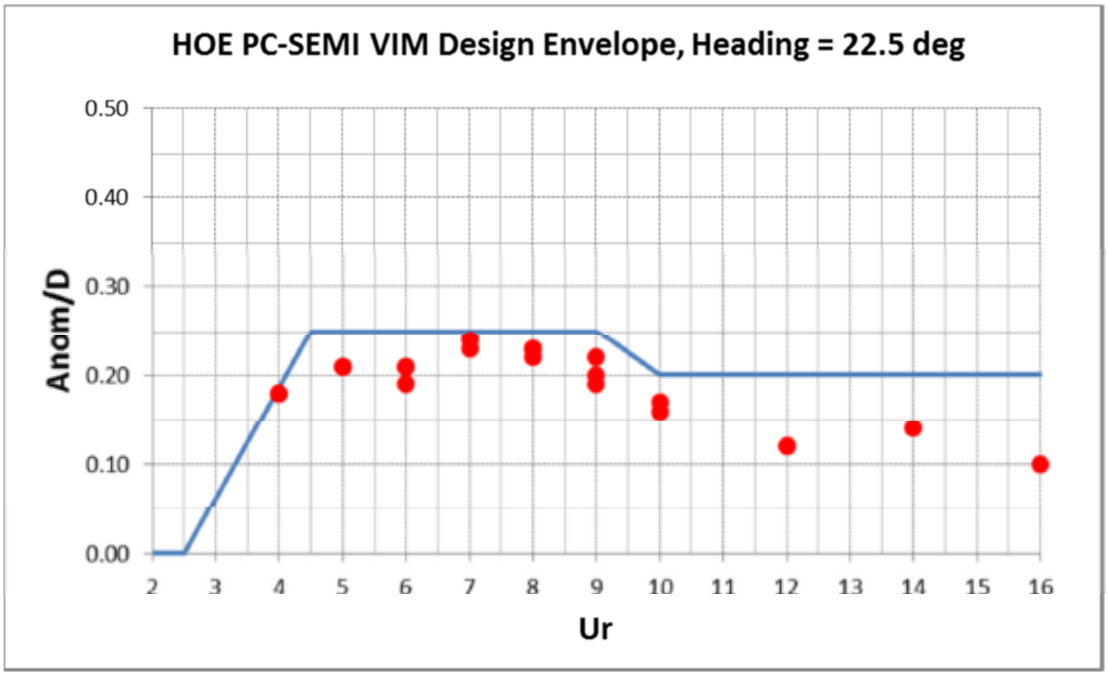

Figure 6-5 VIM Design Envelope for 22.5 degree Heading

6.3 Technology Qualification (TQ) of Riser Tensioner Assembly

For the HOE PC semi concept, the riser tensioner has a 28' stroke and is designed to take impact load due to top up or bottom out under survival and accidental conditions. The design has considered options with or without keel guide. The qualification of the riser tensioning system has gone through a Technology Qualification in accordance with DNV-RP-A203 (DNV GL, 2013) as described in Section 4.2. The qualification was carried out in three phases:

I. Qualification Basis and Technology Assessment

II. Threat Assessment and Qualification Plan

III. Qualification Execution and Performance Assessment.

In Phase I, DNV GL assisted in identifying the critical parameters and facilitated a workshop to identify elements of new technology and their criticality. In Phase II, DNV GL facilitated workshops for a Failure Mode Effect and Criticality Assessment (FMECA) to determine potential failure modes and mechanisms to form the basis for a threat register. No formal qualification plan was developed by HOE; instead HOE addressed the identified threats through documentation presented to DNV GL.

It is concluded that:

- The concept can be brought to comply with the specified functional requirements, and can thus be considered to be qualified for the intended purpose. Some components have not yet been fully specified. No testing was considered necessary, but it is assumed that a final design, manufacturing, and quality processes in accordance with applicable codes, standards and good engineering practice are acceptable and will be carried out.

Based on the following limitations:

- The tensioner intended to be used for the dry tree semi is supposed to be the same as the one applied on a Spar project of similar water depth, and has been in service since 2009. There are no major differences from the existing tensioner, except for the proposed application on a semisubmersible compared to the existing spar application. This difference in application was the focus of this TQ process.
- Detailed drawings have not been made available to DNV GL, which will be required for the final verification by DNV GL at later design stage.

Further details of the TQ can be found in *Appendix B-1*.

6.4 Feasibility of Quayside Integration

A constructability study was performed by HOE. The scope of work included the following constructability aspects:

- Hull Structure Fabrication
- Topside integration
- Dry Transportation

- Wet tow

Details can be found in HOE's Conceptual Design Report, Section 8.

DNV GL's Marine Operations Specialist conducted a document review of the above study. The intention is to confirm the feasibility of quayside integration and transportation of the integrated platform to the operation site in GOM. The feasibility is confirmed with some comments for further evaluation at a later design stage; details can be found in the Approval in Principal report for the HOE concept attached in Appendix C-1.

6.4.1 Topside Integration

The topside integration considers two options:

- Quayside integration
- Offshore integration

The feasibility of quayside lifting was confirmed conceptually using the geometry, hook height, capacity and reach of the Kiewit Offshore Services (KOS) Heavy Lifting Device (HLD) and the CIMC Raffles gantry crane. It is concluded that that quayside integration is feasible with the existing capability at KOS and will be feasible with the upgraded gantry crane planned for CIMC Raffles.

DNV GL has conducted a document review of the above study and agreed that the quayside integration is conceptually feasible but some details are not presented in the study report (e.g., assumptions on lift weights, heights, radii and clearance requirements compared with crane capacities for CIMC Raffles topside integration, extent of required gantry upgrade, etc.) and should be verified at later design stage.

6.4.2 Dry Transportation

The dry transportation study also included two options:

- Dry Transportation of the hull only
- Dry Transportation of the fully integrated platform

The feasibility of dry transportation of the hull only and of the fully integrated platform options were confirmed conceptually using the geometry of the PC-Semi hull, the geometry of an existing Dockwise dry transport vessel (Blue Marlin), hull-hull clearances and the capacity of the dry transport vessel.

DNV GL has conducted a document review of the above study and we agree that dry transportation of the fully integrated platform from South East Asia to the GOM is conceptually feasible. But due to the height of the fully integrated platform, the transport will not be able to pass through the Suez Canal (height limitation 68m) and will have to go around the Cape of Good Hope where the weather can be quite rough. However, this is not uncommon for offshore structures, but requires careful detail planning during the project phase.

6.4.3 Wet Tow

The wet tow study included the following options:

- Wet tow of the fully integrated platform in the channel
- Wet tow of the fully integrated hull in deep water

The feasibility of wet transportation of the fully integrated platform was confirmed conceptually using the geometry of PC-Semi hull, draft of the platform during wet tow and draft and width restriction of channels.

DNV GL has conducted a document review of the above study and agreed that wet tow of the fully integrated platform in the channel is feasible, but requires accuracy and careful preparation. The details can be worked out at a later design stage.

6.5 Engineering Design and Third Party Evaluation

Further engineering work and AiP were identified by previous projects as requirements to mature the HOE PC semi concept. HOE has conducted this engineering work and documented the design analyses. The updates on the design basis have also resulted in design configuration changes and a revision of some engineering work. The updated study is presented in the HOE Conceptual Design Report.

The third party evaluation by DNV GL follows the AiP process, which is described in Section 4.1.

The Approval in Principle breaks down the overall concept to various systems and disciplines, and then focus attention on critical elements where novelties are involved or where the design is affected by novelties. For the HOE PC semi these includes:

- Global motions
- Riser and riser tensioner design
- Mooring design
- Construction, transportation and installation
- Structural design
- SIMOP (Simultaneous operation of drilling and production)

Details of the AiP process, results and conclusion can be found in *Appendix C-1*.

7 KFD DEEPWATER DRY TREE SEMI CONCEPT

7.1 General

The Kvaerner Deepwater Dry Tree Semi (DWDTS) hull is built on a conventional deep water semi-submersible concept with four (4) corner columns and a ring pontoon (Figure 7-1). The hull size is 308 ft. by 308 ft. and the total height is 215 ft. The proposed draft is 145 ft. Freeboard is 70 ft. to the bottom of the deck box and 105 ft. to the top of the deck box from mean waterline. The mooring system of the DWDTS consists of 16 mooring lines clustered in four groups (4x4) with chain-polyester rope-chain segments for each line. The topside facilities are modularized and supported by a deck box structure with overall dimensions 254 ft. long (EW), 354 ft. wide (SN), and 35 ft. deep. The process module is on the north side of the deck and the living quarter is on the south end. The well-bay is arranged in the center of the deck to accommodate production and drilling systems.

Key dimensions are presented in Table 7-1. General configurations of the concept can be seen from the Figures 7-2 and 7-3. Further details of the design concept can be found in KFD's "Dry Tree Semi Conceptual Design Report", Doc. No. KFD-RP-ZZZ-0001 in *Appendix A-2*.

Figure 7-1 Kvaerner Deepwater Dry Tree Semi

Table 7-1 Key Design Data for Kvaerner Deepwater Dry Tree Semi

DWDTS Hull and Mooring Configuration		
Hull Dimensions		
	Water depth (ft)	**8,000**
	Draft (ft)	**145**
	Main column c-c distance (ft)	**236**
	Main column width (ft)	**72**
	Column height (ft)	**215**
	Pontoon height (ft)	**35**
	Pontoon width (ft)	**67**
Load Balance		
	Topside weight (st)	**34,600**
	Hull weight (with fluid) (st)	**46,404**
	Riser loads (st)	**17,740**
	Mooring loads (st)	**4,137**
	Ballast water (st)	**40,906**
	Total platform displacement (st)	**143,787**
Mooring		
	Number of mooring lines	**16**
	Chain size/diameter (in)	**6.0**
	Polyester rope size/diameter (in)	**10.75**

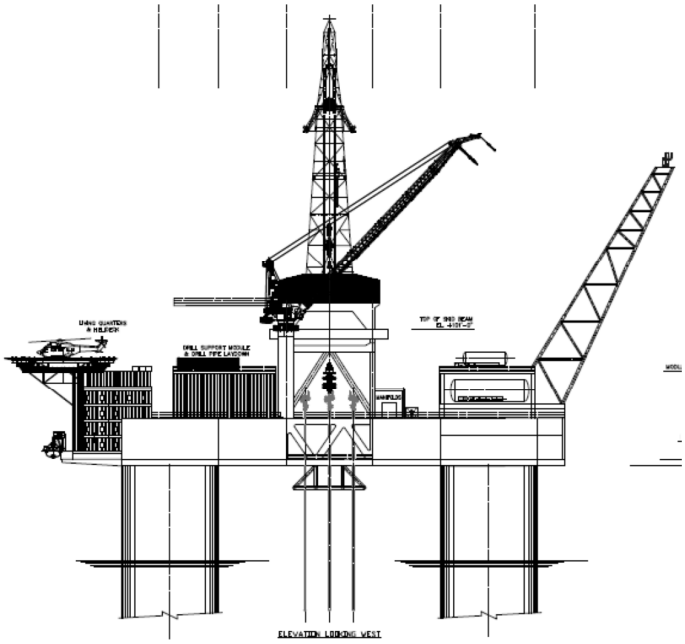

Figure 7-2 Kvaerner DWDTS, Profile View

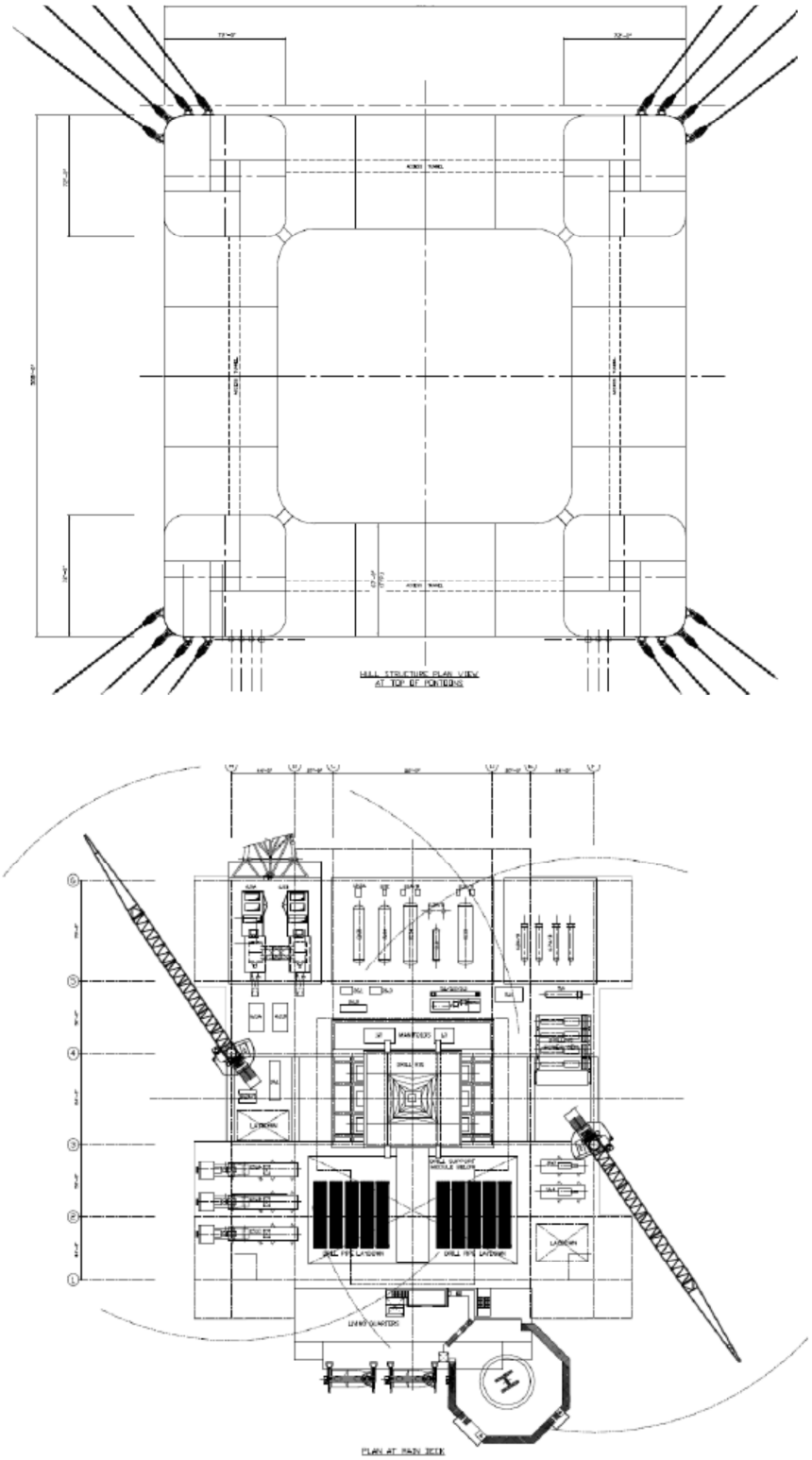

Figure 7-3 General Arrangement

The DWDTS concept has undergone some development under previous projects (e.g. DeepStar projects), the following has been identified as the critical issues based on this development and defined as the main scope to be addressed in this project:

1. Conceptual Design: Further engineering with appropriate documentation of the conceptual design, including hull global design, air-gap, stability, mooring, and riser configuration.
2. Riser Interfaces with Topsides and Hull: Further enhancement of structural design of riser interfaces with topside and hull structures. The riser tensioner is designed to bottom out/top up under 1000-year hurricane. The high impact load on the supporting structure should be carefully accounted for in design.
3. Qualification of Riser Tensioning System: The proposed riser tensioning system uses a push up type RAM style tensioner, which is similar to what has been used on a spar or a TLP, but the tensioner strokes calculated for this dry tree semi are higher than typical for spars or TLPs. Such application should be carefully qualified, which includes:
    a. Analyze structural integrity and stability of riser tensioning system
    b. Perform a scaled model test of riser tensioner
    c. Conduct a technical qualification of the riser tensioner system
4. Vortex-Induced Motion: Perform a scaled model test of hull vortex-induced-motion (VIM)
5. Approval-in-Principal: Pursue an Approval-in-Principle (AiP) by DNV GL.

7.2 Engineering Design

Further engineering work was identified by previous projects as requirements to mature the KFD DWDTS concept. KFD has conducted further concept design work and documented the design analyses. The updates on design basis have also resulted in design configuration changes and revision of some engineering work. The updated study is presented in the KFD's "Dry Tree Semi Conceptual Design Report" in *Appendix A-2*. The engineering work covers riser tensioning system, global performance, mooring system design, top tension risers design, structural design, constructability, and model tests.

The design analysis has focused on global motions, air-gap evaluation, and mooring and riser design analysis. Due to the criticality of these design aspects, DNV GL has also conducted limited independent analysis on air-gap calculation and top tension riser analysis for the governing load case. DNV GL has arrived at similar results as the Designer and has requested KFD to perform additional analysis on the risers to address compressive loads. This is not considered to be a barrier to the feasibility of the concept but needs to be carefully addressed in the next design phase. For further details, refer to the Approval-in-Principal report attached in *Appendix C-3*.

7.3 Further Enhancement of Structural Design

KFD has conducted a global structural analysis as well as local rule scantling check. DNV GL has conducted limited independent analysis on local rule scantling check. The preliminary check concluded that the proposed scantlings should have no problem complying with DNV-OS-C201 in terms of global structural integrity and local rule scantlings with some details to be further developed in the next design phase. Details can be found in Section 8 of the KFD's Dry Tree Semi Conceptual Design Report in *Appendix C-3*.

7.4 Technology Qualification (TQ) of Riser Tensioner System

The top tension riser tensioner stroke for this dry tree semi concept is calculated to be 35' under 1000-year hurricane. The riser tensioning system is designed to bottom out or top up under 1000-year hurricane. Because the tensioner stroke is higher than those for spars and TLP's in operation, the riser tensioning system is considered to be one of the critical elements for this design. A full technology qualification is conducted for the riser tensioning system in accordance with DNV-RP-A203.

7.4.1 Introduction of Riser Tensioning System

Each of the top tensioned risers on the proposed DWDTS is supported by a RAM style tensioning system designed by MHD Offshore Group, which consists of cylinders, high pressure and low pressure APV's, a support frame, spool joint centralizers and a control panel (Figures 7-4 and 7-5).

Each RAM style riser tensioner system is an assembly of multiple components: 6 RAM tensioner cylinders with 35' stroke length; 18 high pressure accumulators with 3,000 psi MAWP; 6 low pressure accumulators; 1 riser spool joint sleeve; 4 upper centralizers and 4 lower centralizers; 1 tensioner support cassette; 1 load transfer ring; 1 control panel; and 1 lower centralizer cassette.

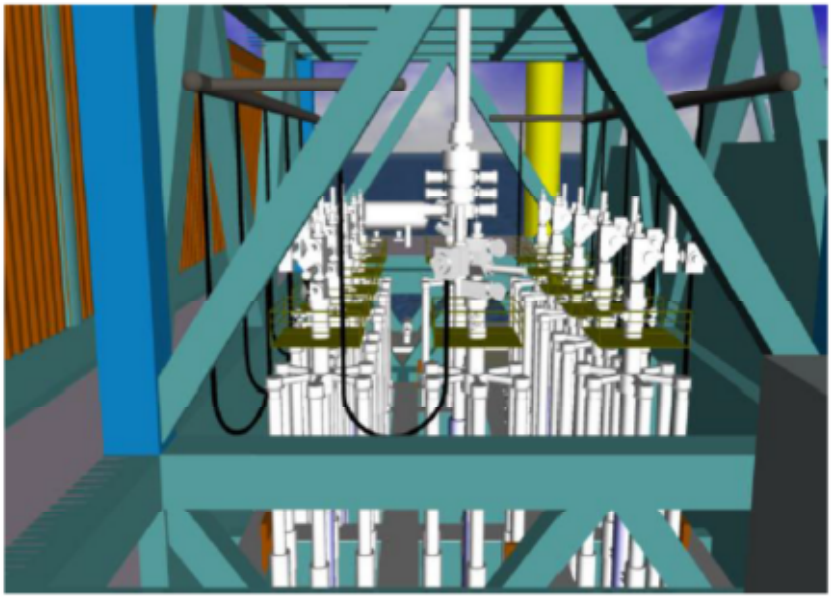

Figure 7-4 Riser Tensioner Overview

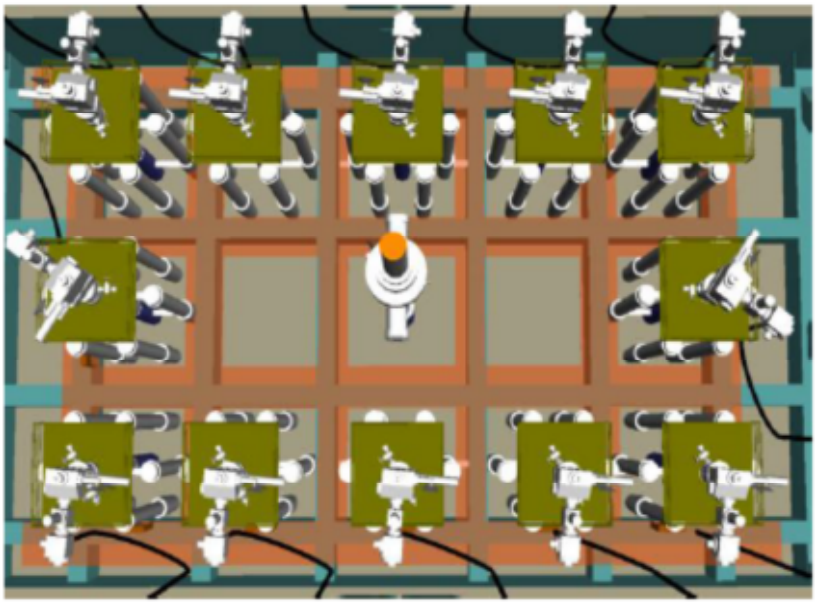

Figure 7-5 Arrangement of Riser Tensioners in Wellbay

7.4.2 Technology Qualification

The Technology Qualification (TQ) process is defined in DNV Recommended Practice, DNV-RP-A203 and described in Section 4.2 of this report.

For this concept, the qualification was carried out in three phases:

I. Qualification Basis and Technology Assessment

II. Threat Assessment and Qualification Plan

III. Qualification Execution and Performance Assessment.

In Phase I, DNV GL has assisted in identifying the critical parameters and to facilitate a workshop to identify elements of new technology and their criticality. In Phase II, DNV GL has facilitated workshops for a Failure Mode Effect and Criticality Assessment (FMECA) to determine potential failure modes and mechanisms to form the basis for a threat register and for the development of the Qualification Plan. In Phase III, DNV GL has verified Client's activities according to the Qualification Plan.

Based on the KFD report on the Qualification Plan and execution, it is concluded that:

The RAM-style tensioner concept as presented by KFD can be brought to comply with the specified functional requirements, and can thus be considered to be qualified for the intended purpose.

Within the following limitations:

- Detailed drawings have not been made available to DNVGL and will be required for final verification at later design stage. Some components have not yet been fully specified, but can be sourced. It is

assumed that a final design in accordance with applicable codes, standards and good engineering practice will be carried out and subjected to final verification.

7.4.3 Model Test

As part of the qualification execution, a 1/5 scale model test of the tensioner system was carried out under KFD's supervision June 4 - 6, 2013 at Maritime Hydraulic, Moncton, Canada. The test was witnessed by DNV GL as well as industry specialists. During the test, the riser tensioner system was supported by a test stand in accordance with the DWDTS well-bay design (see figure).

The model test program covers various loading conditions, including operating, extreme, and survival conditions. Damage condition with two (2) cylinders offline were also tested under both 10-year Winter Storm operating condition and 100-year Hurricane extreme condition. Procedures of removal and re-installation of a failure cylinder were also tested under 10-year Winter Storm operating condition.

The proposed long stroke riser tensioner is able to perform the required functions at normal, extreme, and survival conditions. No abnormal behavior was observed during the model test for both inside or outside the tensioner stroke limits.

At survival conditions (1000-year hurricane), the tensioner was tested extensively with bottom-out and top-up (i.e. exceeding the tensioner stroke limits) situations, and it withstood the severe loads without damaging the riser tensioner components and supporting structures, as well as impairing tensioner functions.

At a cylinder damaged condition, it is possible to remove and re-install a cylinder, but will require a properly designed material handling system.

Further details of the riser tensioner test can be found in Section 10.3 of KFD's dry tree semi conceptual design report in *Appendix A-2*.

7.5 VIM Model Test

The hull Vortex Induced Motion (VIM) model test was performed in FORCE Technology's towing tank in Denmark as requested by KFD; using a scale of 1:60 for the DWDTS platform. The purpose of the tests was to investigate VIM characteristics and quantify VIM response amplitude at loop current conditions.

The VIM tests were performed at multiple headings and tow speeds. The base case includes 45 tow tests for five (5) headings (0, 11.25, 22.5, 33.75 and 45 degree) at nine (9) reduced velocities. Sensitivity cases were also performed to investigate strake effects on suppression of VIM.

The following results have been extracted from the VIM Model test report; details can be found in the Kvaerner report attached in Appendix A-2. The model test results showed the max VIM A/D response, defined as 1.41 x Standard deviation of transverse response, occurs at 22.5 degree current heading. The value of max A/D is approximately 0.52. The correlated VIM response design curves used for the DWDTS VIM assessment are presented in Figure 7-6. The VIM impact on the mooring lines was investigated by KFD

in the analysis based on the curves derived in the model tests. DNVGL agrees that the mooring fatigue capacity is found acceptable.

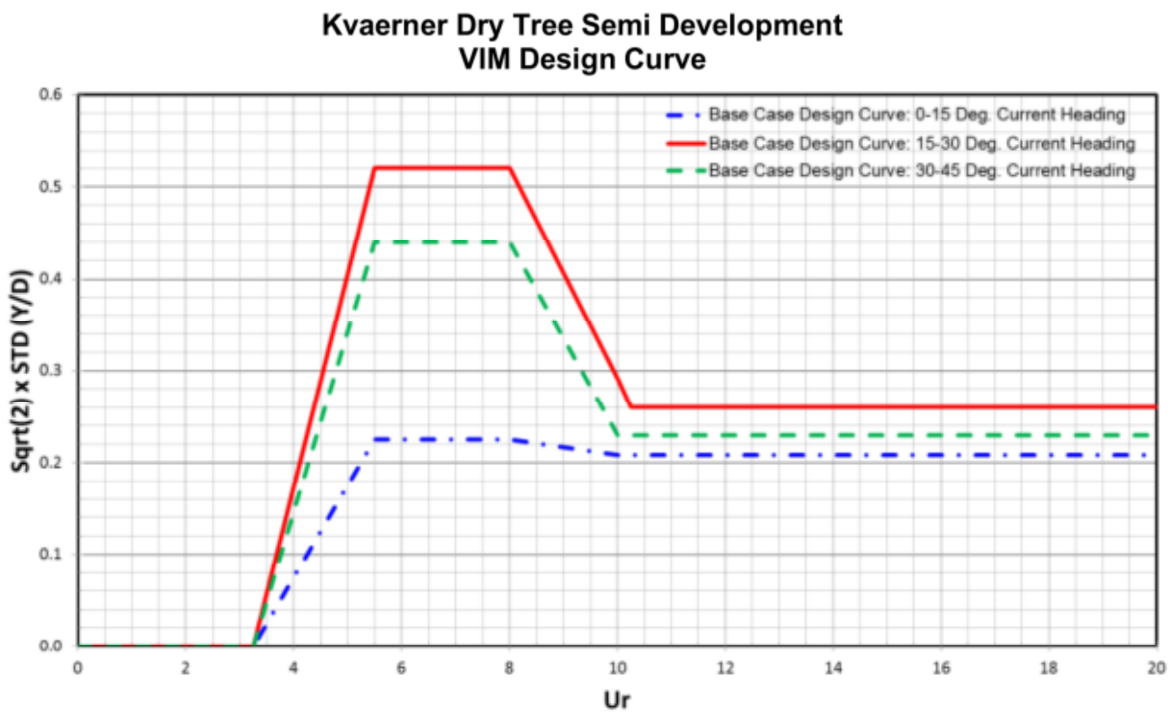

Figure 7-6 VIM Response Design Curve for KFD Concept

7.6 Approval in Principle (AiP)

The Approval in Principal process is the same as what has been applied to the HOE PC semi concept and has been fully described in Section 4.1 of this report.

The Approval in Principle is to systematically break down the overall concept to various systems and disciplines and then focus attention on critical elements where novelties are involved or affected by novelties in the design. For the Kvaerner DWDTS concept, these include:

- Global Motions
- Riser and Riser Tensioner Design
- Mooring Design
- Structural Design
- SIMOP (Simultaneous operation of drilling and production)

Details of AiP process, results, conclusion, and action items for the way forward can be found in *Appendix C-3.*

8 CONCEPT EVALUATION AND INDUSTRY PARTICIPATION

This project actively engaged subject matter specialists to evaluate the concepts starting from establishing the design basis, to model tests and Conceptual HAZID workshops. A WPG (working project group) was established in the very beginning of the project engaging subject matter specialists from Chevron, ConocoPhillips, Statoil, TOTAL, Marathon Oil and RPSEA. WPG meetings were held on regular basis (every 1-2 months) until the final workshop was conducted.

The project participants (DNV GL, HOE, and KFD) also published several papers and held presentations at OTC Houston, OTC Brazil and RPSEA conferences. A list of OTC papers is presented as follows:

- OTC 23919-MS, "Deepwater Dry Tree Semi Technology Readiness-Perspectives of Operator and Classification Society", 2013
- OTC 23926-MS, "An Evaluation of Strength, Fatigue and Operational Performance of Dry Tree Semisubmersible Riser Tesioning Equipment", 2013
- OTC 2391-MS, "A Project Oriented and Technology Robust Dry Tree Semi Concept", 2013
- 13OTCB-P-556-OTC, "Dry Tree Solutions for Ultra-Deepwater in Offshore Brazil", 2013

The objective of such industry participation and publication was to seek advice and feedback from the subject matter specialists and end users to ensure that the concept development is in line with industry practice and meets the requirements of a safe operation in GOM.

9 CONCLUSIONS

Based on all the studies, tests, qualifications, and evaluations, it may be concluded that both dry tree semi concepts (i.e. HOE PC Semi concept and Kvaerner Deepwater dry tree semi) are conceptually feasible and can be regarded as 'project ready' provided all comments and suggested actions in this report are properly addressed in the next project phase.

10 REFERENCES

1. DNV GL (2013), "Qualification Procedures for New Technology," DNV-RP-A203.
2. HOE (2011), "Ultra Deepwater Dry Tree System for Drilling and Production – Stage 2 Summary Report," HOE Report No. H08130-G-RPT-GN-15003 prepared for RPSEA 1402 project.
3. Lee, M.-Y., J. Zheng and P. Poll (2014), "The State of Dry-Tree Semi-Submersible Platforms for Deepwater Gulf of Mexico," OMAE2014-23236.
4. Steensen, Anders J. (2014), "DEMO 2000, a key for technological development and industrial success," Presentation made April 24, 2014.

Appendix A-1 HOE Conceptual Design Report

Appendix A-2 KFD Conceptual Design Report

Appendix B-1 Technology Qualification Report for HOE Tensioning System

Appendix B-2 Technology Qualification Report for KFD Tensioning System

Appendix C-1 Approval-in-Principal Report for HOE Concept

Appendix C-2 Approval-in-Principal Statement for HOE Concept

Appendix C-3 Approval-in-Principal Report for KFD Concept

Appendix C-4 Approval-in-Principal Statement for KFD Concept

About DNV GL

Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16,000 professionals are dedicated to helping our customers make the world safer, smarter and greener.